GER-4006

Communication Supported Instantaneous O/C Schemes: Comparison and Analysis

Communication Supported Instantaneous O/C Schemes – – Comparison and Analysis

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Abstract—This paper presents selected methods of implementing instantaneous over-current (IOC) protection for distribution feeders. An overview of IOC element coordination issues and possible solutions is presented. A review of communication supported IOC schemes follows. Binary, serial and LAN (UCA2) based communication schemes are evaluated, with discussion of implementations. Communication supported IOC based schemes applied as a feeder's protection, bus protection and backup are also discussed. The local, remote and distributed backup protection concepts based on the UCA2 LAN communication are reviewed. Timing requirements and reliability assessment will be discussed as well.

Keywords: radial feeder protection, Instantaneous Overcurrent, protection coordination, peer-to-peer communication.

I. OVERVIEW OF IOC ELEMENT COORDINATION ISSUES

The instantaneous overcurrent (IOC) protection of power system networks is a simple, effective and attractive engineering solution. As many other elegant engineering methods, however, it has its own limitations. The coordination interval delays the operation of the relays, making it impractical when several levels of distribution buses are to be protected. This limitation could be overcome by supplying the local protection with the status of other protections in the fault path. This type of communication is often called peer-to-peer communication. In this paper we will discuss applications of the LAN type communications with some comparative analysis of other methods of communication.

The need for time coordination of the IOC elements comes from the requirement to trip only the faulted zone of the network.

The speed of the fault clearing is always the top requirement in the protection application. The IOC elements provide the fast response to the fault, but applied in the scheme, they must be delayed to achieve the coordination required to discriminate the faulted zone of the network.

The faulted zone is defined as the part of the network, which could be isolated from the sources of fault energy other than energy storing loads. In simple single source networks with one source and radial feeders branching out of the buses (Fig.1), the rule translates into tripping the breaker closest to the fault on the source side. The network topology always makes the flow of the fault current from the source to the fault. To avoid miscoordination, all except the most downstream protection has to be delayed to allow the closest protection to the fault to operate first. This principle applies to all O/C protections in the radial feeder network. It could easily be noticed that the closest protection to the source relay, where the fault level is highest, is delayed the most. This is exactly contrary to the principle of clearing fastest that part of the network affected the most.

When more than one source contributes to the fault current there are several possible patterns of the fault current flow. A standard non-directional O/C element will not be able to differentiate between the downstream or upstream fault. To secure correct scheme operation a directional function must be added.

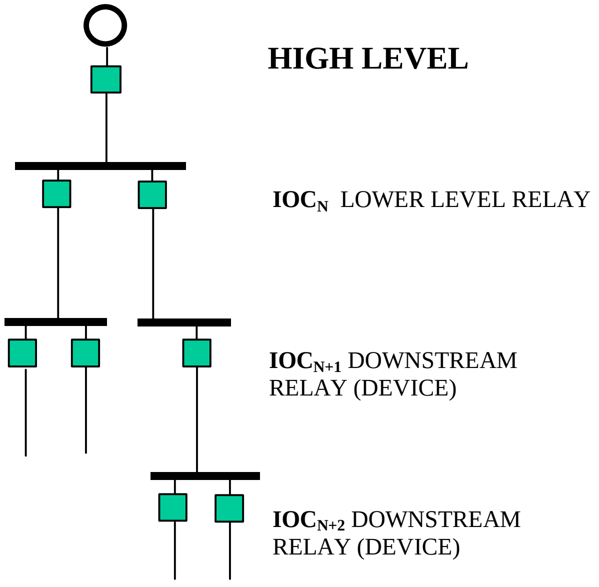

Fig. 1 Typical radial system

The paper presented at the annual Canadian *Protection and Control Forum*:
Toronto, June 1, 2001
Edmonton, June 4, 2001
Vancouver, June 7, 2001

II. TYPICAL PER-TO-PEER COMMUNICATIONS USED BY IOC

To achieve the coordination of the IOC elements all tripping devices must reconcile the priority of the tripping. It is quite easy to accomplish this if all relays communicate their status to each other. In practical applications, we deal with either binary “contact” type communication, or the LAN Ethernet networks.

The very simple form of communication between the protective relays could be achieved by connecting the output contact from the one device to the input of the other. This binary type of communication is equivalent to sending one bit, either 0 or 1, reflecting open or closed contact. Even devices designed without communication ports could provide this primitive communication. Physical distance limitations and the risk of induced coupled voltages would limit the practicality of the application in many cases.

A recent application of the Local Area Networks (LAN) to the field of power system protective relaying overcomes limitations and provides some attractive enhancements in applying some basic schemes well. The Ethernet based LAN networks are beginning to be applied in the substation environment with protective relays connecting directly to the LAN network.

In this paper we will discuss the application of LAN type communications with some comparative analysis of other solutions.

Other communication alternatives are based on dedicated proprietary communication schemes using serial port links. Serial port applications must consider the priorities of writing the state of the relay into the communication buffers, which will affect the relay's ability to transfer the signal to other devices. Physical distance considerations are the limiting factor too. Therefore, the schemes based on the serial link communication are left out of the scope of this paper.

III. BINARY (CONTACT) COMMUNICATION

Two possible ways of implementing the reverse interlocking scheme with the “binary” contact communication are as follows.

Every relay in the scheme communicates its own status to the relay above, to let it decide whether to trip or block. In wired contact type communication, the decision of the higher-level relay is based on the information received only from the relay below. The communication takes place in pairs. All the relays in the fault path pick up about the same time and every one blocks its upstream counterpart. The relay closest to the fault should not receive the blocking signal from the relay below the fault, because there is no infeed to the fault. Consequently a selective trip will follow.

The second scenario is a little more advanced, in the sense that every relay sends the blocking signal to the higher-level device either when it detected the fault or it received a blocking signal from the lower positioned relay along the fault path. Certain hardware designs might not allow this implementation. Some form of programmable logic is required to accomplish this task. Time delay of the communication coordination is slightly different than the pair type setup.

In the first case any relay failure to detect the fault or send the blocking signal will cause the relay above it to operate, violating the coordination principle. The second type is more dependable since the relay must fail to pick up the fault condition and fail to retransmit the received signal to make the relay above operate.

IV. LAN BASED COMMUNICATION SCHEMES

When Local Area Network (LAN) is applied to communicate the status of the relay for the purpose of blocking, any relay in the fault path would receive the blocking signal from all relays located downstream. A failure to either pick up the fault or to transmit the blocking signal will not affect the operation of the scheme as long as at least one relay downstream along the fault path operates correctly. The LAN communication is more dependable than the wired binary type one. Typical implementation is based on fiber optic connections, to reduce the effect of the field interference with communication signals. Ethernet type networks are most widely accepted for relay peer-to-peer communications.

V. REVIEW OF COMMUNICATION SUPPORTED IOC SCHEMES

A. Reverse Interlocking Scheme – Permissive vs. Blocking Scheme

A Permissive IOC Scheme relay will trip if permitted by all downstream devices. The Permissive scheme will operate if its own element operates and it receives all permission signals from all downstream devices. None of the downstream protections can either pick up or operate for the fault. These conditions translate into the statement that no fault is detected by any lower positioned relays. The Nth relay will trip only if all downstream protections will declare non-operation.

$$\mathbf{T_N = IOC_N\ ?\ [(PSR_{N+1})\ ?\ (PSR_{N+2})\ ?\ \ldots\ ?\ PSR_Z]\ ?\ t_{DEL}}$$

$$\mathbf{PSR_{N+1} = \overline{(N+1)}_{IOC}}$$

The above Boolean equation could be transformed into equivalent form:

$$\mathbf{T_N = IOC_N\ ?\ [\overline{(IOC)_{N+1}}\ ?\ \overline{(IOC)_{N+2}}\ ?\ \ldots\ ?\ \overline{IOC_Z}]\ ?\ t_{DEL}}$$

$$\mathbf{= IOC_N\ ?\ \overline{[(IOC)_{B+1}\ V\ (IOC)_{N+2}\ V\ \ldots\ V\ IOC_Z]}\ ?\ t_{DEL}}$$

As it will be shown below, it is a logical equivalent to the Blocking IOC Scheme Boolean equation. This is intuitively equivalent to the statement that there is only one correct scheme behavior, which is independent of the implementation.

However, the Blocking IOC Scheme has some significant implementation advantages. Only the blocking scheme will be analyzed in detail.

T_N – Nth protection operation (trip)
IOC_N – Nth protection IOC elements picks-up.
PSR_{N+1} – permissive signal received from the (N+1)th protection. N+1 protection does not operate
$t_{DEL} = t_N + t_{N+1} + t_{N+2} + \dots + t_Z$
$t_{DEL} = \max_{t_i \, ? \, (t_N, t_{N+1}, \dots t_Z)} t_i$

The relay under consideration in the Blocking IOC Scheme (Reverse Interlocking) will trip if not blocked by any downstream device.

Nth protective relay in the Blocking Scheme will operate if its own element operates and it does not receive any blocking signal from any downstream devices. Every received blocking signal indicates that downstream protection did operate. These conditions translate into the statement that no fault is detected by any lower positioned relays.

$$\mathbf{T_N = N_{IOC}\ ?\ \overline{(BSR_{N+1})\ V\ (BSR_{N+2})\ V\ \dots\ V\ BSR_Z}\ ?\ t_{DEL}}$$

$$\mathbf{= N_{IOC}\ ?\ \overline{[(IOC)_{N+1}\ V\ (IOC)_{N+2}\ V\ \dots\ V\ IOC_Z]}\ ?\ t_{DEL}}$$

$$\mathbf{= N_{IOC}\ ?\ [\overline{(IOC)_{N+1}}\ ?\ \overline{(IOC)_{N+2}}\ ?\ \dots\ ?\ \overline{IOC_Z}]\ ?\ t_{DEL}}$$

$$\mathbf{BSR_{N+1} = (IOC)_{N+1}}$$

N_{IOC} – Nth protection IOC elements picks up.
BSR_{N+1} – blocking signal received from the (N+1)th protection.

The above Boolean equations assume that every relay in the scheme is able to receive the signal from all lower level devices. This statement is true for LAN type communication. When the binary ”contact” type communication is used every relay receives a signal only from the one relay below it. In effect, the trip condition for any relay in the scheme should be expressed as set of Boolean equitation describing the pairs of relays.

It could be observed that in the Permissive IOC Scheme every relay positioned below the fault must send the permissive signal to the relay expected to operate. All relays located below the fault must permit the relay under consideration to operate. Even one missed signal from the lower device will prevent the device under consideration from correct operation. The IOC operation will fail to clear the fault.

In the Blocking IOC Scheme the designated relay expected to operate will trip if it does not receive a signal from the relays positioned below the fault. It is enough that only one blocking signal is received to prevent the relay from operation.

The scheme effectiveness and reliability depends very much on the type of the communication and specific way it is implemented.

If binary communication with the pair model is used, a failure of the relay to either pick up or to send the blocking signal will cause miscoordination. Besides the relay closest to the fault, other higher positioned ones will trip as well. A much bigger part of the network will be disconnected from the source unnecessarily. It should be noted that any particular relay could properly generate the blocking signal, but still malfunction and trip in the absence of a blocking signal from the relay downstream. In the LAN type communicating scheme, a failure of one relay to either pick up or send the signal will not affect the higher level devices since its operation is dependent on any blocking signal received from any the lower devices. Only in the case that all downstream devices fail will it miscoordinate.

This observation supports the requirement that the highest device, which is the closest to the source, requires the highest level of security. If the communication fails, the highest number of circuits will be affected. The redundancy is inherently built into the LAN communication scheme, which provides the highest level of security, by default.

B. Time Delay Setting

As described above all relays should respond to the fault instantaneously and send their blocking signal to the higher-level devices with approximately the same time delay. In practical application, there will be a statistical dispersion of the response time. The coordination interval is required to allow the reception of the blocking signal. This time delay accounts for the slowest responding IOC element in the fault path. The input and output contact response time for the binary communication should be analyzed. Time delays in the range of 20 – 50 ms are applied. In the case of the LAN, the protocol implementation will define the required time. Again, time delays in range of 16 ms should be applied.

C. Protection of Parallel Feeders

Parallel feeder, for the purpose of this discussion, is defined as the minimum two lines terminated at the same buses.

Protection of parallel feeders poses special consideration for the reverse interlocking scheme application, since the fault energy comes though more than one path. The parallel path of fault current creates a scenario of multiple source fault infeeds. The distinction between the lower and higher-level device in the path is lost. In a typical configuration, every parallel feeder is connected through the breaker to the bus. The reverse interlocking scheme for all forward faults could be implemented in the same way as for the true radial scheme. The only difference in the logic of operation is associated with the load side protection of the parallel feeders.

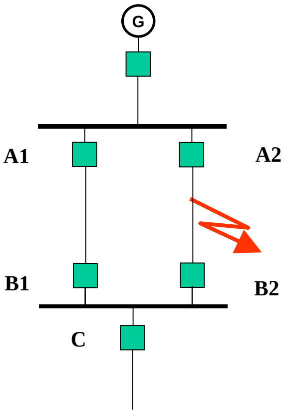

Fig.2. Fault on a parallel feeder.

For the fault as shown in the Fig.2, only breakers A2 and B2 should trip. However, protection associated with the breaker C will not operate so protections B1 and B2 will trip because both see the fault and no blocking signal has been received. B2 operation is correct but the B1 is wrong. To solve this problem we would like the B1and B2 protection tripping logic to be dependent on the blocking signal received from all the breakers on the bus, not only the downstream breakers.

$$\mathbf{T_{B1} = \{ IOC_{B1}\ ?\ \overline{(BSR_C)}\ ?\ \overline{(BSR_{B2REV})}\ ?\ t_{DEL}\ \}\ V\ \ IOCREV_{B1}}$$

and respectively for the breaker B2:

$$\mathbf{T_{B2} = \{ IOC_{B2}\ ?\ \overline{(BSR_C)}\ ?\ \overline{(BSR_{B1REV})}\ ?\ t_{DEL}\ \}\ V\ \ IOCREV_{B2}}$$

IOC_{B1} – Instantaneous Over Current (non-directional) element associated with breaker B1

$IOCREV_{B1}$ – Instantaneous Over Current (directional, looking toward the source) element associated with breaker B1

The first logical equations states that tripping will take place after the time delay $\mathbf{t_{DEL}}$ if the non-directional element $\mathbf{IOCREV_{B1}}$ will operate and neither blocking signal $\mathbf{BSR_C}$ is received from the breaker C nor the blocking signal from the directional element $\mathbf{BSR_{B2REV}}$ looking toward source.

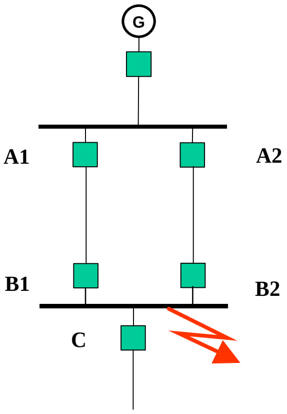

Fig.3. Bus fault.

If the fault is located at the distribution bus it can be seen from the tripping equation that only breakers B1 and B2 will trip.

D. Simultaneous Fault Protection

Simultaneous faults create special requirements in case two or more faults are located in the different fault paths.

When simultaneous faults happen within the same faulted zone, no special consideration is required. Ideally, we would like to operate the higher level breaker only relaying on the protection event logging capability to record that more than one fault has been cleared. Tripping two respective breakers simultaneously will accomplish both fault clearings, but the lower breaker tripping action may be considered unnecessary.

Two faults in different zones will create a problem if the first fault detected by the lower relay will block the upper device from operation. In fact, contact based communication has the advantage that only one relay will be blocked. In the case of LAN type communication, more devices will be adversely affected. The sequential clearing will follow. If applied relay provides more than one IOC element, it is possible to set the second one with a time delay greater than the typical clearing time, to provide the backup tripping.

VI. PRACTICAL CONSIDERATION

A. Ethernet vs. Other protocols for Substation Applications

Several protocols are used in substations, and there is no final agreement on which one will be standardized around the world. There is an imminent possibility that no standard protocol will be agreed on. However, the Ethernet is a well-supported, publicly held and stable protocol with good prospects for future advancement - it has been accepted more widely than any other protocol.

The Fast Ethernet 100base-T10 has been available for the past few years and the 1000 Mb or “gigabyte” Ethernet will soon be available commercially. These factors explain its growing acceptance and expansion into industrial and utility applications.

B. UCA2/MMS

The UCA protocol developed by the Electric Power Research Institute (EPRI) is gaining wide acceptance as utility choice of protocol. The Utility Communication Architecture version 2 (UCA2) is gaining momentum as more vendors and utilities become involved. A four-document set has been produced by the UCA2 group: *Introduction, Profiles, CASM, and GOMSFE*. The *Profiles* document specifies a number of acceptable protocol stacks based on the OSI seven-layer model.

Ethernet and TCP/IP, as well as serial and TP4/CLNP protocol stacks are supported. The top, or application, layer specified by UCA2 is the Manufacturing Message Specification (MMS), an existing protocol with a history of use in robotics and other manufacturing environments. The *CASM* (Common Application Service Models) document specifies a number of features that UCA2 compliant devices may implement and maps these features to MMS services. The *GOMSFE* (Generic Object Models for Substation & Feeder Equipment) document describes object-oriented data structures that can be used by specific UCA2 compliant devices. Examples include protection relays, capacitor bank controllers, tap changers, and RTUs.

One particularly interesting feature of UCA2 is the fast peer-to-peer exchange of digital state information provided by the GOOSE (Generic Object Oriented Substation Event) data structure. This feature uses the multicast capability of Ethernet with the connectionless OSI protocol stack. The GOOSE data structure contains a number of digital points, some standardized for all UCA2 devices, and some available for user-defined specialization. Whenever one of these points changes state within an IED, a sequence of repeating MMS messages is transmitted, each containing a GOOSE data structure. Other IEDs, if so programmed, may use the digital states in their own internal logic. This feature allows hardwired interconnections to be replaced by GOOSE messages on a LAN. Since the GOOSE data structure is fixed, IEDs from different vendors can interoperate and share data on the same Ethernet LAN. Note that IEDs not programmed to listen to GOOSE messages from other devices will simply ignore the messages.

C. Physical Distance considerations in Feeder's Protection

Contact based, hardwired communication is very limited by the physical distance between the relays in the string. Signals are 125V DC battery voltage levels, and are switched on or off. When extending the length of the cable, some typical problems related to antenna effects, coupled voltages, and switching transients could make this scheme very difficult to implement and troubleshoot. Every application requires detailed analysis and selection of cables to assure a secure operation.

When fiber optic substation LAN is used, the distance between the relays becomes a standard application. For example, a Fiber Adapter converting the signal from the twisted pair to the fiber optic cable extends the transmission by 2 km. There are several wire and fiber hubs, converters and switches allowing the design scheme to be able to cover kilometers of distance between the IEDs. Another important advantage is the fiber optic immunity to the EMI. Fiber optic based connections are secure and dependable as well as more and more affordable.

VII. BUS PROTECTION

Bus protection through the Reverse Interlocking Scheme in the radial system is not much different than fast clearing of the fault on the feeder.

Without multiple infeeds to the bus, the fast IOC elements provide adequate protection. The Reverse Interlocking Scheme described above provides satisfactory protection of the distribution buses.

VIII. LOCAL, REMOTE AND DISTRIBUTED BACKUP

Local backups were traditionally reserved to the higher voltage level substations because of the perceived importance and cost of additional equipment. In a full redundant system, all protection's functions would be duplicated. Many applications require the entire protection functionality of redundant relays to be based on different technology. Backup protections would typically be slower than primary protection and not necessarily provide all the functions. The lower, distribution level substations had to rely on the remote backups, like distance zones extended into the distribution transformers, or they simply did not have it. With new LAN based communications and the GOOSE mechanism available in the IEDs, there is an option to provide a local backup without the necessity to invest in additional protective equipment.

The Reverse Interlocking Scheme described in the previous paragraph is a form of the distributed back-up protection. A special version of this scheme could be applied as a fast overcurrent bus protection

IX. CONCLUSIONS

Significant operational improvements in the fault time clearing could be achieved when the traditional type IOC protections are used with the modern LAN based peer-to peer communications. Some forms of protections as breakers fail or back-up, either considered as impractical or not economically viable, could be implemented in the low voltage distribution systems when communication between the relays is provided.

X. APPENDIX – TERMS AND DEFINITIONS

Radial network –	part of the power system with single source of the load or fault energy. Loads do not contribute to the faults.
High Protection –	the protection located closer to the source in the same current flow path.
Low protection –	the protection located closer to the load in the same current flow path.
Upstream device –	the protective relay located closer to the source
Downstream device –	the protective relay located closer to the load
Fault Path –	physical path of fault energy from the source to the fault.
N –	N-th relay from the source in the load current path operates
N+2 –	N+2-th relay from the source in the load current path operates
Z –	last protective relay in particular path
t_{DEL} –	total time delay for the relay to accommodate receiving the communication signals
V –	logical operator OR
? –	logical operator AND
$\overline{\text{N+1}}$ –	Negation of the N+1 relay operation. N+1-th relay from the source in the load current path does not operate

BIOGRAPHIES

Bogdan Kasztenny (M'95, SM’98) received his M.Sc. and Ph.D. degrees from the Wroclaw University of Technology (WUT), Poland. He joined the Department of Electrical Engineering of WUT after his graduation. Later he was with the Southern Illinois and Texas A&M Universities. Currently, Dr. Kasztenny works for GE Power Management as a Chief Application Engineer. Bogdan is a Senior Member of IEEE and has published more than 100 papers on protection and control.

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