SYNERGISM BETWEEN INTELLIGENT DEVICES AND COMMUNICATION SYSTEMS FOR OUTAGE MAPPING IN DISTRIBUTION NETWORKS

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ABSTRACT

Remote Service Restoration in a Distribution Network has to be preceded by Fault Isolation. To perform the fault isolation correctly, it is pertinent that when a fault occurs, it is detected in a timely fashion. And also, the extent of the service territory that is affected should be accurately identified.

This paper describes a methodology how fault detection and outage mapping can be automated using the present state of the art of computer technology, communication technology and intelligent devices. The design and the operational issues form the major part of the discussion in this paper.

INTRODUCTION

One of the useful functions that enhances electric customer services is the ability to quickly detect an outage, determine the extent of it and restore services to the customers. At one time an electric utility depends on calls from customers and the SCADA system to determine that an outage has occurred. All these incoming information have to be related to parts of the distribution network and the protective devices that operate to isolate the fault. This is necessary for the maintenance and repair crew to enable them to find the cause and the exact geographical location of the fault.

Normally one has to rely on the maintenance and repair crews' memory or sets of network drawings to identify the part of the network that is suffering from loss of power.

Many electric utilities have implemented remote meter reading, two-way demand side management functions and to some limited extent a few distribution control functions. These things imply that a two-way communication is available. Fault detection and outage mapping seem to be natural candidates for increasing the functional capability of the system. With the introduction of digital computers, communication networks and intelligent digital electronic devices a high degree of automation of the outage detection and mapping function can be accomplished. The criteria that can be used as a measure how well the system operates is the **outage mapping response time.** It is the period of time measured from the start of an event that causes the outage to the moment the information is displayed on the operator's computer screen.

This outage mapping response time can be separated into two major components.

- Outage detection and communication response time.
- Computer processing time of incoming information and displaying the results on the screen.

The system designer has to take into consideration forced outages for maintenance and repairs, blackouts due to generation or transmission line faults and rolling blackouts for emergency demand reduction. This paper restricts itself to the discussion of unpredictable outages caused by faults at the distribution network.

SEVERAL SYSTEM OPERATIONAL MODELS

The following system components are assumed to be in place. An intelligent fault detector is installed at the medium voltage substation that is linked by a communication network to a control center. Intelligent devices or transponders are scattered throughout the distribution network linked by a two-way communication network to a control center. These transponders can be remote meter reading or two way demand side management transponders. Also a computer for outage mapping is available at the control center. In the next chapters, the operational and design requirements will be discussed in details.

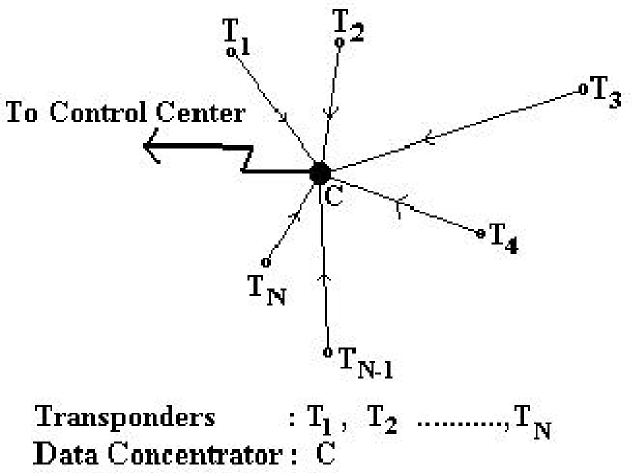
Assume a fault occurs at some location in the distribution network triggering an outage. Some qualifiers should be made concerning the location of the fault and the extent of an outage. A disastrous major transformer failure at the medium voltage or transmission substation causes the whole service territory served by that transformer to be out of power. This case is excluded from this study. Another exclusion is an outage at a single residence because of a fault inside the customer premises. Only one customer suffers an outage in this case.

With these components in place, several outage mapping operating scenarios can be described. They will be used as references for discussions.

a. Operational model 1 - the unsolicited inbound method.

Transponders at the remote sites are constantly communicating through data concentrators to the control center reporting network conditions. They are capable to maintain communication for a certain period of time even during an electric outage. As soon as an outage is sensed, the transponder reports the new state of the network because of an outage. The transponders do not need any commands from the control center and are in constant communications with the data concentrators. All stored information at the data concentrators is retrieved by the control center using high power two-way communication network.

Since all transponders linked to a concentrator are continually transmitting to the data concentrator with random time delays, there are bound to be collisions. The communication channel behaves like an Aloha channel since no handshake or acknowledgments are used in this one -way communication. The total traffic is assumed to have a Poisson distribution [1-2].



The unit transponders concentrator model.
Fig. 1

In the limiting case the amount of time it takes to hear all N transponders at least once without error is

$$\Delta t = (\tau / D)\, \varepsilon^{2ND} \qquad (1)$$

N is the number of transponders, τ the packet length in seconds and the normalized traffic load is $D = \tau \lambda_i$. The parameter λ_i is the average arrival rate in packets or messages per second.

Fig. 2 shows the relationship between D and Δt for various values of N, assuming a packet length of $\tau = 0.1$ second. For N = 200 the minimum value of Δt occurs approximately at D = 0.0025 and hence $\lambda_i = (0.0025 / 0.1) = 0.025$ messages per second. If one needs all 200 information to arrive first before a decision can be made concerning the extent of the outage, then Δt is a good measure to use for time delay in calculating the outage mapping time. The time delay due to communication between concentrator and control center is a small fraction of the total time.

Another major consideration is the need for a power source at the transponders and data concentrators. They have to be able to continue signaling despite the outage.

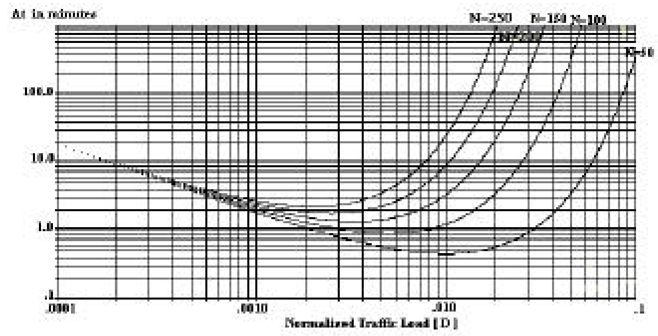


Fig. 2

b. Operational model 2 - the total polling method.

The central control computer constantly send polling commands to the transponders and each one of them responds back. The transponders are powered by the electric network and loose all communication capability when power is lost. If an outage occurs, some of the transponders become deenergized and do not respond back to the polling command. By relating the non-responding transponders to the medium voltage circuit, one can infer which part of the circuit is deenergized.

The time delay $\mathbf{T_{del}}$ due to communication per data concentrator to one transponder can be calculated as follows:

$$T_{del} = T_{outb1} + T_{proc1} + T_{outb2} + T_{proc2} + T_{inb2} + T_{proc1} + T_{inb1} \qquad (2)$$

- T_{outb1} : Communication time between control center and data concentrator (outbound)
- T_{outb2} : Communication time between data concentrator to transponder (outbound)
- T_{inb1} : Communication time between data concentrator and control center (inbound)
- T_{inb2} : Communication time between transponder and data concentrator (inbound)
- T_{proc1} : Communication processing at the data concentrator
- T_{proc2} : Communication processing at the transponder.

For N transponders per data concentrator the total time delay becomes $T_{totdel} = (NT_{del})$**.** If there are M of such data concentrators, the total system time delay becomes

(MNT_{del}). Each transponder has to wait (MNT_{del}) seconds before it is polled again.

If a group command can be used allowing n_o transponders to respond simultaneously each using a different communication channel, then the communication time delay for N transponders per data concentrator becomes:

$$T_{totdel} = (N / n_o) * T_{del} \qquad (3)$$

If communication between the control center and the M data concentrators and from the concentrators to the transponders vice versa can operate simultaneously in a non interfering mode then the total system delay is the same as T_{totdel}.

c. Operational model 3 - the limited polling method.

This method relies upon an intelligent electronic device at the medium voltage substation. It activates a polling sequence if a fault is sensed on the circuit served by the medium voltage substation bus. Only those transponders on that circuit are polled. The ones which do not respond to the polling command are assumed to be connected to that part of the circuit which is deenergized.

By assigning the addresses of the transponders to be polled in a certain fashion, the polling time can be drastically reduced.

Hence, if the intelligent electronic device at the medium voltage substation bus indicates that a fault has occurred, e.g. circuit 2 on phase B to neutral, then only those transponders on phase B of circuit 2 has to be polled. The more intelligent the device is, the lesser the number of transponders that have to be polled and the lesser the time delay will be to determine the extent of the outage.

In this paper only the limited polling technique is discussed in great detail, using the synergism between the intelligent electronic device and communication as the kernel for outage mapping. The hierarchical structure of the network further enhances the system operation by taking advantage of the selective coordination of the protective devices.

THE HIERARCHICAL STRUCTURE OF A POWER NETWORK

Power networks, in particular medium voltage networks for power distribution are designed with an inherent hierarchical structure. The selective coordination of protective devices in the circuit is such that a fault at the circuit minimizes the number of customers suffering from an outage. For instance, fuses near the customer end on the network are coordinated with a recloser in such a way that a fault at the remote end will cause a fuse to blow first. The recloser may react but the selective coordination dictates that the fuse will open first before the recloser goes into a permanently open condition. Hence only the customers beyond the open fuse will experience loss of power.

A typical single-phase hierarchical diagram of a network is shown in Fig. 3. The protective devices indicated by the same letters belong to the same peer level, e.g. B_1, B_2 and B_3. The next level are the ones indicated by the letter R. The subscript of R_{21} means that the protective device is the first one of the R-level on circuit number 2. The same reasoning can be applied to the F-level. In this diagram the S-level is the lowest in the hierarchy.

The relationship between hierarchical level to fault location is as follows. A fault at location 1 causes R_{11} to open. A fault at location 2 causes B_2 to open and a fault at location 3 causes S_{2111} to open.

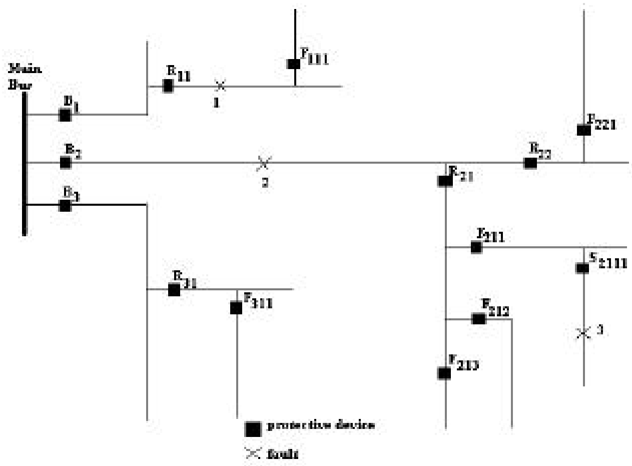


Fig. 3

These protective devices can be circuit breakers, reclosers and fuses. These devices are actually the local intelligence coordinated in such a way to perform the initial fault isolation function**.**

THE INTELLIGENT FAULT DETECTOR

The various protective devices have different operating characteristics that can easily be distinguished one from another. A fuse typically opens in one or two cycles of the power frequency. The load after the fault is smaller compared to that before the fault and it may be difficult to determine the difference. The reason is that fuses are typically installed at the laterals and branches where the loads are relatively small. A recloser protects a larger segment of the network. When it operates, it opens and recloses several times. During the closure, the fault current lasts for quite a few cycles and during contact opening, the load current at the bus is reduced substantially. If a fault occurs causing a circuit breaker of a main feeder to open at the substation bus, a large amount of load is lost. An intelligent fault detector can be designed and programmed to distinguish the various types of protective device operation. The detection algorithm can be set up as follows:

- 100% initial load current
  fault current duration < = 2 cycles
  load current Δ * 100 %, where $\Delta < 1$.
  then a fuse has operated.
  Trigger an alarm and polling sequence.

- 100% initial load current
  fault current duration > 2 cycles
  load current Δ_1*100% and duration > 2 cycles
  fault current duration > 2 cycles
  load current Δ_1*100% and duration > 2 cycles
  \- - - - - - - - -
  load current Δ_2*100% and duration > 2cycles.
  If $\Delta_2 = 1$. then the fault is cleared and network is back in its original state.
  If $\Delta_2 = \Delta_1$ and $\Delta_1 < 1$, then part of the network is disconnected because the recloser is open.
  Trigger an alarm and polling sequence

- 100% initial load current
  fault current duration > 2 cycles
  load current = 0 on the feeder
  feeder circuit breaker is open at the substation.
  Trigger an alarm and polling sequence

- 100% initial load current
  load current increases or decreases and stays at a fixed level for relatively prolonged period of time
  Do not trigger any alarm and polling sequence.

The 100% initial load current provides a dynamic reference for determining loss of load due to a protective device operation.

If a current transformer is installed on each phase of the feeder, the intelligence can be enhanced to determine what phase wire is experiencing the fault. A single-phase fault occurs on one phase wire only. A line to line fault causes the fault current to flow on two wires and a three-phase fault appears on all three phases.

The threshold value for a fault current can easily be estimated. If the substation transformer impedance is Z%, then the maximum RMS fault current is approximately (100% / Z%) times the nominal load current. Applying a reasonable multiplying factor of less than 1 but larger than 0.5 to the maximum anticipated peak RMS fault current will give adequately good result

This device eliminates the need to poll areas that do not suffer from any outages due to a fault. In addition it also pinpoints the part of the network beyond the protective device that is suffering from the outage.

ALLOCATION OF TRANSPONDERS FOR OUTAGE MAPPING

All transponders used for polling do not have independent power supplies. When power is lost at the transponders, the transponders are totally disabled and will not respond to any command.

Referring to Fig. 3, it is assumed that the protective devices labeled by the capital letter F are fuses and are at the lowest level in the hierarchy for phase A. The circuit beyond B_2 has four type F protective devices and assume that F_{221}, F_{211}, F_{212} and F_{213} protect phase A only. Two transponders located on part of the circuit protected by a fuse are used for polling. They can be assigned the following addresses for polling:

For F_{221} PNAF22101 and PNAF22102
For F_{211} PNAF21101 and PNAF21102
For F_{212} PNAF21201 and PNAF21202
For F_{213} PNAF21301 and PNAF21302

Proceeding now to the next level, the protective devices labeled by the letter R are assumed to be reclosers. For part of the network on phase A between R_{21} and F_{211}, F_{212} and F_{213} two transponders are assigned for polling. For part of the network on phase A between R_{22} and F_{221} two transponders are assigned for polling. The following addresses can be assigned to them:

For R_{21} PNAR2101 and PNAR2102
For R_{22} PNAR2201 and PNAR2202

For the highest level in the hierarchy, the part of the network between the circuit breaker B_2 and the reclosers R_{21} and R_{22} can have two transponders with the following addresses assigned:

For B_2 PNAB201 and PNAB202

This method of labeling the transponder addresses here is used for convenience sake in this paper. The address contains all the necessary information concerning the bus, feeder, phase and type of protective device. As an example:

For PNAF21202 from left to right

P is used to indicate that the transponder is assigned for outage mapping function.
N is the bus number.
A is the phase
F is the type of protective device
21 is the number to indicate the relationship with R_{21}
2 is the fuse number under R_{21}
02 is the transponder number

The reason for assigning certain transponders for outage mapping and the method of address design will be clarified in the next sections.

THE OUTAGE DETECTION AND THE POLLING SEQUENCE

Assume a fault occurs on phase A on feeder number 2. In the example used for reference above, the fault can occur between the main breaker and the reclosers, between a recloser and a fuse or between a fuse and beyond. Hence there are three possible cases. The intelligent fault detector has the ability to distinguish each of the cases. Each of the cases and their relationship with the polling function will be discussed in great detail next.

Case 1: The fault beyond a fuse.

The fault detector only knows that a fuse has blown but it does not know which one. After it triggers an alarm it activates a polling sequence. All transponders on phase A beyond the fuses have to be polled. Their addresses have been defined in the previous section. Suppose the eight transponders give the following responses:

PNAF22101 :	no response *
PNAF22102 :	response
PNAF21101 :	response
PNAF21102 :	response
PNAF21201 :	no response
PNAF21202 :	no response
PNAF21301 :	response
PNAF21302 :	no response *

The following inference rule can be applied:

A fuse is assumed to have opened if both transponders used for polling do not respond to a polling command.

The no responses with the asterisk * indicate that there is a communication problem. The other transponder on the same circuit does respond and this can only happen if there is no outage on the circuit serving that transponder.

From the results shown above apparently fuse F_{212} has opened. In the operating scenario above only 8 transponders have to be polled. The main reason that two transponders are assigned per circuit segment is to insure that at least one would respond if the circuit segment remains energized. Putting three transponders per circuit segment beyond the fuses will render the outage determination even more reliable.

Case 2: The fault is between a recloser and fuses.

When a recloser operates, the fault detector does not know whether R_{21} or R_{22} has operated. For this reason transponders PNAR2101, PNAR2102, PNAR2201 and PNAR2202 are polled. Using the method described in case 1 to determine which recloser has operated based on the results of polling, one quickly determines which recloser has operated and has gone into a lockout state.

Case 3: The fault is between the breaker and reclosers.

Only two transponders PNAB201 and PNAB202 need to be polled to determine whether the breaker is open or not. The closer the fault is at the protective device of a higher hierarchy the lesser the number of transponders to poll and the faster the system performs.

POLLING CONTROL AND DATA BASE ISSUES

Up to this point no mention is made how responsibilities for polling are shared by the devices and the control center. For a total Outage Mapping system integration, several options are available.

The Centralized Control

The control center is completely in charge of the Outage Mapping operation. When an intelligent fault detector detects a fault, it transmits to the control center all necessary information for polling to the control center. This information contains the name of the medium voltage substation, the medium voltage bus number, the feeder number, the phase and the protective device that has operated. Based on the information received, the control center computer searches its database to obtain the addresses of the transponders to be polled. Subsequently a polling command to the transponders is issued by the control center. The responses from the transponders are analyzed and a determination can be made which part of the network is out of power. This last statement will be discussed in greater detail later.

The Distributed Control

The burden of polling can be shared amongst the medium voltage substations. A control computer dedicated to outage mapping and communication control is installed at the substation. It has all the transponder addresses assigned to support the outage mapping function for the network served by the medium voltage substation. The intelligence to choose the right transponders to poll based on information supplied by the intelligent fault detector is also provided. The local computer at this substation can also issue polling commands, decode transponder responses and determine which protective device has operated. The result of the polling is subsequently transmitted to the main control center.

For two-way systems, which use the medium and low voltage network for communication medium, this distributed control is a natural part of the total system design [3-6].

Network Data and Data Base Management

Outage Mapping derives its greatest benefit if the outage mapping information can be transmitted quickly to the repair and maintenance department and also customer service department of an electric utility. Information, such as recloser R_{21} is open, is not very useful to the maintenance crew. Pertinent information about part of the network that suffers an outage, the topographical information and the location of the protective device should be easily retrieved from a database. Such a database is probably the most complex and time consuming to design. In the USA, AMFM (Area Map and Facilities Management) systems are available for such purposes described above. In effect, the whole distribution network including the area topology is digitized. Also, segments of the network under each protective device where the outage mapping transponders are located have to be related to the transponder assigned addresses. The communication path parameters for reaching those transponders by means of the communication network have to be defined also. These are the main items that are essential for the central control computer to have in order to operate the outage mapping efficiently. Searching through piles of network drawings to determine the extent of an outage is hereby eliminated.

Another important issue is the data base management. Network changes occur routinely. Some are temporary due to maintenance; others are more permanent due to system expansion. These changes may require adding transponders for outage mapping, reassigning addresses to existing transponders, reconfiguration of the connectivity of the network segments, etc. The database has to be kept up to date.

Another major issue is the destination of the Outage Mapping information. For a large electric service territory there may be several maintenance and repair service centers. Then information format should be easily interpreted and understood by the recipients. The information should contain not only network information, but also geographical information and the type and class of protective device that has operated.

CONCLUSION

This paper presents a methodology for implementing an Outage Mapping capability, which can be superimposed on an existing two-way system for meter reading and other customer services. The use of an intelligent fault detector at the medium voltage substation eliminates unnecessary communications for outage mapping**.** The synergism between the intelligent fault detector and the existing communication system reduces the time needed for determining the extent of the outage. It eliminates the need to rely on customer calls to determine the extent of the outage.

The database and its management are complex and are an indispensable part of the outage mapping function. A good database that is well maintained to keep up with the constant changes in the network configuration accounts for a substantial part of the timesavings for outage mapping. It should be clearly understood that Outage Mapping is not an add-on to a communication system only, but it also requires database support to make the Outage Mapping operationally optimum.

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