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A novel PRP based deterministic, redundant and resilient IEC 61850 substation communication architecture☆

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Summary A secure, reliable, redundant, resilient, time critical, efficient and interoperable substation communication network (SCN) is a prerequisite for a viable Substation Automation System (SAS). Due to emergence of IEC 61850 as a global standard for substation automation, the interoperability issues among components of substation from different vendors are resolved. The communication network must be fault tolerant and any substantial levels of disturbances should not affect the normal operation of the SAS. Due to digitization in SCN, the communication methodology is mainly focused on exchange of encrypted packet information. Failure of the communication mechanism, even for the order of milliseconds, would lead to catastrophic effects within the substation and also impacts the operation of grid, if not cleared timely. The high reliability of such a system is only possible under a redundant communication network which has a zero switchover time. Hence IEC 62439-3 based redundant protocols such as Parallel Redundancy Protocol (PRP) recommended to be used in SCNs to achieve redundancy and seamless recovery in case of a failure. PRP based SAS along with detailed analysis of underlying process for implementing PRP protocol and its comparison with existing conventional protocols based SCN reported in literature is presented.
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Introduction

Due to recent advances in the field of Information and Communication Technology (ICT) and a high level of emphasis on automation in electrical grid has led to accomplish the challenges set forth for realizing a Smart Grid. With the emergence of IEC 61850 as a global standard for substation automation, the major issues of interconnectivity

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and interoperability of various devices from different vendors/manufacturers installed within a substation has been resolved. Also the communication infrastructure of a substation laid down mainly on Ethernet based LAN, allows control centres to be interconnected and helps in better data processing, planning and decision making.

However, in case of failure of the substation communication network (SCN) at any point in the network link, the whole SCN is down and if a fault arises at this instant, it would be unmonitored and could lead to triggering of cascaded events. The probability of occurrence of fault at the instant of network failure is less, but it cannot be overlooked since if this happens the cascaded effects could lead to partial or even complete system failure leading to black outs. Authors in (Ali et al., 2015) proposed a redundant ring network utilizing the concept of primary and backup ports on modern IEDs. In case of failure the IED automatically configures using DHP and critical messages are managed by RSTP. The technique offers a robust network but network switchover times are large and port switching time for IEDs is substantial. Sidhu and Yin (2007) evaluated reliability rates for a test substation network for different types of network topologies and authors in (Liu et al., 2014) proposed a reliable network based upon cobweb topology for reliability and determinacy in SCN. However, there is less work being done in providing a redundant network required for preventing a catastrophe in a SCN arising due to failure of LAN.

The problem of LAN failure in a SCN can be solved by providing complete redundancy of the communication network. The IEC 62493-3 (IEC, 2012) proposes duplication of the LAN in the communication network to provide zero switchover periods in case of any single LAN failure and this protocol is termed as Parallel Redundancy Protocol (PRP). It provides a reliable, resilient, available, secure, seamless communication architecture which can be duly employed in a substation. PRP provides a bumpless communication architecture with zero network switchover periods and has been widely employed in substations. The PRP duplicates the incoming message packet and sends them via two different LANs which are independent of each other. On reception the packet which arrives first at the destination is treated as the final packet and the other of the pair is discarded. Authors in (Araujo and Lazaro, 2015), discussed a technique for frame discarding mechanism in a PRP network with its evaluation on a FPGA based network for best and worst case scenario. However, in case of failure of any LAN either of the two packets reach the destination providing complete reliability.

Authors in this paper propose a reliable, redundant, resilient, available, secure, deterministic SCN based on PRP network. The proposed architecture provides zero network switchover times with the use of minimum number of Ethernet switches required for the purpose to minimize cost. The proposed model also accommodates conventional IEDs of the substation having no capability of PRP by employing a Redundancy box at the interface level. This optimizes the cost further by providing reusability to the already employed devices. This paper has been divided into five sections. The next section describes brief background about PRP, Sections ''PRP based substation communication network'' and ''Analysis of the proposed PRP based SCN'' present novel PRP based SAS architecture and its analysis respectively. Finally, the last section presents the conclusion of paper.

Background of Parallel Redundancy Protocol

The Parallel Redundancy Protocol (PRP), IEC 62439-3 standard, a preferred protocol for redundant data transfer with zero switchover periods in an Ethernet based Communication Networks. The PRP provides a redundant, fool proof, reliable communication with elimination of network reconfiguration and provides seamless data transfer in a network. The redundancy in PRP networks is achieved by duplicating the incoming data packets and thereon transmitting them onto two different but similar (topology) LAN's. For transmitting of data on to two different LAN networks, the nodes are equipped with dual ports which are called as Dual Attached Node (DAN). A DAN is a terminology adopted for a PRP enabled node which has two Ethernet ports used for duplicity. On reception of the data packets at receiver end, the packet which reaches first is accepted as the final data packet, and the duplicated one is discarded.

The PRP enabled node has same MAC address on both Ethernet ports of the DAN since the source and destination MAC address remains same for the node. The PRP operates as a layer 2 protocol of the OSI model and provides complete transparency to the upper layers. The PRP appends a Redundancy Control Trailer (RCT) to the pre-existing Ethernet frame, and consists of a sequence number (SeqNr) of 16 bit, a LAN identifier (LanId) of 4 bit, Frame size (LSDU size) of 12 bit and a PRP suffix of 16 bit. The PRP scheme works with zero switchover period as long as both the LANs are operating successfully. The legacy Singly Attached Nodes (SANs) may be connected to a PRP redundant network by using a redundancy box (RedBox), which makes a SAN to behave as a DAN. However, a node lacking PRP capability works fairly well in a PRP based network, when it is connected to any one of the LAN. Since data packets without a RCT trailer are transparently handled by the PRP appending mechanism at the Ethernet layer.

The state transition diagram for operation of PRP enabled node with typical states and the functions which takes Boolean values (*true* or *false*) in case of transition from one state to another state is shown in Fig. 1. The waiting time period in the destroy state is normally equal to or greater than PRP packet window.

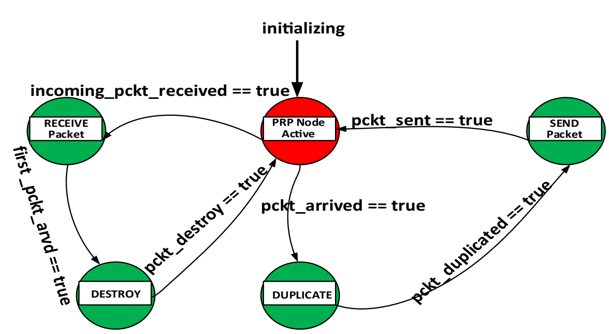

Figure 1 State diagram of a PRP enabled node.

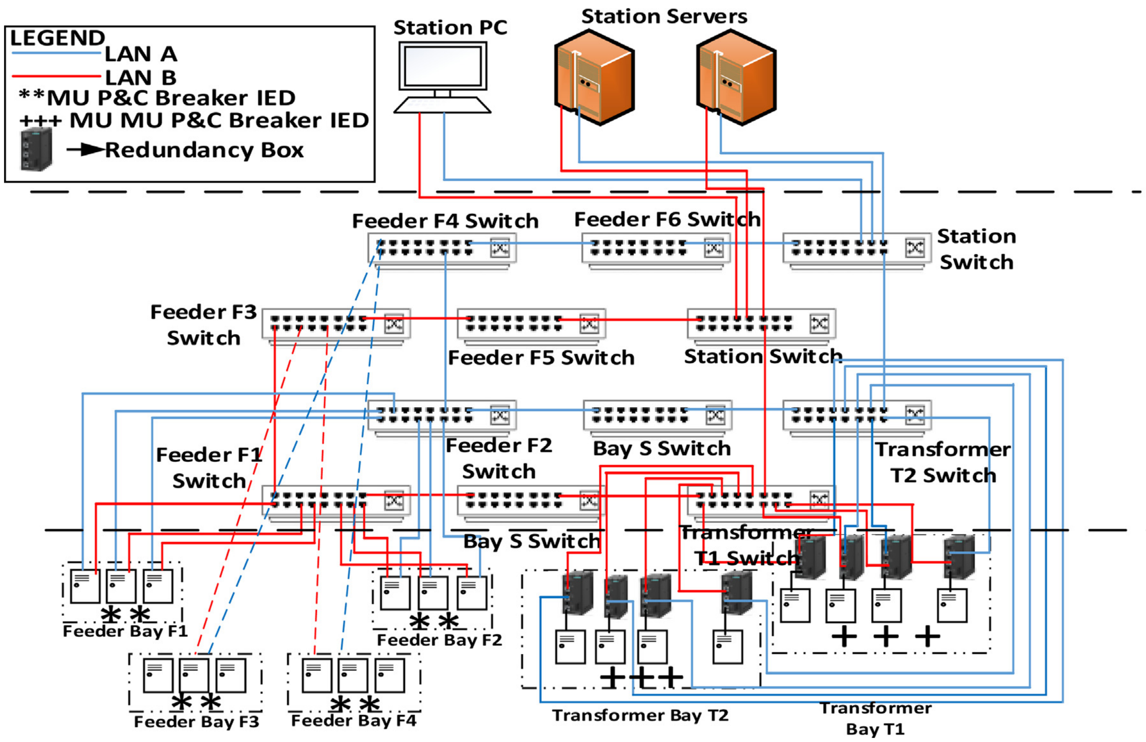

Figure 2 Novel PRP architecture.

Table 1 Comparison among existing and proposed SCN architectures.

Parameter	Cobweb architecture (Liu et al., 2014)	SCN proposed in (Ali et al., 2015)	Proposed architecture
Redundancy level	2	1	Multiple
Single point of failure	No	Yes	No
Switch over time	RSTP configuration time	RSTP configuration time	Zero
Number of switches	10	10	15

PRP based substation communication network

The novel PRP enabled network for a substation communication network with minimum number of switches for a typical substation is shown in Fig. 2. The feeder bays (F1 to F6), transformer bays (T1, T2) and the busbar bay of the typical substation having respective IEDs (MU IED, P&C IED and Breaker IED) are shown. The connections have been shown for the feeders F1, F2 and remaining connections are omitted in the figure for the sake of clarity. As depicted in SCN architecture, the feeder switch 1 in LAN A and feeder switch 2 in LAN B has connections from both the feeder bays 1 and 2. This technique is used to provide optimization in the number of switches employed for the proposed PRP scheme. The cost incurred in providing a fool proof, reliable, resilient, zero switchover network is in installation of two different LANs. This cost directly depends on number of switches used in LAN. Thus optimization of number of switches employed to realize PRP architecture results in an economic PRP enabled architecture. Also, in the proposed scheme there is a high rate of switch utilization which results in higher efficiency of the overall network (Kim and Park, 2004).

Analysis of the proposed PRP based SCN

The proposed PRP based SCN provides a reliable, redundant communication architecture with a zero switchover network time by employing duplicated but independent LAN rings at the switch level. Also at the process level, the IEDs are PRP enabled and conventional IEDs are provided with PRP conditionality by employing a redundancy box at bay level as shown in Fig. 1. The proposed architecture guarantees delivery of packets to the destination as long as one of the LAN is in working condition.

A comparison has been done among various architectures proposed for a SCN in literature (Ali et al., 2015; Sidhu and Yin, 2007; Liu et al., 2014). The parameters for comparison along with the results have been tabulated in Table 1

Conclusion

A novel reliable, redundant, secure, available, deterministic PRP based SCN with zero network reconfiguration time has been proposed in the paper. The proposed architecture requires minimum number of components (in terms of switches) to be employed for forming two LANs. This architecture provides implementation of PRP scheme in a SCN with minimum cost. Further the proposal provides reusability of conventional IEDs already employed in a SCN to function as a DAN by using a Redundancy Box. This further leads to cost reduction in implementation of PRP scheme which was a major drawback of economics involved in its deployment.

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