LINK REDUNDANCY IN THE PROCESS BUS ACCORDING TO IEC 61850 ED.2: EXPERIENCE WITH RSTP, PRP AND HSR PROTOCOLS

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Abstract

This work aims to approach the Link redundancy to support the process bus, as mentioned in the second Edition of the IEC 61850, detailing options and to comparing the available protocols.

An IEC 61850 network implemented with link redundancy, consisting of a Merging Unit and an IED, were submitted to the contingency of breaking one of the communication paths. Test results of this study were made using three protocols: RSTP, PRP and HSR. The behaviour and effects of the Recovery times were evaluated and discussed.

1 Introduction

IEC 61850 is an undeniable technological advance for every Protection, Automation and Control (PAC) system. The standard presents the implementation of communication, in the Substation Automation System (SAS), over Ethernet network through two buses: the station and the process [1].

When defining the station and process buses, IEC 61850 does not define the topology type. It is up to the engineering, given the substation's specificities, to achieve the best network architecture. The topology will define the path taken by the information. It is known that network failures can interrupt this path, generating loss of information. Thus, with the advancement of SAS implementation based on IEC 61850, it becomes necessary to ensure maximum availability of the deployed data network.

For GOOSE and Sampled Values (SV) messages, their critical times must be considered. According to the WG 10 of TC 57, the network recovery time defined for the station bus must be between 400ms and 0ms (according to the application), whereas for the process bus it must be 0ms.

One of the biggest fears of professionals in the field is the loss of communication in the process bus. If this happens, the protection would become blind, without receiving the voltage and current signals from the system. Therefore, the implementation of redundancy protocols in the substation communication network is essential issue.

Failure in connections between IEC 61850 network devices must not occur, as it will put the PAC system of the entire substation at risk. To minimize these types of errors in SAS, Ethernet network redundancy strategies must be defined.

In this work there are three main redundancy protocols: RSTP, PRP and HSR, were analysed.

2 TYPES OF REDUNDANCY

Some implementations of redundancy in the Ethernet network are already widespread. Currently, the most used protocol is the Rapid Spanning Tree Protocol (RSTP). This protocol is characterized by an algorithm (on the Switch) capable of determining the best path that a message should follow. In a network with RSTP, if one of the paths fails, all existing traffic will be transferred to the "healthy" link. However, the time spent on this action will be, at best, in terms of milliseconds.

Considering the process bus in a 60Hz system with 4800 frames/second (one frame every 208.33 μs) and a network recovery time by RSTP in the order of 50ms, there would be a loss of 240 packets. As each packet carries the information of one sample and 80 samples make up one cycle, the loss of 240 frames means the loss of three complete cycles. This situation will make any protection system unfeasible.

The concept of link redundancy was included in the second edition of IEC 61850, parts 8 and 9, suggesting the use of the IEC 62439-3 standard. It is noteworthy that the link redundancy is treated, in IEC 61850, as an option. In IEC 62439-3 there are two viable solutions for implementing redundancy in an IEC 61850 data network, achieving both network recovery time requirements and enabling node redundancy [2].

The PRP (Parallel Redundancy Protocol) allows the implementation of redundancy through two independent parallel paths, allowing a null network recovery time (recovery time = 0 ms). PRP can be implemented in Mesh (Ring-Star Hybrid) networks.

HSR (High-availability Seamless Redundancy) is a specific link redundancy, used for Ring topologies. As also PRP, the network recovery time is null (recovery time = 0 ms).

2.1 RSTP

RSTP (Rapid Spanning Tree Protocol – IEEE 802.1w) is an evolution of STP (Spanning Tree Protocol – IEEE 802.1D). These protocols allow a redundancy of communication paths where only one path is active. To prevent data from circulating indefinitely on the network (loop), the other paths must be on stand-by. In case of loss of communication along the active path, RSTP / STP reorganises the routes in order to activate the new communication path. RSTP was optimized to improve STP switching times since these were too slow for industrial applications.

Figure 1 below exemplifies an RSTP network, where the solid lines connecting the switches are the active paths and the dashed lines are the blocked paths (stand by).

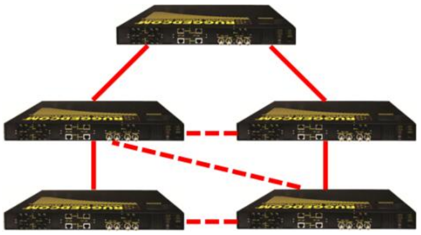


Figure 1 – RSTP Network

2.2 PRP

Defined in IEC 62439-3, the PRP (Parallel Redundancy Protocol) duplicates the frame (information) and sends the duplicated frames along parallel and isolated paths. The receiver process one frame and discards the duplicated. Due to communication paths are parallel and isolated; failure in one path does not affect the other. Therefore, the recovery time of communication routes is null. Developed for Mesh (Hybrid Ring-Star) networks, redundancy is implemented by duplicating the number of Switches [3].

Figure 2 below exemplifies a PRP network. DANP (Dual Attached Node with PRP) represent devices that implement redundancy through PRP, SAN (Single Attached Node) represents devices that do not implement any redundancy protocol. SANs can be inserted into a PRP network directly on Switches or through RedBox (Redundancy Box) [3] [4].

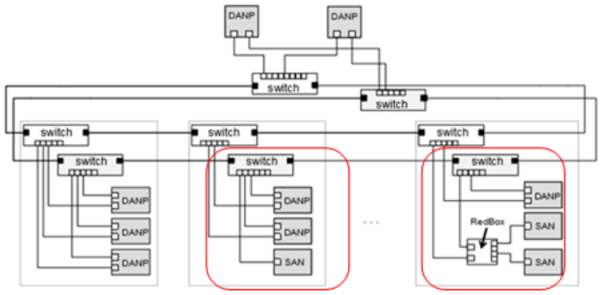


Figure 2 - PRP Network

2.3 HSR

Also defined in IEC 62439-3 and based on PRP, HSR (High-availability Seamless Redundancy) was a protocol developed to be implemented for Ring networks. A source node sends the duplicated frames in both directions of the network, the receiver process one frame and discards the duplicated. Due to the network topology there is no need for switches. Therefore, redundancy is implemented at IEDs that make up the network.

Figure 3 below exemplifies an HSR network. As will be explained later, SAN devices can only be inserted into an HSR network through a RedBox. DANH (Dual Attached Node with HSR) represents a device that implements redundancy by HSR [5].

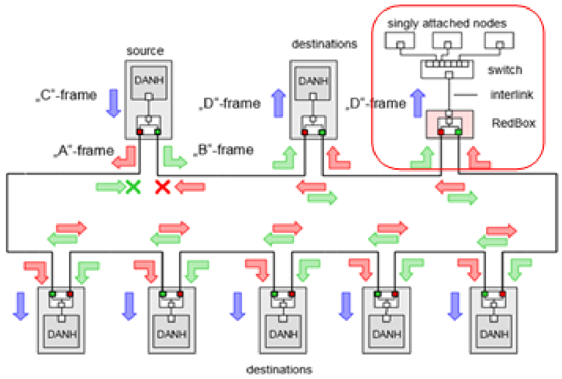


Figure 3 - HSR Network

3 COMPARISON BETWEEN THE THREE REDUNDANCY PROTOCOLS

Comparing PRP/HSR with RSTP, it is clearly demonstrated that the main advantage of the first ones is the zero recovery time of the communication routes. In applications that cannot wait for the network to be recovered, RSTP becomes an issue. Therefore, the PRP/HSR is decisive, as if there is a loss of one of the communication paths, the duplicated path is already available, thus not requiring time for recovery.

Between PRP and HSR, the main conceptual difference is in the implementation of these protocols, due to the network topology. PRP works in a mesh network, whose redundancy happens with Switches. The HSR, on the other hand, works in a ring network, whose redundancy occurs in the devices (IEDs) themselves.

4 IMPORTANT CONSIDERATIONS ABOUT PRP/HSR

One of the main characteristics of PRP and HSR redundancy protocols is that they are transparent to the network application layer. That is, as redundancies occur in the second layer of the network (Ethernet), the application layer does not identify the network redundancy. Through an HSR network (Figure 4) and a PRP network (Figure 5), figures below are a clear example about this case [3].

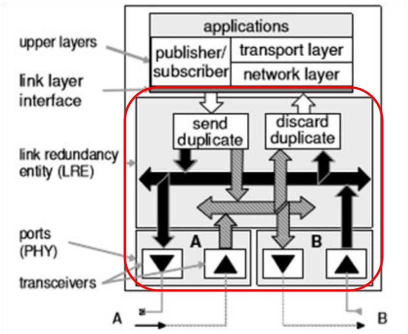


Figure 4 - Redundancy Transparency for the Application Layer: HSR

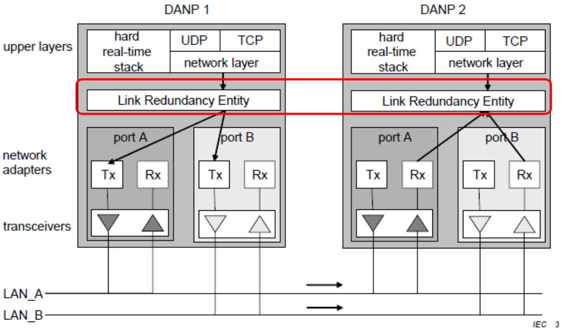


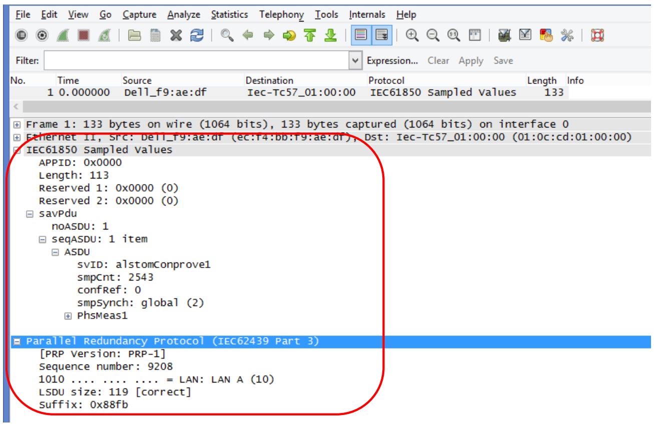
Figure 5 - Redundancy Transparency for the Application Layer: PRP

Observing Figures 4 and 5 above, it is important to notice that the entire redundancy protocol, that is, the duplication of outgoing frames or the discard of the duplicated received frame, is developed in the so-called LRE (Link Redundancy Entity). This is an additional layer that would not be included if there were no link redundancy. LRE works with two active Ethernet ports, but application layer just recognize only one port. This way the redundancy becomes transparent to the application layer.

In both PRP frame and HSR frame, one of the most important information is the Sequence Number (SeqNr). Whenever a DANP or a DANH send information to the network, the SeqNr is incremented. Based on this number and the Source Address, the target DANP or DANH is able to detect the duplication.

SeqNr is also responsible to highlight one of the main structural differences between a PRP frame and an HSR frame. Unlike the PRP frame, the SeqNr, in the HSR frame, is not inserted after the payload, but is inserted in the header. This way, DANH can recognize the duplication before receiving the frame completely.

In Figures 6 and 7 below, examples of SV frames will be shown, which were captured through the network protocol analyzer WireShark, PRP (Figure 6) and HSR (Figure 7).

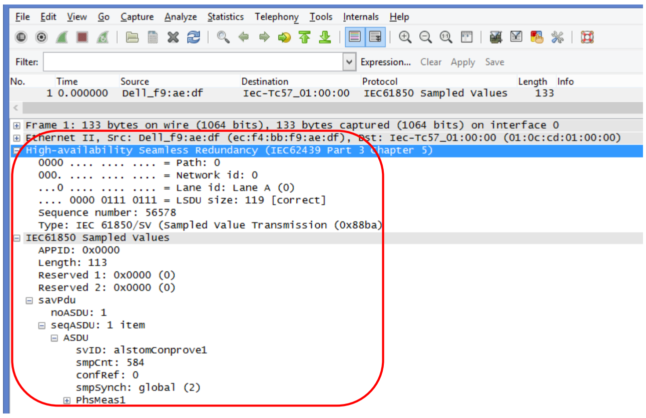

File Edit View Go Capture Analyze Statistics Telephony Tools Internals Help
Filter:
Expression... Clear Apply Save

```
No.   Time        Source         Destination          Protocol                  Length  Info
    1 0.000000    Dell_f9:ae:df  Iec-Tc57_01:00:00    IEC61850 Sampled Values   133

⊞ Frame 1: 133 bytes on wire (1064 bits), 133 bytes captured (1064 bits) on interface 0
⊞ Ethernet II, Src: Dell_f9:ae:df (ec:f4:bb:f9:ae:df), Dst: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
⊟ IEC61850 Sampled Values
    APPID: 0x0000
    Length: 113
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ⊟ savPdu
      noASDU: 1
    ⊟ seqASDU: 1 item
      ⊟ ASDU
          svID: alstomConprove1
          smpCnt: 2543
          confRef: 0
          smpSynch: global (2)
        ⊞ PhsMeas1

⊟ Parallel Redundancy Protocol (IEC62439 Part 3)
    [PRP Version: PRP-1]
    Sequence number: 9208
    1010 .... .... .... = LAN: LAN A (10)
    LSDU size: 119 [correct]
    Suffix: 0x88fb
```

Figure 6 - Redundant SV Frame by PRP


File Edit View Go Capture Analyze Statistics Telephony Tools Internals Help
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Expression... Clear Apply Save

```
No.   Time        Source         Destination          Protocol                  Length  Info
    1 0.000000    Dell_f9:ae:df  Iec-Tc57_01:00:00    IEC61850 Sampled Values   133

⊞ Frame 1: 133 bytes on wire (1064 bits), 133 bytes captured (1064 bits) on interface 0
⊞ Ethernet II, Src: Dell_f9:ae:df (ec:f4:bb:f9:ae:df), Dst: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
⊟ High-availability Seamless Redundancy (IEC62439 Part 3 Chapter 5)
    0000 .... .... .... = Path: 0
    000. .... .... .... = Network id: 0
    ...0 .... .... .... = Lane id: Lane A (0)
    .... 0000 0111 0111 = LSDU size: 119 [correct]
    Sequence number: 56578
    Type: IEC 61850/SV (Sampled Value Transmission (0x88ba)
⊟ IEC61850 Sampled Values
    APPID: 0x0000
    Length: 113
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ⊟ savPdu
      noASDU: 1
    ⊟ seqASDU: 1 item
      ⊟ ASDU
          svID: alstomConprove1
          smpCnt: 584
          confRef: 0
          smpSynch: global (2)
        ⊞ PhsMeas1
```

Figure 7 - Redundant SV Frame by HSR

5 CASE STUDY

Tests were performed on the redundancy of the Process Bus using three protocols: RSTP, PRP and HSR. For each case, the system performance was verified with the loss of one link using an electronic switch that opened the circuit isolating one of the paths (contingency).

The Process Bus was represented by a test set configured to publish SV frames as a Merging Unit, and a protection IED supporting IEC 61850-9-2 LE. Faults were injected along with the opening of one path. The IED Trip times were verified when this link was lost, in each redundancy protocol, and so it was possible to compare and analyze the influence over each solution.

To carry out the tests, the following equipment was used: Conprove CE-6710 Test Set with accessory for electronic switching of redundancy links (Conprove Ethernet Switching Box), MultimSV software, Ruggedcom Switch RSG2288, Ruggedcom Switch RS940G, RedBox Ruggedcom RS950G and the IED GE/Alstom MiCOM P446-9-2LE. The system is illustrated in Figure 8.

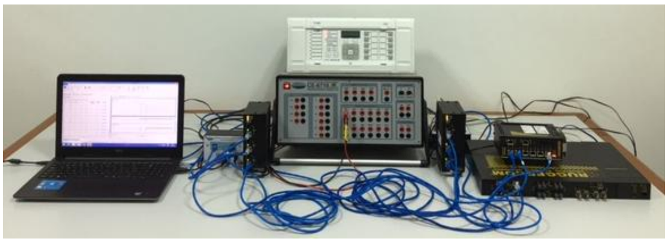


Figure 8 - Test Setup

An important IED configuration parameter for this case, especially those involving RSTP, once it does not have null recovery time of communication routes, is the Loss Rate Level. This parameter has minimum and maximum values of 1.25% and 15%, respectively. If the amount of packet loss within a cycle exceeds the value configured in this parameter, the IED under test blocks the protection function and generate an alarm signal.

5.1 Tests Structure

In the case studies, the test structure was assembled with the CE-6710 Test Set publishing Sampled Values frames with 8 values (3 currents + neutral and 3 voltages + neutral) to the IED MiCOM P446-9-2LE through the 3 types of redundancy. For each protocol, one of the redundant signals was controlled by the electronic switcher. The trip signal from the protection function was received in one of the test set´s binary inputs for analysis of the times in each case.

The entire test process, including the electronic switching of the redundancy link, was controlled by the "Distance" software. The switch was opened at the moment the fault starts.

The IED was tested with the distance protection function enabled and the settings defined for the test was: 4 Ω line impedance and 70º phase angle. For the study case, point tests were defined within the Z1 zone, which was parameterized with time t = 0s. Also, the Loss Rate Level parameter has been set to be 15%.

In each case, the Trip times was evaluated 50 times by repeating the tests and with these data a statistical analysis was performed, calculating the minimum, average, maximum and standard deviation times.

For each of the 3 protocols, 2 tests were performed, a control reference test, with the system operating normally, and a second verification test when there was a contingency of opening one communication path, totalling 6 tests.

5.2 RSTP

To analyze the influence of RSTP redundancy on the Process Bus, two conditions were analyzed: without contingency and with contingency. The Sampled Values frames were published to the IED by the test set with the RSTP redundancy being performed by the Switches. The active path was the one that contains the electronic switcher. Figures 9 and 10 below illustrate the test structure.

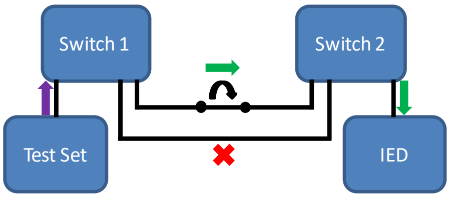


Figure 9 - (a) RSTP without Contingency

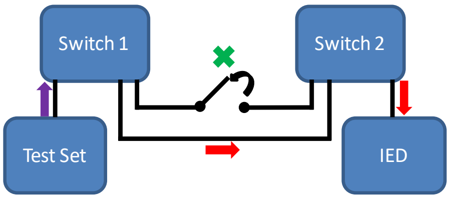


Figure 10 - RSTP with Contingency

5.3 PRP

To analyze the influence of PRP redundancy on the Process Bus, two conditions were analyzed: without contingency and with contingency. In this case, the Sampled Values frames were published to the IED by the test set with the PRP redundancy being performed by the RedBoxes and Switches. Figures 11 and 12 below illustrate the test structure.

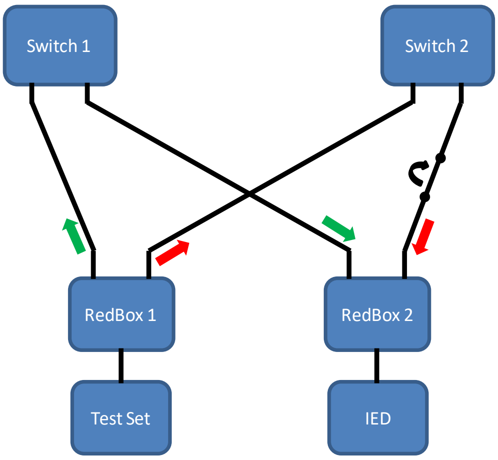


Figure 11 - PRP without Contingency

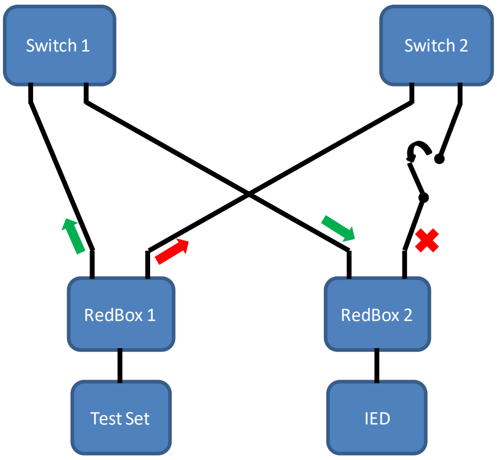


Figure 12 - PRP with Contingency

5.4 HSR

To analyze the influence of HSR redundancy on the Process Bus, two conditions were analyzed: without contingency and with contingency. In this case, the Sampled Values frames were published to the IED by the test set with the HSR redundancy being performed by the RedBoxes. Figures 13 and 14 below illustrate the test structure.

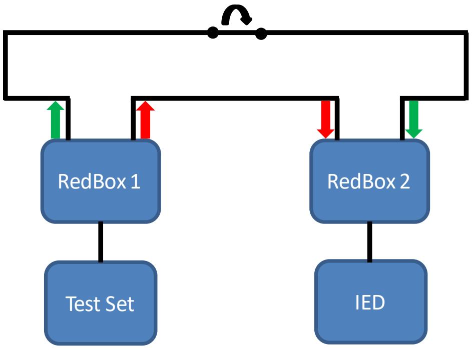


Figure 13 - HSR without Contingency

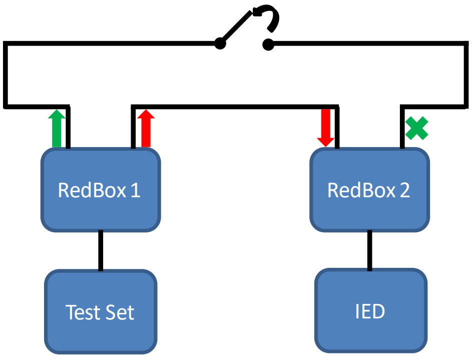


Figure 14 - HSR with Contingency

6 ANALYSIS OF RESULTS

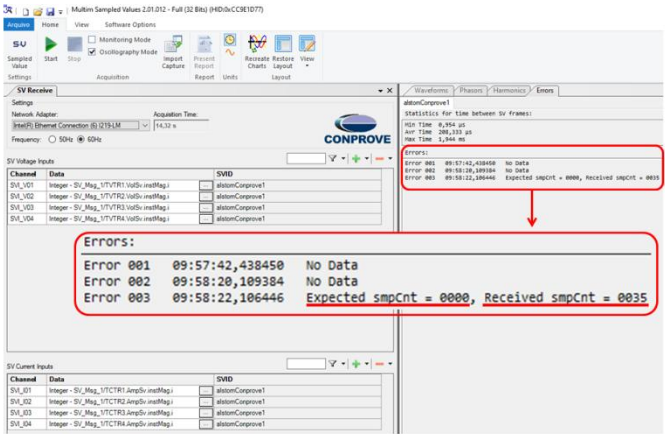
Table 1 below compares the results of cases with RSTP, PRP and HSR protocols; without and with contingency.

Table 1 - Results of Study Case

Protocol	**Contingency**	**Min. T. (ms)**	**Aver. T. (ms)**	**Max. T. (ms)**	**Standard Dev.**
RSTP	No	15.76	16.28	16.91	0.3125
	Yes	363.0	364.17	365.8	0.5998
PRP	No	16.39	16.85	17.74	0.3522
	Yes	16.32	16.89	18.09	0.4100
HSR	No	16.18	16.65	17.43	0.3132
	Yes	15.97	16.68	17.92	0.5559

Analyzing the case of RSTP with contingency, it is clear that average trip time was much higher than the case of RSTP without contingency, thus demonstrating the influence of the network recovery time of this protocol on the Process Bus. However, it is important to note that the time required for the Switch to activate the communication link back again was not the total time of 364.17ms. Within this time, are included the recovery times of the network by the RSTP protocol and the time for reactivation of the IED protection function that was blocked by the amount of packets lost.

Through the analysis of the CONPROVE MultimSV software (Figure 15), it was possible to observe the losses of SV packets during the RSTP contingency and, thus, calculate the time spent by the Switch to recover the communication link.



Settings

Network Adapter: Intel(R) Ethernet Connection (6) I219-LM

Acquisition Time: 14,32 s

Frequency: ○ 50Hz ● 60Hz

SV Voltage Inputs

Channel	Data	SVID
SVI_V01	Integer - SV_Mag_1/TVTR1.VolSv.instMag.i	alstomConprove1
SVI_V02	Integer - SV_Mag_1/TVTR2.VolSv.instMag.i	alstomConprove1
SVI_V03	Integer - SV_Mag_1/TVTR3.VolSv.instMag.i	alstomConprove1
SVI_V04	Integer - SV_Mag_1/TVTR4.VolSv.instMag.i	alstomConprove1

SV Current Inputs

Channel	Data	SVID
SVI_I01	Integer - SV_Mag_1/TCTR1.AmpSv.instMag.i	alstomConprove1
SVI_I02	Integer - SV_Mag_1/TCTR2.AmpSv.instMag.i	alstomConprove1
SVI_I03	Integer - SV_Mag_1/TCTR3.AmpSv.instMag.i	alstomConprove1
SVI_I04	Integer - SV_Mag_1/TCTR4.AmpSv.instMag.i	alstomConprove1

```
alstomConprove1
Statistics for time between SV frames:
Min Time  0,954 µs
Avr Time  208,333 µs
Max Time  1,944 ms
Errors:
Error 001   09:57:42,438450   No Data
Error 002   09:58:20,109384   No Data
Error 003   09:58:22,106446   Expected smpCnt = 0000, Received smpCnt = 0035
```

```
Errors:
Error 001    09:57:42,438450    No Data
Error 002    09:58:20,109384    No Data
Error 003    09:58:22,106446    Expected smpCnt = 0000, Received smpCnt = 0035
```

Figure 15 - Analysis of Packet Loss by MultimSV

Looking at Figure 15, in the RSTP contingency, 35 SV packets were lost. The network recovery time was 35 packets at 208.33µs each, this time being 7.69ms. This time was shorter than usual for RSTP, as Ruggedcom has an RSTP enhancement tool, eRSTP (enhanced RSTP). Thus, as the two switches used were from the same manufacturer, it was possible to optimize the time to restore the lost link.

Therefore, the loss of 35 packets exceeds the Loss Rate Level setting (15% of 80 points of a cycle is 12 packets) of the IED. So, protection was inhibited and the Trip time was greatly increased. Of the 364.17ms of the average Trip time in the case of RSTP with contingency, only 7.69ms were for link recovery by the Switch. Therefore, 356.48ms was the time taken by the IED to recover the protection function and act.

Analyzing the average Trip times of PRP and HSR cases, in contingency, through Table 1, it is clear that there were no significant changes in relation to the average Trip times of the same cases without contingency. This fact demonstrates the null recovery time characteristic of the communication network with these protocols.

Figures 16 and 17 show two comparative graphics of the study case without and with contingency, respectively, illustrating the influence on the network recovery time through the average Trip times in each case. Figure 18 shows a graphic of the difference between the average Trip times in the network with contingency and in the network without contingency for each redundancy protocol.

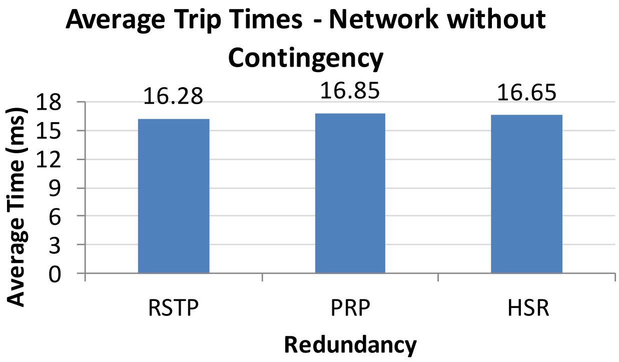


Figure 16 - Comparative Graphics: without Contingency

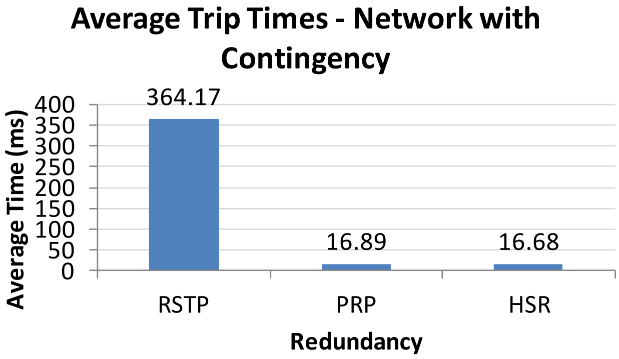


Figure 17 - Comparative Graphics: with Contingency

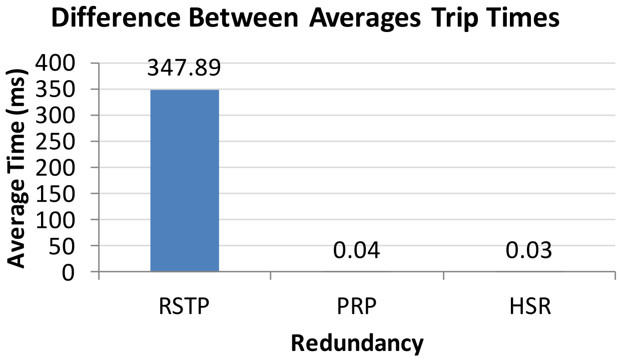


Figure 18 - Comparative Graphics: difference with Contingency and without Contingency

Through the results shown above, it is possible to confirm the vulnerability of the implementation of a redundancy by RSTP in the Process Bus because the loss of SV packets due to recovery time of communication routes when link is lost. Therefore, the ideal would be to implement a redundancy by PRP or HSR due to the null communication recovery time, thus maintaining the integrity of the network in the Process Bus.

7 CONCLUSIONS

In this paper, the three most used redundancy protocols were compared: RSTP, PRP and HSR, pointing out that their performance affects feasibility to the use in the Process Bus. The loss of link in each case was simulated and the network recovery times were statistically analyzed through comparative tables and graphics using the average IED Trip times.

It was possible to prove that even with the recovery time of only 7.69ms achieved by RSTP, the large number of lost packets (35) led to the inhibition of the protection function. Trip delays were exaggerated, moving the average time from 16.28ms to 364.17ms.

PRP and HSR protocols obtained a negligible time difference, demonstrating equivalent performance when communication path was lost. Therefore, due to the zero network recovery time and no loss of SV packets, these two protocols are really the most suitable for maintaining the integrity of the communication network in the Process Bus.

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