FRAMEWORK FOR PROCESS BUS RELIABILITY ANALYSIS

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ABSTRACT

Several pilot projects related to the Process Bus are being executed with the main goal to certify the reliability of the network as the mean to transmit information which is critical to the integrity of the protection system. This paper presents a methodology to evaluate the process bus reliability based on the reliability model for various network topologies. Considering the MTBF of the elements of the protection system, the reliability level of the whole system was determined and the results were analyzed.

INTRODUCTION

In the power sector the system security is vital to keep the stability in energy supply to consumers. Traditionally, protection engineers are conservative with respect to preserving the integrity of all the elements that make up this system. Depending on the voltage levels in substations, the use of redundancy in protection schemes is used to mitigate the risks of problems [1].

In conventional substations, every device in the relay room, such as protective relays and digital fault recorders, has its own acquisition system. All the cables from the switchyard (including those from the instrumentation transformers), are directly connected to the analogue inputs of these devices. IEC 61850 [2] process bus has changed this approach. The network is being considered as the means of data transportation from the switchyard to the relay room [3]. Both utilities and system integrators recognize the benefits and the economic viability of using Ethernet communication network to interconnect Intelligent Electronic Devices (IEDs) inside the substation control house. IEC 61850 considers this level of communication as the Station Bus.

In addition to the Station Bus, IEC 61850 considers another level of communication, namely, the Process Bus. The Process Bus is intended to replace most of the copper cables used in conventional installations to connect field devices, such as instrument transformers, circuit breakers, etc., to IEDs by messages in a fiber optic communication network. Within this context, current and the voltage signals are sampled and converted to digital values, which are then transmitted through the network in standardized messages known as Sampled Measurement Values, as described in IEC 61850-9-2 [4] and IEC 61869 [5]. This conversion is performed by a device called Merging Unit (MU).

The use of Process Bus in power systems has been considered the newest wave of technological evolution. However, it has not been widely adopted yet, probably because power system professionals are not so confident about using Ethernet networks to transmit information which is critical to the system secure operation. Different network approaches provide different reliability levels. In this paper, the reliability of different topologies is obtained by using a methodology for creating models based on the reliability of each element that makes up the structure of the whole network communication, from the measuring elements (merging unit) up to the command to the drive (protection relay). Based on the estimation of the MTBF (Mean Time Between Failures) of each element of the network, the reliability of the system is obtained, and it is possible to evaluate the effect of the redundancy.

RELIABILITY

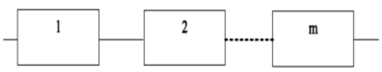
A widely accepted definition of reliability is that it is the probability of a device performing its function properly, for a certain period of time, under given operating conditions [6]. The use of redundant systems has been considered in several situations. According to [7], redundancy is the existence of more than one means to perform a given function. This consideration is closely linked to reliability and suggests an improvement in the conditions of the system being analyzed.

The methodology to provide the reliability level of the protection system is based on the creation of reliability models that relates the individual reliability of all the units that compose it. Considering these models, quantitative levels of reliability of the whole system is obtained. Depending on the complexity of the system, different approaches can be used to provide the reliability model of the system. Some methods are shown as follows.

Block Diagrams

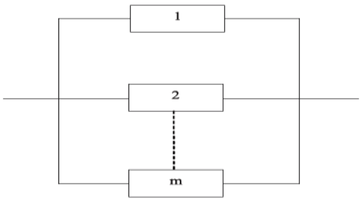
In block diagram models each block represents a unit. In the series configuration, all the units must work normally for the system success. For independent failing units, the reliability of the m-series system is shown in figure 1a. In the parallel configuration, at least one such unit must operate normally for the system success. The m-parallel system reliability is shown in figure 1b. Mixed configuration considers the composition of the series and the parallel models for creating a specific model.

R_s and R_{ps} are the reliability level for the series and parallel models, respectively and, R_i is the reliability level for the i-th unit of the diagram.



$$R_s = \prod_{i=1}^{m} R$$

a) series configuration



$$R_{ps} = 1 - \prod_{i=1}^{m} (1 - R_i)$$

b) parallel configuration

Figure 1 – Block diagrams.

Complex methods

More complex systems require more specific methods to provide a reliability model. The fault tree is a deductive system analysis by which the analyst postulates that the system could fail in a certain way and attempts to find out how the system or its components could contribute to this failure. It represents the occurrence of an event by the relationship of a set of entities called "gates" and the Boolean algebra between them.

Another method is based on the Boolean logic tables. Considering different scenarios, a logic table is created, the conditions of success are determined, and the probability of the occurrence of these scenarios is calculated to provide the level of reliability of the system.

PROCESS BUS RELIABILITY MODELS

The conventional protection systems, from the point of view of interconnection between switchyard equipment and IEDs, are simple structures that are composed of the protection relay which is installed in the control room and the cables that connect it with the switchyard elements. Regarding the level of reliability, the protection system is related to the level of reliability of the wiring, instrument transformers, and protection relays. For the IEC 61850 Process Bus, different topologies for the network can be created with the final goal of realizing the interconnection of multiple transmitters and receivers of data information. For a more practical analysis, some scenarios that tend to be more common choices for building the process bus are considered.

The purpose of this paper is to analyze the reliability of the protection system in order to compare the reliability of different topologies of the process bus and the conventional approach. For the analysis, the communication structures and the devices inserted in it will be evaluated. Because of the length of the cables from the switchyard elements to the merging units are inherently short, these cables were not considered in the analysis. For simplicity, digital instrument transformers won't be considered in this study. As such, both the conventional approach and process bus share the same instrument transformers and their reliability is not part of the models.

In order to provide the reliability model for the conventional architecture, the copper cables and the protective relay were considered. The reliability model is based on the series block diagram, shown in (1). In some cases, the redundant protective relays are demanded to enhance the reliability of the system. Two protection relays with independent wiring have been considered. The model considers a composition of series and parallel block diagrams, such model is shown in (2).

$$R_S = R_{CC1} * R_{RL1} \quad (1)$$
$$R_{SR} = [1 - (1 - R_{CC1} * R_{RL1})*(1 - R_{CC2} * R_{RL2})] \quad (2)$$

Where, R_S, R_{SR}, R_{CC1}, R_{CC2} and R_{RL} are the reliability level of the protection system without and with redundancy, copper cables that connects the switchyard elements to the relays, and protective relays respectively. Thus based on the communication architecture of each scenario, a model related to the reliability of the protection system in the process bus approach is established, according to the following:

Scenario 1: One merging unit, one relay and one switch

It is considered that a merging unit installed in the switchyard and close to some field element, such as a current transformer (CT), is connected to a protective relay through a switch. Both protective relay and MU are connected to this switch via a fiber optic cable. The relay, the switch and the cable which interconnects them are in the relay room, while the MU is installed in an appropriate panel in the switchyard and the cables that connect it to the relay room are housed in conduits crossing the substation. Figure 2 illustrates this interconnection.

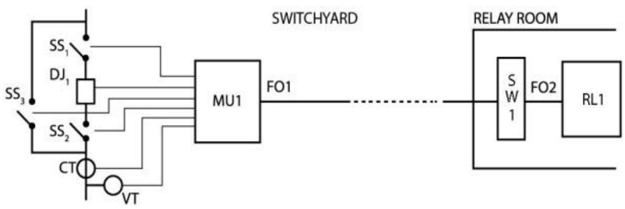


Figure 2 – Network topology for a simple process bus.

To obtain the model of this topology, which is a very basic process bus, the block diagram of a series model was considered. The reliability model for this scenario is shown in (3).

$$R_{SIST} = R_{MU1} * R_{FO1} * R_{SW1} * R_{F02} * R_{RL1} \quad (3)$$

Where, R_{SIST}, R_{MU1}, R_{FO1}, R_{F02}, R_{SW1}, and R_{RL1} are the reliability level of the protection system, merging unit, optical fibers 1 and 2, switch and protective relay, respectively.

Scenario 4: Two merging units (redundant acquisition) and one relay with redundant Ethernet ports, two switches

Performing the integration of the topology of Scenarios 2 and 3, one obtains a system that considers the redundancy of MUs and communication structure. In this context, a topology where the most vulnerable parts in the system are duplicated in order to mitigate the risk of failure is presented. Two MUs measuring the same switchyard signals are interconnected to two switches installed in the control room by a redundant link. A protective relay with redundant network ports and able to manage the information from two merging units is connected to these switches. This topology is shown below.

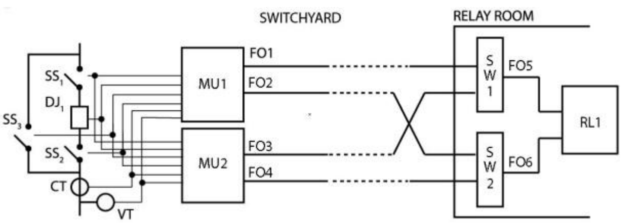


Figure 3 – Process bus with redundant acquisition and redundant network architecture.

In order to model this system the FTA method was used considering a fault in the protection system as the event to be mapped. A fault tree consists of several levels of events connected by AND and OR logic gates. The resulting model was obtained by describing logically the set of possibilities of failure for all the units that are part of the protection system being analyzed (MUs, network structure and relay).

After substituting the logic gates diagram by mathematical expressions, the result is the reliability model shown in (6). From this model it is possible to obtain quantitatively the rate of failure of the protection system described in this topology.

$$R_{SIST}=$$
$$[1 - [1 - [1 - ((1 - R_{FO1})*(1 - R_{FO3})*R_{FO5}* R_{SW1})]*[1 - ((1 - R_{FO2})*(1 - R_{FO4})*R_{FO6}*R_{SW2})]]] *$$
$$[1 - [(1 - R_{MU1})*(1 - R_{MU2})]] *$$
$$[1 - [(1 - R_{FO1})*(1 - R_{FO2})*(1 - R_{MU2})]] *$$
$$[1 - [(1 - R_{FO3})*(1 - R_{FO4})*(1 - R_{MU1})]] * R_{RL1} \qquad (6)$$

Where, R_{SIST}, R_{MU1}, R_{MU2}, R_{FO1}, R_{F02}, R_{F03}, R_{F04}, R_{SW1}, R_{SW2}, and R_{RL1} are the reliability levels of the protection system, merging units 1 and 2, optical fibers 1, 2, 3 and 4, switches 1 and 2, and protective relay, respectively.

Scenario 5: Two merging units (redundant acquisition) and two relays (redundant protection) with redundant Ethernet ports, two switches

Depending on the voltage level of the power line and the element that is being protected, it is mandatory that the protection system consider a double measurement of voltage and current, so that there is a relay for primary protection and a backup in case of failure of the primary one [1].
Typically, in the conventional system, two independent sets of cables from the CT and the VT are taken to the relay room to be connected to each protective relay. An equivalent process bus topology considers the use of two MUs with redundant network ports connected to the switches by fiber optic cables. Protection relays with redundant network ports are also connected to the switches and execute the protection functions by considering the concept of the primary and backup protection scheme. Figure 6 shows this topology.

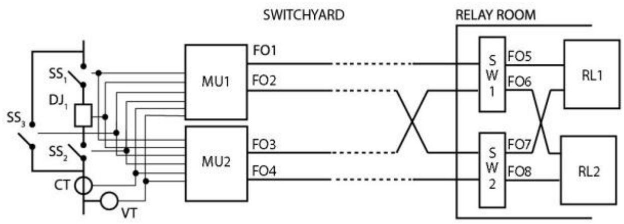


Figure 4 – Process bus with acquisition and protection redundancy.

By using the FTA method, the reliability model of the protection system was obtained considering the failure of the system as the event to be mapped. The resulting model is show in (7).

$$R_{SIST} =$$
$$[1 - [1 - [[1 - ((1 - R_{FO1})*(1 - R_{FO3}))]*[1 - ((1 - R_{FO5})*(1 - R_{FO7}))]*R_{SW1}]] *$$
$$[1 - [[1 - ((1 - R_{FO2})*(1 - R_{FO4}))]*[1 - ((1 - R_{FO6})*(1 - R_{FO8}))]*R_{SW2}]]] *$$
$$[1 - [(1 - R_{MU1})*(1 - R_{MU2})]] * [1 - [(1 - R_{RL1})*(1 - R_{RL2})]]*$$
$$[1 - [(1 - R_{FO1})*(1 - R_{FO2})*(1 - R_{MU2})]] *[1 - [(1 - R_{FO3})*(1 - R_{FO4})*(1 - R_{MU1})]] \qquad (7)$$

Where, R_{SIST}, R_{MU1}, R_{MU2}, R_{FO1}, R_{F02}, R_{F03}, R_{F04}, R_{FO5}, R_{F06}, R_{SW1}, R_{SW2}, R_{RL1}, and R_{RL2} are the reliability level of the protection system, merging units 1 and 2, optical fibers 1, 2, 3, 4, 5 and 6, switches 1 and 2, and protective relay 1 and 2, respectively.

Scenario 6: Ring network topology

In the ring topology, the connection between different IEDs is performed by direct and sequential links between devices, providing a connection in series and forming a ring. In this topology there is no need to use a switch, because each device in the ring has two Ethernet ports that behave equivalently to a switch, transferring packets from one port to another, so that the data is going through the ring according to the criteria established by the network protocol. To ensure the zero recovery time in case of failure of one element of the ring, the HSR protocol (High-availability Seamless Redundancy) [8] is the alternative.

For the study of reliability of the ring topology, a 6-IED ring was assessed illustrating a protection system with several devices connected in a single ring. This case study considered the ring with three merging units and three protective relays, forming a protection system for three bays as shown in Figure 7.

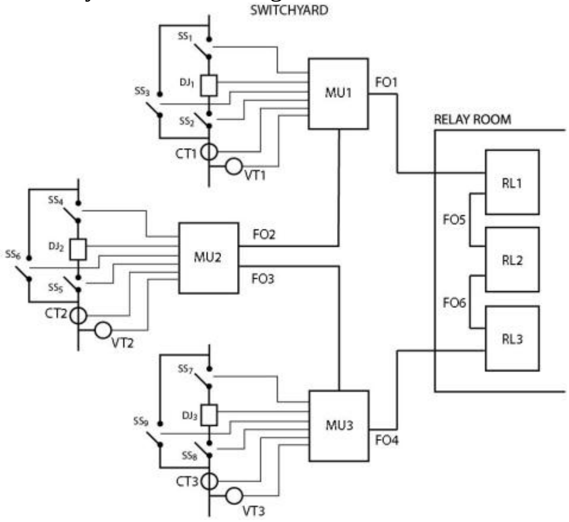


Figure 5 – Three relays and three MUs in a ring topology.

The methodology used for determining the reliability model consists of mapping scenarios that identify the behavior of the protection system considering that at least one merging unit can communicate with a protective relay. For this case study, a combinatorial analysis of the elements that compose the protection system was performed, the scenarios were mapped and the failure hypothesis were evaluated. Equation (8) shows the model of reliability for the ring topology.

$$R_{SIST} = [(R_{FO})^6 * (R_{MU})^3 * (R_{RL})^3] + 6 * [(R_{RL})^3 * (R_{MU})^3 * (R_{FO})^5 * (1 - R_{FO})] + 2 * [(R_{FO})^6 * (R_{MU})^3 * (R_{RL})^2 * (1 - R_{RL})] + 2 * [(R_{FO})^6 * (R_{RL})^3 * (R_{MU})^2 * (1 - R_{MU})] \quad (8)$$

Where, R_{SIST}, R_{MU}, R_{FO}, and R_{RL} are the reliability level of the protection system, merging units, optical fibers, and protective relay, respectively. Performing similar analysis considering a ring of three elements (two MUs and one relay), the model of reliability is shown in (9).

$$R_{SIST} = [(R_{FO})^3 * (R_{MU})^2 * (R_{RL})] + 3 * [(R_{RL}) * (R_{MU})^2 * (R_{FO})^2 * (1 - R_{FO})] + [(R_{FO})^3 * (R_{RL}) * (R_{MU}) * (1 - R_{MU})] \quad (9)$$

RELIABILITY ANALYSIS

Based on the previous section, different network topologies imply different models of reliability. The reliability for the whole protection system depends on each one of the elements that compose it. Each element has a probability of failure which is a function of the characteristics of the project and the components that it is based on.

The reliability of products is closely related to the MTBF (Mean Time Between Failure). This value depends on the number of units analyzed and the time when these devices are in operation. Based on this information, it is possible to estimate the rate of failures of a piece of equipment within a given period of time and, therefore, the probability of failure or, in other words, its reliability level [7]. The reliability of some electronic equipment can be estimated according to (10).

$$R = e^{(-t/MTBF)} \quad (10)$$

Where, R, t and MTBF are the reliability level of the equipment, the time interval for the analysis and the mean time between failures for the equipment, respectively. For a comparison of the reliability between different architectures, the MTBF of each network element was obtained in [9] and by surveying the manufacturers. Based on that, the reliability level of each element was established as shown in Table 1.

Element	MTBF (yrs)	Reliability
Protection relay	300	0,9967
Merging unit	300	0,9967
Switch	100	0,9900
Copper cables	100	0,9900
FO cables in the relay room	100	0,9900
FO cables in the switchyard	100	0,9900

Table 1 – Reliability for each element of the protection system.

Considering the reliability of each element of the protection system and the topology model, the reliability of the entire system can be calculated. The MTBF can vary from manufacturer to manufacturer and, therefore, the reliability level used in the analysis. By using the methodology presented in this paper, new levels of reliability can be verified.

Protection systems based on conventional approach, considering their models of reliability can provide the reliability levels as shown in Table 2.

Architecture	Reliability
No redundancy	0,9867
Primary and backup protection	0,9998

Table 2 – Reliability of conventional protection systems

Considering the process bus approach, based on the reliability of each element of the network and the models of reliability for each topology, the reliability for the protection system considering the scenarios presented in the previous section is shown in Table 3.

Scenario	Network topology	Reliability
1	1 MU, 1 RL, 1 SW	0,9639
4	2 MU & 1 RL (red Eth), 2 SW	0,9965
5	2 MU, 2 R, 2 SW	0,9999
6	Ring with 6 IEDs	0,9911
	Ring with 3 IEDs	0,9930

Table 3 – Reliability levels for the protection system considering process bus approach

CONCLUSIONS

Compared to the process bus, a conventional protection system uses a smaller number of elements, such as the protective relay and the copper cables that connect it to the elements of the switchyard. Therefore the level of reliability is intrinsically high. When considering the protection scheme with redundant relays, the level of reliability is even higher.

When the process bus approach is applied, the protection system as a whole becomes more dependent on electronic devices and their communication links. With a larger number of elements, naturally more vulnerable points appear in the system and the level of reliability may decrease when compared with conventional architectures. It is clear however, that by including different kinds of redundancy in the system the level of reliability increases drastically, ultimately surpassing the conventional approach.

Scenario 1 shows the most basic architecture of process bus. Since the reliability depends on all elements and there is no redundant elements, this topology has the lowest level of reliability. In Scenario 4, both merging units and protective relay support the redundancy protocol. Since each device is connected to two switches, there is a complete parallel way to provide data communication between the IEDs, which makes the structure of the network more robust, and, consequently, increases the level of reliability of the protection system.

The use of Process Bus considering redundancy of measurements and network structure combined with redundant relays, as shown in the Scenario 5, provides the highest level of reliability, surpassing even the reliability of the conventional architecture with primary and backup protection schemes.

The ring topology shown in the Scenario 6 for both 3 and 6 IEDs presented high levels of reliability with fewer devices required, proving as a valid alternative to the PRP approach. It comes however at the cost of limiting the amount of elements in that comprise the network and may impose difficulties in scalability, being therefore more suitable for small applications.

Assessing all topologies presented, it is observed that the higher the level of redundancy, the greater the reliability level of the system. The redundancy in the network structure makes the system more reliable, because it allows multiple paths for data transfer. The redundancy of devices makes the system less dependent of the integrity of the pieces of equipment that compose it.

Because of the characteristics of the IEC 61850-based protocols, the use of Process Bus naturally allows an easier and continuous monitoring of the status of the devices in the network. Additionally, the replacement of the devices becomes simpler because there are fewer cables connected to them. Another very important factor to be considered is the drastic increase in safety, since only the merging unit receives signals from a CT. This means the control room environment is not subject to the dangers of CT circuit interruption. Considering the results of the reliability levels and the non-quantifiable aspects of the process bus, its use is very encouraging.

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