High Performance Communication Redundancy in a Digital Substation based on IEC 62439-3 with a Station Bus Configuration

Shantanu Kumar,[1,3] *Member, IEEE,* Narottam Das,[1,2] *Senior Member, IEEE,* and Syed Islam,[1] *Senior Member, IEEE*

[1]Department of Electrical and Computer Engineering, Curtin University, Perth, WA 6845, Australia

[2]School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba, QLD 4350, Australia

[3]Asset Performance Department, Western Power, Perth, WA 6000, Australia

e-mails: shantanu.kumar@postgrad.curtin.edu.au, narottam.das@usq.edu.au, and s.islam@curtin.edu.au

Abstract*— High speed communication is critical in a digital substation from protection, control and automation perspectives. Although International Electro-technical Commission (IEC) 61850 standard has proven to be a reliable guide for the substation automation and communication systems, yet it has few shortcomings in offering redundancies in the protection architecture, which has been addressed better in IEC 62439-3 standard encompassing Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). Due to single port failure, data losses and interoperability issues related to multi-vendor equipment, IEC working committee had to look beyond IEC 61850 standard. The enhanced features in a Doubly Attached Node components based on IEC 62439-3 provides redundancy in protection having two active frames circulating data packets in the ring. These frames send out copies in the ring and should one of the frame is lost, the other copy manages to reach the destination node via an alternate path, ensuring flawless data transfer at a significant faster speed using multi-vendor equipment and fault resilient circuits. The PRP and HSR topologies provides higher performance in a digitally protected substation and promise better future over the IEC 61850 standard due to its faster processing capabilities, increased availability and minimum delay in data packet transfer and wireless communication in the network. This paper exhibits the performance of PRP and HSR topologies focusing on the redundancy achievement within the network and at the end nodes of a station bus ring architecture, based on IEC 62439-3.

***Index Terms*— Ethernet, IEC 61850, IEC 62439-3, PRP and HSR.**

I. Introduction

Faults are occurring in a power system network frequently and must be cleared immediately in order to meet the stability requirement. Additionally, as substations operate round the clock and hardly shut down for maintenance, protection system involved must isolate the primary plant in the faulted zone immediately. Under such dynamic conditions, file and data transfer over Ethernet in a digital protection scheme, if experienced a mal-function, could spell disaster for the protection scheme. Utilities and industries have been striving to have reliable communications between substation switchyard assets and substation automation systems (SAS) that can monitor, record and clear system disturbances within the least possible time as exhibited in Table-I. In the entire scheme of SAS, communication topologies play a major role in the digital substation based on IEC 61850. The shortcomings encountered in IEC 61850, using Ethernet communication linking devices in a digital substation could have issues, such as high availability and single point failure which may jeopardize mission critical protection and control applications. Although, IEC 61850 lays down certain guidelines for communication at station, bay and process level components, yet there are issues related to redundancies offered, with respect to loss of data packets at nodes of Intelligent Electronic Devices (IEDs) and switches [1]. Further, the timing requirement of a protection scheme to operate being very critical, such as interlocking and blocking, protection scheme must act within 4-ms as per the IEC 61850-5 standard exhibited in Table-I.

Table-I: Communication recovery time based on IEC 61850-5.

Communication Partners	Application Recovery time (in ms)	Communication Recovery Time (in ms)
Client - Server SC to IED	800	400
IED to IED, reverse blocking, interlocking	12	4
Trip GOOSE	8	4
Bus Bar Protection	< 1	seamless
Sampled Values	Less than a view consecutive samples	seamless

The recent development by IEC TC57 working group uses IEC 62439-3 to address the redundancy in protection leveraging on the SAS. This upgraded version of IEC 61850 i.e., IEC 62439-3, identifies the requirement of redundancies in network devices, components and configurations. As per the IEC 62439-3, SAS should regularly monitor and check at an interval of 1 minute scanning the entire network for non-IEC 61850 and IEC 61850 compliant devices. The IEC 62439-3 standard further elaborates on “bump-less” and seamless communication redundancies, which makes it acceptable to satisfy zero recovery time in the event of a fault occurrence.

As per this standard, configuration errors are reported at an interval of every minute. The IEC 62439-3 standard not only checks redundancies in the network, but also at the nodes and other compliant devices connected in the network. Although the cost is twice as compared to a conventional protection scheme due to installation of higher network infrastructure using PRP topology, the reliability gained in protection could not be overemphasized. Manufacturers are working towards upgrading an IEC 61850 protection scheme using redundant boxes (Red boxes) and single attached nodes (SAN) IEDs to be fully compliant to IEC 62439-3 standard but not many digital substations have been proven with this new technology. In the basic architecture of PRP topology, there are two independent Local Area Networks (LANs), which provides seamless switchover during a link failure. Additionally, in this topology the IEDs connected have two ports for fiber optic terminations that makes it doubly attached nodes in parallel (DANP). Further, in DANP IEDs, information is accepted at both nodes that enables availability of the frame in the event of failure of a port [2]. When a fault cause interruption in one route blocking the frame, the other frame routes itself, using alternate path and reaches the destination node travelling via the second link route. This ensures zero interruption in the network operation, while achieving redundancy in protection. While PRP topology is more complex in structure, HSR has an advantage of being connected in a simple architecture, using DANP and SAN IEDs linked in a ring, providing a parallel network.

The major difference between the PRP and HSR network is, PRP manages two networks in duplicate, while HSR achieves this on a single ring network. In HSR network, if an error occurs in the copy of a certain frame, the other frame and its copy, routes itself to reach the destination node, using alternate path. HSR network sends signals in two different directions within the ring. Each message in the loop carries a sequence number, which is accepted or rejected at the node depending on signal packets it carries [3]. Further, HSR scheme has an advantage of having a simple scheme with less hardware, but higher traffic in the link that could lead to data clogging. This shortcoming is negated by applying bi-directional data communication. This means, in case of a link failure, there are no stoppage to the data transfer in a healthier ring. In this paper, tests of these two topologies have been simulated using an Optimized Network Engineering Tool (OPNET) simulator manufactured by Riverbed modeler, to determine the delay encountered and traffic load of data packets reaching out to various nodes in bits/sec, in a digital substation in a station bus configuration [4]. The frame stacks carry Generic Object Oriented Substation Events (GOOSE) that delivers real time and mission critical messages to the IEDs when the stacks of the GOOSE arrive at IEDs. Hence, it is important to reduce the network traffic and bandwidth [5-10].

II. Node Structures in PRP and HSR Topologies

A) PRP Node Structure

In a PRP node structure shown in Fig. 1, DANP has two Ethernet adapters but one MAC and IP address. Resilience is achieved by sending frames in two different directions in the ring. It provides seamless or bump-less redundancies which in other words, data is made available with zero delays during a link failure. In the event of a fault, interruption in one path, prevents a frame to arrive at the node, while the other frame reaches the node using alternate link, 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 the station bus and process bus are distinct and underline the protection redundancy requirement. In a station bus, delay up to a magnitude of 100-ms are tolerable for interlocking and trip, but for a reverse blocking, only 4-ms tolerance is acceptable as enumerated in IEC 61850-5 and shown in communication recovery time in Table-I.

There are significant advantages in employing PRP topology such as compatibility with Rapid Spanning Tree Protocol (RSTP) devices and user friendly interface with IEC 61850 components. It is a transparent network and achieves zero recovery time in a fault scenario. It tolerates any single network component failure and doesn’t rely on other protocols. It allows nodes not equipped for redundancy to operate with time synchronization.

In Fig. 1, a duplicate PRP network is shown in the block diagram. It has two layers of redundancies with Medium Access Control (MAC) and Internet Protocol (IP) address present in each of the adapters. Link Redundancy Entity (LRE) acts as buffer between upper layer and ports. In a source node, LRE duplicates the frames while at the destination node and keeps a track of the duplicate node. If a link or port is damaged, LRE shall continue to receive copies of the frames through an alternative path, while discarding the error frames. Additionally, in LRE, modification is achieved by the software and processor. The advantages offered in PRP are multifold, such as availability of the SAS function through zero recovery time for a single link failure and deployment of multi-vendor products in a parallel ring, with reduced possibility of interoperability issues. The PRP topology in a station bus configuration is deemed better than a conventional control system, which supports peer to peer communication and data exchanges.

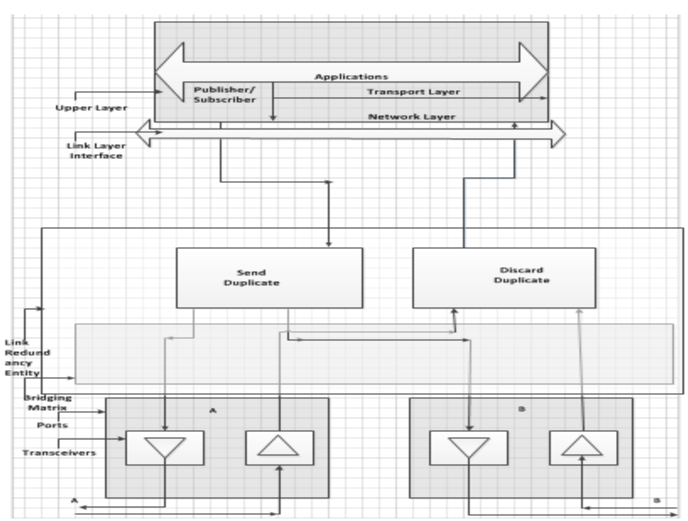

Fig. 1: Node structure of PRP [6].

B) High Availability HSR Node Structure

In HSR topology, IEDs are daisy chained in a ring. Frames are sent in opposite directions at the same time. During a fault, error frames are discarded while healthier frames arrive at the destination node with zero recovery time, similar to the PRP topology. This ensures no down time in the network. For example, when the unicast frames are sent in a loop, the frames broadcast messages to every node in the loop, with significant chances of getting acceptance at least by one node in the IED. HSR communication in the network is sustained by the duplication of frames. IEC 62439-3 stipulates that, in the event of reduced traffic in the network, each node shall forward the frames within 5µs. With duplicated frame messages travelling in opposite directions in the loop, frame messages are never lost and this feature enables zero-fault recovery time, in the event of a node or link failure while securing the SAS network to a healthy condition from protection perspective. However, the major disadvantage of the HSR topology is in the duplication of messages within the ring, which could cause slowdown of frames due to data clogging in the traffic.

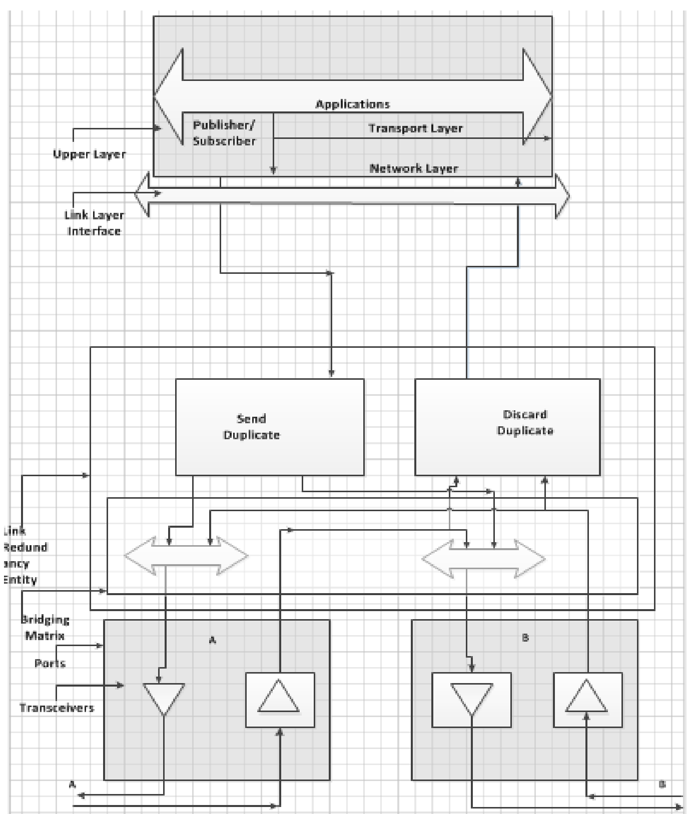

Fig. 2: Node structure of HSR [6].

In Fig. 2, it is noted that the bridging logic forwards from port A to port B and vice versa. The duplication of frames are more pronounced in HSR than PRP. The disadvantage of HSR is duplicate detection of frames that could cause flooding in the ring structure. It is observed that in the bridging logic, clock synchronization of PRP and HSR relies on IEEE 1588 V2.

III. Network Topologies in a Station bus Configuration

The Single Line Diagram (SLD) exhibited in Fig. 3 shows a typical 132/22-kV high voltage zone substation. Here, we have investigated the performance of a protection system based on PRP and HSR structure using OPNET simulator in a station bus topology, having two Ethernet ports on IEDs in the ring.

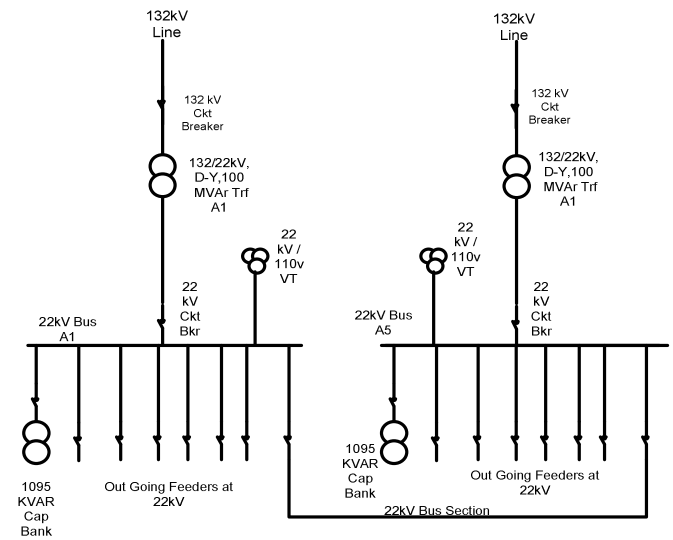

Fig. 3. The SLD of a 132/22-kV zone substation.

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. In this scheme, every IED has 2 layers of links providing seamless N-1 redundancy.

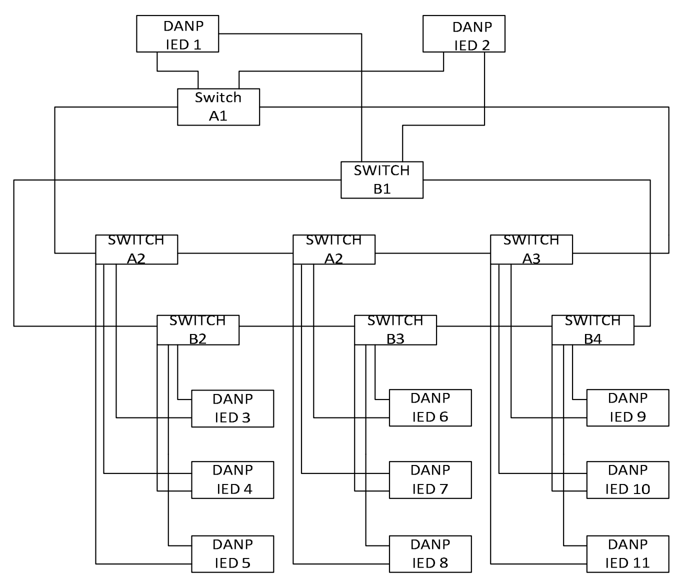

Fig. 4: PRP connection diagram.

B) Protection Scheme in a HSR Topology

In HSR topology, the nodes of the IEDs are either connected in the DANP or Single Attached Nodes (SAN) via a Red box as shown in Fig. 5 in a ring structure. When two frames are sent out in different direction in the loop, the frame with error is blocked while the other reaches to the destination node, completing the loop preventing loss of frames. The transmittal of frames in two different directions, keep the communication channel on a high availability mode. Failure and error with frames makes the network vulnerable, which is eliminated by bi-directional communication.

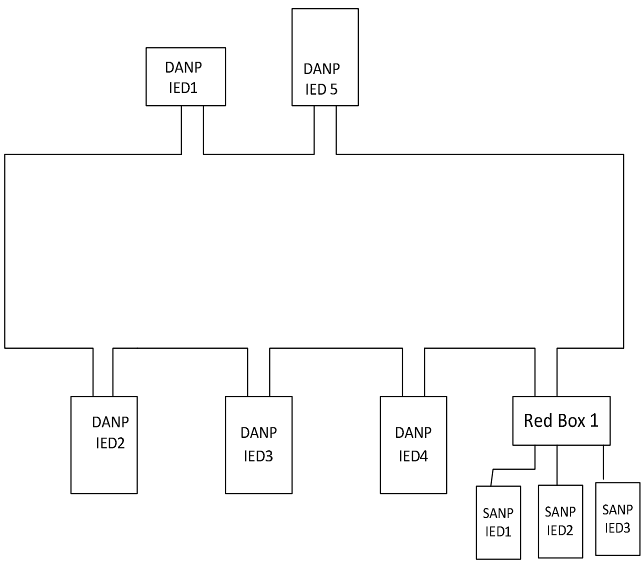

Fig. 5: HSR LAN in a single ring.

IV. Simulation Results and Discussion

A) PRP Simulation

Using an OPNET simulator, the overall delay at nodes of IEDs and switches were carried out for GOOSE traffic/ messages. Figs. 6 and 7 exhibits Ethernet delay at the DANP nodes for an overall PRP connected protection scheme within a 132/11-kV zone substation.

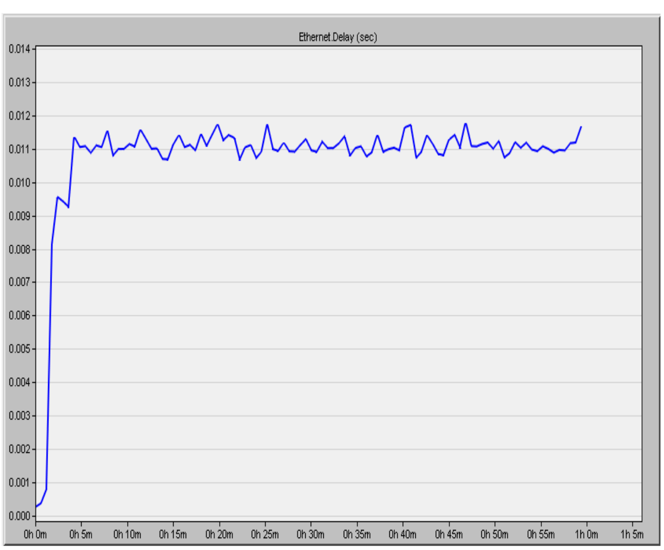

Fig. 6: Ethernet delays based on PRP topology.

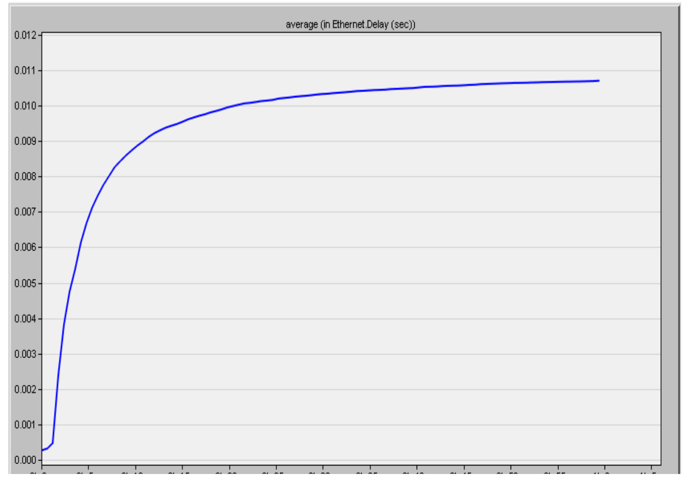

Fig. 7: Average Ethernet delay in a PRP topology.

B) HSR Simulation

Figs. 8 and 9 exhibits, delay in Ethernet network at the DANP and SAN nodes in an overall ring topology. Here, all IEDs connected in the ring are HSR compatible devices but SAN devices connected uses a Red box.

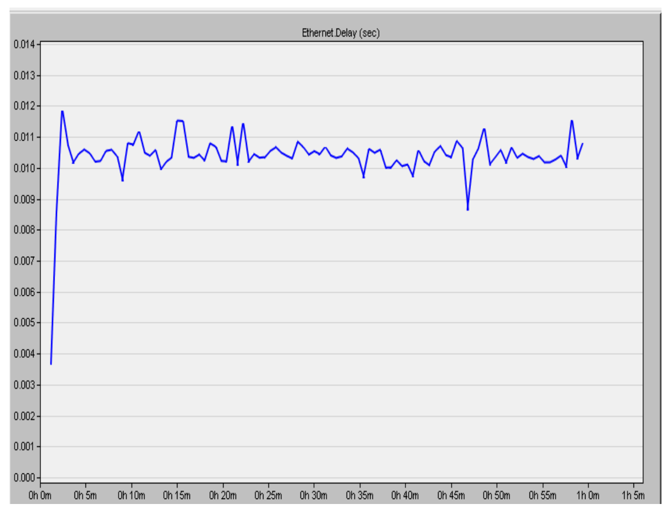

Fig. 8: Ethernet delays based on HSR topology.

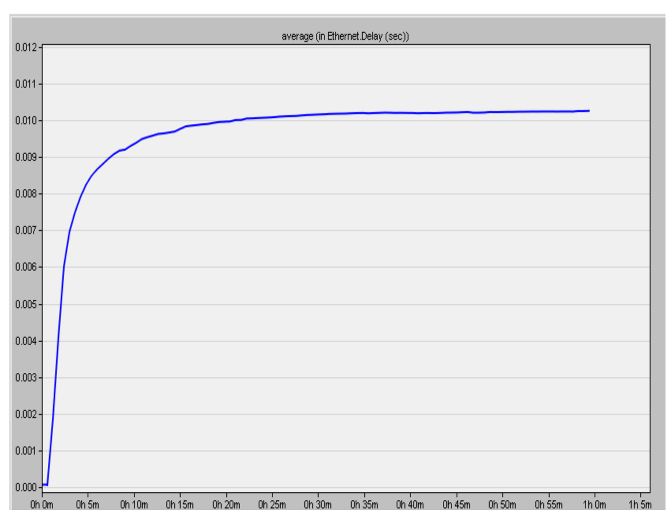

Fig. 9: Average Ethernet delays in a HSR topology.

The OPNET simulation for both i.e., PRP and HSR topologies were carried out with the following parameters as listed in Table-II.

Table-II: OPNET simulation for PRP and HSR topologies

	PRP	HSR
Events	4,003,753	2,433,189
Average Speed (events/sec)	762,474	695,195
Time elapsed (sec)	5.3	3.5
Duration of simulation (Hrs)	1	1
DES Log	8 entries	8 entries

It was observed that traffic delay at nodes were lower in HSR compared to the PRP due to its simplicity in topology construction, but in terms of reliability, PRP offered better protection due to interlinks and duplication in the ring. The PRP rings are virtually local area network (LAN), which is twice costly with respect to infrastructure installation as opposed to HSR ring, but more resilient to faults, due to duplicated rings in the scheme. On the hand, HSR topology has a simple architecture, having multiple IEDs in switching end nodes and effective in less complex network. The notable features in both the schemes i.e. PRP and HSR are, old IEDs with single port based on IEC 61850 could be upgraded to IEC 62439-3 using Red box connected via fiber optic multiplexing adapters as shown in Fig. 5.

V. Conclusion

This paper presents an implementation and performance analysis of a PRP and HSR seamless communication redundancies in a SAS network based on IEC 62439-3, due to shortcomings encountered in IEC 61850, as it could not address the protection redundancies with clarity. Based on the simulation results in a typical 132/11-kV single bus zone substation having station bus architecture, reliability and performance of the communication network could be addressed well using PRP/HSR topologies. The simulation validates the speed of frames arriving at nodes to IEC 62439-3 standard. PRP and HSR topologies in the protection scheme, offer significant advantages, in terms of redundancies offered that were resilient to failures.

As substation devices need to be continuously monitored for the loss of data and frames, IEC 62439-3 standard does well to fulfil the gap by providing adequate N-1 features in PRP/HSR topologies which allow frames to travel faster in two alternate paths at a high speed. Comparison of two topologies in terms of speed and traffic load at nodes indicate PRP to be more reliable than HSR topology although the cost of the infrastructure is doubled in the former, while the latter is faster in frame transfer due to simple structure. Both topologies promise enhanced fault tolerance strength in protection and redundancy is based on IEC 62439-3 standard which seems to be the future of automation and protection. However, there are few shortcomings in PRP that needs to be investigated further, due to challenges in time synchronization based on IEEE 1588 V2.

References

[1] V. Bharadwaj, M. I. Singh, S. Pardesi, and R. Arora "A review on various standards for digital substation." *in Proc. of 2005 IEEE Conference*, ICGCCEE, 2014.

[2] C. Hoga, "New Ethernet Technologies for Substation Automation*",* Powertech 2007, Lusanne, AB, Canada.

[3] H. Kirrman, M. Hanssonand, and M. H. P. Muri, "IEC 62439 PRP: Bumpless Recovery for highly available, hard real-time industrial networks." *in Emerging Technologies and Factory Automation, IEEE Conference, 2007.*

[4] M. Goraj and R. Harada, "Migration paths for IEC 61850 substation communication networks towards superb redundancy based on hybrid PRP and HSR topologies", DPSP, 2012, IET Conference.

[5] H. Kirrmann and D. Illie, "Performance of a full-hardware PTP implementation for an IEC 62439-3 redundant IEC 61850 substation automation network", ABB Switzerland, IEEE conference, 2008.

[6] Industrial Communication Networks – High Availability Automation Network – Part 3: Parallel Redundancy Protocol and High-availability Seamless Redundancy (HSR), IEC-62439-3, 2012.

[7] V. Bharadwaj, M.Inder Singh, S.Pardeshi, and R. Arora, "A review on various standards for digital substation", in proc. of the International conference, ICGCCEE IEEE, 2014.

[8] S. A. Nsaif and M. R. Jong, ICT Convergence (ICTC), International Conference on DOI, "RURT; A novel approach for removing the unnecessary redundant traffic in any HSR closed-loop network type", in proc. of the IEEE conference, 2013.

[9] H. Heine and D. Bindrich, "Designing reliable high-performance IEC 61850 Substation communication networks based on PRP and HSR topologies", Electricity Distribution (Cired 2013), 22nd international Conference and Exhibition, IET Conference publications, 2013.

[10] H. Heine and O. Kleinberg, "The high-availability seamless redundancy protocol (HSR) robust fault-tolerant networking and loop prevention through duplicate discard", Factory communication systems (WFCS), in *proc. of the 9th* IEEE international workshop, 2012.