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Abstract: This paper presents a novel Loss of Mains (LoM) protection method based on IEC 61850 Manufacturing Messages Specification (MMS) protocol over wireless Global System for Mobile Communication (GSM) based access point name (APN) mechanism. LoM or anti islanding protection is a key requirement in modern power distribution grids where there is significant amount of distributed energy resources (DER). The future Smart Grids are based on extensive communication capabilities and thus the communication based LoM approaches will also become dominant. The IEC 61850 standard based systems are gaining ground in the substation communication, and therefore, it is natural to expand this technology deeper into the distribution network. Using this standard for LoM protection, also enables some advanced approaches utilizing large variety of information available in the Smart Grid. There is a specific part of the standard, IEC 61850-7-420, which defines logical nodes (LNs) suitable for this purpose; but, there are no available devices applying this part of the standard yet. In this research, a light-weight implementation of IEDs (Intelligent Electronic Devices) is developed using a low-cost open microcontroller platform, Beagle Bone, and an open source software. Using this platform, a wireless LoM solution based on IEC 61850 MMS protocol has been developed and demonstrated. This paper introduces object modelling according to IEC 61850-7-420 defined LNs and an implementation applying direct client server MMS based communication between light-weight IEDs. The performance of the wireless application using the developed platform is demonstrated by measuring the message latencies.

In this paper, a novel LoM protection concept is proposed based on the standardized communication solution brought by IEC 61850 and specific LNs for DERs defined in IEC 61850-7-420. A light-weight implementation of an IEC 61850 based IED is developed in order to reduce large overhead information and complexity of the standard. In addition to LoM function, the developed solution has the ability to monitor DERs status. The available monitoring information can be shared among various distribution management systems (DMS), enabling distributed decision approach for various purposes.

Keywords: Light-Weight IEC 61850; Loss of Mains; IEC 61850-7-420; Distributed Energy Resources; Smart grid

1 Introduction

Lately, renewable energy sources integrated in electrical grid have been gaining more interest and are increasing rapidly. This means that the amount of distributed generation (DG) increases in the distribution networks. Modern Smart Grids also employ other types of energy resources, such as energy storages. Thus, the term distributed energy resources (DER) is preferred nowadays. However, DERs integration as an inherent part of SG is a key issue. In order to take full benefit of the new functionalities enabled by DERs, an appropriate automation functionality will be needed. Islanding or loss-of-mains (LoM) is one from the fault detection functionalities which is mandatory for the integrated DERs operation requirements. Islanding represents the case where, a segment(s) from the electrical grid is isolated from the main utility supply due to maintenance schedule or a fault resulting in a situation where at least one DER unit continues to energize the islanded segment. This creates an 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 to the maintenance personnel. Thus, in present-day distribution networks, without wide-scale implementation of micro grids, islanding is an unwanted situation. In order to limit the risks mentioned above, the DER units in the islanded network section should be rapidly discon-

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nected. As a result, anti-islanding has been extensively studied and discussed by both industry and academia and several LoM protection techniques have been proposed [4–7]. However, 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, naturally completed by voltage and frequency protection. There is no general protection operation time requirement, but, in Finland, as short as 150ms operation time requirement is recommended for LoM protection [9].

Exchanging real-time information becomes a dominant task for any successive system operation. Therefore, cost-effective seamless communication system for integrating the DERs into SG is needed. In particular, Electrical Power Research Institute EPRI and IEEE raised the concept of Utility Communication Architecture UCA in early 1990s. The standard IEC 61850 was defined as the common international standard in 1997. IEC 61850 standard became one of the most promising and powerful solutions for the power industry and expected to support power system evolution. The key feature of IEC 61850 is a uniform framework for all the related system levels, considering various aspects that are common in the substation site such as data models, communication solution, engineering and conformity testing. IEC 61850-7-420 was published in 2009 as an extension of the IEC 61850 standard. IEC 61850-7-420 offered standardization for four different DER (photovoltaic, fuel cell, reciprocating engine and combined heat and power system) data models within different predefined LNs. The positive impacts of the IEC61850 standard in smart grid operation are, clearly, increase in the power quality and reduction in the outage response time.

In this paper, a novel LoM protection concept is proposed upon the standardized communication solution brought by IEC 61850 and specific LNs for DERs defined in IEC 61850-7-420. IEC 61850 light-weight version is presented and implemented in order to reduce large overhead information and complexity of the IEC 61850. Wireless communication is used to link the designed light-weight IEC 61850 IEDs since, wireless solutions have shown the greatest potential for smart distribution system operations (available anywhere at a very low cost). Moreover, with the fast development of security features such as secure socket layers (SSL), 128-bit encryption and available private network applications such as virtual private network (VPN), access point name APN, the security risks of using the wireless communication over a Global System for Mobile Communication (GSM) public network are highly reduced. In addition to the LoM function, the developed solution has the ability to monitor DERs status. The available monitoring information can be shared among various distributed DMSs, enabling distributed decision approach [10].

2 Active Distribution Management Systems (DMS)

Until recently, power distribution systems operated through a top-down operation model where electricity flows in one direction and did not require extensive management and monitoring IEDs. However, this model is changing with high DERs penetration scattered along the distribution system. In order to make the distribution system operation smarter, it will require more advanced distributed active DMS than those used in the past. A well-structured and configured communication system between relevant DMS units needs to be assigned based on the agreed standard (IEC 61850). These advanced distributed active DMS and preassigned communication systems would allow maximal integration of DER, making the most of existing grid while maintaining the power security standards upon the associated advance monitoring and controlling functions. Also, this system allows interaction between power distribution system planning, access (connection) and operational timeslots offering real-time flexibility that can reduce investment needs. Distributed active DMS in general may include the following monitoring and control functions :

- Monitoring: capabilities to monitor and gather the available information such as, state/mode, voltage, current, frequency, power factor and other operational parameters based on direct client-server or publisher-subscriber communication.
- Data processing: which is one of the most important features that need to be fulfilled by distributed active DMS, since, large amounts of real-time data needs to be handled.
- Estimation: a suitable state estimation tool needs to be designed and an inaccurate data compensation function needs to be defined.
- Controlling: capability of execution control algorithms in order to determine dispatch actions that are needed for active components to fulfil real-time distribution managements' operation requirements.

Figure 1 illustrates the active DMS IEDs with the available features in power distribution network based on the IEC 61850 standard that offered full interoperability among power distribution network instruments.

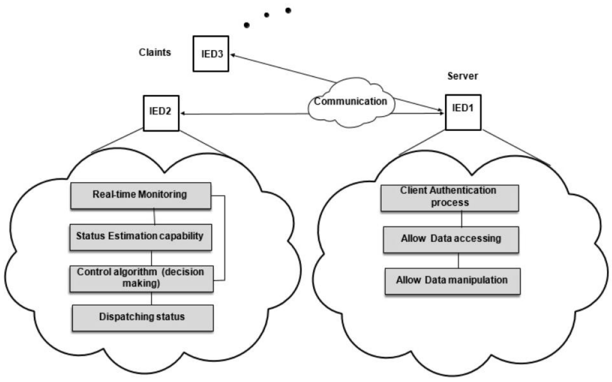

Figure 1: Distributed DMS IEDs overall concept

3 IEC 6180-7-420

Telecommunication and data transfer are from the most dominated cornerstones of smart grid. IEC 61850-7-420 specify various types of LNs and information modeling that is applicable for various DERs (e.g. fuel cell systems, photo-voltaic (PV), combined heat and power (CHP) etc.) [11]. The predefined LNs facilitate communication and integration of different DERs into the utility protection and automation systems. Utilities and various DER manufacturers are expected to achieve benefits from utilizing the IEC 61850-7-420 in terms of reducing the installation and maintenance costs. Furthermore, offering standardization for various DERs data models will improve the interoperability among the different DERs and distributed automation systems (DAS) and consequently improve the reliability and availability of the grid.

IEC 91850-7-420 standard addresses the information modelling for various DERs LNs whereas, other IEC 61850 implementation aspects such as the services modelling, assigned system configuration language and mapping schemes over the defined protocols are covered within the previous ten parts of the IEC 61850 first version [12]. From the proposed LoM protection point of view, two DER LNs have been considered: DPST and DRCS. The DPST LN provides real-time ECPs status and measurements, (ECPs and electrical connection points are usually associated with each DER, load, line, bus etc. that need to connect to the local electrical system network). The DRCS LN defines the control status of individual DER or group of the same DER type that are controlled with individual controller. More details about the data modeling of the DPST and DRCS LNs are given in Section 5.

4 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 on various solutions [12]. The solutions are written using various programming languages such as C, C#, Java etc. that automatically generate the low-level machine code files. These files contain the definitions of the data structures that build up the complete data model and also the pre-configured values provided by the substation configuration language (SCL) file. They are intended to be included in the designed function code file to efficiently access the IED data model within different operating systems. Embedded Linux open-source operating systems running on microcontrollers have recently become increasingly popular in both industry and academia, since, they offer a high stability, networking ability and extremely affordable prices.

With the developed light-weight MDS IEDs, communication among different DERs is achieved based on IEC 61850 protocols such as GOOSE, sample value (SV) and Manufacturing Message Specification (MMS). The used communication techniques are based on client-server or publisher-subscriber with a predefined application programing interface (API) functions such as “IedServer iedserver = IedServer_create( )” to create a server, “IedConnection_connect( )” to connect a client. API functions take arguments based on the preassigned variables and parameters [13].

In this paper DMSs unit microcontrollers are implemented as native IEC 61850 IEDs. The designed IEDs are running based on the light-weight IEC 61850. Data can be exchanged among active distributed DMS systems regardless of the communication system technology and medium which is one of the most powerful features of the IEC 61850. Therefore the state of-the-art communication system has been set out to fundamentally transfer different DMS IEDs capabilities. MMS (client-server) over GSM APN mechanism has been used. The data model tree of DMS light-weight IEC 61850 IED server can be accessed and manipulated by different DMS light-weight IEC 61850 client IEDs (for instance an embedded Linux microcontroller, regular PCs with different operating systems running from the open source libraries etc.). One of the most dominated computer networking protocol that is commonly used in WAN is the Internet. In this work, wireless communication over GSM APN mechanism has been used to exchange data among different mobile DMS IEDs and to ping the public Internet network, while there is no centralized decision maker. DMS IED clients access DMS IED server data model and use these data to make their own decision based on individual monitoring and observation.

5 Server Data Object Modeling Based on IEC 61850-7-420

In this section, virtualization for the proposed prototyped electrical system unit components had been made. The virtualization task was implemented based on the data object modelling using the IEC 61850-7-420 LNs. Figure 5 shows a simple electrical system that consists of four different DERs. Different active DMS IEDs are distributed over the electrical system topology through different distributed data points. These distributed active DMS IEDs are used for monitoring and LoM protection function purposes.

IEC 61850-7-420 has various DERs LNs that support different measurement parameters. In our previous study [14] and also in this study, two LNs were selected. The LNs are DPST and DRCS that represent the ECPs status and the DERs operation status respectively [15]. The two selected LNs provided the required information for the proposed LoM protection through different data objects. Figure 2 illustrates the LNs data structure listed in a tree format down to data objects.

According to the proposed LoM protection, DPST.ECPConn data object from the DPST LN which indicates the connection status of the DER at specific ECP is modelled. When this data parameter is set to “True”, it indicates that DER is connected to the electrical grid through the ECP, and not connected to the electrical grid if is set to “False”. Furthermore, DRCS.ECPConn and DRCS.ModOnConn data objects from the DRCS LN are also modelled. The DRCS.ECPConn indicates that the DERs are electrically connected to the ECP when this data parameter is set to “True” and vice versa. DRCS.ModOnConn indicates whether the DER is in operation mode (“ON”) and electrically connected when this data parameter is set to “True”, or electrically connected and not in the operation mode when it set to “False”. The DPST and DRCS LNs data attributes are updated continuously within the active DMS IED server data model. While active DMS IED clients are in real-time monitoring, these data attributes individually use the IEC 61850 MMS protocol over the GSM wireless communication system network. LoM control decision status can be released based on these monitoring, observation, estimation and processing tasks within different active DMS IED clients using the distributed decision making approach.

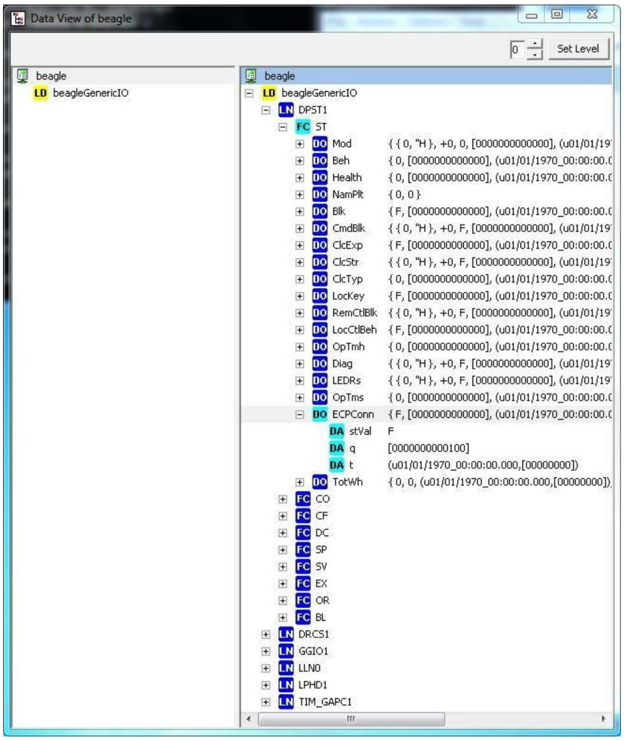

Figure 2: DMS IED data object modeling

6 IEC 61850-90-x

“The scope of IEC 61850 is no longer limited to substations” [6]. When the first scope of the IEC 61850 was prepared, it was intended to exchange information among the devices within the SAS. However, the global incoming booming of the DERs that needs to be integrated to the energy grid though the micro-grid concept, and their impacts on the distribution power systems turn into raising challenges. These challenges stimulate the utilities and DER manufacturers to announce the concept of growing need to define and standardize the communications outside the individual SAS that may include various SASs or micro grids over the telecommunication network.

As a result, a series of IEC/TR 61850-90-x have been published since 2010 as an extension of the IEC 61850 standard and to address these issues. IEC/TR 61850-90-1:2010 specifies the communication among various SASs and provides a comprehensive overview of different issues that are related to the inter-SASs using the IEC 61850 implementation aspects that had been covered within the previous IEC 61850 10 part's first version as illustrated in Figure **??**. In-

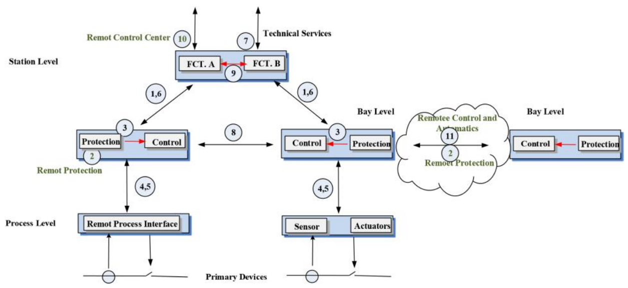

Figure 3: Logical interfaces between substation A and substation B.

terfaces (IF2, IF11) share the same characteristics of data exchange between substations on protection, automation and control distributed functions.

IEC/TR 61850-90-2 report considers the communication between the substations and the control centers, which is under preparation. The third report from the series is IEC/TR 6185090-3:2013. This considers the communication networks and systems for power utility automation using IEC 61850 for condition monitoring diagnosis and analysis. Consequently, IEC/TR 61850-90-4:2013 provides the engineering guideline for communication, considering the local area network limited to the requirements of IEC 61850 based SAS. Whereas, IEC/TR 61850-905:2012 provides the ability to exchange digital status and synchronous phasor measurements over a wide area monitoring protection and control (WAMPAC) among different phasor measurement units (PMUs) and control centre. The synchronous phasor measurement data content and use is defined by the IEEE C37.118, while the exchanging concept is compliant with the IEC 61850 definitions.

IEC/TR 61850-90-5 [7] supports the synchro-phasor's real-time exchange of measurement technical requirements that had been defined within the IEEE C37.118 standard by implementing the previously defined IEC 61850 protocols (GOOSE, SV). However, IEC/TR 61850-90-5 defines new routable mechanism through the new routable control block for the GOOSE and SV which are RG and RSV respectively. The mapped data by RG and RSV control blocks are encapsulated in a session protocol data unit (SPDU), in which the included data sets may contain information other than just the synchro-phasor's measurements. The encapsulated data is transmitted via the multicast UDP/IP services that improve the delivery priority through implementing the Differential Service Control Protocol (DSCP). The DSCP limits the probability of delivery packets lost upon the router congestion, by adding the priority tagging to the delivered packets. Consequently, according to the IEC/TR 61850-90-5 specifications, "source filtering" through the Internet Group Management Protocol Version 3 (IGMPv3) was specified. The IGMPv3 enables the subscriber hosts to register on a router and assign which group they want to receive multicast traffic from. As a result, the router does not need to deliver the packets over all the available paths, however, it determines the appropriate dedicated paths upon the registered subscriber hosts that improve the multicast delivery mechanism. Whereas, IEC/TR 61850-90-5 security is provided through the "perfect forward" security upon the encrypted key rotation between the publisher and the subscriber. The subscriber is announced beforehand about the next key rotation and the subscriber needs to detect the synchronization status with the current key.

At this point, IEC/TR 61850-90-12 was published in 2015, which provides definitions, guidelines and recommendations upon the existing standards and protocols for the WAN communication engineers. It considers the inter substation communications, substation to-control centre and inter control centre communications. Moreover, different issues related to utilities communication over WAN such as topology, redundancy, jitter and QoS have been addressed to facilitate understanding the technologies and integrating different selected components through the conduct testing.

7 LoM APplication of Light-Weight IEC 61850 Over GSM-APN Based Direct Clients-Server Wireless Connection

Wireless communication solutions for automation distribution networks have gained great potential since they can be implemented virtually anywhere at a very low-cost. Two different alternative solutions are applicable for utilities exploring wireless solutions. The first solution is to install a private (owner operated) wireless network. The second solution is to implement their wireless communication solution over an existing infrastructure of a public GSM network. The first solution offers more benefits due to more control over their communication system. However, this option requires more evaluation since, not just a significant up-front investment in infrastructure is needed to be recognized, but also the on-going operation and maintenance costs can be substantial. Whereas, the second solution allows a utility to avoid all these costs, and the saving costs can be weighed against (i) the network being public, (ii) sharing band-width with other users and (ii) security issues. From the inter-substation's communication viewpoint, two different kinds of communication network architecture are applicable, a gateway approach and a tunnelling approach. In the gateway approach used today, the only need is to add the use of IEC 61850 interface for the tele-protection equipment. However, it uses a low speed communication channel with specific tele-protection communication equipment. Whereas, the tunnelling approach uses a high speed direct bi-directional communication channel. This communication channel supports different kinds of the IEC 61850 communication protocols based on the communication between substations. In our case study, a special mechanism called APN communication solution is used, which is a gateway between the GSM and the public Internet. APN specifies how the mobile units in our case study activate DMS IEDs connected to Internet, other mobile units and a host site. It also determines what IP addresses need to assign by the carrier to the mobile units, what security methods are used, and how the GSM data network connects to the APN network. Therefore, a mobile unit's data connection must activate a Subscriber Identity Module (SIM) that contains the user's subscription information to present itself to the carrier and configure the preassigned APN profile by the carrier. At this standpoint, the carrier specifies all the above-mentioned parameters based on the customized APN logging profile. Figure 4 illustrates the "mob.uwasa" APN communication network.

From Figure 4, it is apparent that the APN communication system network offers a valuable and secure solution since, the mobile units, need to identify themselves to the carrier at first to start the data communication session. Moreover, the whole APN communication system network is beyond the operator and the local host firewalls so that the mobile units can ping the outside world but, not the other way (the mobile units are not seen from outside world).

8 Case Study

For better understanding of the LoM protection, a simple power electrical system network with simple GSM APN wireless communication system network has been defined in Figure 5. A wide area network (WAN) setup for the power electrical system communication network that includes five active DMS IEDs, one data concentrator and 2Mbit/sec APN wireless over GSM communication network has been established and illustrated in Figure 6. For the active DMS IED1 server, a light-weight IEC 61850 microcontroller is designed and modelled according to the IEC 61850-7-420 DERs LNs as a server. It is continuously monitoring the status of the ECP (feeder breaker) and updating the data attributes that are associated with. Active DMS IED2, IED3, IED4, and IED5 are also lightweight native IEC 61850 microcontroller that are configured as clients. These clients are connecting with DMS IED1 over the wireless GSM APN communication network. In addition, they allow to access the active DMS IED1 data object model. Therefore, active DMS IED clients observe any changes within the data attributes of the active DMS IED1 server data object model. These monitoring and observation tasks are facilitating the proper implementation of the proposed LoM protection function. Two different LoM scenarios have been defined and tested based on the above configuration setup. The first LoM testing scenario is by changing the DPST.ECPConn data object of the feeder ECP from "true" to "false" in DMS IED1 server. 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 active DMS IED1 server. 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 bus bar is opened (e.g. due to main transformer failure). The changing statuses in these two scenarios update the associated data attributes within active DMS IED1 sever data object model. Both scenarios represent a LoM situation that needs to be detected. In order to study the performance of the proposed LoM protection function over the GSM APN wireless communication system based on the WAN configure setup in terms of speed for communication channel, main and standard deviation of the round trip communication latencies had been measured and calculated as defined in Section 9.

9 Round Trip Latency Measurement Concept

Measuring and calculating mean and standard deviation of the round-trip time for the IEC 61850 MMS protocol connection between the client-server-client involve seven individual times that may affect the connection channel per-

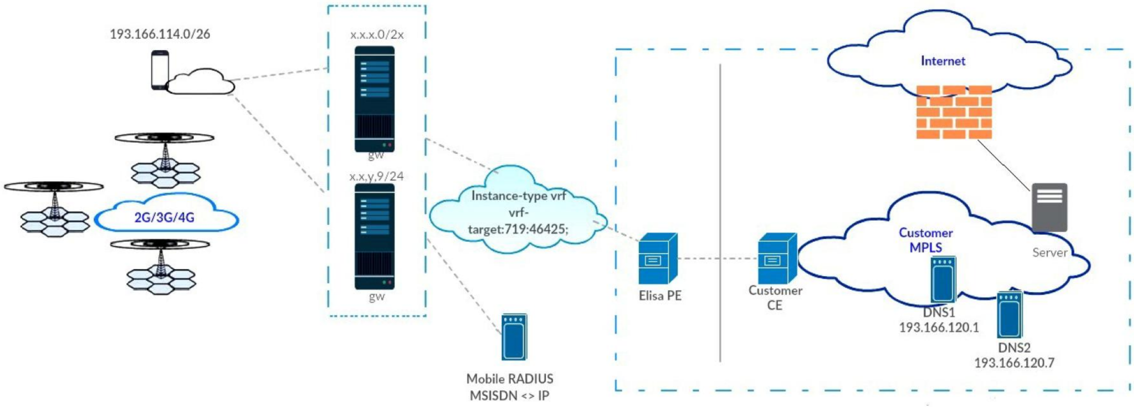

Figure 4: APN mob.uwasa communication system network configuration

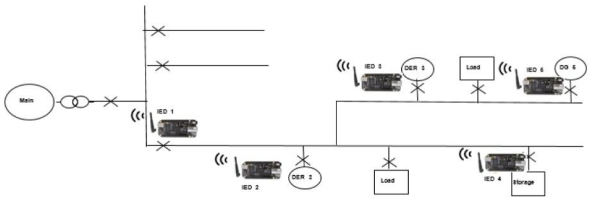

Figure 5: Power system with APN GSM wireless communication network

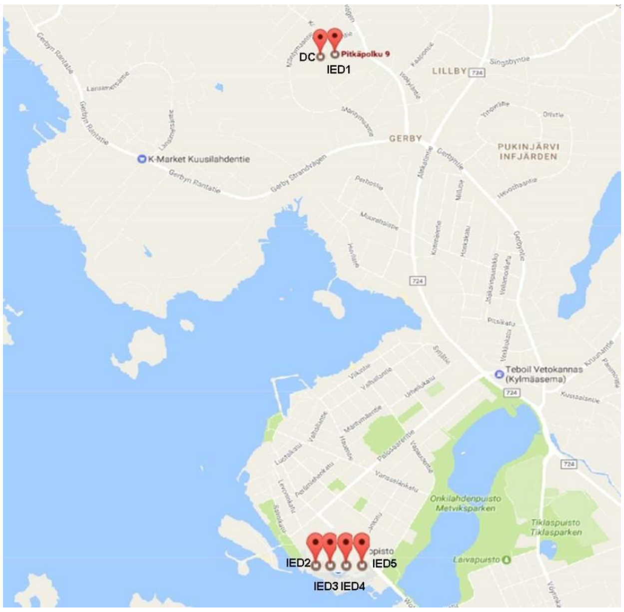

Figure 6: Communication network WAN locations

formance as illustrated in (1) and (2)

$$t_{RT} = t_{out.TS} + t_{net} + t_{in.DUT} + t_{App} + t_{out.DUT} + t_{net} + t_{in.TS} \quad (1)$$

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

where t_{RT} is the mean round trip time, $t_{out.TS}$, and $t_{in.TS}$ are the mean times in and out of the client IED (test system) that attempts to connect to the server. $t_{in.DUT}$, and $t_{out.DUT}$ are the mean times in and out of the device under test (DUT), t_{App} is the application mean time within the DUT, $\sigma^2{}_{RT}$ is the round trip variance and the rest of the variables in Equation (2) are variances of the items in Equation (1), respectively.

In our case study, round-trip time between active DMS IED1 server and active DMS IEDs clients for both scenarios had been measured. The measuring task is accomplished by reading the time stamp of the server when it started updating the status of the defined data attributes within the server data model and the time stamp of the client when it sent the dispatch output signal based on the monitoring and internal processing of the server data attribute statuses. At this point, it is preferable to mention here that all active DMS IEDs are synchronous based on the Coordinated Universal Time (UTC) server over the Internet and the accuracy of pooling network time protocol (NTP) can be achieved up to 1ms. The round trip time is measured based on the difference between active DMS IED1 server time stamp and the response of the active DMS IED client time stamp. This round trip time includes all the seven individual times as illustrated in equation (1) in which the performance evaluation of the proposed LoM protection based GSM APN wireless light-weight IEC 61850 method is reflected.

10 Testing Results

In this section, test results of the LoM based wireless WAN setup are presented. Changing of the main supply DPST.ECPConn or the DRCS.ModOnConn data objects to false signify disconnection of the main supply from the electrical grid or the connection is not in operation (but the main supply is electrically connected to the grid), respectively. In both cases, there is a LoM situation and DERs must be disconnected or changed to the island operation mode. By accessing the active DMS IED1 server data object model, the main supply status is eventually observed by all the active DMS IEDs clients and the LoM situation is properly handled even with high penetration of DERs. The changing of data attribute status in active DMS IED1 for both scenarios initiate and release the dispatching LoM control status. This dispatching LoM control status can be seen as a change in the output pin 44 within active DMS IED client board in response to the proper implementation of the LoM protection function. According to the test scenarios, 100 trials of DPST.ECPConn and DRCS.ModOnConn status changes had been made within active DMS IED1 server. All active DMS IED1 data attributes are updated based on the new statuses. Active DMS IED clients implement real time monitoring and observation of these changes. As per the results, there were no LoM situations that were not observed or detected. Round trip time for testing scenarios was calculated as in equation (1). For the graphical representation of the acquired times, two functions of the Matlab software; hist(X) and ecdf(X) were 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 than 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 scenario one, active DMS IED1 DPST.ECPConn status change and the change in output pin 44 active DMS IED clients as responding the round trip latencies histograms are illustrated in Figures (10.1-10.4).

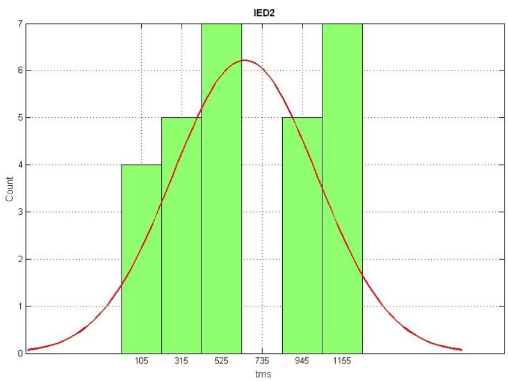

Figure 7: Histogram for the DPST.ECPConn based IED1-IED2 round trip time

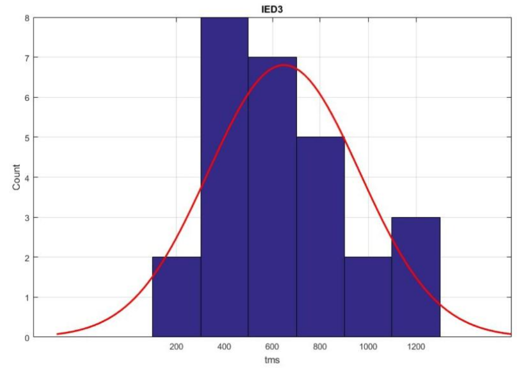

Figure 8: Histogram for the DPST.ECPConn based IED1-IED3 round trip time

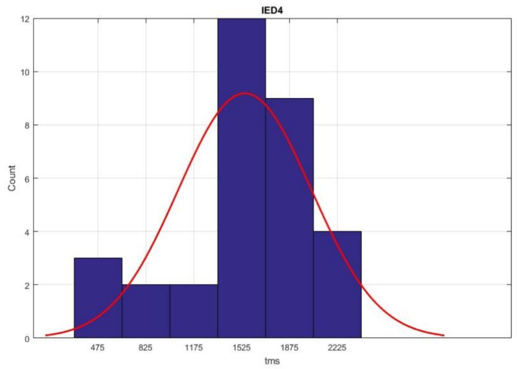

Figure 9: Histogram for the DPST.ECPConn based IED1-IED4 round trip time

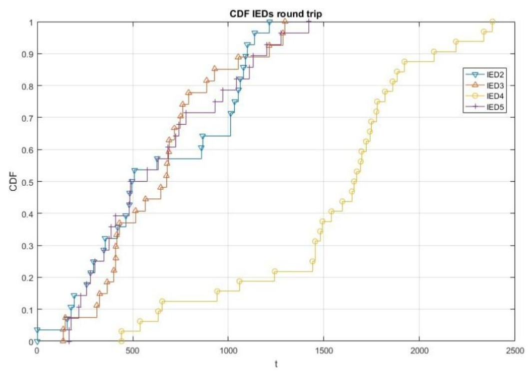

Figure 10: Histogram for the DPST.ECPConn based IED1-IED5 round trip time

In this paper scenario one result are presented since there are no big differences between the results from both

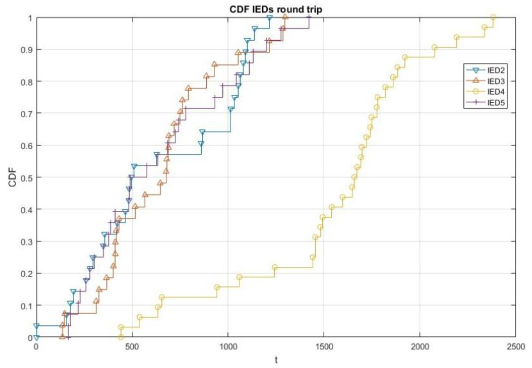

Figure 11: Probability CDF for the DMS IED1- DMS IEDs clients' round trip time

scenarios. However, scenario two represents another LoM situation among others.

11 Discussion

Wireless communication solutions for automation distribution networks based IEC 61850 provide a promising alternative for LoM protection and maintaining DERs selective operation even with high DERs penetration within the distribution system. From the results obtained, it can be seen that, active DMS IEDs clients are inherently capable of observing and responding to all the different changes in the main supply data attributes status. This also enables some advanced operational scenarios. These functionalities have proven to be possible with the newly introduced light-weight IEC 61850 embedded microcontroller based active DMS IED clients. Since a separate wireless over the GSM APN communication mechanism system is applied, the method is less susceptible to the electrical grid events compared to PLC based alternatives. As discussed in [8], the voltage drop for PLC transmitted signal during a three phase fault was considerable and large transients in the signal appeared after clearing the fault.

The test results show that the wireless over GSM APN communication channel had slightly different round trip times depending on the communication channel quality between the client and the server, mobile broadband dongle model, frame ware version of the mobile broadband dongle and end active DMS IED client data processing time. The results also behave according to the normal distribution model, which was expected. Since the APN over the GSM communication network is assigned fixed speed and with some value of priority from the carrier upon some extra cost added over the normal subscription. Using the normal distribution probability density function, the mean and the standard deviation of the round trip time's latencies had been calculated in (Table 1). The mean round trip latency of active DMS IED1-IED4 was greater than other active DMS IED clients, since the mobile broadband dongle used was an old Huawei E353 version that supports only 2-3G communication. In general, the implementation of the light-weight IEC 61850 within the microcontroller and the execution of different client-server or publisher subscriber codes add more extra latencies to the overall round trip time. However, the results obtained for both scenarios are within the acceptable assigned range (1000 ms) for the WAMPAC/IEC 61850-90-5/. The CDF graph Figure 11 shows that around three quarters of the samples had times ≤ 1000 ms (except DMS IED4). Therefore, the round trip latency does not limit the applicability of the LoM protection based wireless communication over GSM APN network. Moreover, from the LoM communication method point of view, the proposed LoM method enables flexible solution that no pre-established communicating system infrastructure is required, since the existing public GSM communication network has been used.

Light-weight IEC 61850 within inexpensive embedded microcontroller is a promising solution that reduces the time, complexity and overhead information associated with IEC 61850 implementation. Moreover, it allows modelling 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, 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 the WAN setup testing and comparing purposes, inexpensive microcontrollers are applied as light-weight native IEC61850 active DMS IEDs. The main objective of using the light-weight IEC 61850 microcontroller IEDs was to verify the implementation of the light-weight IEC 61850 MMS wireless based LoM protection application. This also enabled to prove the correctness of the design, modelling 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 monitoring other different data objects from other LNs of DERs to be used within other protection and controlling functions. 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

Table 1: Mean and standard deviation round trip times

	DPST.ECPConn			
	IED1-IED2	IED1-IED3	IED1-IED4	IED1-IED5
Mean value	645.434ms	648.222ms	1548.406ms	636.714ms
Std. dev.	377.384	316.597	486.493	370.383

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 based on the strongest fault signature captured by the observer active DMS IED within the electrical grid [18].

More practical testing results are still needed for more analysis and to obtain results under different circumstances and state-of-the-art wireless communication technologies and techniques, since wireless communication technologies are being developed rapidly [19].

12 Conclusion

This paper has presented the novel LoM method based on MMS IEC 61850 within the wide area network monitoring. Favourable wireless GSM APN communication network has been used based on practical WAN setup. The results show that, all the different main grid connection status changes in real-time updated within the active DMS IED1 server are observed and processed by all active DMS IEDs clients and within the allowable time range. Thus, the method offers viable solutions for LoM protection that is also capable of avoiding the nuisance tripping. Furthermore, the introduced light-weight IEC 61850 IEDs provide a platform to some advanced control and protection functions. By extending the monitoring data object that include different DERs LNs data attributes, situation awareness type of solutions can be developed fulfilling the most advanced smart grid operation requirements. The proposed LoM based MMS IEC 61850 supports different grid configurations and is fully functional even with the high penetration of DERs. In such a situation, the question is not only to have LoM protection operation but also to enable smooth transition to islanded operation in some parts of the system. Next steps in our research will be the verification of the proposed method in different state-of-the-art wireless communication technologies and techniques with different circumstances.

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