Protection Redundancy in a Digital Network within a High Voltage Utility Substation based on IEC 62439-3

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1 Introduction

Zero recovery time is an important feature in a protection scheme during a fault scenario. For a protection to maintain its resilience, it is expected that a failure of a link or switch should not jeopardise the overall protection.

Development in the protection scheme highlighting the issues based on two complementary protocols i.e., Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). These two topologies could mitigate the issue of redundancy to a large extent by - building this feature within the protection scheme. It overcomes a link or a switch or a node failure during a zero switchover or delay time. Further, issues arising due to single port failure and interoperability issues related to multi-vendor equipment could be addressed better in IEC 62439-2 published in 2010 taking into account all the shortcomings of Ethernet network failures of a digital protection scheme. In the protection scheme, the Intelligent Electronic Devices (IEDs) with Doubly Attached Node (DAN) components provide redundancy in protection with two active frames in the ring. PRP and HSR topologies not only provide means of redundancies in the protection scheme and communication network but also facilitate standardization of the Ethernet protocols that were vendor specific with number of interoperability issues.

In this paper, the author compared the performances between PRP and HSR topologies using Optimized Network Engineering Tool (OPNET) modeller. This software based simulation validated the results of these two topologies and recommended its application in a utility operated high voltage substation.

2 Background of Protection Redundancy in a Digital Substation

Modern digital substations are expected to work reliably providing adequate redundancies in the protection to the network and interconnecting substations. Lack of redundancy in the protection scheme cause not only costly downtime, but also have high starting cost and loss of valuable data in the event of protection failure. This has an enormous impact on operator’s technical ability and financial resources.

Ethernet is the backbone of digital technology which is constantly shaping the automation requirement of a digital substation. However, for its large scale implementation in utilities, it needs to be tested further on its performance which shall give confidence to its operators. Although, IEC 61850 lays down certain guidelines for communication protocol at station, bay and process level components, yet there are few issues related to redundancies in the scheme, as frames often are lost at nodes and switches during its circulation in the ring [1]. Furthermore, the timing requirement of the protection scheme to operate during a fault being very critical, such as interlocking and blocking, the protection IEDs must act quickly within 4-ms as per IEC 61850-5 standard exhibited as in Table-I. Within such challenging environment, the redundant structure of an Ethernet topology plays a crucial role in providing the necessary reliability. This is achieved by having the redundancy built into the system i.e. the entire network is duplicated including the communication, media and system channels.

Table-I: Communication recovery time based on IEC 61850-5 Ed. 2 [2].

Communication Partners	Application Recovery time (in ms)	Communication Recovery Time (in ms)
Client - Server SC to IED	800	400
NTP , SNMP	500	300
IED to IED, reverse blocking, interlocking	12	4
Trip GOOSE	8	4
Bus Bar Protection	< 1	seamless
Sampled Values	< 2	0

In a most recent development by IEC TC57 working group which was published in 2010 it has used IEC 62439-3 Ed. 1 and 2 standards to address redundancy issues in a digital protection of a SAS network. Leveraging on this IEC 62439-3 standard, PRP and HSR topologies provide seamless recovery during a single link failure. IEC 62439-3, Edition 2 published in 2012 have undertaken few changes with respect to:-

- Tagging of PRP frames
- Clarification on interoperability
- Consideration of clock synchronization
- Simplifying the testing and commissioning procedure.

It may be noted, in PRP topology, a Doubly Attached Node (DAN) enabled equipment could be connected as shown in Fig. 1 with frames circulated in two parallel network. This is a layer 2 redundancy with equipment connected in a cross structured link. It supports GOOSE and SV traffic in a station and process bus structure.

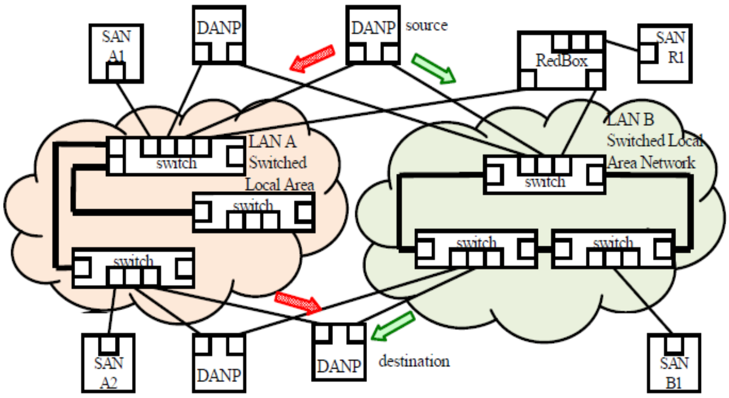

Fig. 1: PRP Network in a digital protection scheme [1].

Fig. 2 shows a typical HSR network in a ring topology wherein IEDs are connected in DAN with two independent paths for frame circulation. In this topology the source sends two frames in opposite direction within the ring ensuring at least one reaches the node.

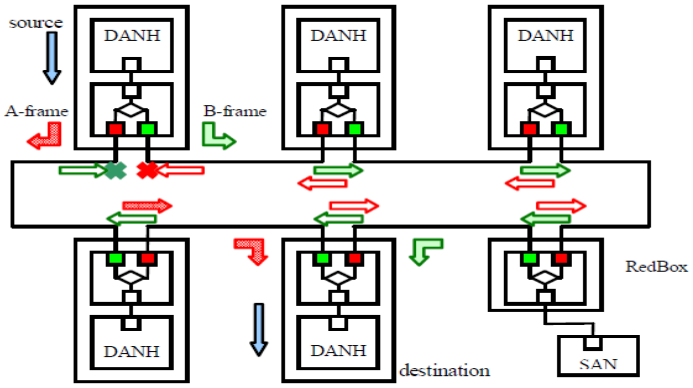

Fig. 2: HSR Topology in a digital protection scheme [1].

In both the topologies i.e., PRP and HSR, Link Redundancy Entity (LRE) act as a buffer between port and the upper layer. It manages the frame traffic transition and substation IEDs having a Single Attached Node (SAN) which has been shown in Fig.1 and Fig.2 [1]. By introducing Red boxes in the PRP/HSR topologies, standard SAN IED device are modified to act as DAN device and thereby establishes redundancies in the digital network. Furthermore, in this scheme, one host port is connected to a standard IED, while the two other ports are meant for redundancies.

As per IEC 62439-3 guidelines, SAS scheme must regularly monitor and check frames at every min interval for Sampled Values (SV) and GOOSE checking for the loss of missing frames. IEC 62439-3 not only checks for redundancies in the network, but also at the nodes and other compliant devices connected to the protection circuit. Although the initial capital cost of PRP topology in the digital protection scheme is more expensive than IEC 61850 hard wired connection due to duplication of protection infrastructure, it offers reliability and redundancy negating other financial disadvantages. Operators use Rapid Spanning Tree Protocol (RSTP) devices in conjunction with Red boxes which are fully compliant to IEC 62439-3 standard. However, in today's world, there are only handful of utilities around the world, which operate using PRP/HSR protection topologies in its schemes

Inspite of the advantages that these two topologies offer, there are few differences in PRP and HSR topologies such as PRP topology have two Local Area Networks (LAN) in duplication while HSR achieves this on a single ring structure. PRP attaches a trailer at the end of each frame known as Redundancy Control Trailer (RCT) while in a HSR network it attaches a tag. IEC 62439-3 Ed.1 defines RCT for 4 bytes tag while Ed.2 extends it to 6 bytes. Ed.1 defines methods of supervision of frames while Ed. 2 lays down new guide lines to manage HSR. All HSR traffic gets recognized based on Ed. 2. The other notable difference between first and second edition of IEC 62439-3 is related to frame length. Ed. 1 has a restriction of 4 bytes for PRP, but that restriction has been lifted in Ed.2. Both PRP and HSR now have 6 bytes in Ed.2. Last but not the least, difference between Ed.1 and Ed.2 are based on sequence numbering of circulating frames, method of handling duplicate frames and node tables, clock synchronization etc. [2].

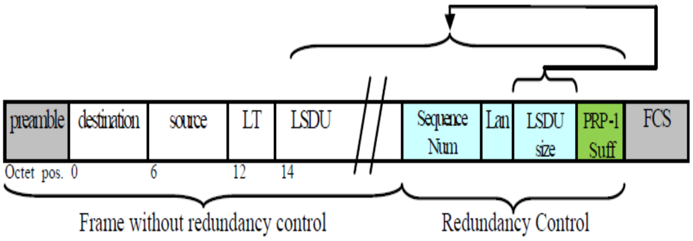

Fig. 3: PRP with RCT frame [2].

Figs. 3 and 4 exhibit typical PRP and HSR tags respectively in the frames just before the addresses.

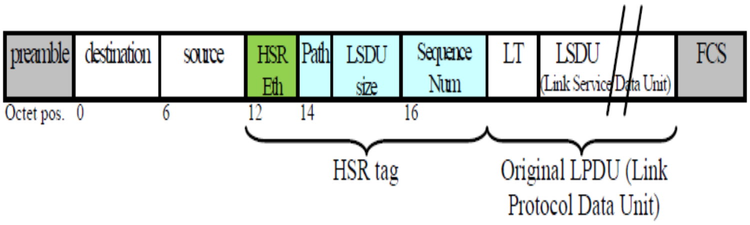

Fig. 4: HSR Frame with the tag at the front [2].

Few other disadvantages of HSR topology are, if it accepts undesirable circulating frames, the ring could have a link failure, traffic could clog up due to the error in the frames. The HSR network sends signals in two opposite directions within the ring. Each message in the loop carries a sequence number, which accepts or rejects a frame at the node depending on the signal packets and byte sizes [3]. Hence, HSR scheme has the advantage of not only being simple in structure but utilises less hardware and accommodates higher traffic within the link that could lead to data clogging. This shortcoming is negated by applying bi-directional data communication channels which means, in case of a link failure, there would be a continuous data transfer within the healthier loop.

In this paper, a software based simulation has been implemented in a laboratory environment based an OPNET or Riverbed modeller solutions offering simulation based performance evaluation. The simulation result exhibits performance delay encountered and traffic load in data packets reaching out to various nodes in bits/sec based on these two seamless topologies. The frame stack carry Generic Object Oriented Substation Events (GOOSE) delivers real time and mission critical messages to the IEDs that exhibit latency and delay in the overall network. Hence, it is important to reduce the network traffic and its bandwidth [4].

Summarizing the benefits of PRP and HSR topologies [5-7]:-

- Seamless protocol is achieved using these two topologies
- Availability of the SAS function through zero recovery time from a single link failure
- No time delay in the event of a fault due to transmission of frames in duplicates
- Easy coupling between PRP and HSR network to have best of both the features i.e. Combination of PRP and HSR, making the protection scheme robust, reliable and economical
- Tolerates any single network component failure
- Allowing nodes not equipped for redundancy to operate by linking it using Red boxes in the network
- Support time synchronization
- Reduction in interoperability related issues for different manufacturer products.

This paper is divided into 6 sections. Section 1 is introduction, Section 2 provides the background of protection redundancy in a digital substation. Section 3 deals with the node structures in PRP and HSR topologies, Section 4 is the network topologies in a substation bus configuration. Section 5 presents the simulation results and discussion. Finally, the conclusion is in section 6.

3 Node Structures in PRP and HSR Topologies

A) PRP Node Structure

In a PRP node structure shown in Fig. 5, DANP equipment has two Ethernet adapters with one Medium Access Control (MAC) and Internet Protocol (IP) address. Resilience of the network is achieved by sending frames in two opposite directions in the ring. It provides bump-less redundancies which in other words, data is made available having zero delay during a link failure. In the event of a fault, any interruption that could prevent a frame from arriving at the node that may cause other healthy frames to seek an alternative route, fulfilling the requirement of redundancy in the protection scheme. In this study, a station bus configuration has been considered to keep the structure simple. The timing requirement of a station and process bus topologies are distinct, which underlines the protection redundancy requirement. In a station bus, a delay up to a magnitude of 100-ms are tolerable for interlocking and trip, but in a reverse blocking, only 4-ms tolerance is acceptable as enumerated in IEC 61850-5 and also exhibited in Table-I for the communication recovery time

In Fig. 5, a cross linked duplicate PRP network is shown in the form of a block diagram. It has two layers of redundancies with MAC and IP address present in each adapters. Furthermore, Link Redundancy Entity (LRE) acts as a buffer between upper layer and ports. In a source node, LRE duplicates the frames, while at the destination node it monitors the packet flow in a duplicate loop. If a link or port is damaged, LRE shall continue to receive copies of the frame through an alternative path, while discarding the error frame. Additionally, in LRE, modification is achieved by the software and processor.

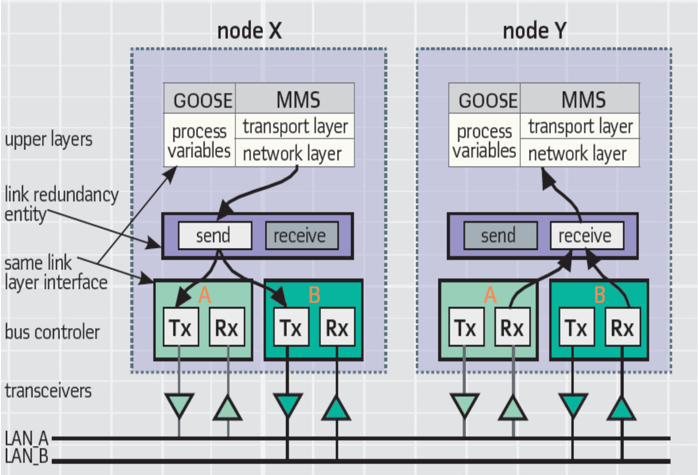

Fig. 5: Node structure of PRP [6].

B) High Availability HSR Node Structure

In HSR topology, IEDs are daisy chained in a ring. Frames are sent in opposite direction and at the same time within the loop. During a fault, error frames are discarded while healthier frame arrive at the destination node with zero recovery time, which is similar to the PRP topology choosing an alternative route. This ensures no down time in the network. As an example, when unicast frames are sent in the loop, the frames broadcast messages to every node in the loop, with significant chances of getting acceptance at least by one IED. IEC 62439-3 stipulates, in the event of a reduced traffic in the network, each node shall forward the frames within 5µs. In other words, with duplicated frame messages travelling in opposite directions in the loop, frame messages are never lost. This feature in HSR topology enables frames are never lost and the scheme offers total protection with zero-fault recovery time, in the event of a node or link failure. It restores SAS network to a healthier condition quicker than the conventional protection system to clear a fault. However, the major disadvantage of the HSR topology is in duplication of messages within the ring that could cause slowdown of frames due to data clogging in Ethernet traffic.

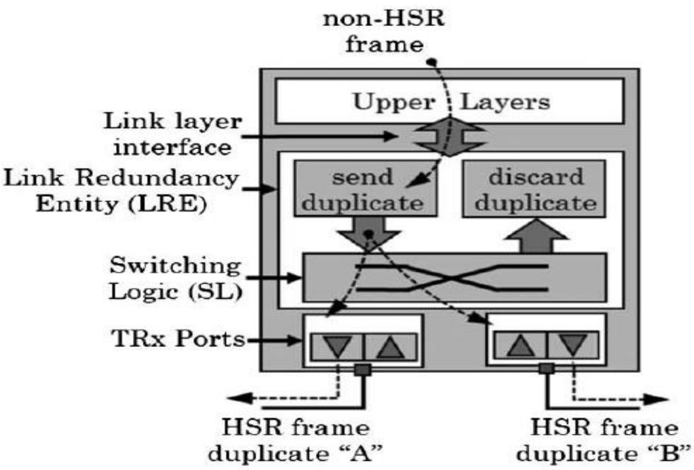

Fig. 6: Node structure of HSR [7].

In Fig. 6, a block diagram of HSR topology is shown which has a bridging logic between two ports A and B and vice versa. The duplication of the frames are more pronounced in HSR than in PRP. The disadvantage of HSR is to duplicate detection of frames that could cause flooding in the ring structure leading to slowing down of traffic. It is observed that in the bridging logic, clock synchronization of PRP and HSR relies on IEEE 1588 V2.

4 Network Topologies in a Station Bus Configuration

A Single Line Diagram (SLD) has been exhibited in Fig. 7 which show a typical 132/22-kV high voltage zone substation in a single bus configuration. Here, we have investigated the performance of a protection system based on PRP and HSR topology using OPNET simulator in a station bus configuration, having Ethernet ports on IEDs. RSTP devices IEDs in conjunction with Red boxes are used to transform it to PRP and HSR configuration.

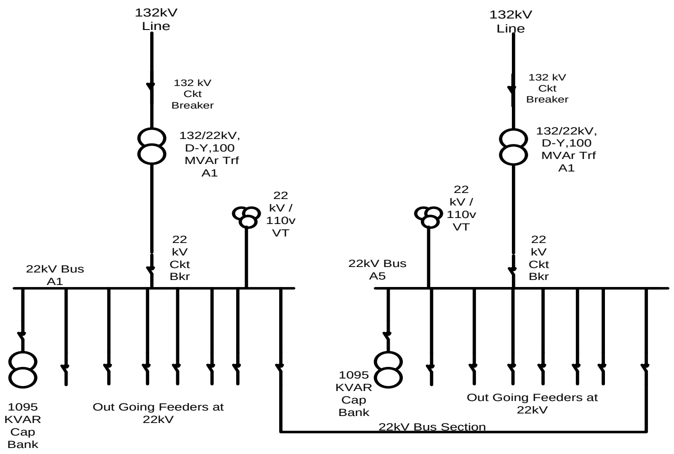

Fig. 7. The SLD of a 132/22-kV zone substation [8].

A) Protection Scheme in a PRP Topology

The IEDs in the block diagram shown in Fig. 4 are connected to switches in duplicated rings interlinked in a meshed structure having two independent Local Area Network (LAN). In this scheme, every IED has 2 layers of links providing seamless N-1 redundancy. In Fig.7 incomer and outgoing of Transformers, bus bars and outgoing feeders all are protected via IEDs and it is simulated in an OPNET platform for PRP and HSR topologies.

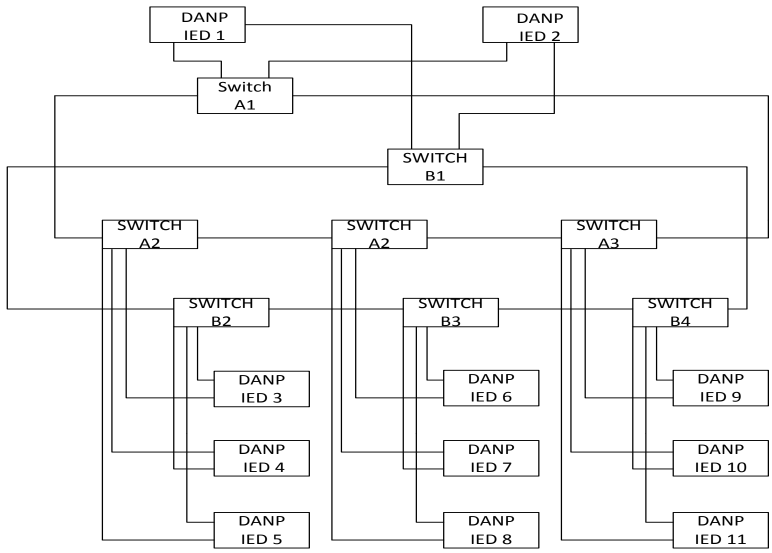

Fig. 8: PRP connection diagram.

B) Protection Scheme in a HSR Topology

In HSR topology, the nodes of the IEDs are either connected in DANP or SAN scheme using a Red box as shown in Fig. 9 in a ring structure. When two or more frames are sent out in opposite direction within the loop, the error prone frame is blocked but allows the healthier frames to reach its destination, preventing the loss. The transmission of frames in opposite directions, keep the communication channel on a high availability mode. Failure and error in the frames could make the network vulnerable due to decline in the protection reliability. This situation is eliminated using bi-directional communication.

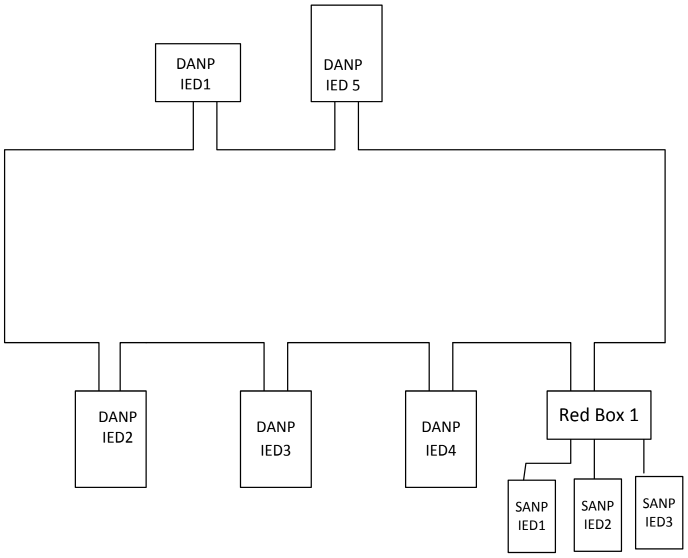

Fig. 9: HSR LAN in a single ring.

5 Simulation Results and Discussion

A) PRP Simulation

An OPNET simulator was used to verify the performance of an overall delay in the PRP network topology at the nodes of IEDs and switches. This simulation involved GOOSE traffic messages floating around in the duplicate local area network. Fig. 10 exhibits the Ethernet delay at the DANP nodes for an overall End to End delay of a PRP connected protection scheme of a typical 132/22-kV zone substation in a utility environment.

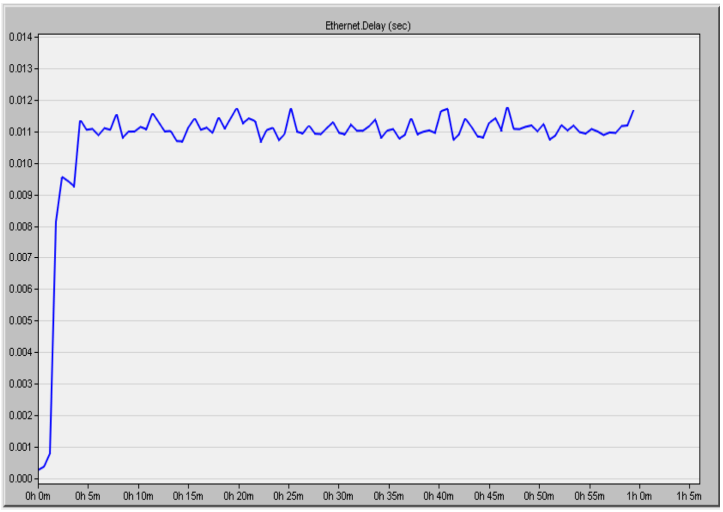

Fig. 10: Ethernet delays based on PRP topology.

Fig. 10 shows the overall Ethernet delay i.e., End-to-End delay in the topology which is encountered in all Ethernet connected IED devices and peripherals such as switches, media converters and Merging Units etc.

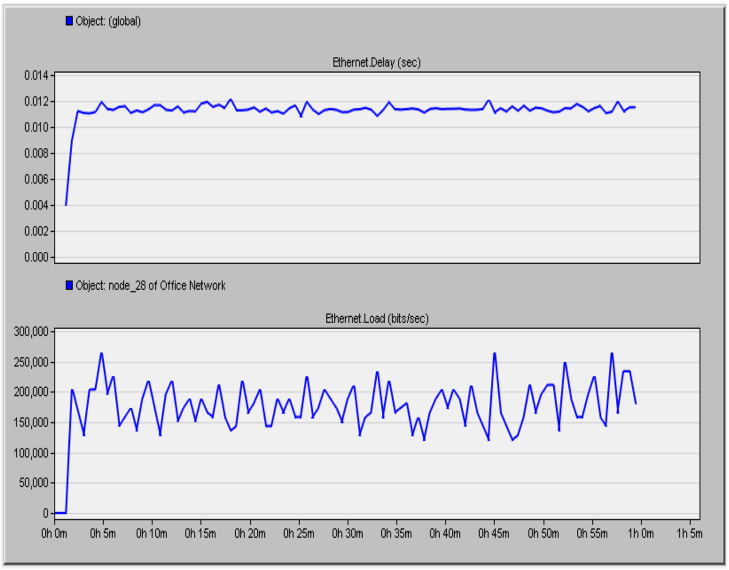

Fig. 11: Average Ethernet delay at nodes in PRP topology vs overall Ethernet End to End delay.

Fig. 11 compares the average Ethernet delay and Ethernet load in a PRP topology protection scheme simulated using OPNET modeller.

B) HSR Simulation

Figs. 12 and 13 exhibits delay in Ethernet network at the DANP and SAN nodes of an overall HSR ring topology. Here, connected IEDs in the ring are HSR compatible devices with few SAN IEDs that need Red box to support this topology. The reason for inserting Red boxes into the scheme is to prove the performance of SAN IEDs operating in RSTP scheme in a substation that could later be modified from conventional structure to a new structure without making these devices obsolete and carrying out wholesale change, in the event of the protection upgrade based on IEC 61850 to IEC 62439-3 scheme. Fig. 12 and 13 compares average Ethernet delay at nodes in HSR topology vs overall Ethernet End to End delay.

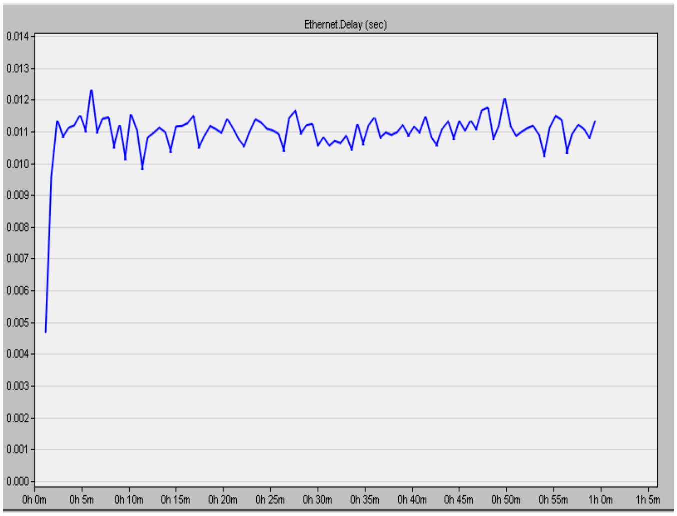

Fig. 12: Ethernet delays based on HSR topology.

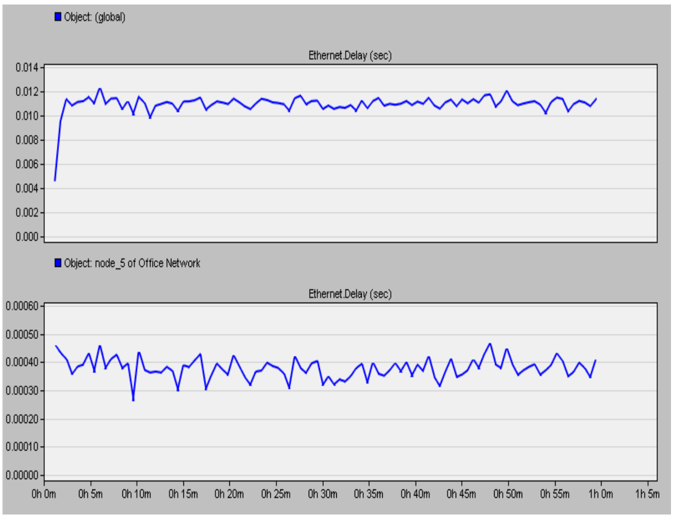

Fig. 13: Average Ethernet delays in a HSR topology node vs the overall delay.

The OPNET simulation of PRP and HSR topologies for performance evaluation were carried out based on the following parameters as listed in Table-II.

Table-II: OPNET simulation for PRP and HSR topologies.

	PRP	HSR
Events	12,550,473	1,599,890
Average Speed (events/sec)	2,453,573	1,700,890
Time elapsed (sec)	4	2
Duration of simulation (Hrs)	1	1
DES Log	6 entries	6 entries

The OPNET simulation results indicate that the Ethernet traffic delay at the nodes were slightly higher for PRP in comparison to HSR topology due to slow down of frames in the loop due to its meshed structure as frames clog up at too many nodes travelling via nodes The other notable conclusion inferred with respect to this simulation is reliability. It is noted that PRP offered better protection reliability due to cross links and duplication of the ring with minimal chances of failure. PRP rings are virtually local area networks (LAN) which are resilient to faults, due to duplication of rings in the scheme. On the other hand, HSR topology having a simple architecture, with multiple IEDs in switching end nodes which are effective in lesser complex digital protection network. The notable features in both these topologies i.e., PRP and HSR are, IEC 61850 devices having single port which could be used in IEC 62439-3 with Red boxes inserted and connected via fibre optic multiplexing adapters as shown in Fig. 5. This offers flexibility and upgradation to a newer scheme without suffering from obsolescence.

6 Conclusion

All protection schemes within the substation require zero recovery time in the event of a fault. In other words, the circuit must provide zero recovery time to bounce back into active normal mode after suffering a failure. With the advancement in technology, it is possible to achieve these objectives using PRP and HSR topologies leveraging on IEC 62439-3 standard which offer fail-independent protection scheme to a digital protection network.

This paper validated on an OPNET software platform the performance analysis of two digital network topologies on an Ethernet platform i.e., PRP and HSR based on IEC 62439-3 standard. The OPNET software simulation results were performed on a typical zone substation of a 132/22-kV station bus architecture which exhibits higher reliability and enhanced performance of a digital communication network. It validated the speed of frames arriving at nodes as per IEC 62439-3 and the result encourages its application in future use within the utilities.

Both topologies promise enhanced fault tolerance and reliability in protection and redundancy. These topologies promise to be the future of automation and protection of digital protection scheme within the utilities and in the industrial environment.

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References

[1] J. A. Araujo, J. Lazaro, A. Astaloa, A. Zuloaga, and N. Moeira, "Duplicate and Circulating frames discard methods for PRP and HSR (IEC 62439-3)." *in Proc. of the 2013 Electricity Distribution, CIRED 2013, DOI 10.1049/cp.2013.0836, Stockholm, Sweden.*pl check all refs.

[2] C. Hoga,"Seamless Communication Redundancy of IEC 62439" in Proc. of The international Conference on Advanced Power System Automation and Protection 2011, DOI 10.1109/APAP.2011.6180451, Beijing, China.

[3] J. A. A raujo, J. Lazaro, A. Astaloa, A. Zuloaga, and A. Garcia, "PRP and HSR Version 1 (IEC 62439-3 Ed.2) Improvements and a Prototype implementation" in the Proc. of 2013 Industrial Electronics Society, IECON 2013, DOI 10.1109/IECON.2013.6699845, Vienna, Austria.

[4] G. Antonova, L.Frisk, and J. C. Tournier, "Communication Redundancy for Substation Automation" in Proc. of the 64th Annual conference for Protective Engineers, 2012, DOI 10.1109/CPRE.2011.6035636, College Station, Tx, USA.

[5] International Standard IEC 62439-3, Edition 3.0, "Industrial Communication Networks High Availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR)", 2012.

[6] H. Kirrmann, P. Rietmann, and S. Kunsman, "Standard IEC 61850 - Network redundancy using 62439", Offprint of article in PAC World, Fall 2008.

[7] Y. M. Allawi, D. Lee, K. Lee, and J-K. K. Rhee. "Cost effective Topology design for HSR resilient Mesh Networks" in proc. of the Electricity Distribution (CIRED 2013), 22nd International Conference an Exhibition, 10.1049/cp.2013.0836, Stockholm.

[8] S. Kumar, N. Das, S. Islam, "Causes and mitigation of sympathetic tripping phenomenon based on IEC 61850," Australian Protection Symposium 2014, Sydney, Australia.

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