IEC 61850 Digital Substation Design Tutorial for Novices

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Abstract—A substation protection and control system based on the concepts of IEC 61850 can be built faster, more efficiently, and more repeatably by replacing physical wiring with digital communications. For a utility, it means replacing easily understood and easily learned wiring with the complexity of data modeling, data flows, and communications networks. This involves learning & understanding several standards. These standards mainly include IEC 61850, IEEE 1588 v2, IEC 62439-3, and IEC 61869. Most of these standards have multiple parts, editions and revisions. For example, IEC 61850 consists of ten main parts with several other associated parts still being edited and added. IEEE 1588 has multiple profiles applicable to the power utility sector and so on. Hence, the research and design can be quite intimidating and discouraging for a new user to go through all of these before starting a project.

National Grid is actively working on their first substation with a fully digital protection and control system and has had to develop the knowledge and understanding necessary to support this project. This paper describes the step by step approach used by National Grid for designing the architecture, selecting different components, and testing the system for a fully digital substation project. The paper answers questions like where do we start? What redundancy protocol to use? What time synchronization profile to use? By describing the process National Grid has worked through, this paper is intended to be used as a foundation for other utilities to approach IEC 61850-based digital substation design.

I. INTRODUCTION

Introduction of IEC 61850 has paved the path to the realization of digital substations. A substation protection and control system based on the concepts of IEC 61850 can be built faster, more efficiently, and more repeatably by replacing physical wiring with digital communications. This involves learning & understanding several standards. These standards mainly include IEC 61850, IEEE 1588 v2, IEC 62439-3, and IEC 61869. Most of these standards have multiple parts, editions and revisions. For example, IEC 61850 consists of ten main parts with several other associated parts still being edited and added. IEEE 1588 has multiple profiles applicable to the power utility sector and so on. When a utility decides to implement an "IEC 61850 Digital substation", the user must understand that to design such substation, the user not only has to research IEC 61850 but also must research the other

standards that the IEC 61850 standard relies on; this aspect is mostly overlooked. For a new user to want to understand and create a digital substation design, this can be extremely overwhelming.

This paper is based on the experiences of the authors, written as a tutorial that would have been nice to have in our early endeavors into the world of digital substation design. It is written as a tutorial for novices on digital substation design to give a guide to where to start and what key concepts or items that you need to consider when creating a digital substation design. The goal is to provide the reader with a good starting point and to point out some key concepts to keep in mind when creating a design.

II. DIGITAL SUBSTATION CONCEPTUAL DESIGN

A. Conceptual Design Step One

When at the initial phase of implementation of digital substation design, one must first decide what the goal is and what you are trying to accomplish. To understand the conceptual design of a digital substation, the user first must enhance his knowledge base. Learning the basic concepts about IEC 61850 is the first step. The IEC 61850 standard is comprised of ten main parts with several other associated parts still being edited and added. For this paper, we will focus on the following parts to provide the user with a good foundation.

- IEC 61850-5 Communication requirements for functions and device models. This part discussed communication requirements for interoperability.

- IEC 61850-6 Configuration description language for communication in electrical substations related to IEDs. This part defines the configuration description language that really makes the IEC 61850 standard powerful and vendor agnostic. The Substation Configuration Language (SCL) is an extensible Markup Language (XML) based language.

- IEC 61850-7 This part provides the power utility data models and data object definitions. Part 7-4 Basic communication structure, compatible logical nodes classes and data objects. Part 7-4 is a key part of the standard to understand the data

available for your digital substation design and is constantly used for reference throughout the digital substation design phase.

- IEC 61850-8 & -9 These parts discuss mapping of the classes and services to communication stacks

- IEC 61850-10 Conformance testing

- IEC/TR61850-90-4 Network engineering guidelines

B. Conceputal Design Step Two

Once the user has navigated through the standard, the next step is to understand the current standards and practices that their organization utilizes and why your current system is designed that way. The P&C standards & practices in the utility exist for a reason, and it might not be possible to completely change the design. A utility's current P & C practices tend to limit your digital substation design. Based on utility experience it is the author's opinion that there are two parts to a P & C standard. First being the protection and control philosophy based on decades of experience, theory, and art. The other is the cultural differences in designs that were based on past organizational experiences. As you work your way through it, you would find certain aspects of your current P&C standard that could be improved or simplified, while for others, you might face some limitation due to the technology available.

C. Conceputal Design Step Three

In a utility exists multiple stakeholders when designing, building and maintaining a substation. The success of implementing IEC 61850 to current design practices relies on pulling the stakeholders upfront at the beginning of your initiative. By pulling all parties in up front, they are part of the design, they own it too. The customers for engineering are the traveling operators, power control center, and protection and telecommunication technicians. You need to know what your customers want and what would make their job more efficient. You cannot work in a vacuum when creating a design. "People fear the future because they do not see their place in it"

D. Conceputal Design Step Four

The user needs to take a top down approach on the digital substation design. Maintain protection and control philosophy but minimize the limitations of the design due to the technology available. What do I want my system to do, how do I want it to perform?

E. Conceputal Design Step Five

The most essential part to the success of implementing a digital substation is to invest in a lab. Find a real project to fund the lab project, the cost can be capitalized on a project or spread out over multiple projects. The lab is crucial for proving the design, evaluating equipment, testing schemes, working with stakeholders such as protection technicians, and training. The lab was the single most important part of implementing IEC61850 that accelerated the National Grid team knowledge base of how IEC 61850 works.

F. Conceputal Design National Grid Approach

National Grid started with a top down approach to digital substation design. A dedicated department comprised of experienced protection and control engineers was created to focus on digital substation design. With protection and control experience we lacked IEC 61850 knowledge base, therefore we evaluated multiple consultants to help train and create digital substation standards along with us. They were there to bridge the gap of IEC 61850 knowledge. As a group we realized quick that we had to have some basic understanding of the appropriate standards and network knowledge.

III. IED DATA MODEL & SERVICES

Next step in the design process is to select the substation IEDs with the correct IEC 61850 data model and services.

The object-oriented data model of IEC 61850 defines the functions of an IED in terms of logical nodes that can communicate with each other. Fig. 1. shows an example of the data model of an IEC 61850 IED. The physical device (LPHD) is divided into multiple Logical Devices. The Logical Devices further breaks down into Logical Nodes.
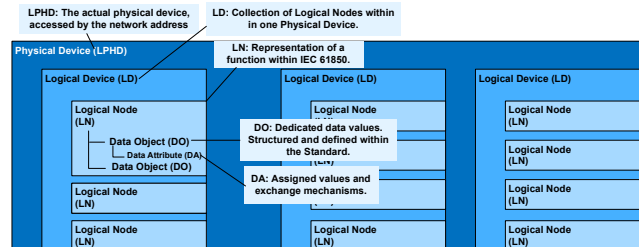

Fig. 1. Data Model Hierarchy

When deciding on the specification of the IEC 61850 IEDs for the P&C applications, the user should finalize the functions required in the IEDs and create a list of the data models required in the IEDs accordingly. A good reference to learn more about IEC 61850 data models is IEC 61850-7-4 which defines different data model semantics. It is a good practice to utilize the logical nodes to the full potential and try to avoid using generic logical nodes such as GAPC or GGIO unless it is truly necessary.

One important point while defining the data model of the IED is that the user should ensure that the selected logical nodes have all the required data objects. E.g. Consider the case of the LN CSWI as shown in Fig. 2. CSWI is the logical node for switchgear control.

Fig. 2. CSWI Class Example [1]

As can be seen from above, LN CSWI has only one mandatory data object as "Pos", which means that an IED having only "CSWI.Pos" can technically claim that it supports LN CSWI. But does that meet your requirement?

When we looked at our requirements for LN CSWI, we found that we needed to have the other "optional" items as highlighted above in our IEDs. Therefore, specifying and selecting the right IED is very important, otherwise you might end up using the generic signals from LN GGIO.

While specifying the IEDs, the user should also define what other services & capabilities are required in the device. e.g. the user should define:

- how many GOOSE and Sampled Value inputs should be supported by the IED

- how many GOOSE control blocks, buffered and unbuffered report control blocks are required

- how many MMS clients should be supported

- Other services required such as MMS File Transfer etc.

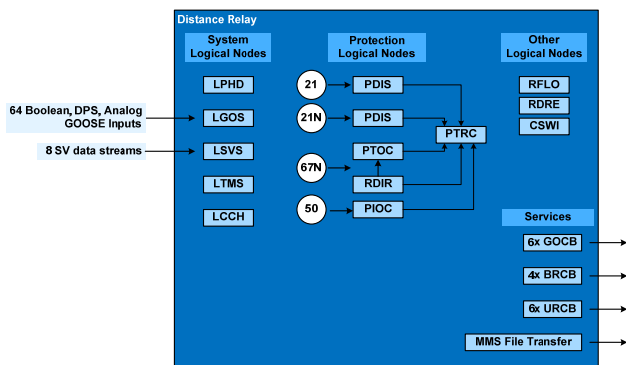Fig. 3 & Fig. 4. shows the example of the data model of a distance relay and Bay Controller:

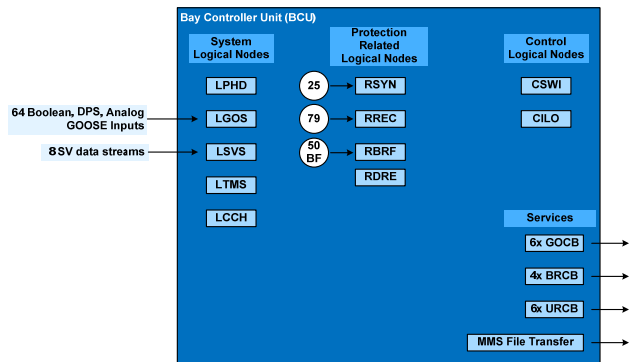Fig. 3. Data Model Example of a Distance Relay

Fig. 4. Data Model Example of a Bay Controller Unit

As the National grid IEC61850 team explored the standard and the data modeling available for our use, it was time to decide how to create data map for a standard National grid substation. The configuration files and data mapping are all based on IEC 61850 therefore it does not matter what make & model of IEDs are used as long as they support the required data model. Protection data mapping is straightforward and is consistent with current protection philosophies. An example of national grid approach in protection IED data mapping design. A protection IED will perform protection and anything associated with protection. An IED that will perform a Line distance with back up directional overcurrent functionality shall contain the following logical nodes: PDIS (multiple instances) and PDEF. These logical nodes reside in the IED and are assigned to a trip matrix. The actual output logical node that can be seen on the network would be PTRC which is the logical node for trip.
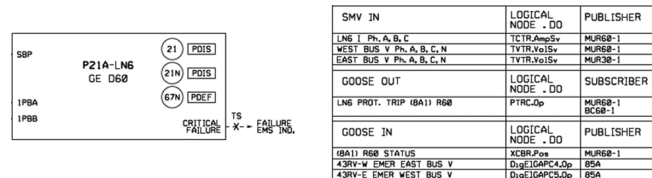

Fig. 5. Line Protection IED Data Map Example

Control, unlike protection is not as straightforward. Conventional substation uses mechanical switches to operate physical primary switchgear and electromechanical relays for functionalities such as lockout relay. There is a new device to consider in your design to perform these said control functions and that is a bay controller. A BCU (Bay Controller Unit) is an IED that provides physical control of equipment such as circuit breakers and disconnect switches. These devices have the capability to control multiple physical devices within a single IED. At National grid we took the following approach to our design. Although a bay controller can control multiple physical devices out in the yard we chose to maintain a bay controller per circuit breaker and the circuit breaker's associated isolating disconnect switches. This decision was made due to regulatory requirements for maintenance and operation within our territory. There was an opportunity to utilize this device for not just control but also use this device for to provide breaker

failure, lock out, auto synchronization and auto reclosing functionalities.

An example of bay controller design at National Grid. Within the bay controller we utilize protection related functions breaker failure (RBRF), lock out, Auto synchronization (RSYN), and Auto reclosing (RREC). For control functionality CSWI was chosen to be used in the bay controller as well. CSWI is the logical node for switch control and is used for to control all switching conditions. It is important to point out one key point in this example and that is lockout functionality data mapping. Currently the standard does not specify a logical node for lockout functionality. Therefore, lockout functionality is open to interpretation and left up to users to decide what logical node makes sense for the user design. The closest thing in the standard to lockout is the logical node is CILO which is interlocking (ANSI 3). The decision was made by this author to utilize a data attribute within the logical node CSWI to perform lock out blocking functionality. The decision was done because CSWI is already being used for control of the equipment and therefore lockout blocking function made sense to be mapped to the CSWI.BlkCls.

Fig. 6. Bay Controller Data Map Example

IV. SUBSTATION NETWORK DESIGN

We, the authors, when we started as newbies to IEC 61850, we quickly realized just as you, as the reader would, that the digital substations require networks, but we were not network experts. Best resource that provided us with the basic network knowledge were IEC/TR 61850- 90-4 and IEC 62439-3. Reading these resources provides the basic tools to help in the decision making of network architecture in a digital substation. Proper network design for a digital substation is critical for the success of the substation. Unlike a conventional substation, sections of the network now become part of the protection and control scheme. When starting our digital substation design, we quickly realized the need to have networks in a substation multiple Local area networks (LANs) exist in a substation, fist being station bus. Station bus is the non-critical local area network that provides information to SCADA. Non-protection critical information such as Energy Management System (EMS) control and status communicate within this network using non-critical protocols such as Manufacturing Messaging System (MMS). If information is slow or packets are lost on this network the substation functionality and safety are still intact, therefore a redundancy protocol such as Rapid Spanning Tree Protocol (802.1w) could be used.

Process bus is the LAN infrastructure that communicates to the merging units and IEDs. This network requires a robust and reliable network as this is now your protection scheme. All sample value information for the IEDs reside on this network

as well as any critical trip, status and block commands. Any information lost will have a major impact to reliability and safety of your substation. A high precision clock synchronization and a "bump less" network is required for this network, meaning a failure of a port or path will not affect the performance of the device (seamless). IEC61850 90-4 Communication Networks and Systems for Power Utility Automation provides the guidance for proper engineering of local area networks based on requirements of IEC 61850.

Although National grid approach to Digital Network architecture design involved segregating multiple local area networks in a substation there is nothing that prevents the user to combine SCADA, Sample Values, GOOSE, MMS, etc. into one local area network. The National Grid engineering team chose network segregation due to the following factors. The station bus in non-critical information utilizing mainly MMS messages and therefore maintaining this information on a robust network such as process bus introduces the potential probability of non-critical network information effecting critical protection and control information. The redundancy in the non-critical network can be provided by a less robust network architecture. The ownership and interests of the two networks are also properly managed by segregation.

The process bus is the critical network and requires a robust network, sample values and GOOSE messages reside on this network. There is one overall station bus LAN in the substation, but the process bus networks are separated into two separate networks one for system one and one for system two with diverse equipment manufacturers used in each system. This reduces any configuration issues, firmware, cyber security patches, etc. from one system effecting the other protection system. This design also follows Northeast Power Coordinating Council (NPCC) Directory 4 practices. We use a zero-recovery network protocol because of the reconfiguration time of as long as 1ms (RSTP being 5ms per hop) will have an undesirable impact on the protection performance.
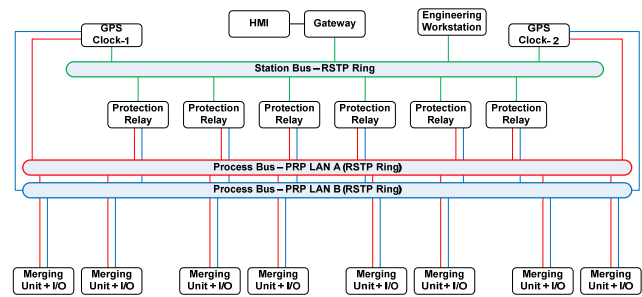

Fig. 7. General Network Architecture

V. RELIABILITY & REDUNDANCY DESIGN

IEC62439-3 discusses industrial communication network protocols, Parallel Redundancy Protocol (PRP) and High Availability Seamless Redundancy (HSR). These two protocols are widely used for IEC 61850 process bus design for seamless network communication. Most manufacturers support either

one or both protocols. Each protocol has pros and cons and based on the user's design goals and requirements.

Parallel Redundancy protocol (PRP) provides a seamless failover in the event of a network component failure, the failure is completely invisible to the Intelligent Electronic Devices (IED). End nodes from each device are connected to two similar LANS which operate independently in parallel. This redundancy protocol allows for easy network expansion, however multiple network switches. National grid design team chose PRP as the process bus network redundancy protocol. This was chosen over other protocols due to no network configuration needed in the switches, the edge devices just need to enable PRP. The flexibility for future configuration changes, an IED or test equipment can be easily connected without the break of the existing network devices.
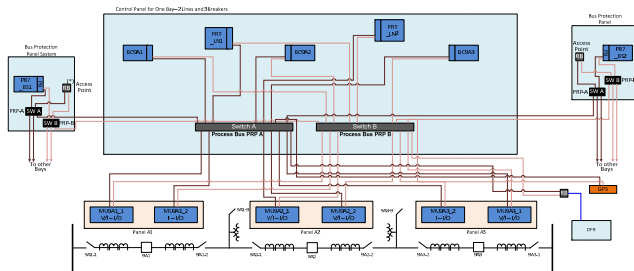

Fig. 8. PRP Architecture Example

High Availability Seamless Redundancy (HSR) also provides a seamless failover in the event of a network component failure, the failure is completely invisible to the Intelligent Electronic Devices (IED). End nodes from each device are connected in a loop between devices. This redundancy protocol allows for minimal use of network switches as the device ports are switching port which act as a bridge.
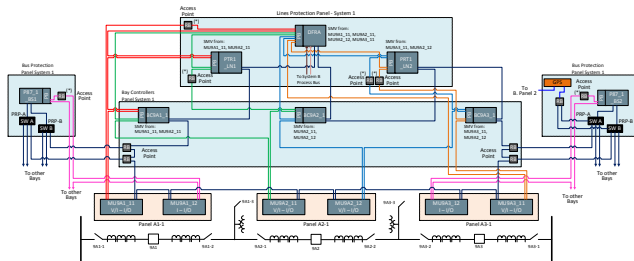

Fig. 9. HSR Network Example

In order to maintain simplicity & flexibility of the network, and to minimize the change from the current networking practices, we decided to go with PRP.

VI. TIME SYNCHRONIZZATION FACTORS

Time synchronization is one of the key components in a digital substation design. Conventional substations have been using time synchronization mainly for the time tagging of the events and files; And the unavailability of the time sync wouldn't affect the core protection and control functions. However, in digital substations, time synchronization is not only used for basic date & time sync of the IEDs, events etc.,

but is also required to synchronize the sampling in Merging Units and hence the protection & control functions could be directly affected due to unavailability of the correct synchronization. e.g. current and voltage sampled values required by a distance protection relay must be synchronized with reference to a common source, else this would introduce a phase shift and could cause a mis-operation.

It is also important to understand the difference between "absolute" time sync and "relative" time sync. An absolute time sync of an IED refers to the "date & time" synchronization of the IED with reference to a global time-traceable source, such as GPS. e.g. time tagging of events require an absolute time synchronization, PMU requires an absolute time sync. A "relative" time sync refers to the synchronization of the devices relative to each other. e.g. in the previous example of a distance relay working with current & voltage samples, these current & voltage sample need to be synchronized with reference to a common source. This common source need not to be a global time-traceable source. e.g. 1 PPS signal is not a source for an absolute time but could be used to synchronize the devices, such as merging units within a few μs of accuracy.

IEC 61850 defines different time synchronization classes based on different accuracy requirements for different applications as per Fig. 10.

Time synchronization class	Accuracy [μs] Synchronization error	Application
TL	> 10 000	Low time synchronization accuracy – miscellaneous
T0	10 000	Time tagging of events with an accuracy of 10 ms
T1	1 000	Time tagging of events with an accuracy of 1 ms
T2	100	Time tagging of zero crossings and of data for the distributed synchrocheck. Time tags to support point on wave switching
T3	25	Miscellaneous
T4	4	Time tagging of samples respectively synchronized sampling
T5	1	High precision time tagging of samples respectively high synchronized sampling

Fig. 10. Time synchronization classes for different applications

Different time sync methods, such as SNTP, 1 PPS, IRIG-B and PTP, could be used to meet different accuracy requirements. E.g. SNTP, which has been in use in the power industry for a very long time, provides an accuracy of a few ms, and therefore is suitable for the standard time-tagging of events to meet Sync Class T0 and T1. PTP as defined in IEEE 1588-2008 is a highly accurate time-sync mechanism that could meet the accuracy requirements of time-sync class T4 and T5. Both PTP and SNTP are based on the Ethernet network and do not require any extra wiring. To keep the substation design simple, the authors recommend using PTP and SNTP, with preference to PTP wherever possible.

IEEE 1588-2008 defines the core mechanism of the PTP. IEEE PSRC defined a specific PTP profile for power system called as IEEE C37.238-2011 which was later split into IEC 61850-9-3 and IEEE C37.238-2017. PSRC report [2] summarizes the differences between all these profiles. Below table [2] in Fig.11 shows how different PTP profiles meet different requirement and would help the user to choose the right profile.

Fig. 11. How different PTP profiles meet the Power Utility User Requirements

However, it is possible to have multiple PTP profiles in a given network, in order to maintain the simplicity and ease of troubleshooting, it is recommended to use only one profile in the substation network, either IEC 61850-9-3 or IEEE C37.238-2017.

VII. REDUNDANCY OF CLOCKS

Since time server clocks are one of the key components in a digital substation, it is important to ensure the availability of the master clock in a given system. This is achieved by adding multiple clocks in the network and utilizing redundant networks. IEEE 1588v2 defines Best Master Clock Algorithm (BMCA) to select the Grandmaster clock out of these multiple available ordinary master-capable clocks on the network. Slave clocks running PTPv2 would run BMCA and automatically synchronize to the selected grandmaster clock. It is recommended to define two master-capable clocks supporting IEEE C37.238-2017 & SNTP for the substation network.

Selected PTP clocks (Master & Slaves) should also be able to operate in redundant LAN architectures as per IEC 62439-3:2016 Annex A

For the IEDs synchronizing using SNTP, it is recommended to select the IEDs that allows to define multiple SNTP master clocks. Also, the Ethernet switches selected for the substation network should also support the "Transparent Clock" functionality as described in IEEE 1588v2 to maintain the desired μs accuracy.

VIII. NETWORK TRAFFIC SEGREGATION

Majority of the network traffic in a digital substation is in the form of multicast GOOSE and Sampled values. If the network is not properly managed, this multicast traffic can cause significant increase in the bandwidth utilization across the substation network. Therefore, it is very important to design the network architecture in such a way that the traffic is only limited to the ports where it's intended to flow. This is achieved by segregating the network traffic using different mechanisms such as Multicast filtering, V-LAN filtering and Access control list.

Multicast Filtering: All Goose & SV multicast frames have a "destination" multicast address in the header of the frames. The Ethernet switches used in the network use this "destination address" to limit the forwarding of the multicast messages only to the ports requiring this message. Let's consider the following network:

Fig 12. Ethernet switch connecting Goose Publisher and Subscriber

IED A is publishing GOOSE messages with the following parameters:

SETTING	PARAMETER
TxGOOSE1 MODE	GOOSE
TxGOOSE1 GoCB name	L90_GoCB01
TxGOOSE1 GoID	L90_TxGOOSE1
TxGOOSE1 DatSet	TT6DataSet1
TxGOOSE1 DST MAC	01-0C-CD-01-00-02
TxGOOSE1 VLAN PRIORITY	4
TxGOOSE1 VLAN ID	2

Fig. 13. Parameters for Goose Control Block of IED-A

The destination MAC of the above Goose message is 01-0C-CD-01-00-02. IED B, connected on port 8 is the subscriber of this GOOSE message. With the help of the below static* MAC filtering in the switch, we can ensure that the above GOOSE message is only forwarded to port 8.

Fig. 14. MAC Filtering showing how a GOOSE with a given Dst MAC is forwarded to a given port

Same concept can be used to limit the Sampled value traffic. Similarly, the user can create "multicast domain" where all the devices in the domain receive a certain multicast address.

*Dynamic multicast filtering is also possible provided that all the end IEDs and Ethernet switches support GMRP/MMRP. However, this approach is not recommended as it could result in unpredicted network.

V-LAN Filtering: VLAN allows to create a logical separation within a physical network. With the use of V-LAN tag available in the GOOSE/SV frames, the user can limit the multicast traffic. Let's consider the network shown in Fig. 12 with the help of following V-LAN configuration in the Ethernet switch, the user can make sure that GOOSE message with V-LAN Id=2 is limited to port 7 & 8 only.

Fig. 15. V-LAN Filtering defined in the switch

It is to be noted that VLAN filtering applies to all the traffic and is not limited to only multicast messages. Care must be taken during the engineering to configure the network correctly so that the traffic without VLAN is managed properly. Ethernet switches now a days offer a great flexibility to decide whether a given port only allows the tagged frames, or untagged frames or both tagged and untagged frames; similarly, the user can choose to retain or delete the VLAN tag on the egress. E.g.

Port VLAN Configuration

Port	Mode	Port VLAN	Port Type	Ingress Filtering	Ingress Acceptance	Egress Tagging	Allowed VLANs	Forbidden VLANs
*	<>	1	<>	☑	<>	<>	1	
1	Hybrid ▾	1	C-Port ▾	☐	Tagged and Untagged ▾	Untag Port VLAN ▾	2	

Fig. 16. Configuration for ingress & egress traffic

In the above picture, the port 1 allows both the tagged and untagged VLAN traffic on the ingress, however for the tagged traffic, only VLAN=2 is allowed. And when the traffic is sent out of this port, all the original incoming VLAN tags are maintained. For a different use case, the user can also define a range of "forbidden" VLANs.
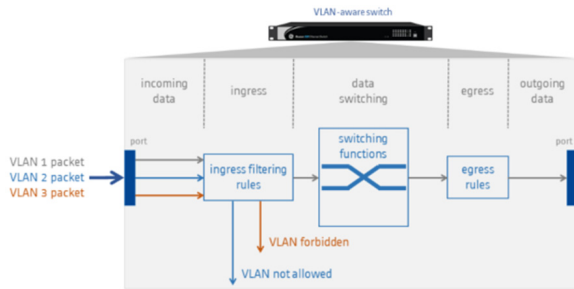

Fig. 17. V-LAN Mechanism in the Ethernet Switch

ACL: **Access Control List** can also be used to allow or deny an Ethernet traffic on the ports of the switch. Since ACL allows to control the ingress traffic to the switch, it can be used to completely block a certain type of traffic, such as GOOSE and SV.

e.g. the Ether Type for GOOSE is 0x88B8. we can utilize ACL to block all GOOSE messages on a given port/all ports of the switch:

Ingress Port	Policy / Bitmask	Frame Type	Action	Rate Limiter	Port Redirect
Port 8	Any	EType- 0x88b8	Deny	Disabled	Disabled

Fig. 18. Access Control List for all GOOSE messages

In the above Fig. 18., ACL blocks all GOOSE messages on Port 8. This policy could be applied to all the ports of the switch. Similarly, by using EtherType 0x88BA, we can create a ACL for Sampled values.

Recommendation: What to use?

However, the method of filtering depends on the application use case and the IEDs supporting these mechanisms, the good thing is that all the above three methods can co-exist in a given network. New users might find V-LANs easier to use than multicast filtering, just because V-LAN Ids are just standard decimal numbers and are easier to remember, assign & manage. So, the user could define V-LAN Ids for the GOOSE & SV and define the VLAN filters on the Ethernet switches. However, it is still recommended to define unique destination multicast addresses for all the GOOSE & SV in the substation as it would help the end devices to filter-out the unwanted messages quickly in case the IED is receiving unwanted messages for any reason.

ACL could be used on the switches connecting the station bus HMI, gateway as these don't need any GOOSE & SV. However, the engineering workstation on the station bus might need access to the SV and Goose

IX. CONCLUSION

In conclusion you must first understand what you want to accomplish and why you want to change your standard substation design that you have been doing for so long. Base your design options on the limitation of your current protection and control practices and not on the technology available. Second, start with the IEC 61850 standard parts recommended in this paper as a starting guide. You will realize that these parts will guide you to other sections of the standard you require in a more systematic order. Seek out basic networking knowledge other than IEC61850 -90-4 and so on. Networking basics are the key to a successful design.

As experienced IEC 61850 users we look back to the time we were IEC 61850 newbies there was very little documentation to help a new user understand and navigate through the extraordinary amount of information and knowledge required to utilize the standard. Because of this it can be overwhelming and discouraging for a new user. Do not let this prevent you from digital substation design as the pros are worth the effort to design a digital substation. Once you devote enough energy and time you will soon realize that the standard is actually very easy and intuitive if you know what and where to look for information. We had to make decisions on how to create a good digital substation design just as you will have to. Hopefully the background we provided in this paper can help you make yours and remember there is no design option that is wrong.

REFERENCES

[1] IEC 61850-7-4, IEC 61850-5 Ed 2.0
[2] Revision of IEEE Std C37.238, Power Profile for IEEE-1588: Why The Big Changes? By: IEEE PSCC Task Force P1 Members and Guests
[3] IEC/TR 61850-90-4 Ed 1.0