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Author(s): Mekkanen, Mike; Kauhaniemi, Kimmo; Kumpulainen, Lauri; Memon, Aushiq

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LIGHT-WEIGHT IEC 61850 GOOSE BASED LOM PROTECTION FOR SMART GRID

Mike MEKKANEN, Kimmo KAUHANIEMI, Lauri KUMPULAINEN and Aushiq MEMON
Assistant professor, Professor, Professor and Ph. D student- Finland
mmekka@uva.fi, kimmo.kauhaniemi@uva.fi, lauri.kumpulainen@uva.fi and aushiq.ali.memon@uva.fi

ABSTRACT

This paper presents a novel Loss of Mains (LoM) protection method based on IEC 61850 General Object Oriented Substation Event (GOOSE) protocol. With the increased penetration of distributed generation (DG), the requirements for LoM or anti-islanding protection has become common in the electric utilities. The development of Smart Grids including extensive communication capabilities enables also communication based LoM approaches. Since IEC 61850 standard based systems are the mainstream in the substation communication, expanding this technology deeper in the distribution network provides interesting solution for communication based LoM protection. The standard IEC 61850-7-420 defines logical nodes (LNs) suitable for this purpose but there are not yet available devices applying this part of the standard. Therefore in this research, a light-weight 61850 GOOSE based LoM solution has been developed and demonstrated applying a microcontroller and available open source software. This paper introduces object modeling according to IEC 61850-7-420 defined LNs and an implementation applying GOOSE messages and microcontroller. The validity of the light-weight implementation is demonstrated with a simple laboratory setup that has been used for measuring the message latencies.

INTRODUCTION

The interest towards renewable energy sources has been increasing rapidly during this century. This means that amount of distributed generation (DG) increases in the distribution networks. Modern Smart Grids employ also other types of energy resources, such as energy storages. Thus the term distributed energy resources (DER) is nowadays preferred. Islanding represents the case where, a segment(s) from the electrical grid is isolated from the main utility supply due to the maintenance schedule or a fault resulting a situation where at least one DER unit might continue to energize the islanded segment. This creates unacceptable situation in terms of power quality [1] [2]. Moreover, it may cause various kinds of problems relating to the proper operation of the protection system as indicated in [3]. Lastly, it provides a potential hazard for the maintenance personnel. Thus in present-day distribution networks, without wide-scale implementation of microgrids, islanding is an unwanted situation.

To avoid the risks indicated above, the DER units in the islanded network section should be rapidly disconnected.

As a result, anti-islanding gained high attention from both industry and academia, several LoM protection techniques have been proposed. A recent international report [4] categorizes the techniques into three categories: passive, active and communication based protection. The passive detection methods make decisions based on the measured electrical quantities, such as voltage and frequency and may result in nuisance tripping when made more sensitive [5], [6]. In active LoM detection methods, disturbances are injected into the network and islands are detected based on the system responses to the injected disturbance. Active techniques result in higher costs, increased system complexity, and require long time to implement. Thus they are rarely been used [7]. The communication based methods use typically the circuit-breaker (CB) status signals to alert and trip DERs when islands are formed. Transfer trip schemes and power line carrier (PLC) based methods fall into this category. For these techniques there is no common communication standard and protocol enabling all the various functions for monitoring, controlling and protection. PLC requires that the applied signal is carefully chosen depending on the system characteristics [8] and also costly. Existing transfer trip schemes are costly and complex with multiple DERs [4]. A universally accepted, cost-effective and reliable LoM method is still missing. According to [4], currently the transfer trip scheme seems to be the typical method. There is no general protection operation time requirement, but various recommendations are given in the standards applied. Exchanging real-time information becomes a dominant task for any successive system operation. The standard IEC 61850 had been defined as the common international standard in 1997 became one of the most promising and powerful solutions for the power industry. In this paper, a novel LoM protection concept has been proposed upon the standardized communication solution brought by IEC 61850 and specific LNs for DERs defined in IEC 61850-7-420 [9]. IEC 61850 light-weight version has been presented and implemented in order to reduce large overhead information and complexity of the IEC 61850. In addition to LoM function, the developed solution has the ability to monitor DERs status. The available monitoring information can be shared among the various distributed DERs unit controllers, enabling distributed decision approach [10].

LIGHT-WEIGHT IEC 61850

Although IEC 61850 standards offer many benefits, research and development tasks can be more costly and time consuming. However, IEC 61850 implementation complexities may be reduced with the increased

availability of different open source libraries upon various solutions [11] [12]. Those solutions had been written by various programming languages such as C, C#, Java, etc. that automatically generate the low-level machine code files. With the developed light-weight IEDs, communication among different DERs is achieved based on IEC 61850 protocols such as GOOSE, sample value (SV) and Manufacturing Message Specification (MMS). In this work DERs unit microcontrollers are implemented as native IEC 61850 IEDs. The designed IEDs are running based on the light-weight IEC 61850. GOOSE (publisher-subscriber) multicast communication techniques is used. In addition Ethernet links had been used to exchange data among different DERs IEDs, while there is no centralized decision maker. GOOSE subscribers access and use data to make their own decision based on individual monitoring and observation. Data can be exchanged among DERs regardless of the communication system technology and medium which is one of the most powerful features of the IEC 61850.

IEC 61850-7-420 LNS

In this section proposed prototyped electrical system units components virtualization is made. The virtualization task was implemented based on the data object modeling using the IEC 61850-7-420 LNs. Fig. 1 shows a simple electrical system where there is two different DERs in one feeder. Different IEDS are distributed over the communication system network through different distributed data points. These distributed IEDs are used for monitoring and LoM protection function purposes.
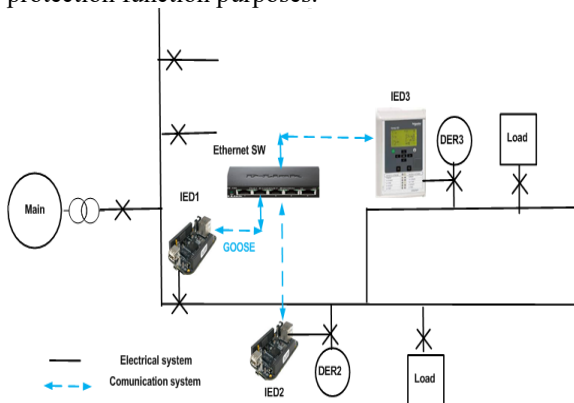

Figure 1. Case study laboratory test setup

Two LNs are selected, DPST and DRCS that represent the ECPs status and the DERs operation status respectively [9] [14]. According to the proposed LoM protection, DPST.ECPConn and DRCS.ECPConn data objects are modeled that indicate the connection status of the DERs at specific ECP. While, the DRCS.ModOnConn indicates whether the DER is in operation mode "ON" when this data parameter is set to "True". The DPST and DRCS LNs data objects are grouped in single data set and published within GOOSE message over the communication system network. LoM control decision status can be extracted from subscribing to the published GOOSE message within different DERs

IEDs based on the distributed decision making approach.

IEC 61850 GOOSE

Multicasting GOOSE has been designed to replace the hard wired legacy interlocking signal. This protocol ensures the same event message is subscribed by multiple IED subscribers based on multicast service. GOOSE messages exhibit high priority (4) and reliability. In order to increase the GOOSE reliability several replicas of the original GOOSE message need to be published within very short intervals when any of the GOOSE dataset parameters status had been changed. This technique ensures that at least one copy from the original message can be received by different subscribers and system operates as expected. Subscriber IEDs need to be configured based on the publisher GOOSE messages parameters. The GOOSE protocol has turned out to be a flexible tool. It can serve different applications with different performance requirements and varying data types [15]. Therefore, it is natural to pursue smart LoM application based on IEC 61850 GOOSE. In order to implement the proposed LoM protection based on GOOSE, different IEC 61850 publisher and subscriber IEDs need to be first configured. Within the different GOOSE subscribers final smart LoM protection decision making functions are designed. The smart LoM protection distributed decision making algorithm was proposed in our previous work [13].

LABORATORY SETUP AND CASE STUDY

For easy understanding of the GOOSE based smart LoM protection, a simple electrical system with simple Ethernet communication system network has been defined in Fig 1. A laboratory setup for the electrical communication system network that includes three different IEDs, 1000Mbit/sec Ethernet link and Ethernet switch has been established. For IED1 a light-weight IEC 61850 microcontroller is designed and modeled according to the IEC 61850-7-420 DERs LNs. It is continuously publishing the status of the ECP (feeder breaker) through the 146 bytes GOOSE message. IED2 is also a light-weight native IEC 61850 microcontroller, whereas IED3 is a normal commercial feeder protection relay, Vamp 52. Both IED2 and IED3 are configured to subscribe to the IED1 GOOSE messages for proper implementation of the proposed LoM protection function. Two different LoM scenarios had been defined and tested based on the above laboratory setup. The first LoM testing scenario is by changing the DPST.ECPConn data object of the feeder ECP from "true" to "false" in IED1. This change of the DPST.ECPConn data object from "true" to "false" indicates that the feeder breaker is opened and thus the connection to main grid is lost.
In the second scenario the DRCS.ModOnConn data object of the feeder ECP is changed from "true" to "false" in IED1. This change of the data object indicates that the feeder breaker is closed but there is no power supply available. In practice this means that the main infeed breaker of the substation busbar is opened (e.g. due to main transformer failure). The changing statuses in these two scenarios are published within IED1 GOOSE message. Both scenarios represent a LoM situation that needs to be detected. In order to study the performance

of the proposed setup in terms of communication system latency the main and standard deviation of the GOOSE messages round trip latencies had been measured and calculated. GOOSE round trip time involves seven individual times that may affect the GOOSE performance as illustrated in equations (1) and (2).

$$\bar{t}_{RT} = \bar{t}_{out.TS} + \bar{t}_{net} + \bar{t}_{in.DUT} + \bar{t}_{App} + \bar{t}_{out.DUT}$$
$$+ \bar{t}_{net} + \bar{t}_{in.TS} \qquad (1)$$

$$\sigma^2_{RT} = \sigma^2_{out.TS} + \sigma^2_{net} + \sigma^2_{in.DUT} + \sigma^2_{App}$$
$$+ \sigma^2_{out.DUT} + \sigma^2_{net} + \sigma^2_{in.TS} \qquad (2)$$

Where $\bar{t}_{RT}$ is the mean round trip time, $\bar{t}_{out.TS}$, and $\bar{t}_{in.TS}$ are the mean times in and out for the publisher IED (test system) that publishes the GOOSE message. $\bar{t}_{in.DUT}$, and $\bar{t}_{out.DUT}$ are the mean times in and out for the device under test (DUT), $\bar{t}_{App}$ is the application mean time within the DUT, σ^2_{RT} is the round trip variance and the rest variables in equation (2) are variances of the items in equation (1), respectively. Time synchronizations for IED1 and IED2 are set based on the coordinated universal time (UTC) server over the internet connections. IED3 is synchronized based on the IED configuration tool Vampset with the host PC upon the UTC server.

CASE STUDY TESTING RESULTS

According to the test scenarios 50 trials of DPST.ECPConn and DRCS.ModOnConn status changes are made and published within GOOSE messages from IED1. All the IED1 GOOSE messages had been subscribed and analyzed within IED2 and IED3. Another GOOSE message are published upon receiving the IED1 GOOSE. All the GOOSE messages are recorded with the IEDScout for the round trip analyzing purposes. Graphical representation of the acquired times two functions from Matlab software; hist(X) and ecdf(X) are used. The hist(X) function creates a histogram depicting the distribution of the results over the time. The ecdf(X) function is called empirical CDF and indicates the proportion of X values less or equal to x. We can use these plots to assess the distribution of data, estimate percentiles or compare different distribution-graphs with each other. The results for the first scenario (IED1 DPST.ECPConn status change initiates the GOOSE and both IED2 and IED3 send GOOSE response) round trip latencies histograms are illustrated in Figure 2.
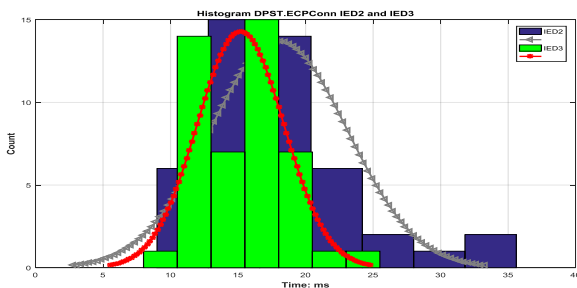

Figure 2. (RT) Histogram for the DPST.ECPConn

The results for the second scenario (IED1 DRCS.ModOnConn status change initiates the GOOSE) round trip latencies histograms are illustrated in Figure 3.
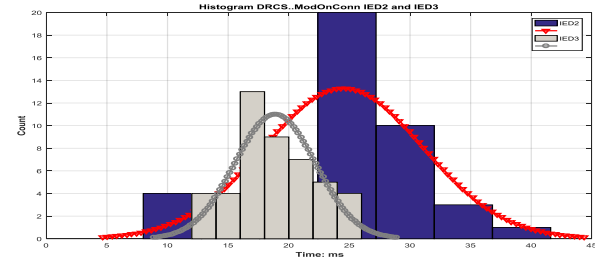

Figure 3. (RT) Histogram for the DRCS.ModOnConn

Cumulative distribution functions for the GOOSE round trip latencies for both scenarios are illustrated in Fig. 8.
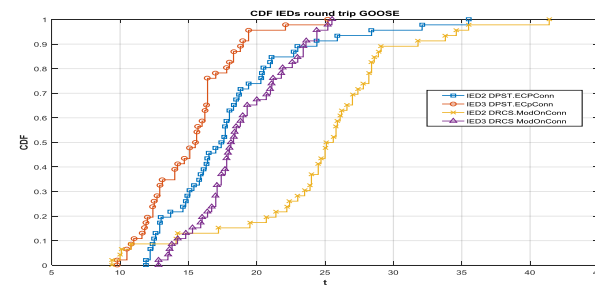

Figure 4. (RT) Probability CDF for the IEDs

DISCUSSIONS

IEC 61850 based GOOSE messages provide a promising alternative for LoM protection and maintaining DERs selective operation. These functionalities have proven to be possible both with the newly introduced light-weight IEC 61850 embedded microcontroller based IED2 and the commercial protection relay IED3. Since a separate communication system is applied the method is less susceptible to the electrical grid events compared to PLC based alternatives as discussed in [8]. The test results show that the communication channel had slightly different round trip times depending on the scenario and receiving end IED and also behave according to normal distribution model, which was expected. Since there was no other traffic within the communication channel in this test, and GOOSE messages with high priority (4), short packet length were used. The Ethernet communication system turned out to have very high reliability and also the standard deviations remained in low values. and mentioned in Table 1.

Table 1. (RT) GOOSE mean and standard deviation

	DPST.ECPConn		DRCS.ModOnConn	
	IED1-IED2	IED1-IED3	IED1-IED2	IED1-IED3
Mean val.	18.0065ms	15.1804ms	24.5065ms	18.8717ms
Std. dev.	5.0830	3.2090	6.6271	3.3322

The mean round trip GOOSE messages latencies of IED1-IED2 was more than the IED1-IED3, since the microcontrollers CPU speed is just 1000 Mbit/sec and the local integrated Ethernet adapter speed is 100 Mbit/sec. Moreover, the implementation of the light-weight IEC 61850 within the microcontroller and the execution of

different publisher subscriber codes add more extra latencies to the overall round trip time. However, the achieved results for both scenarios are within the acceptable recommended range. From the CDF graph (Fig. 8), we can see that around 98% of the samples (times) $\leq$ 36 ms. Therefore, the round trip GOOSE message latency does not limit the applicability of the LoM protection based GOOSE within different IEDs. Moreover, from the LoM communication method point view, the proposed LoM method enables solutions for the multi-direction energization issues. Light-weight IEC 61850 within inexpensive embedded microcontroller FPGA is promising solution that reduces the time, complexity and overhead information associated with IEC 61850 implementation. Moreover, it allows modeling different IEC 61850-7-420 DERs LNs that do not exist yet within the commercial IEDs for developing, testing and research purposes. As indicated in [7] and [8], the PLC based methods need external devices to inject signal, while here there is no need to connect external devices to the electrical grid which increases the system complexity and cost. In the proposed method the existing IEDs and communication systems can be used. For laboratory testing and comparing purposes inexpensive microcontrollers are applied as light-weight native IEC61850 IEDs. The main objective of adding the light-weight IEC 61850 microcontroller IEDs was to verify the implementation of the light-weight IEC 61850 GOOSE based LoM protection application. This also enabled to prove the correctness of the design, modeling and implementation of different DERs LNs (LNs brought by the IEC 61850-7-420 standard) within the embedded systems. Moreover, the proposed LoM protection can be extended to a promising new type of supervisory situation awareness solution by integrating other different data objects from other LNs of DERs to be published in the GOOSE messages data sets. These are, for instance, DCCT: economic dispatch parameters for DER operation, and DSCC: control of energy and ancillary services schedules. These DERs data objects can be used to achieve optimal grid operation and protection parameters. Furthermore, the monitored parameters can be used to classify different grid events in real-time. For example, the region in which a fault occurs can be predicted basing on the strongest fault signature captured by the publisher IEDs within the electrical grid [16].

More testing results are still needed for other communication technologies for instance wireless communication, since wireless communication technologies are being developed rapidly. Further questions that may arise and were not within the scope of this paper are for example the cybersecurity issues.

CONCLUSION

In this paper novel LoM method based on IEC 61850 GOOSE messages was proposed. The proposed GOOSE based LoM method had been implemented and tested within laboratory setup. The achieved results show that all the different main grid connection status changes are observed and processed by different IEDs and within the

allowable time range. Thus the method offers viable solutions for LoM protection that is also capable to avoid the nuisance tripping. Furthermore, the introduced light-weight IEC 61850 IEDs provide a platform to some advanced control and protection functions. By extending the GOOSE messages data set with different DERs LNs data objects, situation awareness type of solutions can be developed fulfilling the most advanced smart grid operation requirements. The proposed LoM based GOOSE supports different grid configurations and is fully functional even with the high penetration of DERs. In such a situation the question is not anymore to only have LoM protection operation but also to enable smooth transition to islanded operation in some parts of the system.

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