DESIGNING RELIABLE HIGH-PERFORMANCE IEC61850 SUBSTATION COMMUNICATION NETWORKS BASED ON PRP AND HSR TOPOLOGIES

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ABSTRACT

In this paper the usage of new redundancy mechanisms defined in IEC62439-3 and their influence on substation networks is discussed.
This paper gives a short overview of PRP and HSR and outlines how the usage of these new redundancy protocols influences substation network design. Since new IEC62439-3 network redundancy mechanisms require new or adapted network architectures the paper starts with a discussion about the network requirements for different voltage levels and types of devices. Especially protection devices and substation controller are addressed. Different network structures are discussed and their advantages and disadvantages concerning reliability, complexity and performance. Among others the usage of RSTP as additional redundancy mechanism in PRP networks and the position of RedBoxes and devices at different locations are discussed.

INTRODUCTION

Using the advantages of wide spread and field proven technology in a huge variety of applications, Ethernet also became a state of the art communication protocol for the power utility field. In substation automation IEC 61850 [1] opened this field of application and defined requirements and services for Ethernet communication devices.
Two services are highly critical: the Generic Object Oriented Substation Event (GOOSE) defined in IEC 61850-8-1 [2] and Sampled Values defined in IEC 61850-9-2 [3]. Both use ISO-OSI Layer 2 communication and pose new and very challenging requirements to Ethernet communication systems since failure in the communication system could result in damage to high-voltage switchgears and even cause power outages.
For usage in substations the whole communication system has to fulfil the requirements mentioned above even in absolute worst case situations. This means end devices and Ethernet switches designed for IEC 61850 communications both have to be regarded. To secure communication, redundancy protocols are inevitable in power utility applications.
Following RSTP [4] on the way of enhancing the reliability of substation communication PRP and HSR [5] offer full redundancy mechanisms without reconfiguration time. While this feature is being paid with doubling the network topology in PRP, HSR offers a more advanced concept.

This paper gives an introduction to both protocols starting with characteristics they share and outlining the differences between them. Regarding drawbacks and advantages of each protocol, different topologies are compared.

BASICS OF PRP AND HSR

The protocols regarded in this paper both offer n-1 redundancy which means the communication is still fully functional in case of one single error in any given place of the network. The basic principle of redundancy is offering two paths for message transportation. In case of one being blocked, the other one is still available. Seamless redundancy [5] improves this concept by switching over from one path to the other unnoticed by the device application. The main problem in redundancy protocols is inherently given by the concept of using two paths: Pure Ethernet protocols rely on getting each packet only once. This means the communication has to be organized in a way which prohibits the arrival of the same packet via both paths at the device application in any case. While RSTP always blocks one path and thus avoids duplicates, HSR and PRP use both paths at the same time and eliminate duplicates when receiving them [6]. This means in case of intact communication packets always arrive twice. Therefore, they have to be compared with a table containing former received packets before handing them to the application. The protocol headers of PRP and HSR mainly result from the data needed for this task. In contrast to RSTP no additional network information is required.

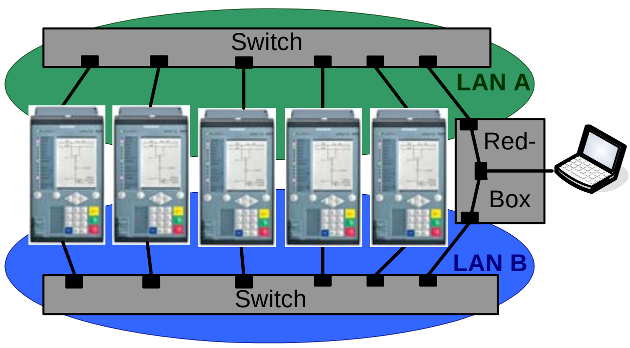

Figure 1. basic PRP topology

Devices supporting PRP or HSR are called DANP (dual attached node PRP) or DANH (dual attached node HSR) respectively. A device without any of these protocols is called SAN (single attached note) and can benefit from

redundant networks by using a RedBox (Redundancy Box). PRP relies on two fully separated, redundant data paths connecting one device to each other. Therefore PRP networks are based on a doubled star topology as shown in Figure 1.
For performance consideration in Ethernet networks, latency and throughput are taken into account. Latency defines the transportation delay between transmitting and receiving device. This is strongly influenced by the number of hops, meaning the number of network devices a message has to pass.
Throughput defines the maximal amount of data possibly transmitted. The performance of a basic PRP network both in latency and throughput is very high since the number of hops is small. Nevertheless, the doubled structure leads to a lot of Ethernet cables and a high effort to build up the system. The limitation of two strictly separated networks in PRP emerges the need of a very careful build up. Creating a connection by inserting a single additional Ethernet cable between both networks LAN A and LAN B leads to a total network crash of both PRP networks. However, once build up and tested thoroughly the network works stable even under critical circumstances since the DANPs use both the networks LAN A and LAN B for data transfer. In case of both networks being faultless, packets are always received twice with the latter being discarded. If one of these networks is blocked, data is still being received from the other. Obviously building two identical networks doubles the costs. This drawback is being eliminated by HSR which is based on a ring topology as shown in Figure 2.

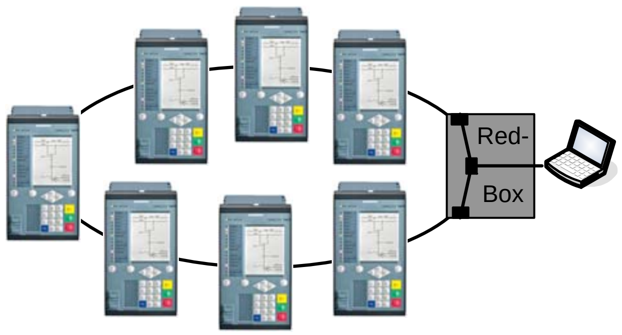

Figure 2. basic HSR topology

While PRP relies on receiving each data twice and discarding the superfluous second dataset, HSR devices also forward received data to the next element which allows a ring topology. This ring topology eliminates the necessity of doubling connections but still offers n-1 redundancy. The usage of the ring topology leads to easy build up. All devices have to be connected just from one port to one neighbour and from the other port to the other neighbour until first and last device are connected and closing the ring. To connect HSR rings to each other special switches, so called QuadBoxes, have to be used. To be redundant also in the connection of rings two of these QuadBoxes should be used for each connection. If one fails the seamless redundancy is still available using the other.

PURE PRP AND HSR NETWORKS

Depending on the substation requirements, some network structures are more advantageous than others.
In a typical substation mainly protection devices, power quality devices and substation controller communicate with each other. To select the best fitting network topology for a substation, different parameters have to be considered. The most important in mission critical systems is naturally the reliability. Nevertheless, complexity and performance do also have to be considered. A substation network structure should be as simple as possible to prevent parameterization errors. Since only correctly built up and parameterized networks guarantee error free behaviour even in critical situations. This make easy to handle protocols preferable. The performance of the communication network in a substation is an additional factor that has to be considered when building up a substation network. It has to be taken in consideration that the devices communicate with each other and with the substation controller. Mission critical signals, e.g. trip signals, which have to be transported as fast as possible are only transmitted between devices usually without influence on the substation controller. Therefore a short latency between devices with such applications is very important.

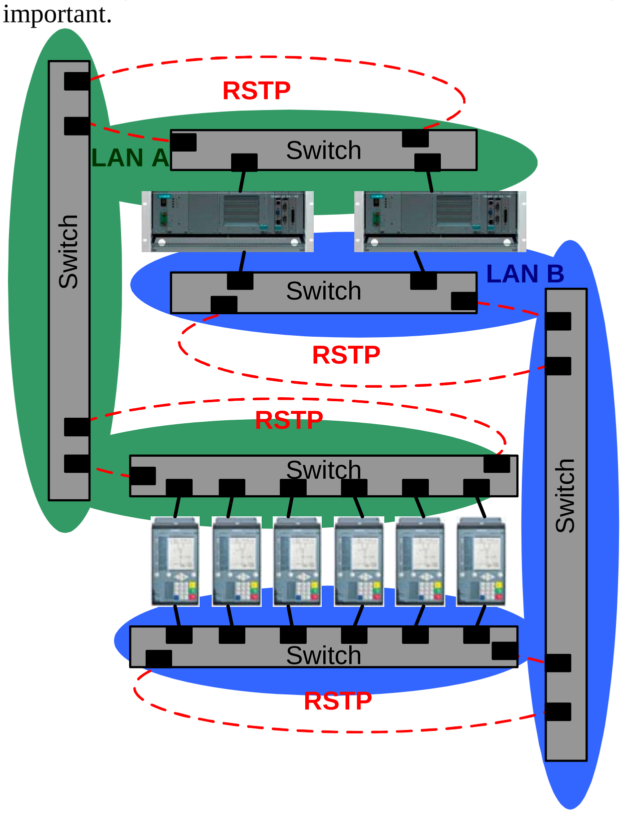

Figure 3. advanced PRP structure using RSTP

Most devices communicate only with a subset of the other devices while all devices communicate with the substation controller. This implies a higher throughput is needed between the devices and the substation controller.
In a pure PRP structure all devices and substation controller are connected in parallel to both networks. To further structure the network every voltage level can be built up

using separated switches. Due to the use of PRP as redundancy protocol a seamless redundancy mechanism is available and highest reliability achievable. The reliability of the overall system could be further improved by building up an RSTP network for the switches of each LAN A and LAN B as shown in Figure 3 .

That means, every single network itself consists not only of a star topology but contains an RSTP ring consisting of all switches. The idea is an additional redundancy mechanism to be not only seamless fault tolerant due to PRP but to enable also every single network to be tolerant to a single failure. Therefore if an error in one PRP network occurs the other PRP network is used as communication path. In the meantime the RSTP in the faulty PRP network reconfigures the network. Since simultaneous errors in both networks are not treated this does not lead to additional reliability but increases the reaction time of the network supervisor who has to deal with network errors.

Like a pure PRP structure, a pure HSR structure can be used as well for building up a substation network. In this structure all devices are connected by one or more connected HSR rings. To further structure the network every voltage level can be build up with a separated HSR ring where only devices for this voltage level are included. Using a ring topology can significantly reduce the available bandwidth. All devices in the ring have to share one network. The bandwidth each device can use is the total available bandwidth divided by the number of devices in the ring. Thus bigger rings mean lower throughput. Therefore in big substations, separate rings are needed. Originating from serial protocols where bandwidth was very low, protection devices are designed to use only a small amount of the available Ethernet bandwidth. The number of communication connections needed by a single protection device is rather small in contrast to substation controllers which communicate with all protection devices. This leads to the need of a larger bandwidth for the substation controller. In big substations a small ring only consisting of the substation controller and larger rings consisting only of devices as shown in Figure 4 can solve this problem by regulating the used bandwidth.

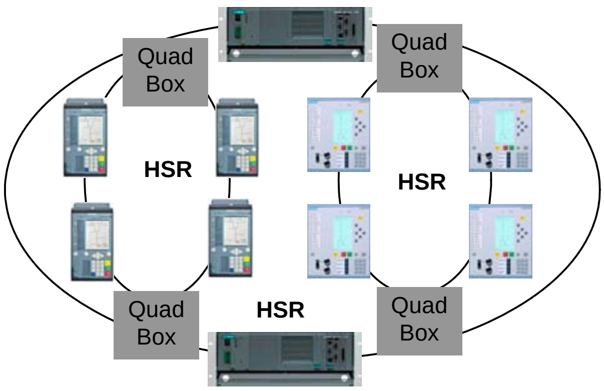

Figure 4. pure HSR structure in a substation

Another drawback of ring topologies is a significant raise of latency since a message has to be transported over multiple hops. As each hop includes additional delay special measures have to be taken to reduce forwarding delay to an absolute minimum. First of all the two QuadBoxes should not be direct neighbours but divide the ring in two parts of equal size. This simple method reduces the maximum number of hops between any two devices. Additionally the latency per hop for the ring devices has to be reduced to a minimum of less than 10 us. This is accomplished by using cut through switching technology. In this technology a message is already forwarded after the header is received and a forwarding decision to the device, the other port of the device or both can be made. When using HSR the duplicate discard algorithm has to be finished before forwarding a telegram. The device has to check whether the device has already forwarded this telegram in this direction to avoid circulating frames [7]. The structure of HSR telegrams, which puts the redundancy information before the payload, allows fast decision making in the devices.

Network components needed for substation applications have not only to be capable of understanding the HSR header but also have to meet the enhanced forwarding requirements.

COMBINING PRP AND HSR NETWORKS

Using pure PRP and pure HSR has some drawbacks that can be overcome by combining both protocols. PRP and HSR were developed to work interoperable. Since both protocols use the same duplicate identify mechanism, redundancy information is passed through protocol borders. This allows combined redundant connections. Additionally special measures were implemented in the standard [5] to prevent loopback of PRP telegrams via HSR rings. To accomplish this, PRP path information stays in the HSR telegram after passing the border from PRP to HSR. This enables RedBoxes from HSR to PRP to distinguish between messages originally from the HSR ring and messages originally from the PRP network. To prevent loopbacks to the messages originally from the PRP network are not forwarded to the PRP network.

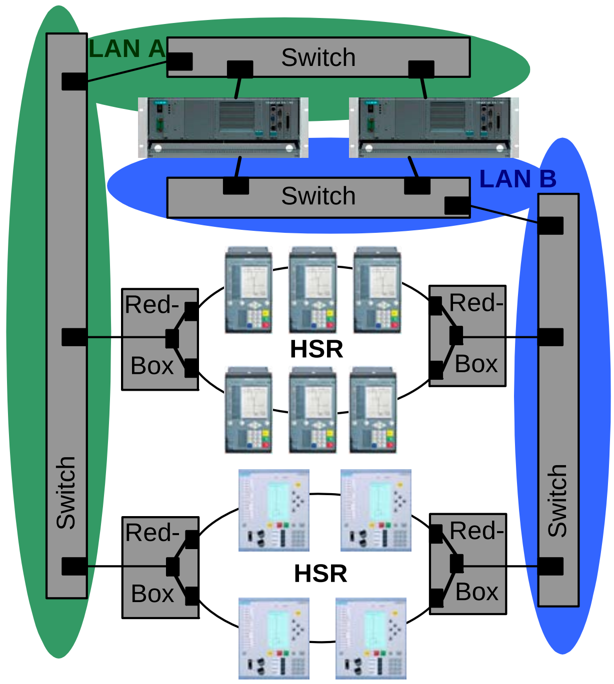

Figure 5. combined PRP and HSR structure

Thus building up an HSR ring between two PRP networks does not illegally connect the networks. This feature can be used to generate a more sophisticated structure based on a PRP structure with underlying HSR rings. This allows the usage of PRP only devices in the same network with HSR rings, taking advantage of both protocols. Additionally substation controllers which need a lot of bandwidth and would be placed in a small separate HSR ring as shown in Figure 4 can be placed as PRP nodes.
To additionally structure this network every voltage level can be built up with separated HSR ring where only devices for this voltage level are included. Since with HSR and PRP only seamless redundancy mechanism are used and due to the similarity between both protocols seamless crossing between PRP and HSR is possible, the whole network achieves highest reliability. The redundancy mechanism in the devices is easy to configure. Only the redundancy protocol has to be selected, no further settings are needed. The usage of ring topology for the majority of the devices leads to easy build up.
For the connection between the PRP networks and the HSR rings RedBoxes are used. To be redundant and to have access to both PRP networks two of these RedBoxes should be used per ring. If one fails the seamless redundancy is still available through the other. The RedBoxes divide the HSR rings in two parts of equal size minimizing the maximum number of hops. This reduces the maximum latency like the symmetric placing of the QuadBoxes in a pure HSR network. Additional measures like cut through switching in the HSR devices guarantee low latency in the rings. The reduced bandwidth need of protection devices secures sufficient throughput for all devices.
Introducing HSR rings in the PRP network for device connection also reduces the amount of switch ports needed in the PRP network and the number of Ethernet cables used to connect all devices. Whereas in pure PRP structures every device needs a connection to one switch port in each PRP network in underlying HSR rings the devices share switch ports. A whole ring can be connected to where in pure PRP only a single device was placed. Ring topology also halves the amount of cable needed leading to fewer build up effort and reduces complexity of the whole substation network.

CONCLUSION AND OUTLOOK

PRP and HSR are new Ethernet redundancy technologies designed to fit highest availability requirements. The protocols enable transportation of mission critical signals like trip signals over Ethernet networks both in parallel networks and in ring topologies. Each of them offers highest reliability for substation communication services. Combining both protocols even strengthens the advantages and reduces the drawbacks of a pure PRP or HSR approach. With combined PRP and HSR networks seamless redundancy becomes a tool that is very flexible concerning installation and topology requirements. As both protocols use similar mechanisms for duplicate discarding they can be combined redundantly without loosing seamless availability. Special measures were taken to allow building up HSR rings between two PRP networks that do not connect the networks. As the PRP networks are still separated from each other installing a ring does not lead to a PRP network crash. Additionally the combined technologies offer a well structured network meeting any performance needs connected devices and applications have.
After finishing the IEC 62439-3 standardization PRP and HSR rapidly achieved great acceptance both by energy automation device vendors implementing the standard in their devices and by power utilities using PRP and HSR to improve the reliability of their substations. Additional measures to widen the application area like introducing PRP for IP networks [8] were taken. Interoperability between both standards and different vendors was shown at various opportunities. The protocols are already changing the network structure of substation networks and will continue to do so.

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