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Implementation of QOS in the process bus for Digital Substations

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1. SUMMARY

Electrical utilities around the world are gradually understanding the importance of the automation of the assets within generation, transmission and distribution facilities, due to the multiple benefits that automation and digitalization has shown in recent time. This not only allows remote control in terms of supervision and control, but also allows having real-time information that in the past was not available. In this context, the internal networks related to the control systems have migrated to the digitalization of the substation at level 0, that is, to digitize the information exchanged between the high voltage assets, such as instrument transformers, circuit breakers, disconnectors, busbars and transmission lines, and control and protection assets, such as protection relays, energy meters, controllers, among others.

The implementation of the Process Bus within the digital substation is taking every day more relevance in the electrical power systems. Many utilities and vendors are making great efforts in practical implementation of the substation projects with digital technologies.

During 2018, a pilot project was developed by Transelec, in a joint effort with different vendors, which had the purpose of understanding all the aspects related to process bus technology in the digital substation, according to IEC 61850-9-2 [1] standard.

The complete scheme considered for this testing consisted of merging units and digital relays devices provided by four different vendors, with communication interfaces, which allow the interoperability using digital information in accordance to IEC61850-9-2 process bus and IEC61850-8-1 station bus.

In this proof of concept, many tests were planned in three main areas: protection systems, communication network and interoperability. Focusing on the aspects related to the networking topic, the following concepts were developed:

- Redundancy verification in PRP and HSR topologies.
- Network Overload in order to verify the robustness of the communication architecture.

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- Implementation of Quality of Service (IEEE 802.1p) for supporting to the Sample Values and Goose Data.

These proofs allowed, in one sense, to know deeply the different issues related to the process bus technology and the IEC61850 standard as background of their implementation process. On the other hand, it was possible to realize the importance of an appropriate implementation of the communication network design, as well as the quality and robustness of the network equipment (redboxes) used.

The purpose of this paper is to show in detail the relevance that the implementation of Quality of Service (QoS) have for the traffic information over the protection and control equipment on Substation Automation Systems (SAS), according to IEEE 802.1Q [2].

This paper presents the main testings that were developed in Transelec's pilot project, the obtained data and results, and then, the explanation of the relevance that the implementation of QoS has in the process bus, in order to protect Samples Values and Goose Data traffic integrity. Those concepts are the core for a suitable network traffic, which in case of the process bus in digital substations, are essentially the heart of the PAC system.

KEYWORDS
IEC 61850 - Process Bus - Digital Substation - Quality of Service (QoS) - IEEE 802.1p - Substation Automation Systems (SAS) - Communication networks in protection - automation and control systems (PACS)

2. INTRODUCTION

2.1. Context

Transelec is the main and biggest electrical transmission utility in the Chilean interconnected power system, operating overhead lines and substations in the following voltage: 13, 23, 66, 110, 220 and 500 kV. The facilities of Transelec consist in 9,672 circuit kilometers and 61 substations and it extends through most of the Chilean territory.

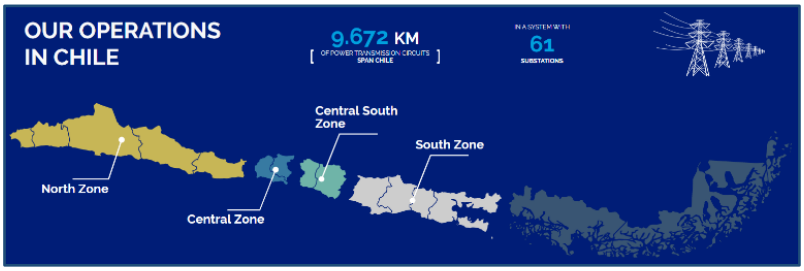

Figure 2-1. Transelec's presence in Chile, with 9,672 circuit kilometers and 61 substations.

The growth of Transelec in terms of its facilities has taken place in conjunction with the electrification of the country, so Transelec's assets have 4 important characteristics to highlight:

1) Age of assets: Transelec has assets in multiple stages of its life cycle. The oldest facilities are from the mid-40s, while the most recent substations were put into service during 2019.
2) Climate diversity: The facilities are spread throughout the country, so they have specific requirements for each geographical area.
3) Assets of multiple suppliers: The same growth of the facilities during the time and the renewal plans have defined a portfolio of multi-brand assets.
4) Free market and Open Access in transmission: The Chilean electricity sector is competitive and regulated. The growth of the transmission is decreed and in the same facility there are assets of multiple owners.

In this context, Transelec has a large-scale reinvestment plan for its assets, which is currently consolidated and in development. In particular, for substation control systems, as mentioned in the previous points, the design of the solutions must consider assets of multiple generations, multiple brands and multiple owners. Under this premise, the development of new technologies related to digital substations has been seen as an opportunity to leverage these concepts and the reason for this exploration in the first instance, which in some way impacts the development of reinvestment works for old assets and the development of new expansion projects decreed by the National Energy Commission.

The digitalization of substations provides opportunities for optimization of the construction deadlines of the projects, reflected through savings in engineering, construction and assembly, commissioning, operation, maintenance and replacement, among others. The pilot project was developed to evaluate the performance and economic potential of opting for these technologies instead of our traditional systems, in addition to developing training for Transelec personnel and establishing concepts of modernization on a larger scale in existing substations.

2.2. Digital substation technology

The importance that Ethernet networks have taken in the context of high voltage substation control systems has increased in recent years, which indicates that it is necessary to adopt design criteria to provide stability and robustness to all services and critical assets that use the communications network in a relevant way.

With the arrival of the concept of process bus in digital substations, the above becomes even more critical, since said bus is at the heart of the substation control and protection information, which at its base are the trigger signals, states of circuit breakers and disconnectors, as well as real-time voltage and current measurements.

It is in this context that the inclusion of quality of service in high availability networks could deliver a solid communication network that allows -in extreme or unwanted cases- to protect information traffic from the Merging Units or from the NCIT to all IED's that require and need this information. Pending the adoption of innovative technologies such as SDN, implementing QOS techniques allow the reduction of the probability of error in non-deterministic networks such as Ethernet.

Under this premise, in addition to the reinvestment needs and competitive potentials indicated in the context, Transelec decided to develop a laboratory to perform functional tests of this technology and this document intends to briefly introduce the test architecture implemented in Transelec's laboratory, to later show the tests performed and the results obtained experimentally.

3. TEST LABORATORY

With the purpose of verifying the different devices that participate in the process bus, whether control, protection or communication, a laboratory was developed, whose objective was to know the digital substation technology and generate the necessary trust to implement it. For this, manufacturers of known reputation with developments on the standard, were invited: ABB, SIEMENS, GE and EFACEC, with protection and control equipment, as well as their respective merging unit.

On the other hand, and given that the equipment that supports communications networks is essential in the process bus, it was decided to invite the company BELDEN due to its trajectory in the development of technologies focused on industrial communication networks.

3.1. Architecture

For the development of the set of tests that were carried out, two network topologies were implemented under the IEC 62439-3 [3] standard: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR), as shown in Figure 3-1 and Figure 3-2.

Through these architectures, it was possible to perform tests of different configurations, such as:

- VLAN segregation, dedicated VLANs for GOOSE messaging, Samples Values, PTP sync signal and network management were created.
- Routing between VLANs for monitoring functions, and remote cybersecurity access.

- PRP and HSR redundancy tests.
- Interface monitoring using port mirroring.
- Implementation of Quality of Service (QoS), based on the IEEE 802.1p standard.

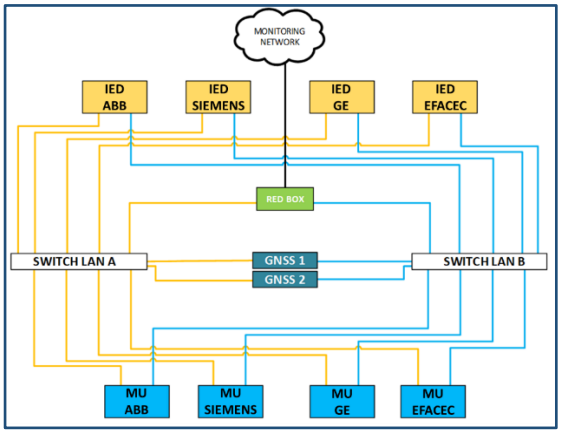

Figure 3-1. Architecture PRP. Process Bus.

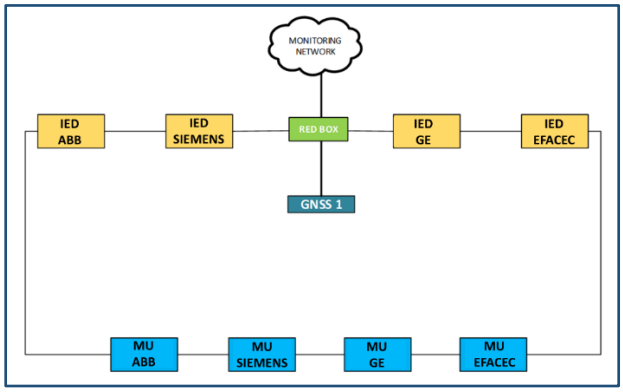

Figure 3-2. Architecture HSR. Process Bus.

3.2. Process Bus Testing

As the original objective of the tests carried out in the laboratory it was to check the operation of the protection and control equipment, through the use of a process bus according to the IEC 61850-9-2 standard and based on the PRP architecture, injections of digital and analog variables were performed through an OMICRON CMC 356 test box in each manufacturer's Merging Unit.

For the evaluation of the behavior of the analogous variables and their correlation with the sample values, controlled injections of voltage and current were made in the merging units in order to compare them with what was recorded by the protection relays, in a permanent regime, and injected COMTRADE records of actual failures to assess their behavior. In the case of digital signals, trigger signals generated by protection functions emitted through dry contacts and GOOSE messaging in parallel were forced, comparing both operating times. All this information was monitored using OMICRON DANEO 400 tool, comparing electrical variables with sample values (see Figure 3-3).

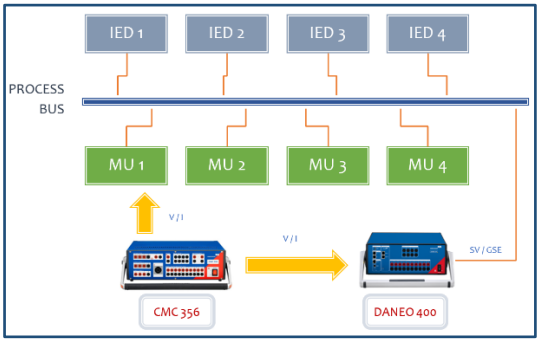

Figure 3-3. Process Bus Testing Architecture.

Through these tests, the consistency of the parameters injected as a reference and those recorded by the protection relay through GOOSE and Samples Values messages were verified.

3.3. Interoperability Tests

On the other hand, during this laboratory integration tests were carried out between different manufacturers. As result, it was found that the data from the merging unit of manufacturer A, can be processed by the protection relays of all manufacturers and vice versa. This allowed the corroboration of the correct implementation of the standard, since interoperability between the different manufacturers is achieved.

3.4. Network Redundancy Tests

Another of the relevant tests carried out in the laboratory was to verify the effectiveness of the redundancy of the PRP and HSR topologies, which were performed simulating communication path failures. Using a tool called HrPing, which allows the generation of ICMP messages at a very high resolution, messages were sent to the various IEDs of the process bus network at a resolution of 1 ms.
By simulating the various failures in the communication routes of the network, it was possible to verify that the ICMP messages were not interrupted because there was still connectivity through other network paths. This allowed the confirmation of the correct functioning of the network, using the null loss of ICMP messages as the test acceptance criteria.

3.5. VLAN and QoS design

Quality of Service (QoS) or Class of Service (CoS) is defined at IEEE 802.1D (formerly 802.1p) and it is used to prioritize traffic in a 8 level categorization. This way, data frames with high priority (hi data availability and low latency requirements) have preference when they are transmitted by the network [4].

The priority trust mode defines how the Ethernet switch handles a received data frame that contains QoS information inside the 3 bits Priority code point (PCP) field of the IEEE 802.1Q tag (now on Q Tag). The trust mode criteria used in this case is that if an incoming frame has the Q Tag, the priority informed at the tag is the one that is used. By the other side, if incoming Ethernet frames are not tagged, the used priority will be defined (configured) at the entry port of the switch. All the Industrial switches used at the process bus lab have a non-blocking switching chip technology. Because of this, every frame once it is *stored and forwarded* by the switching unit, it goes directly to an egress port memory. This egress memory is subdivided in 8 different traffic classes, and each one is associated to a priority at a mapping table as follows:

Traffic Classes	Priority
0	1
1	2
2	0
3	3
4	4
5	5
6	6
7	7

Table 3-1. Priority/Traffic Class Mapping (0 is the default one, and 1 and 2 are lower priority than default.)

This mapping table must be configured on each industrial Ethernet switch of the process bus. There are 6 data services running at the substation process bus. Each one with a special assigned priority. The following table shows each:

Service	Priority
Network Management	7
GSE (Trips)	6
GSE (Events)	5
SV	4
PTP	3
IED Management	0

Table 3-2. Service Priority assignation

The Intelligent Electronic Devices (IED) as the Relay and Mergin Units are configured to generate Goose and Sample Value traffic with a priority informed at the PCP field of the Q tag (as defined in Table 3-2). PTP was defined accordingly as well. This way, considering the trust mode defined, the network is able to keep a service priority end to end.

It is important to mention that all the ingress port at the switching level of the process bus architecture are configured with a 0-priority value (default value). This means that any incoming traffic without an origin priority informed at the PCP field of the Q tag will be treated as a 0-priority value. This traffic is mapped to the 0-traffic class on each egress port buffer, leaving all the hi priority queues (traffic classes) unused for this low priority services.

The traffic class queue management is handled with a strict method. This means that the egress port forward frames that are in the highest traffic class first. If this traffic class is empty, then the port sends the frames that are in the next lower priority.

It is a good practice to apply restriction methods as access control list to avoid cyber-attacks like massive injections of traffic with hi priorities informed in the PCP field of the Q Tag.

4. QUALITY OF SERVICE AND TRAFFIC LOAD NETWORK TESTINGS

The traffic load network test consists in the "garbage" injection traffic, which try to saturate the Process Bus network. That implies that is required to have any access point through which it will be possible to generate and delivery the injected traffic.

The test will be successful every time that the process bus traffic (Samples Values and Gooses) is kept safe, no matter if the network is overloaded or not. This behavior its expected thanks to QoS technique implemented over the network devices.

4.1. Conditions for the test execution

Different test scenarios are described in order to probe de behavior of QoS:

- All protection relays must be subscribed at least to one single Sample Value generated by a Merging Unit.
- We connect a Computer with de OSTINATO application. This application will be used for to inject garbage traffic.

- This computer will be integrated to the process bus through PRP interface at 100 Mbps.
- Thanks to Ostinato, we generate in the process bus network multicast frames. These frames will send different testings with different bandwidths, in according to the follow table.

TEST	BANDWIDTH	% USE NETWORK
T1	10 Mbit/s	10%
T2	30 Mbit/s	30%
T3	50 Mbit/s	50%
T4	60 Mbit/s	60%
T5	**80 Mbit/s**	**80%**
T6	**100 Mbit/s**	**100%**

Table 4-1. Set of executed tests

- For monitoring all testing in the process bus network, it is proposed to check the sample values and gooses trough protection relays. The method for monitoring is to see the data through the station bus via MMS. The protection relays were configured for to replay the process bus information to the station bus network (*see Figure 4-1*).

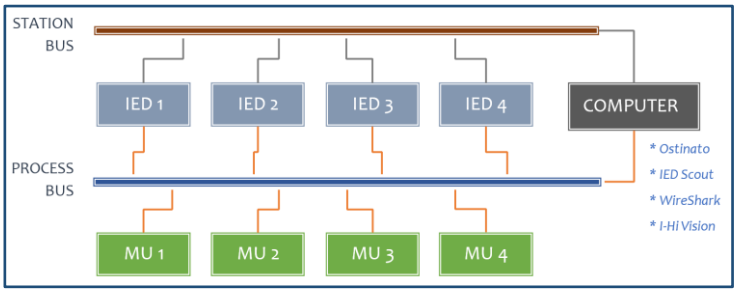

Figure 4-1. Architecture Overview for network traffic and QoS testings.

4.2. Packet Injector

With this tool, it's possible in simple way generate frames of data related with process bus information. In specific, this data is Multicast Layer-2 frames in accordance with Sample Values and Gooses information. The following describes the configuration of the Ostinato application:

- The destination MAC address for injected traffic will have the first 4 octets within the range reserved for Sample Values (01 0C CD 04). The source MAC address will correspond to the MAC of the equipment from where traffic will be injected (COMPUTER).
- Finally, a frame is configured with a package that can grow in traffic per second, which is ready for delivery to the network.
- The way to increase the load in the traffic is increasing the Payload.

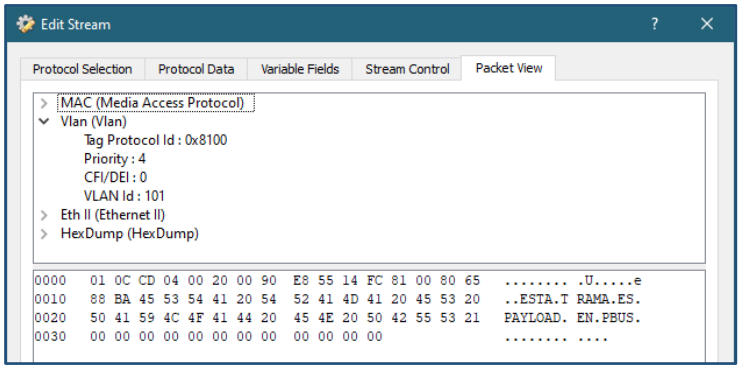

Figure 4-2. Frame result in the application before to inject in the Network.

4.3. Initial condition for the traffic

Prior to injecting any additional packet, the steady state traffic of the process bus network was analyzed. As it is possible to appreciate, a consumption of 15 Mbps is maintained stably.

5. RESULTS OBTAINED

5.1. Approach

The following items show the results of testing based on ***Table 4-1***, which is the criteria to verify if the QoS implemented works as expected. A common criterion accepted in Ethernet Networks is a threshold of 80% of network availability.

The results of the traffic test are shown below. It is important to indicate that only a subset of the test was shown on this paper due to the extensive of the document.

The traffic reflected in the network interface it shows the consumption with respect to 1 Gbps, due to the network interface computer card is 1 Gbps. However, this value must be amplified by a factor of 10, since the Ethernet Switch interface where this connection arrives is 100 Mbps.

It is important to reaffirm that for monitoring all testing in the process bus network, it is proposed check the sample values and gooses trough protection relays. The method to monitor is to see the data through the station bus via MMS. The protection relays were configured to replay the process bus information to the station bus network.

5.2. Packet Injection at 10 Mbps with QoS Enabled.

- The configuration of the test loaded in Ostinato accounts for the average calculation of the package to be injected.
- In the test equipment, it is possible to verify the bandwidth on the network card: 26.6 Mbps.
- When observing the bandwidth in the Wireshark network sniffer, it is observed an average utilization of 25 Mbps.
- Finally, the results could be monitored through IED SCOUT.

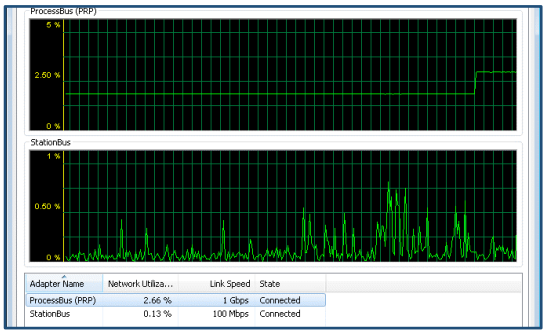

Figure 5-1. Outbound traffic monitored from test computer

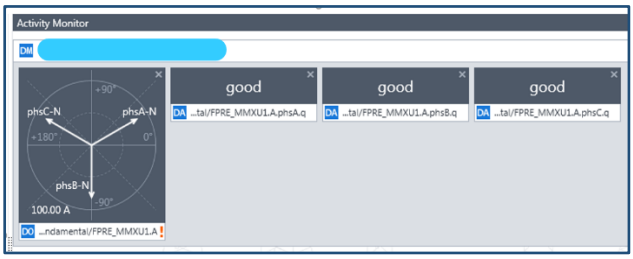

Figure 5-2. Data of Process Bus viewed in the Relays through IED Scout

- Through this supervision, it is possible to verify if the process bus traffic is correctly reaching the protection relays. In this case, the relays reflect that the measurements are being updated.

5.3. Packet Injection at 50 Mbps with QoS Enabled.

- The configuration of the test loaded in Ostinato accounts for the average calculation of the package to be injected.
- In the test equipment, it is possible to verify the bandwidth on the network card: 65.8 Mbps.
- When observing the bandwidth in the Wireshark network sniffer, it is observed an average utilization of 65 Mbps.
- Finally, the results could be monitored through IED SCOUT.

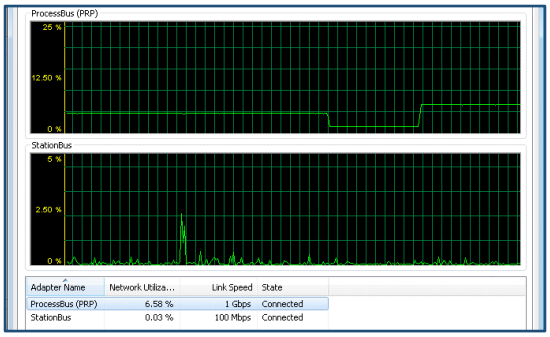

Figure 5-3. Outbound traffic monitored from test computer

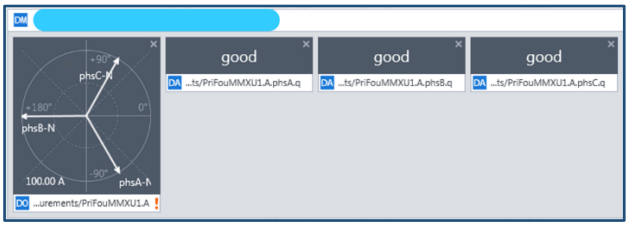

Figure 5-4. Data of Process Bus viewed in the Relays through IED Scout

- Through this supervision, it is possible to verify if the process bus traffic is correctly reaching the protection relays. In this case, the relays reflect that the measurements are being updated.

5.4. Packet Injection at 80 Mbps with QoS Enabled.

- The configuration of the test loaded in Ostinato accounts for the average calculation of the package to be injected.
- In the test equipment, it is possible to verify the bandwidth on the network card: 95.2 Mbps.
- When observing the bandwidth in the Wireshark network sniffer, it is observed an average utilization of 93 Mbps.
- Finally, the results could be monitored through IED SCOUT.

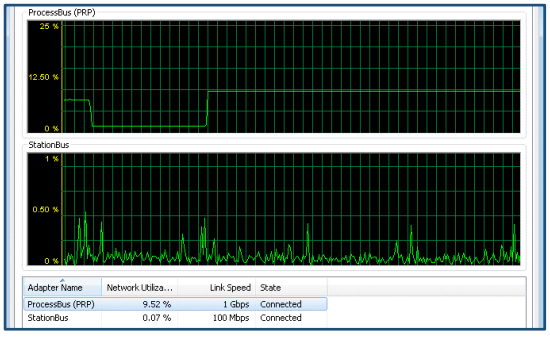

Figure 5-5. Outbound traffic monitored from test computer

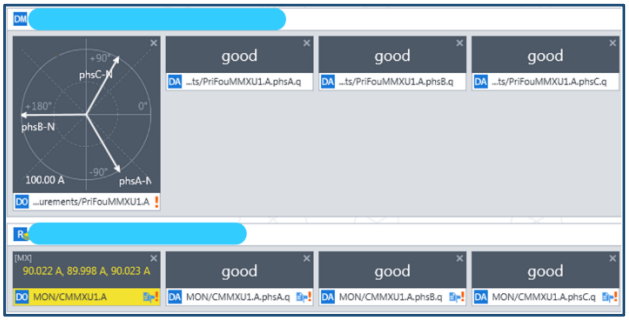

Figure 5-6. Data of Process Bus viewed in the Relays through IED Scout

- Through this supervision, it is possible to verify if the process bus traffic is correctly reaching the protection relays. In this case, the relays reflect that the measurements are being updated.

5.5. Packet Injection at 100 Mbps with QoS Enabled.

- The configuration of the test loaded in Ostinato accounts for the average calculation of the package to be injected.

- In the test equipment, it is possible to verify the bandwidth on the network card: 114.6 Mbps

NOTE: It is very important to indicate that the 114.6 Mbps are the Outbound traffic of the computer interface. On another hand, the maximum traffic in the process bus network is 100 Mbps due to the Ethernet Switch interface is 100 Mbps.

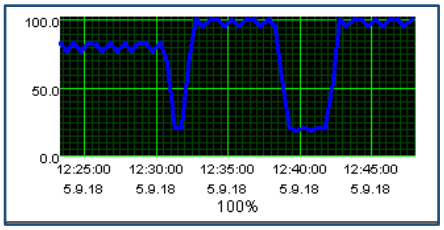

Figure 5-7. Graphic Trend in I-Hi Vision.

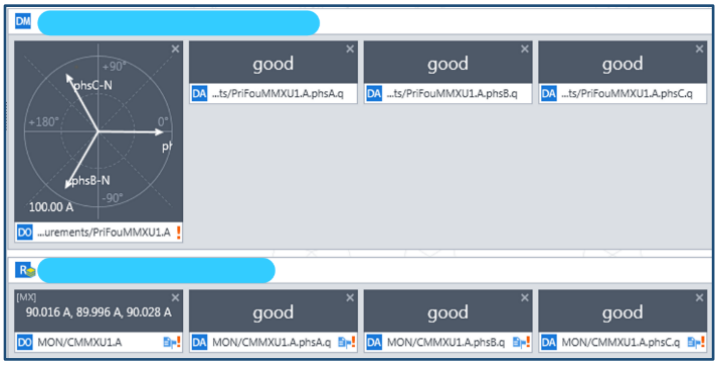

Figure 5-8. Data of Process Bus viewed in the Relays through Ied Scout

- Through this supervision, it is possible to verify if the process bus traffic is correctly reaching the protection relays. In this case, the relays reflect that the measurements are being updated.
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5.6. Test Variant: 100 Mbps Injection with QoS Disabled.

This test has a variant regarding the previous test. The network protection function of the Process Bus data was disabled. This presupposes that, by not counting the QoS feature enabled, the data of the process bus is left unprotected against the different unwanted phenomena of an ethernet network.

- Through the Sniffer, it is possible to appreciate that the traffic on the network is 94 Mbps. This traffic is the sum of the garbage traffic plus the base traffic of the IED's.
- Finally, the results could be monitored through IED SCOUT.

Figure 5-9. Data of Process Bus viewed in the Relays through Ied Scout

Because the network is used over 80% of their capacity and QoS functions are also disabled, the data coming from the process bus is invalid. This behavior is explained due to the lack of network protection features (QoS), resulting in all Sample Values and Gooses traffic with the same priority as the injected garbage data.

6. CONCLUSIONS

As a first concept, this project allowed the reliable evaluation of the technology, comparing it with the traditional technology present in Transelec facilities. The results have shown that Digital Substation Technologies are a valid alternative for the development of new reinvestment projects and for new facilities.

On the other hand, the development of a multi-brand pilot has made possible to simplify the adoption of skills by technical personnel and to extend the vision to a large part of the organization, starting from the management level. The tests are satisfactory for each case in which the Sample Values and Goose are protected by the QoS standards implemented, independently of the supplier. Considering the success that was the development of this pilot as the first step for the adoption of these technologies, it is expected to be able to optimize the overall costs of the life cycle of the assets and take advantage of the benefits presented by their adoption in other areas.

Regarding the results obtained in the laboratory, the QoS implementation presented an advantage used as a network protection mechanism available in the 802.1p and 802.1q standard. In the event of any abnormality within the process bus (broadcast storms, loops, problems with the internal memory of an Ethernet switch, etc.), these protection mechanisms can make a big difference when it comes to safeguarding critical information, which in the case of the process bus, keep the sample values, gooses messages and PTP frames are the crucial ones for the good performance of a high voltage substation control and protection system [5].

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