REDUNDANCY COMMUNICATION ARCHITECTURES AND THE BENEFITS FOR O&G INDUSTRY

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Paper No. PCIC Europe BER-81

Holger Heine
Siemens AG
heine.holger@siemens.com
Germany

Milan Petrovic
Siemens AG
petrovic.milan@siemens.com
Germany

Abstract – IEC 61850 has become a firmly established standard in substation automation. But it is now also more than just an Ethernet-based protocol. With Edition 2, the protocol has expanded into additional power supply areas, because it defines the engineering process, the data and service models, the conformity test, and all the communications functions for substations. This expands the range of applications for protection devices. Multifunction devices are there designed for protecting, automating, measuring, and monitoring high-voltage and medium-voltage networks. The standard enables the use of data from different manufacturers' devices. In addition redundant data transmission within the grid is standardized. For realization there are two new Ethernet redundancy protocols – HSR (high-availability seamless redundancy) and PRP (parallel redundancy protocol). These protocols were designed for mission- and time-critical applications in which communication interruptions or delays may not occur. Both protocols comply with the IEC 62439-3 standard for high-availability industrial Ethernet communications networks. HSR and PRP allow the systems to continue operating even in the event of a malfunction: A communication path remains in place between the two protection devices even if a network error occurs. This is especially important in industries like O&G to prevent system outages.
The article outlines some redundancy architectures and their benefits for the O&G industry.

I. INTRODUCTION

No matter if Industry customers are operating a refinery, an offshore platform, pipeline or even a floating LNG plant, some of the core processes involved in Oil&Gas Industry are strongly dependent on reliable and uninterruptable electrical power supply. Restricted availability of power supply can reduce plant production capabilities dramatically which in turn leads to huge financial impact. Not to mention extreme conditions like blackouts where also working staff can be jeopardized. Hence, it is not difficult to understand why it is a top priority to keep core production processes up and running under any circumstances.

One vital pre-requisite for these production processes running smoothly is as already mentioned, a reliable supply of electrical energy. Depending on location of production site and also on the availability of public (utility) power supply, production plants are usually equipped with interconnections to the public grid and/or own power generation plants. In some cases exclusively own operated power plants are providing the necessary electrical energy. Complexity of these kinds of operating environments requires a so-called Energy Automation System (EAS). Although energy automation systems have been available on the market for some time now (and also under different names like Power Management System, PDCS, ENMCS etc…), it is worth looking into main tasks and benefits that such systems provide in Oil&Gas Industry (but not limited to):

- management of electrical network to ensure and optimize supply of electrical power
- positive effect to electrical power availability as well as to:
  - prevention of damages to equipment
  - loss of productivity due to outages
  - determination and elimination of problems in power supply system
  - reduction of operating costs
  - reduction of energy costs by improved efficiency
- Contribution to compliance with legal regulations

Before we go to present some of present issues with Industry LAN networks, let us look into typical industry Oil&Gas energy automation system architecture (as shown on Figure 2).

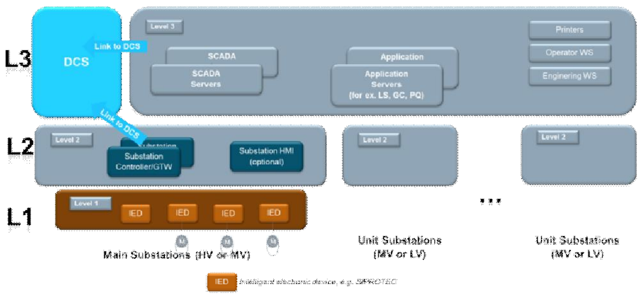

Figure 1. Energy Automation System for Industry

FIELD LEVEL

EAS Architecture starts with a so-called "Level 1" where IEDs are installed, typically in the switchgear compartments (IED stands for *Intelligent Electronic Devices* for example like Protection relays).

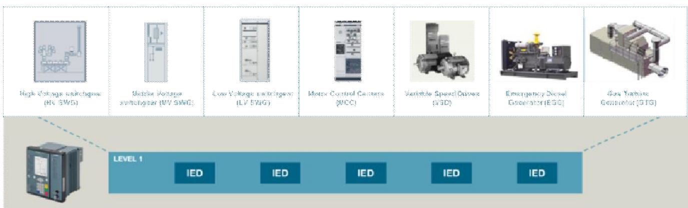

Figure 2. Typical IEDs on Level 1

In case of high voltage levels, a set of separate protection panels housing these devices might be required. These IEDs are located close to the equipment that they are protecting/operating and they have to be self-sustaining, i.e. they should be operating even if there is no connection to the upper hierarchical levels (Level 2 and Level 3).
Apart from Protection relays, other IEDs found on this level are Variable Speed Drives, Motor Control Units, Feeder Control Units, EDGs etc. (please see Figure 2).

SUBSTATION LEVEL

Next hierarchical level of EAS is Level 2, also known as a substation level. It usually consists of Station Controller/Gateway in redundant fashion, which is having the function to collect all relevant information from Level 1 and send it to higher hierarchical levels. Apart from that, purpose of these station controllers is also to offer a certain degree of flexibility during installation and commissioning (for example, if substations will be built one after another and a control center will be commissioned at the end – customers need the possibility to operate those substations during the time when control center is not available).
One more specialty of Level 2 is that, sometimes energy automation supplier due to natural access to protection relay can provide gateway functionality to Process Control System (or also known as DCS, distributed control system) via its or a dedicated set of Station Controllers.

CONTROL CENTER LEVEL

Last hierarchical level is the Control Center level, where all these information gathered from various substations is collected and processed. This is also where certain customer important applications are running (HMI SCADA, PMS applications like Fast Load Shedding, Generation Control, Power Quality and similar). This Control Center acts like an umbrella offering Industry customer full overview and securing control of their respective power grids.

II. TODAY'S NETWORK STRUCTURES IN ELECTRICAL SUBSTATIONS IN THE O&G INDUSTRY

As seen in the Introduction, there could be many substations under one Control Center umbrella; whereas each substation has minimum two / sometimes four network components (i.e. Ethernet switches or routers). Additionally, the total number of IEC61850 IEDs operating can be quite high (and go well over 1.000 IEDs in case of some major Industry projects).

In order to support this, Energy Automation Systems can require a complex network infrastructure and can sometime require careful LAN network design and planning in order to meet these challenges and keep performance levels within acceptable limits.

Figure 3. Typical Oil&Gas plant

Simplest and most straight forward way to realize this complex LAN architecture is by implementing a well-known and established RSTP (Rapid Spanning Tree Protocol) based network.

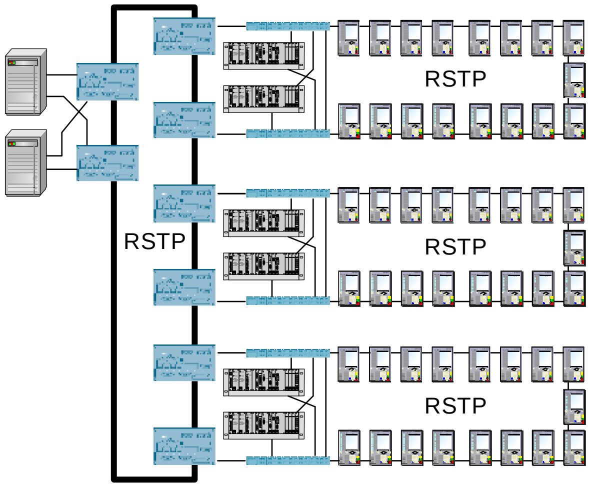

Figure 4. Network topology for big O&G networks

However, there are two sets of problems which could arise from this LAN infrastructure in case of big projects (i.e. involving a lot of substations, which is often the case in O&G Industry):

Problem 1
In RSTP Ring, LAN network loses the possibility to reconfigure after a failure, if:

- there are more than 39 switches / IEDs between the root switch and farthest device considering one single failure on the network
- more than 300-400 RSTP switches / IEDs which are connected in one layer 2 network (exact number is strongly depending on the configuration or architecture)

Problem 2
For fast Load Shedding based on IEC 61850 GOOSE telegrams, maximum allowed GOOSE transmission time between originating and destination IEDs (which could be located in different locations/substations) should not exceed 20ms.

Possible solution for above issues is a combination of a substation router and an Ethernet switch inside of every substation.

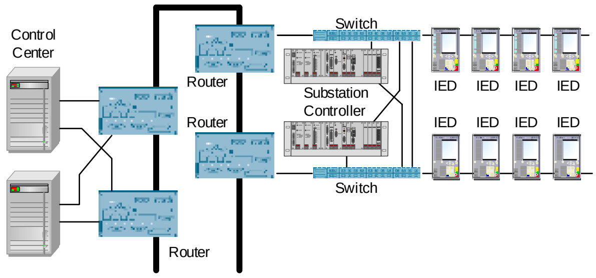

Figure 5. Components in the network

A. Fast Load Shedding application based on IEC61850

Load shedding function maintains stability of electrical grids, especially in critical situations such as a sudden loss of generated power. It then establishes and monitors the balance of generated and consumed loads by shedding consumer feeders with low priority. Automatic load shedding is the only way to prevent deep drops in system frequency or frequency collapse following a large disturbance.

Load shedding can use distributed system architecture and benefits from IEC 61850 standards. At the control center level, the central load shedding controller is based on single or redundant servers. At the bay level, the intelligent electronic devices (IEDs) are used for protection and control.

During critical events, low-priority consumer power must be shed very fast to restore the balance of generated and consumed power. To determine how much power must be shed, the balance of the active power is calculated periodically for each contingency.

The calculation determines which feeders will be shed in case of a critical event based on the available power, spinning reserve, and actual topology. If the critical event happens, fast load shedding will occur within < 70 ms, where an IEC 61850 GOOSE message is sent from originating IED to the IEDs that are protecting the feeders which are to be shed.

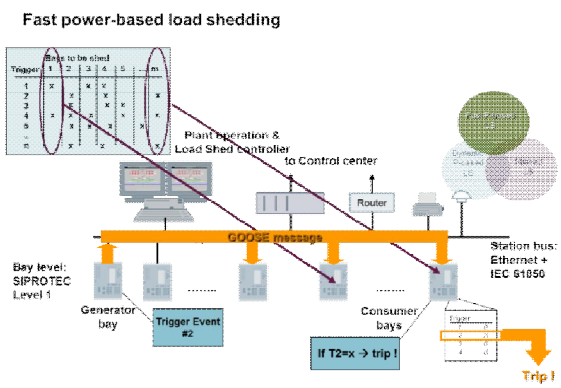

Figure 6. Fast Load shedding principle

As mentioned earlier, for fast Load Shedding and other advanced applications, maximum allowed GOOSE transmission time between originating and destination IEDs should not exceed 20ms.

B. Requirements for Energy Automation System communication network infrastructure

On the example of Load Shedding application based on IEC 61850 GOOSE telegrams we have already demonstrated the advantages this communication protocols provides.

As addressed in Section II, it is seen that two sets of problems can arise. But what if at the same time there is a network failure (for example Ethernet switch has failed and complete network has to be reconfigured) combined with the situation that required fast load shedding, i.e. GOOSE telegram has to be transmitted with maximum 20ms from originating IED (i.e. generator IED) up to the receiving IED (feeder supplying the power to the load that needs to be shed) in order to re-establish the balance between generated and consumed power?

II. RELIABLE NETWORK STRUCTURES FOR LOAD SHEDDING

To transport mission critical signals like trip signals over Ethernet networks new redundancy mechanisms like PRP and HSR were developed. These protocols are designed to fit highest availability requirements. As both protocols use similar mechanisms for duplicate discarding they can be combined redundantly without losing seamless availability. In load shedding applications the transport of GOOSE messages is essential part of the algorithm. In case of a load shedding event in the feed-in a GOOSE message is generated and sent to all loads. Based in this message the loads are switched off. The whole load shedding algorithm relies on the fast and reliable transport of this message. In a network configuration without seamless redundancy this is not given if at the same time a network error occurs. In this case the network reconfigures and for a short but certain time. While the network reconfigures the transportation of messages is not guaranteed. To overcome this restriction the introduction of seamless redundancy mechanisms is a way to handle simultaneous events in the feed-in and on the communication network.

A. Basics of PRP and HSR

On the network side PRP and HSR 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 both protocols is offering two independent paths for message transportation. If one of the paths is blocked, the other path is still available. In contrast to RSTP, which uses only one path at any given time and restructures in case of a network error, HSR and PRP use both paths at the same time. In case of intact communication packets are always received twice. The first message received is passed to the application the second deleted, since it is a duplicate without additional information. For this task PRP and HSR telegrams have an additional protocol header to fast detect duplicates. In contrast to RSTP no additional network information is required.

PRP networks are based on a doubled network topology. The networks themselves are built as star topology and are fully separated as shown in Figure 7.

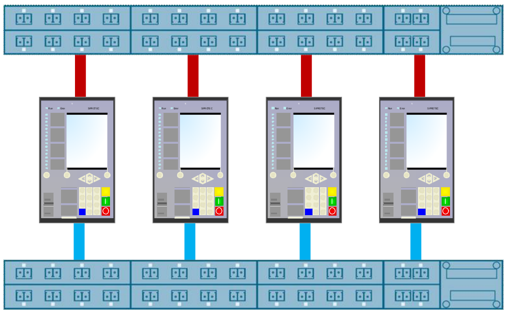

Figure 7. basic PRP topology

Once build up and tested thoroughly the network works stable even under critical circumstances since the devices use both the networks LAN A and LAN B for data transfer. 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 8.

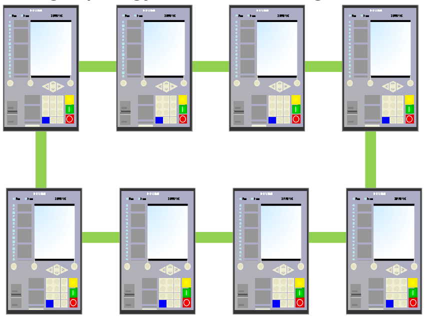

Figure 8. basic HSR topology

In contrast to PRP devices, which relies on receiving each data twice and discarding the superfluous second dataset HSR devices also forward received data to the next network node. This allows a ring topology. The ring topology still offers n-1 redundancy but eliminates the necessity of doubling the whole infrastructure. Ring topology also lead to easy build up. Only connections from one port of a device to one neighbour and from the other port to the other neighbour until the first and last device are connected have to be build.

To connect HSR rings to PRP networks redundantly special switches, so called RedBoxes, have to be used. These RedBoxes convert PRP messages to HSR messages and vice versa. To be redundant also in the connection of PRP and HSR two of these RedBoxes should be used for each connection as shown in Figure 9. If one fails the seamless redundancy is still available using the other. The RedBoxes keep the original redundancy information, thus a receiver can still detect duplicates reliably.

B. PRP and HSR in substation automation within O&G industries

To include seamless redundancy in the networks used for O&G industries two options are possible. The first option is to transfer the complete network topology in a PRP/HSR structure. This guarantees seamless redundancy for all network nodes and for any communication relation. The network shown in Figure 4 transferred to a seamless network is shown in Figure 9.

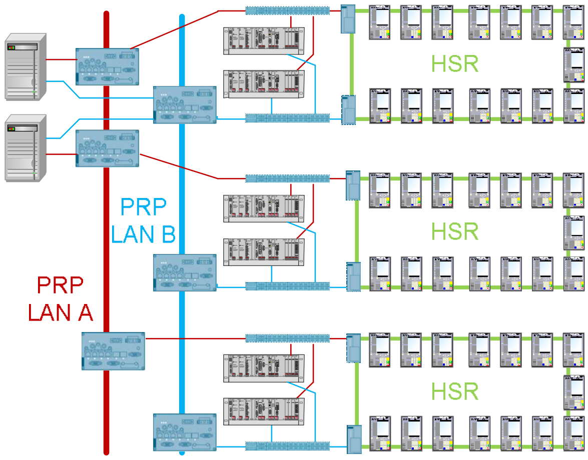

Figure 9. Seamless network topology for big O&G networks

Instead of using RSTP in the substations HSR is used. The router, which themselves build up an RSTP network with redundant access for the inter substation communication are separated. Each of the Routers is assigned to either PRP LAN A or PRP LAN B. The connection between the HSR ring in the substations and the PRP networks on the backbone is done via RedBoxes.

The disadvantage of this structure is obvious. The whole network has to be designed for seamless redundancy. All components have to be HSR or PRP capable. In particular the routers have to treat redundant messages in a different manner. PRP and HSR are optimized for layer 2 networks. The redundancy information is generated and evaluated based on the source MAC address. In ordinary router implementations this information gets lost, since the egress router uses its own MAC address. Especially in already installed systems, which shall be upgraded to load shedding capability, this implies big effort.

On the other side in most systems only the indication of load shedding events requires seamless redundancy. Other applications are not critical. For this scenario another option to upgrade the network to seamless redundancy is to introduce an additional network for load shedding. The original network is kept unchanged. Thus all devices and the network management are unchanged. Only the devices involved in the load shedding are extended. Modern protection and control devices can be equipped with more than one communication interface.

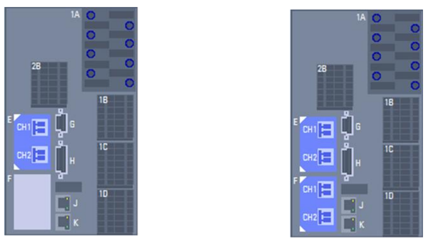

Figure 10. Relay with one / two Ethernet interface(s)

One of the communication interfaces is connected to the normal network as shown in Figure 10. The other interface is connected to an additional network which is used exclusively for the tripping information of the load shedding application.

With this approach the original network structure is kept. This has obvious advantages for already installed networks. On the other side it also allows the integration of devices, which do not support PRP or HSR in the network when they are not part of the tripping scheme for load shedding.

The separate load shedding network is used exclusively for the propagation of the load shedding event. Thus only devices participating in the load shedding participate in this network. The number of devices involved is dramatically smaller than the number of devices in the whole substation. That implies the feasibility of a flat layer 2 network in contrast to the huge number of devices involved in the whole system. Since the complete information exchange, except the load shedding events, is handled via the standard network no connections between the load shedding network and the normal network is needed. That removes the need for additional network components like switches, routers or RedBoxes in that network.

However, it has to be evaluated whether this separated plain layer 2 network fulfils all requirements especially concerning scalability and performance.

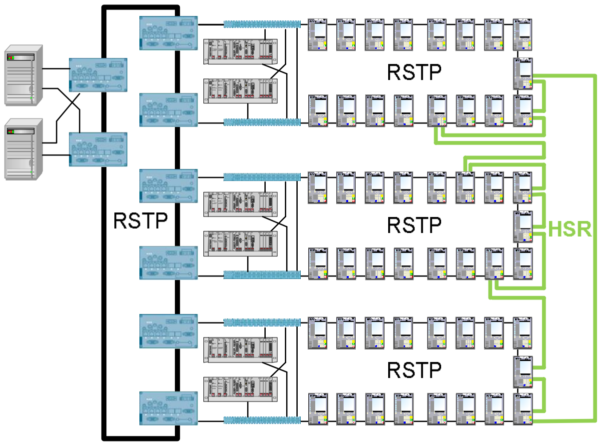

Figure 11. Load shedding IEDs in additional, separate HSR network

C. *Integrating a separate HSR ring*

The integration of an HSR network for the transmission of load shedding events implies a reliable communication network. The redundancy mechanism of HSR is seamless. In a HSR network a single error does not lead to telegram loss. Even though IEC 62439-3 does not state any restrictions for the size of HSR rings real implementations have restrictions. These restrictions are founded on the kind of duplicate filter and the available memory of the duplicate filter integrated in the devices. The duplicate filter in a HSR network mechanism has to evaluate the complete network traffic. The devices have to detect duplicates reliable and fast. This is simple when a telegram and its duplicate arrive within a short period of time. When the path length through the network is asymmetric this period is extended. In case of big ring networks the propagation delay through the network leads to longer delays the duplicate filter has to be capable of.

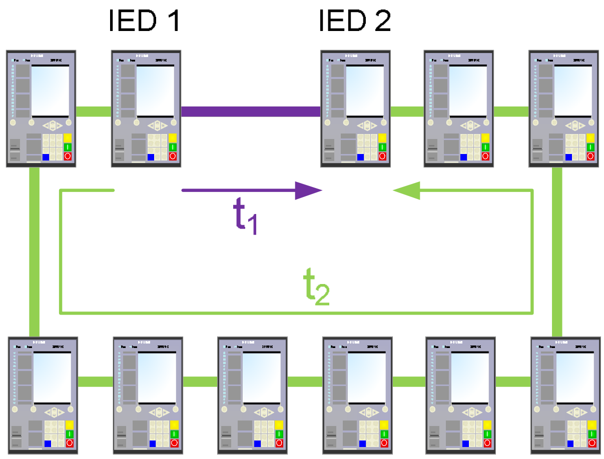

Figure 12. Propagation delays in a HSR network

Figure 12 illustrates the different delay times. A message generated form IED 1, which shall be received by IED 2 is send through two independent ways along the HSR ring. On the direct way from IED 1 to IED 2 no other devices have to be passed. The delay t_1 is low. On the other way though the ring, the message has to pass all other IEDs to reach IED 2 resulting in a delay t_2. For the duplicate filter the time difference $t_2 – t_1$ is significant. It is obvious that the ring size directly influences this difference.

The delay in the worst case scenario can be calculated. It depends on the physical delay on the optical fibre cable and the delay each device the message has to pass introduces. Optical cables transfer data at the speed of "light in glass". This is slower than in a vacuum and typically around 200,000 km/s. The result is a constant latency of 5 ns per m. Since the dimensions of such a network are typically small in reference to the delay times they introduce this delay can be ignored.

The delay each device introduces depends on the switching mechanism it uses. Devices designed for ring networks should implement cut-through switching. In contrast to store-and-forward switching, where the whole Ethernet frame is received, reviewed and then forwarded cut-through switching devices forward messages as soon as possible. In case of HSR the message can be forwarded directly when the sequence number of the HSR tag is received and the duplicate filter dedicated whether the frame is a duplicate. In store and forward devices the delay thus depends on the size of the frame transmitted. In cut through devices the forwarding time is independent of the frame size. An excerpt on the test results done with different implementations in our laboratory can be seen in Figure 13.

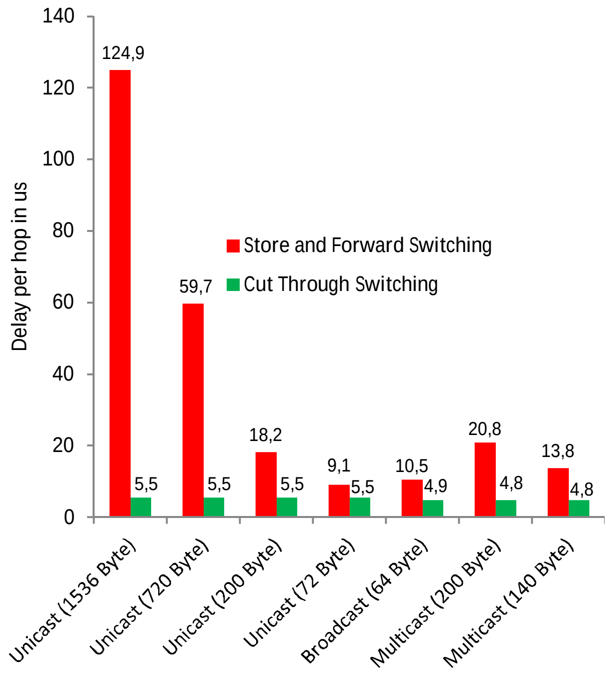

Figure 13. Per hop delay in store and forward / cut through switching nodes

In networks designed for load shedding especially GOOSE messages are transmitted. GOOSE is a multicast. For the load shedding information telegrams with a length of 200 bytes or less are used. In case of store and forward devices each device introduces a delay of 20.8 us. If cut through switching is used each device only generates a delay of 4.8 us. In an HSR networks designed for load shedding a maximum of 200 nodes, representing the feeders to be shed, can be assumed. In such a network the delay asymmetry without the physical delay on the optical fibre cable is 198 times the propagation delay for a single device. This results in a propagation delay of 4118 us for store and forward and 950 us for cut through switching. So for both technologies the maximum propagation delay is within the required quantity for load shedding algorithm. However, also the duplicate filter in the HSR devices has to be considered. In reliable HSR networks reliable duplicates have to be detected certainly.

In principle two ways to implement a duplicate filter effectively are possible. Both use the fact that HSR messages can be uniquely identified via source MAC address and sequence number.

One way to implement a duplicate filter is the table of entries. In this implementation a table which entries represents a message that has been registered in the duplicate filter. To save memory the entries consist not of the full message but of MAC address and sequence number. When a HSR message is received, the list is searched by comparing the message information with the information already in the list.

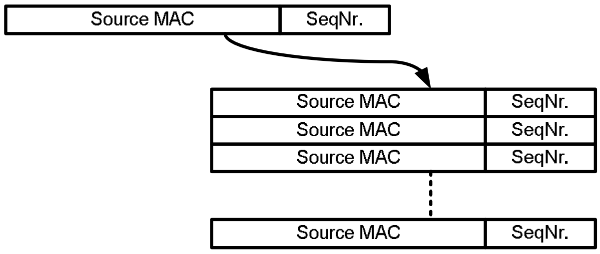

Figure 14. Principle Table of entries duplicate discard filter

If no entry with the same information exists, the message is the first received and needs to be forwarded to the application and on the ring. In that case, a new entry in the table is generated. This entry is later used to identify duplicates of this particular message. If a message was already received there is an entry in the table. The search finds the matching entry and the message can be discarded.

Another way to implement a duplicate discard filter is the sliding window algorithm. This algorithm uses the fact that PRP and HSR sequence number is incremented with every message send. The duplicate discard filter sorts incoming messages according their source MAC address. It monitors the highest received sequence number of this specific MAC address. Furthermore, a window of lower received sequence numbers from this MAC address is monitored. If a message with a lower number and an entry in the sliding window is received.

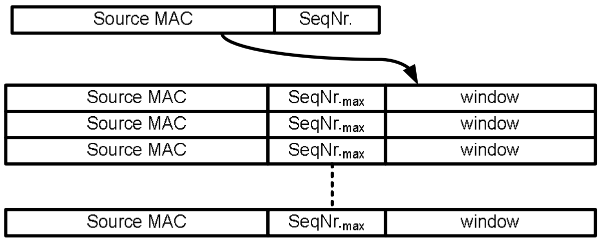

Figure 15. Principle Sliding window duplicate discard filter

The message is a duplicate and discarded. If a new message with a higher sequence number than the highest previously registered number is received, the window slides one number further and the mechanism now monitors the window based on the new highest sequence number.

The advantage of this algorithm in big network structures is the sorting focused on source MAC address. This leads to identical duplicate filter depth to every sender no matter how often the sender emits frames. In contrast with a table of entries implementation, a device which generates a lot of traffic cannot occupy a large portion of the table, and can therefore not dominate or even suppress duplicate discard functionality for other devices.

In the load shedding application the size of the duplicate filter can be estimated, since the traffic is known. When GOOSE is used to indicate a load shedding event the network load is very low when the system is stable no events occur. The GOOSE publishers send periodically every a GOOSE message. The period is normally long since no changes in the system happened. A typical value for the retransmission is 2 second. Only in case of an event this period is decreased. If an event occurs a device sends the information generated by this event in a

GOOSE message as fast as possible. After a certain period of time the message is retransmitted. A typical time for the retransmission is 2 ms. Thus in case of load shedding the worst case scenario is 200 devices generating frames every 2 ms.

If the duplicate filter is implemented as table of entries and the devices designed in store and forward technology the propagation time of 4118 us multiplied by 199 devices divided by the retransmission time of 2 ms leads to the size of the tables of entries of 409. When cut through is used the propagation time is reduced to 950us. This leads to the table size of 95.

If the duplicate filter is implemented as a sliding window algorithm the number of source MAC addresses is defined by the number of other devices in the network. Thus in the application of a ring with 200 devices each device has to treat with 199 entries. For the window size the network delay is divided by the retransmission time. Thus 4118 us or 950 us depending on the switching technology divided by 2 ms. This leads to a window size of 3 or 1 respectively. Even when assuming worst case values as it was tried in this approach load shedding is a critical application. Otherwise the effort to treat simultaneous errors in the feed-in and on the network would not be spend. So when designing filter sizes a reasonable buffer should be planned.

III. CONCLUSIONS

Industrial communication networks differ from utility communication networks. One of the most demanding (and also very beneficial) applications in industrial communication networks is fast load shedding based on IEC 61850 GOOSE telegrams. In fast load shedding schemes a change in feed-in leads to an event on the network. A Goose message is send from the feed-in to all consumers. Based on a predefined schedule load is shed by the consumers. In contrast to load shedding in utility systems the load shedding algorithm has to work faster. Here network delay is one of the main factors. Today even in the biggest communication networks the load shedding message can be transmitted in less than 20 ms. However, today's communication networks are designed to react on errors in the communication network based on reconfiguration algorithms like RSTP. While the network reconfigures communication is not ensured. Should in this time a load shedding event occur, the correct behavior cannot be guaranteed. To overcome this restriction new network architecture based on seamless redundancy protocols PRP and HSR is proposed. Since a complete transition from RSTP based networks to PRP/HSR is often not possible the integration of a second network including only the load shedding nodes is proposed. The devices included in load shedding are extended by a second network interface. They act on both networks. Thus they receive their load shedding matrix unchanged via the RSTP based communication network. They can also be monitored by the substation controller in this network. Only the load shedding events as critical messages are transferred via the additional network. By introducing an additional separate network using HSR the transmission delay can be dramatically reduced. Even in big load shedding networks, where 200 devices are involved, a network delay of less than 1 ms can be reached. The time gained can be used to either reduce the overall performance of the load shedding system or to reduce delay requirements in other components.

To complete the network in an effective manner the devices should be designed with cut-through switching instead of store and forward switching. This not only reduces the transmission time by a factor of four. It also reduces the time difference between a message and its duplicate are received. Thus the duplicate discard algorithm is relieved resulting in more robust networks. Additionally the sliding window algorithm is recommended for duplicate discard especially in big networks. Here a fixed window for each source MAC address guarantees filtering capacity even if one or more nodes send exceptionally many telegrams.

After seamless redundancy protocols proved their capability on utility communication networks also industrial networks are going to include these mechanisms. The goal is the same as in utility networks, increase availability and reliability. Based on the requirements parts of the communication network or the whole network are transferred to PRP, HSR or a combination of both protocols. The advantages are hard to be seen directly, since the benefits are seen only in case of an error. In case of fast load shedding application the benefits are only seen if a network error and a load shedding event occur at the same time. This might appear very seldom. However, the impact of such an event can be dramatically. To minimize risks such scenarios and their impact should be considered. In case the risk is seen as to high seamless redundant networks should be used.

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II. VITA

Holger Heine is the Product Lifecycle Manager within the Energy Automation Business Unit of Siemens Energy Management Division in Germany. Within Protection and Substation utomation group he is responsible for Communication and Process bus in Siemens SIPROTEC devices.
After receiving his diploma summa cum laude in computer engineering from the Technical University in Berlin, Holger started his career with Siemens as part of the development team designing Siemens latest SIPROTEC 5 relay platform. He also developed Siemens SIPROTEC PRP and HSR solutions and participated actively in the standardization of these protocols.
Email: heine.holger@siemens.com

Milan Petrovic graduated from the University of Nis, Serbia in 2003 earning a Master Degree of electrical engineering and computing in the field of telecommunications. He has held various international positions within Siemens since 2005. At present he is working as a Sales and Business Development Manager within Digital Grid Business Unit based in Nuremberg, Germany with focus on Industry customers.
Email. Petrovic.milan@siemens.com