Fault Location System for Radial MV Underground Distribution Cable Networks

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***Abstract*—This paper presents a new fault localization system that utilizes the relays in the distribution cable networks that are equipped with the cable fault detection function. The cable fault is characterized with a short pulse and is self-clearing, therefore it is difficult to pinpoint the fault location. When a cable fault occurs on the networks, there could be a few relays to recognize the fault, but extra effort based on the network topology may be required to determine the faulty branch. The proposed fault localization system is comprised of three tiers, from bottom up, local, neighborhood and central. The proposed system assumes all the relays communicate through the Generic Object Oriented Substation Events (GOOSE) messages to its master processing unit which can be a protection relay or a separate industrial computer in its highest hierarchy in a tier. The proposed fault location system does not require adding any extra device or modifying any existing topology, and it only needs the necessary logic to the master processing unit. The system can be easily implemented or added onto the existing protection system that is able to receive the GOOSE message and is allowed to expand through some user programmable approach. The system communications among the components involved use the IEC61850 GOOSE Protocol, and it is easily scaled up or down depending on the application needs. The system, in particular, is suitable for the Medium Voltage (MV) power distribution networks in petrochemical, pharmaceutical, university, hospital, airport, data center, and other large manufacturing compounds.**

***Index Terms*—Fault Localization, GOOSE, Power Distribution Networks, Cable Fault Detection (CFD), Incipient Fault.**

I. Introduction

The underground cable network is the most popular MV power distribution set up for industrial compounds such as petrochemical, pharmaceutical, university, hospital, airport, data center, and other manufacturing facilities. The cables are usually laid in some type of conduit, metal or concrete, and in some cases, they are buried directly into the ground. The underground cable system is usually very reliable, but the fault does occur due to its insulation breakdown. The cause of a cable fault is primarily due to aging and thermal stress on its insulation layer. The most common form of a cable fault is due to cracks that develop in the insulation layer, which exposes the inner conductor to some foreign objects and forms a conducting bridge to the grounding layer. Initially the crack would be very small, allowing any foreign object such as small metal debris or water droplets to enter. Once the foreign object is burned out, the conducting path disappears, and the system returns to its normal state. If, for instance, the broken cable is exposed to more water, this type of self-clearing fault could be repeated until the foreign objects are completely gone or a sustained solid ground fault develops. The cable incipient fault is so unique, and it could last only a fraction of a cycle with relatively high magnitude, thus rendering the full cycle based Discrete Fourier Transform (DFT) method useless for this purpose. There have been some methods such as travelling wave, wavelet, transient signal analysis, short-window DFT [1-6] reported in the literatures dedicated to cable incipient fault detection. The short-window DFT method has been proven effective in the field and is the easiest to implement. All of the methods focus on fault detection but not exact location. When an incipient fault occurs on the network, all of the relays on its upper stream that are equipped with the CFD function could detect the fault, then extra effort based on the network topology is needed to determine which section the fault is located. This paper assumes the short-window DFT based cable fault detection method is used and that all of the relays installed in the networks are equipped with this function. The focus of this paper will be on the fault localization or faulty branch identification.

The power distribution networks for large industrial compounds are usually designed with a radial structure and backup sources. If one section is faulty, the network can be reconfigured to isolate the faulty section and connect the backup sources to the loads. Therefore, for such power distribution networks, it is more important to first identify the faulty section and then find the exact fault location.

With the advent of the IEC 61850 based GOOSE communication, it becomes possible to build simpler and more cost-effective fault localization system. In this paper, the GOOSE-based fault localization system with the distributed CFD functions on radial MV distribution networks will be presented.

II. Typical MV Power Distribution Networks

Fig. 1 shows two typical MV network arrangements with the left depicting the Main-Tie-Main arrangement and the right depicting the Main-Main arrangement.

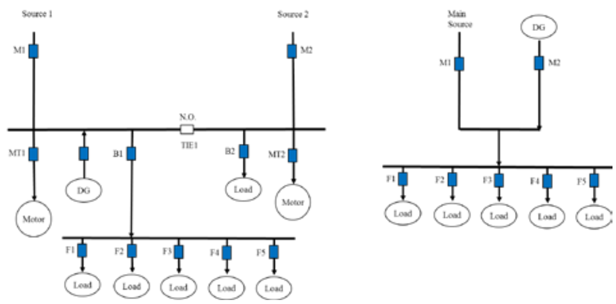

Fig. 1 Typical MV distribution networks

For the Main-Tie-Main arrangement, depending on the operation philosophy of an individual company, there can be many operation styles such as:

a) open transfer in which two sources cannot be paralleled at any time. Normally the tie breaker is open and will be closed only when one of the sources is lost. And when the lost source becomes available, the tie breaker will be opened first and then the lost main breaker will be closed after;

b) close transfer in which two sources are allowed to be paralleled for a short time. The tie breaker is normally open and will be closed after one of the sources is lost; and when the lost source becomes available, the lost main breaker will be closed first and the tie breaker will be opened after.

In each style, there can be further categorization of fast transfer and slow transfer.

Similarly, for the Main-Main arrangement, depending on the operation philosophy of an individual company, there can also be open or close transfers. Regardless of which operation style is being used, normally only one source serves the load, and the other serves as backup. For the open transfer, the backup source is only switched in when the main source is lost and disconnected from the load; when the main source becomes available again, the backup source will be disconnected first, and the main source will then be switched back in. For the close transfer, similarly, the backup source is only switched in when the main source is lost and disconnected from the load; when the main becomes available again, the main source will be switched back in first, and the backup source will be disconnected later. Again, in each operation style of the Main-Main transfer, there can also be further categorization of fast transfer and slow transfer.

Also note that from Fig 1 on the main sources, tie and major loads, breakers are usually used; however, further downward to less important loads, fuses may be used. It is a common practice that at least current measurement is usually accompanied with the breaker installation, and voltage measurement may be available on the main sources and each bus. On the fuse installations, usually neither current nor voltage would be available. With the advent of the non-conventional Voltage Transformer/Current Transformer (VT/CT) and distributed sensor technologies, it becomes economically feasible to have accurate voltage and current measurements on those fuse installations. The benefits of installing voltage and current sensors are not just for normal monitoring and control, but also for fast fault localization and restoration.

III. BRIEF INTRODUCTION OF CFD FUNCTION

The CFD function is an overcurrent function based on the short-window DFT to distinguish between a solid fault and a self-clearing fault. The cable fault (also referred to as the incipient fault) is characterized by three basic attributes: fault current magnitude, fault duration, and self-clearing. The cable fault current can be from a small fraction of a cycle pulse to a few cycles, so its waveform may not always be of sinusoid. Therefore, a non-conventional way such as the short-window DFT is utilized to evaluate its magnitude. The function pickup threshold can be fixed or adaptive to load. The adaptive threshold can make the function detect a fault more sensitively. Separate thresholds of the function for phase and ground can be also used in the high impedance grounding system. The self-clearing fault is defined as the fault in a specified duration the fault current exceeds its pickup threshold first but drops within the specified duration and no trip has occurred. The function is able to detect as short as a quarter cycle pulse. It has been used in the field for several years and proved to be effective in detecting cable fault.

The following three figures show the field collected cable fault current waveforms.

The first case in Fig. 2 shows the fault occurring on phase C and lasting less than a half cycle in a solidly grounded system. Therefore, the neutral current has the same amount of current as phase C. The CFD function can successfully detect such a short pulse.

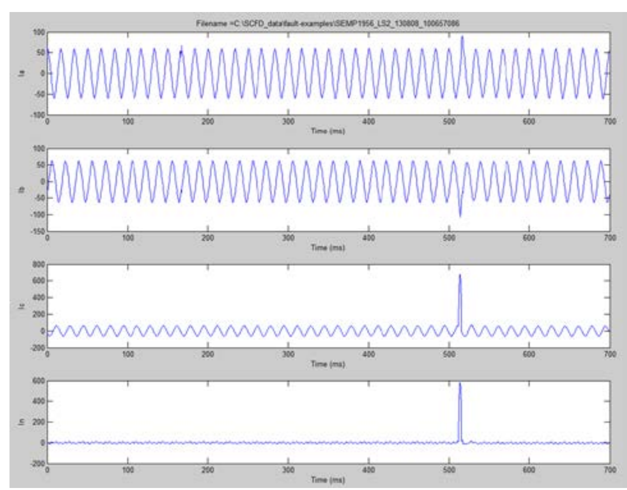

Fig. 2 Cable fault case 1

The second case in Fig. 3 shows the fault occurring on phase B and lasting about a cycle with the neutral channel not being recorded. The function can easily detect the fault in this case.

The third case in Fig. 4 shows a similar case as the second case but with a longer fault duration. In this case, if the instantaneous overcurrent function is enabled, it could pick up and trip this fault. However, if the other overcurrent functions are not able to pick up and trip this fault before the fault disappears, the CFD will still be able to identify this fault as a self-clearing fault.

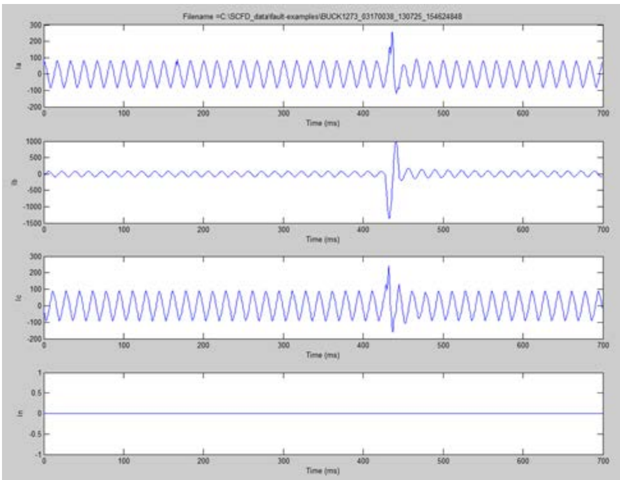

Fig. 3 Cable fault case 2

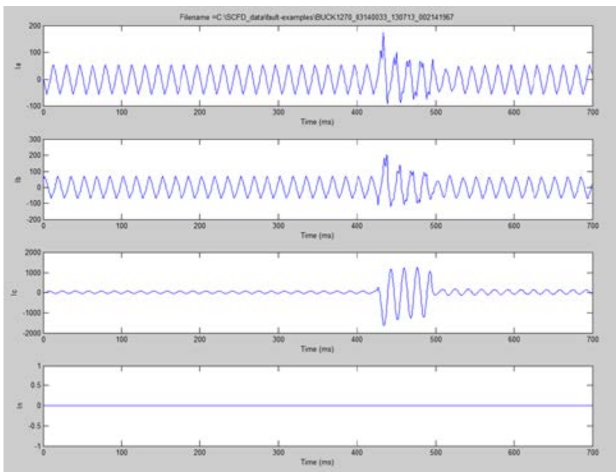

Fig. 4 Cable fault case 3

The CFD function described here can detect a cable fault occurrence, but it cannot automatically detect where the fault occurred. If a fault occurs downstream of the radial hierarchy system, multiple relays upstream could also detect the same fault. To determine the faulty branch or location, further manual operations will be needed, which would be very time-consuming. In the following section, we will explore the digital advantages that the modern relay and communication infrastructure can offer. We try to use the existing resources in the relays and Ethernet communication network among the power cable network to identify the fault branch.

IV. PROPOSED FAULT LOCALIZATION SYSTEM

The modern digital multi-function feeder relays offer a lot of standard functions ranging from metering, monitoring, protection and control, and also comprehensive user configurable logic gates, timers, and counters. For the proposed fault location system, we will use the CFD function for cable fault detection, and we will use the user configurable logic to implement the fault location logic. The communication among relays is assumed to be based on the Ethernet communication network with the IEC 61850 GOOSE protocol.

A. Sensor placement

Placing the voltage and current sensors under the constraints such as observability and cost can be challenging. According to the Kirchhoff's law, it is not necessary to place sensors on all branches that connect to the same node. Without considering redundancy, among B1and F1 to F6, as long as there are four placements, the network is totally observable (refer to Fig. 5 below). However, it may not work well for the purpose of fault localization. For example, if the sensors are placed on branches F4 and F6, branch F5 current can be known. In this case, if a fault occurs on branch F6, it can be uniquely identified; if a fault occurs on branch F5, because no sensor is placed on this branch, branch F4 will be identified. For the sake of fault localization, it is better to place the sensors on all of the concerned branches.

For a large network, processing all of the sensor information at a central computer can be a daunting and time-consuming task. The purpose here is to locate the faulty section as soon as possible. To achieve this goal, the strategy of processing the sensor information is based on the bottom-up hierarchy in three tiers: local, neighborhood, and central. The local tier covers a radial branch tree that consists of the branches that are the closest to loads. The neighborhood tier may contain multiple local tiers, and its processing unit will be a high-end relay or a dedicated computer, which can also directly take the information from relays or sensors. The central tier is at the highest level, and it may contain multiple neighborhood tiers. Its processing unit will be a SCADA workstation.

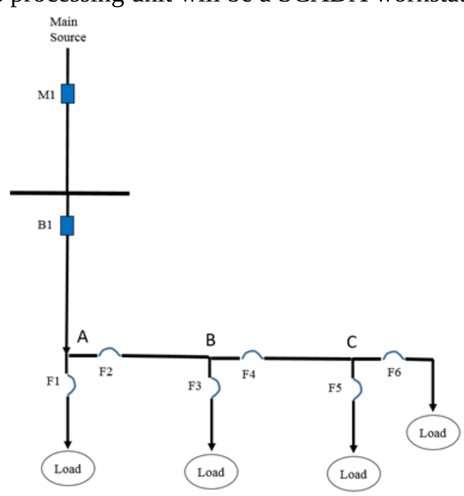

Fig. 5 Sensor placement

B. Local Tier

In the local tier, at least the uppermost branch has a relay that has full programmable capability to process the fault information from downstream. As an example in Fig. 6, the branch B1 and sub-branches underneath can constitute a local tier where a relay is installed on branch B1. In this case, the relay on branch B1 serves as a master processing unit to process the information fed from all of the relays underneath. All communications between the relays are based on the IEC 61850 GOOSE protocol.

Note that in Fig. 6, while some relays use the conventional VT/CT and others use the non-conventional VT/CT, it does not have to be that way. The relay can take either type of VT/CT.

When a fault occurs on branch F5, branches B1 and F5 will report the fault. Since F5 is the lowest in the hierarchy, the fault will be on branch F5. When a fault occurs on branch F2, branches B1and F2 will report the fault. Since F2 is lower in the hierarchy, the fault will be on branch F2 since no other branch recognizes the fault. The basic fault localization logic can be constructed as below:

Fault is on branch B1 if and only if the relay on branch B1 reports the fault; fault is on branch Fx if and only if B1 and Fx report the fault; fault would be on multiple branches if and only if B1 and other branches underneath report the fault.

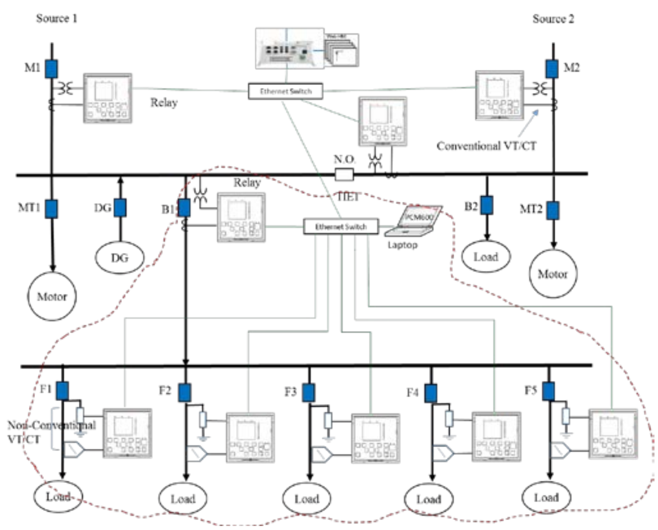

Fig. 6 Local fault localization system

The local tier can be theoretically expressed as a tree such as shown in Fig. 7. Since B1 is the root, any fault inside this tree should be reported by the relay on B1. Starting from the root, the faulty branch can be identified by using the binary search technique. The fault should be on the branch that has a fault indication and on the lower hierarchy.

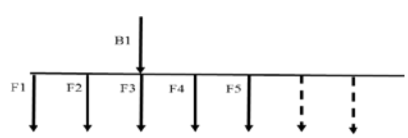

Fig 7 Tree representation of a local tier

All of the relays should work reliably but like any other electronic devices, they cannot be guaranteed to work all of the time. In a hypothetical scenario, the described logic above may not work well if some relays or sensor processing units fail to work when a fault occurs in the network. For example, when a fault occurs on branch F5, branches B1 and F5 should report the fault. But if branch F5 failed to report, the fault will be mis-identified to be in branch B1 based on the tree search technique.

To make the logic more reliable given the possibility of relay or sensor failure, the N-1 criterion may be adopted and also the exhaustive binary search can be used. Whenever there is a fault report from any branch in the tree, a complete search from the root to all leafs will be conducted. Suppose a fault is on branch F5 in Fig. 8: if F5 failed to report and if F2 and F4 both report, applying the N-1 rule, the fault branch can be assigned to F4 and F5 because branch F5 is the lowest in the hierarchy among the branches that report the fault. In this case, the fault section identified was not exact but it is close.

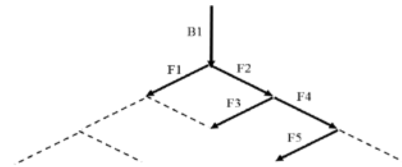

Fig. 8 Binary tree representation of a local tier

Furthermore, the communications among all of the relays and sensor processing units involved are based on the IEC 61850. There is a quality bit associated with each binary or analog value, which can be used to validate the value reported. Also, the logic device healthy status can be used to indicate if the device fails to report or does not see the fault.

C. *Neighborhood Tier*

In the neighborhood tier, it may contain multiple local tiers and the relays and control devices on the main-tie-main (or main-main if the tie breaker does not exist) breakers, as well as the sensors. The master processing unit is the industrial type computer that has much more computation power than the relay. As shown in Fig. 6, the dedicated industrial computer is used as the master in the neighborhood tier. As an alternative, a more comprehensive feeder relay that is able to take care of the whole protection and control needs for the main-tie-main application can be the master in the neighborhood tier. In fact, for a relatively simple radial distribution network, a more comprehensive feeder relay would be a better choice at least from the processing speed point of view.

Some of the approaches mentioned in the local tier can be applied to the neighborhood tier. Obvious differences that are clearly evident in the neighborhood tier is that the simple binary tree hardly exists; instead, some stars are formed. Using Fig. 8 as an example, two stars are formed as shown in Fig. 9 when the tie breaker is open. Then, they become one when the tie breaker is closed. The other difference is that most branches at this level are equipped with a relay, which in most cases is the master in that local tier.

Knowing that main branches M1 and M2 are always sources and the tie breaker status, the exhaustive search can be conducted starting from the main branches. For example, when the tie breaker is open and M2 reports a fault, a search can be conducted among the local tiers that are members of the star that includes the M2 branch. If one (can be more) of the local tiers reports the fault as well, then the fault can be assumed in that local tier. If no local tier sees the fault, then the fault must be in the M2 branch. When the tie breaker is closed, the search can be different depending on how many sources serve the loads. When both the sources are active, the search can be done just like the tie breaker is off. In this case, the fault section can be easily identified if the fault is in a local tier. The fault section may not be easily identified at the first place when the fault is on either main source branch because both main relays would react. Usually the tie breaker is closed only for a short period, so, the chance to get a fault during this period is small. If the tie breaker is also equipped with a relay, the tie branch can be shared with two main stars. With the tie relay fault indication, the fault section can be differentiated between two main source branches.

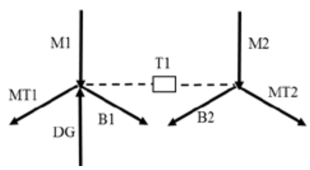

Fig. 9 Neighborhood star

When the tie breaker is closed and only one source serves the loads, the search can be done first in the active source star. If the tie branch reports the fault, then continue searching the local tiers in the other star. There will be no blind spot that the fault section cannot be uniquely determined in this case.

In the neighborhood tier, more sophisticated fault detection, isolation and restoration (FDIR) can be used.

D. *Central Tier*

The central tier is the highest tier in the total fault localization system. In this tier, the central processing unit like Supervisory Control and Data Acquisition (SCADA) collects all of the fault identification results from the neighborhood tiers and takes some actions for the fault isolation and restoration accordingly.

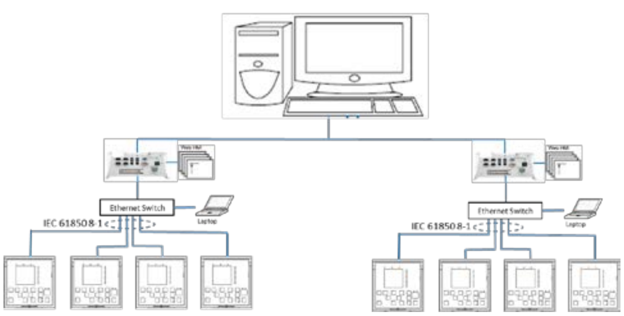

Fig. 10 Central fault localization systems

V. Implementation Example

An exemplary local tier was implemented as shown in Fig. 11 with one feeder relay as the master and four relays on the load branches (dotted line circled portion in Fig. 6). Note that in this example, all of the non-conventional VT/CT sensors are used for the sake of simplifying the simulation. The simulated sensor sources are the OMICRON 256 with a dedicated adaptor that bridges the OMICRON voltage and current outputs to three RJ-45 connectors, which connects to the relay and the measurement modules.

The field recorded cable fault data and the simulated fault waveforms using the power system transient program were played back to provide valid cable faults.

In the default simulation set up shown in Fig. 11, only one phase voltage/current circuit and GOOSE data flow diagram are shown. Note that the set up below is not an exact replica of the local tier shown in Fig. 6, but it is adequate for proving the feasibility of the proposed fault localization concept.

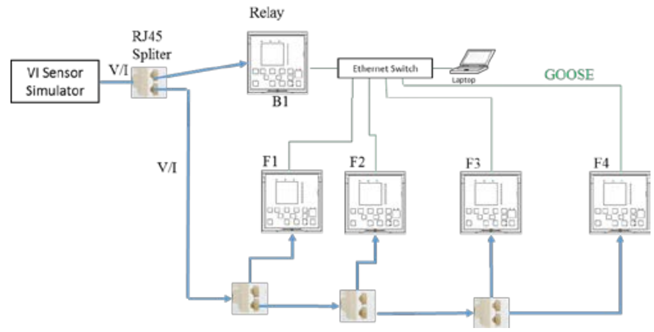

Fig. 11 Simplified simulation system for fault localization

For a fault simulation, depending on the fault location, some manual manipulations of those V/I Ethernet cables may be necessary. For example, for a fault on the F4 branch, F1, F2, and F3 branches will be disconnected; for a fault on the F2 branch, F1 branch plus all of the V/I Ethernet cable to F3 and F4 branches should be disconnected. Since the V/I Ethernet cables carry low energy voltages, they can be disconnected any time during the simulation, thus many dynamic situations can be mimicked.

All of the branches from F1 to F4 publish the GOOSE message for their cable fault indicator and the master B1 subscribes to them.

A simple fault localization logic can be implemented in the relay on the B1 branch as shown in Fig. 12. As shown, only a few AND, OR and NOT gates are needed. The outputs from this logic B1_F and F1_F to F4_F can be further connected to the local LEDs and communicated to the upper level processing unit such as the neighborhood tier, and they can trigger events for further analysis.

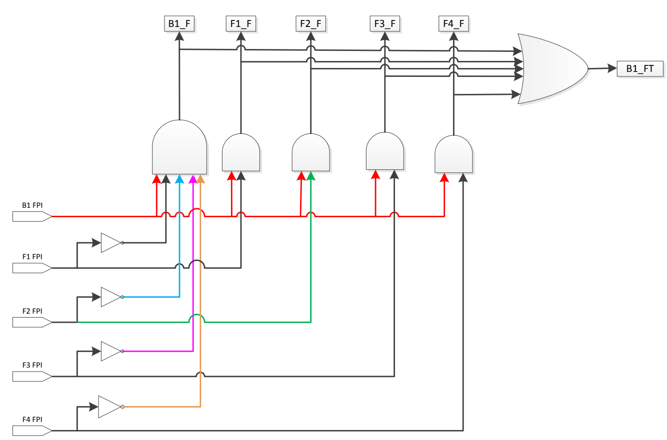

Fig. 12 Fault localization logic in the local master

Similarly, the fault localization logic in the neighborhood tier shown in Fig. 1 (or Fig. 6) can be designed as in Fig. 13 below. Some of the inputs to the neighborhood tier such as B1_FT and B2_FT are fed from the local tiers, the outputs, M1_F and M2_F of the neighborhood tier can be further fed to a central tier.

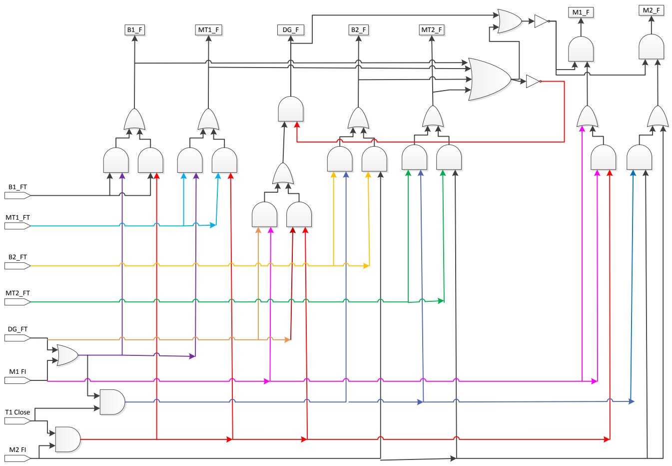

Fig. 13 Fault localization logic in the neighborhood master

As was indicated earlier, the neighborhood master can be a dedicated relay, an industrial type computer, or the relay in the top hierarchy of the neighborhood tier. If the speed of the performance is a concern, either a dedicated or shared relay would be a better choice. As shown from the logic, it is fairly simple and does not need much extra processing power. Usually, the relay on the tie breaker is lightly loaded with protection and control functions; thus, this relay would be a good choice as the neighborhood master.

Compared to the logic implemented for the local tier, the logic for the neighborhood is more involved. In the logic, the distributed generation resource and the tie breaker status are also taken into account.

VI. Conclusion

This paper proposed simple and intuitive fault localization system hierarchy, which includes three tiers for a radial distribution network with the distributed sensors or conventional CTs. The system is especially suitable for a large industrial compound where all feeders are relatively clustered, and the Ethernet communication is their communication backbone. The system is highly scalable and can be modified or expanded easily. The most important thing to note is that no extra relay or computer is needed. The user effort to implement the system is very small and it may only require some simple logic gate configurations. The system response speed is very fast, particularly for a local tier. Once the local relay recognizes the fault, it would take the local master as fast as about 7ms (4 ms processing and 3 ms GOOSE communication delay) to identify the fault section. If the neighborhood tier uses a high-end relay as its master, it could achieve a similar speed performance. Fast fault section identification will speed up fault isolation and restoration, consequently reducing the duration of a power outage and improve power supply reliability.

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