ASSESSMENT OF THE RELIABILITY OF DIGITAL TECHNOLOGY APPLIED TO PRIMARY DISTRIBUTION SUBSTATIONS

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SUMMARY

With the advent of digital substation automation systems (DSAS) from process to station level, new system architectures can be envisioned to replace currently adopted approaches, which have been employed in the last decade. New architectures are expected to bring multiple benefits, including functional performance, reliability, simplification, flexibility and safety.

More evident in transmission substations, where potential savings in equipment and installation are more significant in the total CAPEX/OPEX expenditure, in the primary distribution substation the optimization scenario needs to address the full SAS. Primary distribution substations, in which current cost/benefit analysis usually limits the employment of more performing and reliable solutions, are expected to benefit from fully-digital technologies, improving life-cycle economic performance of the distribution grid, but this has to be carefully evaluated and addressed.

This paper focuses on the evaluation of reliability, which is one of the key aspects of protection, automation and control systems. The authors address the quantification of reliability to compare currently adopted solutions with alternative future high-performing DSAS architectures. Reliability is evaluated through well-established RAM methodology. A measurement of expected lifecycle value benefits/savings is also provided as a means of comparison. Key assumptions and estimations of the reliability and value factors regarding individual system components are stated. For a typical substation topology, the currently employed SAS architecture and an alternative fully digital solution are evaluated.

This paper is a publication of the DSGrid project, cofunded by P2020 innovation and R&D initiative. DSGrid brings partners from the industry and research institutions together to develop next generation digital substation solutions addressing system digitalization including the use of process-close technologies and cybersecurity in T&D applications.

Key words: Digital Substation, Distribution, IEC 61850, PRP, Reliability, RAM methodology

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INTRODUCTION

The architectures of most substation automation systems (SAS) employed today were designed before the introduction of IEC 61850 some decades ago. Since then system digitalization has steadily increased but architectures have, in the general case, not been significantly changed. IEC 61850 brought the station bus into common practice for monitoring and control, but the architectures still often mimic the preceding proprietary-based solutions. The utilization of GOOSE messaging for the implementation of distributed automation, breaker failure and reverse interlocking functions, among other purposes, was one of the major breakthroughs in earlier stages of the adoption of IEC 61850.

Although SAS architectures for primary distribution substations vary significantly between utilities worldwide, a common optimized SAS solution for primary distribution substations nowadays involves the use of single RSTP rings, single P&C IEDs for each MV feeder cubicle and both main and backup protection for each HV panel. Busbar differential is not frequently employed. On HV level distance protection is used, based on impedance estimation methods and sometimes, when this protection cannot provide selective fault clearance, line differential protection is also used. Control functions typically have no redundancy except for station level control and gateway.

Considering latest editions of IEC 61850 as well as related standards and technology, deployment of fully-digital substations is becoming feasible in the industrial practice. Multiple pilots and early industrial projects have been reported. The benefits of fully digital systems, from process to station level, are multiple: increased design flexibility, increased adaptability to lifecycle changes in the substation, practical elimination of CT saturation and open circuit issues, with the subsequent impact on safety, reduced installation, commissioning and maintenance costs associated with the eliminations of wiring and new engineering and testing tools.

It is therefore expected that fully-digital substation architectures enable end-users to optimize solutions by both adding value and reducing TCO. This is of the utmost relevance in the case of primary distribution substations, where potential savings in equipment and installation are not so significant as in transmission substations, and therefore the economic performance during the entire life-cycle and the additional value new solutions can bring must certainly be considered when designing and adopting new solutions.

Another concern related to fully-digital substations is the increase in complexity (from an engineering viewpoint) when considering architectural changes towards digitalization. This can be related to the increase in part count, interfaces and diversity, which impacts both engineering and component cost and is also a factor of potential reliability reduction. It must be noted that digital solutions enclose a trade-off between reduced electrification complexity (which in industrial practice is very mature) and digital system complexity (which in industry-specific engineering methods is emerging or developing).

This paper focuses precisely on the evaluation of reliability, which is one of the key aspects of protection, automation and control systems. In [1] the authors discussed optimization drivers, introduced a set of indicators and compared the performance of different architectures through the presentation of two substation case studies (one for transmission and one for distribution). In this paper, the previous study is further detailed and applied to a concrete example of a 60/30/15 kV primary distribution substation in the Portuguese mainland network, for which a fully digital system targeting the protection, automation and control of the HV side is planned. The currently employed SAS architecture and an alternative fully digital solution are evaluated in terms of reliability, through well-established RAM methodology. For a more detailed description of the main architectural decisions in the design of the new fully-digital SAS, see [2].

SAS ARCHITECTURES FOR PRIMARY DISTRIBUTION SUBSTATIONS

In this section, the automation system's architecture currently applied in primary distribution substations is described and compared to the new design proposed, based on the digital substation concept and applying process-close technology.

Although some specific aspects may vary according to the topology of the substation, generic and standard principles are followed. The study presented in this paper is exemplified with the case of the 60/30/15 kV Montemor-o-Novo substation in the Portuguese mainland network. This substation is composed by three incoming 60 kV lines, one single 60 kV busbar and two three-winding transformers that can be operated in parallel in both secondary and tertiary sides. Its single line diagram is depicted in Figure 1.

Both, the project and the reliability assessment, are focused on the HV side of the substation. The 30 and 15 kV sides, including the MV busbars, the MV feeders and capacitor banks are out of the scope of this study. In fact, in current SAS implementations, a single IED, for each bay, executes all MV protection and control functions, which is a very well optimized and cost-effective solution. The proposed digital substation is applied only in the HV side where the distances between power equipment and protection and control cabinets are greater than in MV side.

Conventional Design

The conventional SAS design is based on a well-established and field-proven architecture. It is supported by state-of-the art numerical protection and control IEDs. All signals, including analogue inputs and binary inputs and outputs are available through wired connections from the switchyard to the main building where the P&C cabinets are installed.

For each bay, typically at least two IEDs are used: one device performing all protection functions and a backup device which executes bay control and overcurrent protections.

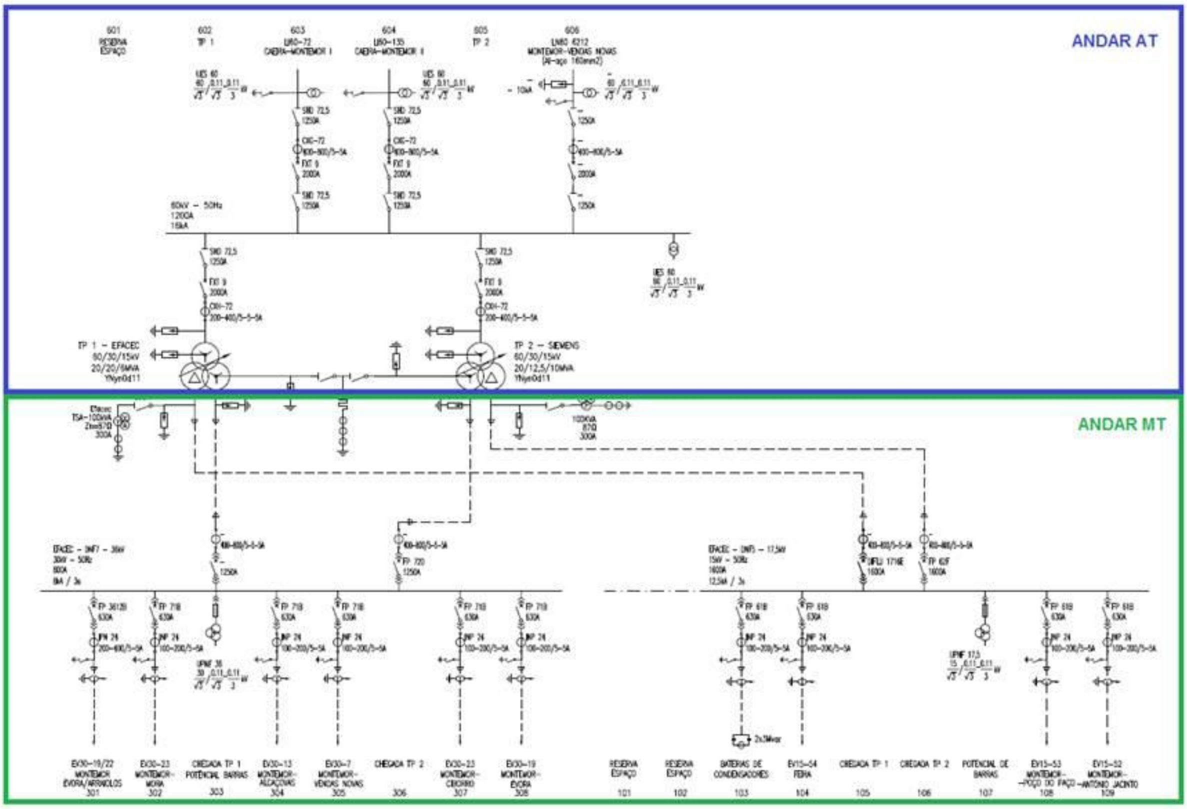

Figure 1. Single line-diagram of Montemor-o-Novo substation.

For instance, the HV line bays, where a Distance main protection is backed up by a multifunction device, performing among others overcurrent protection, measurement functions and bay control. The same solution applies for transformer bays: a device executes the main functions, including Transformer Differential protection; a second IED implements overcurrent backup function and bay control. In the case of transformers, a third device must be considered for voltage control and tap changer supervision. In the case of the HV busbar, a single IED is installed for additional automation functions, including voltage and frequency load shedding.

All IEDs are connected through a local ring area network, with no redundancy between IEDs and switches. Besides guaranteeing the supervision and control by higher station and remote levels, it is also used to implement some distributed automation functions resorting to GOOSE messages exchange, taking advantage of the interoperability provided by the IEC 61850 standard.

Despite its simplicity, this solution guarantees a minimum level of protection redundancy in case of failure of some of its components. For example, the loss of the main protection device for a line or transformer does not compromise the control of that bay and the execution of basic protection functions. It must be noted that further reliability must depend on the power system itself and on the redundancy provided by distinct incoming HV lines and parallel transformers. Nevertheless, this design fits well on the cost constraints and application scope of distribution grid.

Digital Substation Design

A very distinct architecture is proposed in the new design, which is based on process-close technology, by using process level IEDs and bay level protection and control devices with process-bus communication interface compliant with IEC 61850-9-2 standard. Figure 2 represents the architecture of the automation system. In [2] a detailed description of the main assumptions and design decisions taken can be found.

The new process level IEDs are able to perform distinct functions, including the interface with current and voltage transformers (stand-alone merging unit function), the control of circuit breakers and the supervision of all process-level status. In the proposed architecture, main protection and control functions are still executed at bay level, as in the conventional design.

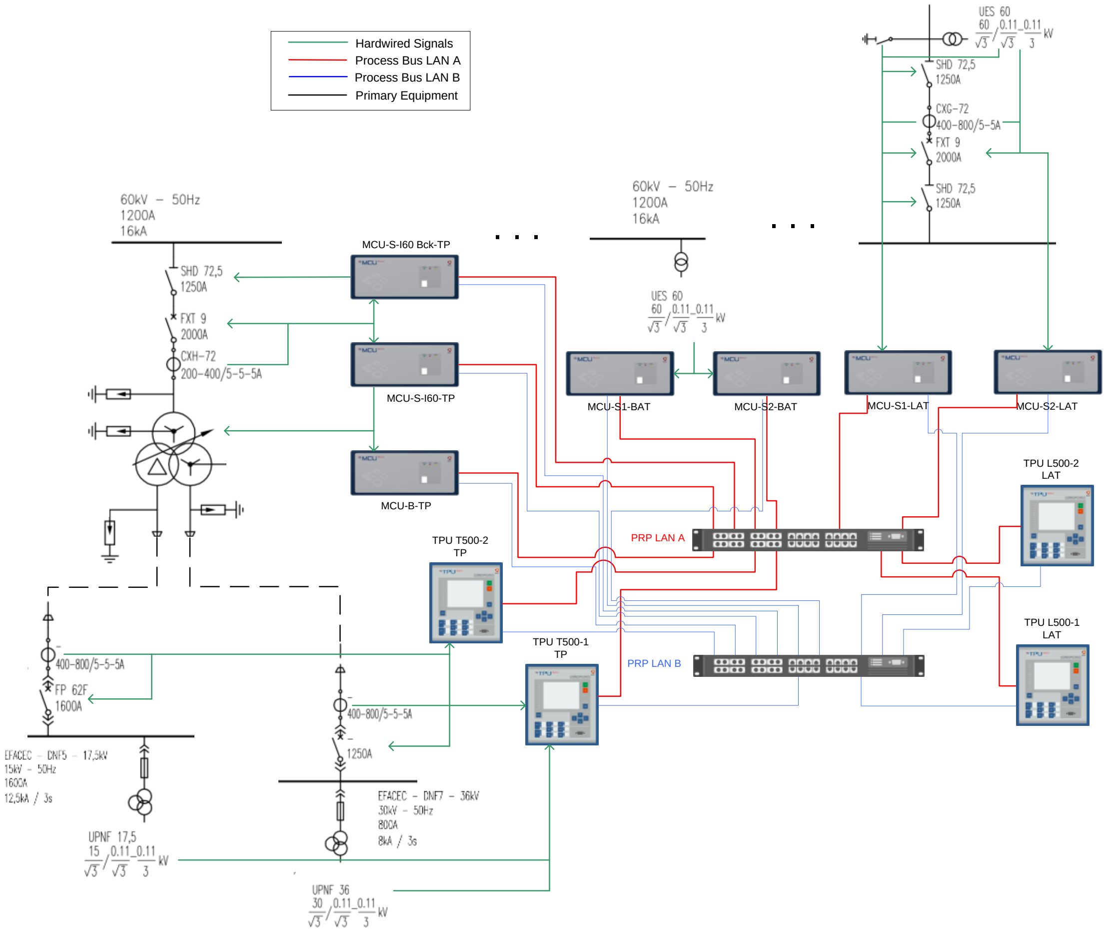

Figure 2. DSAS architecture.

For each bay, at least two process level IEDs are considered. On one hand, due to the maximum I/O capacity of the devices used, this is necessary to accommodate all inputs and outputs per bay. On the other hand, the use of two separate devices increases the reliability of the entire solution, as the most critical signals, such as current inputs or circuit breaker status and output commands are duplicated in both units.

Power transformer bays requires a third process level IED, due to the higher number of inputs required, mainly associated to the voltage regulator, the protection relays and other supervision devices built-in the transformer itself. It must be noted that the inputs and outputs from 15 and 30 kV levels required for the HV side protection are acquired by wired connections, since they are in small number and this avoids the installation of additional merging units in MV cubicles.

In the case of the HV busbar, a complete full-scheme is implemented. Although the number of signals at the busbar is small and one device was enough to process them all. These are critical signals, such as the busbar voltage inputs needed for distance protection in all HV line bays, and for that reason, two merging units had to be considered.

At bay level, and except in the case of the HV busbar, there are two IEDs per bay. Several alternatives for function allocation between both IEDs can be considered since the signals can be subscribed by IEC 61850-9-2 interface from any process-level IED. At the transformer bays, the third IED was removed because voltage control can be executed in any of the other two devices.

For the communication infrastructure at process level, a redundant PRP network is chosen because it is a simple and effective redundant scheme, that can scale well and adapt to different number of bays and substation topologies. Duplicated GPS clocks with PTP interface are considered at both LAN A and LAN B of the PRP network, because accurate and reliable time synchronization is a critical component of this kind of systems.

Table 1 compares both designs, the conventional based on wired connections and the new solution based on process-close technology, enumerating main differences in terms of number of IEDs (bay and process) and number of communication links.

Table 1. Comparison of conventional and digital SAS design.

Indicator	Conventional System	Fully-digital System
Bay IED count	13	11
Process IED count	0	13
LAN link count	13	59

RELIABILITY EVALUATION – MAIN PRINCIPLES AND ASSUMPTIONS

The reliability study consisted of obtaining the MTBF (Mean Time Between Failures) value for the various IEDs, in order to determine the MTBF value of the entire architecture. During the reliability calculation, accomplishment for this products/system was used the MIL-HDBK-217F standard, Notice 2 of 28th February of 1995: Military Handbook, Reliability Prediction of Electronic Equipment. The calculation of reliability and availability was made in the software of Item Software, Item Toolkit version 8.9.2, Module MIL 217, which is based on the standard previously mentioned, and module RBD (Reliability Block Diagram).
For each IED it was necessary to determine the MTBF value of each constituent electronic board. For the performed calculation, it was considered the following considerations: (i) whenever there is no data for the configurable parameters of some components, it is considered the default values of Item Toolkit Program of Item Software; (ii) in the case of “components quality” parameter, all components were considered with high quality. If there is no data, this parameter was considered as default value of Item Toolkit Program of Item Software; (iii) in order to be a more realistic study, adjustment factors were applied to some components; (iv) all calculations were carried out considering an environmental temperature of 25ºC and 55ºC in Ground Benign environment.
From the moment the MTBF of each electronic board was determined, it was possible to determine the MTBF of each IED of both designs through the RBD module.
Finally, it was possible to obtain the MTBF value of both systems, once again through the RBD module. For the study of the conventional architecture, it is pessimistically assumed that the redundancy between IED's does not exist at all (this is the case for main protection functions but not for all the remaining functions), whereas in the digital architecture it must be considered that redundancy exists between some of the functions even in the worst case. In both studies fibre and copper wiring were considered not to fail. Device and function reliability predictions are built from RBD of individual devices, taking into account hardware and functional dependencies and redundancies according to standard reliability theory (see Table 2 and Figure 3).

Table 2. RAM models.

Configuration	Equivalent Failure Rate	Equivalent Repair Rate	Related RBD
Single Component	λ	μ	i
Serial	$\lambda(\infty) = \sum_{i=1}^{n} \lambda i$	$\mu(\infty) = \frac{\sum_{i=1}^{n} \lambda i}{\sum_{i=1}^{n} \frac{\lambda i}{\mu i}}$	i + i+1 i — i+1
Parallel	$\lambda(\infty) = \prod \frac{\lambda i}{\mu i} \times \sum_{i=1}^{n} \mu i$	$\mu(\infty) = \sum_{i=1}^{n} \mu i$	i.i+1 i i+1

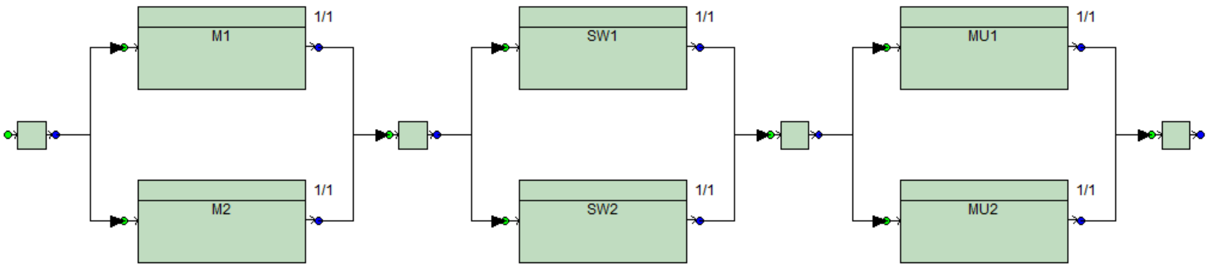

Figure 3. Example RBD for typical bay protection.

RESULTS OBTAINED

In this section, the results of the reliability study that was implemented as discussed previously are presented. Table 3 and Table 4 summarize the results obtained for the MTBF indicator for the main components of both systems, the conventional wired and the new digital system.

Table 3. MTBF indicator for components of conventional SAS.

Component	Temperature [°C]	Equivalent Failure Rate λ [h^{-1}]	MTBF [h]	MTBF [years]
HV Line Main Bay IED	25	3,74E-06	267223	30,50
	55	4,41E-06	226921	25,90
Transformer Main Bay IED	25	3,74E-06	267223	30,50
	55	4,41E-06	226921	25,90
HV Busbar Bay IED / HV Line and Transformer Backup IED	25	2,63E-06	379660	43,34
	55	3,29E-06	303882	34,69
Communication switch	-	5,45E-07	1833470	209,30

Table 4. MTBF indicator for components of fully-digital SAS.

Component	Temperature [°C]	Equivalent Failure Rate λ [h^{-1}]	MTBF [h]	MTBF [years]
HV Line Main and Backup Bay IED / HV Busbar Bay IED	25	2,79E-06	358207	40,89
	55	3,13E-06	319657	36,49
Transformer Main and Backup Bay IED	25	3,28E-06	305305	34,85
	55	3,67E-06	272237	31,08
HV Line Process IED 1	25	1,56E-06	642228	73,31
	55	2,02E-06	493846	56,38
HV Line Process IED 2	25	1,44E-06	693930	79,22
	55	1,82E-06	549684	62,75
HV Busbar Process IED	25	1,23E-06	814595	92,99
	55	1,57E-06	637629	72,79
Transformer Process IED 1	25	1,30E-06	768324	87,71
	55	1,65E-06	605001	69,06
Transformer Process IED 2	25	1,38E-06	723881	82,63
	55	1,75E-06	572568	65,36
Transformer Process IED 3	25	1,84E-06	544768	62,19
	55	2,49E-06	402059	45,90
Communication switch	-	5,45E-07	1833470	209,30

It shows that individual IEDs can present adequate MTBF values, achieved by careful selection of its components and judicious design of its electronic boards. The results are comparable between IEDs used in both proposed system architectures. This happens because there were used protection relays from the same manufacturer and generation in both designs, being the main difference between them the type of process interface available (wired versus IEC 61950-9-2 compliant).

Nevertheless, it can be noted that MTBF is higher in the case of relays with digital interface. This is a natural consequence of the fact these IEDs, although sharing some complex components such as CPU, communication and power supply boards with conventional devices, have a reduced number of components because no input/output boards are needed, which enhances simplicity and thus reliability. Transformer bay IEDs have a slightly reduced MTBF indicator due to the fact they need an extra expansion for the acquisition of the current signals from MV levels through hardwired connections.

Process level IEDs also have excellent reliability indicators. The exact value for each device depends on the particular combination of I/O boards. Notwithstanding the high number of I/O points that need to be acquired at each bay, and so the need for several expansion boards in each IED, these devices benefit from a very simple and effective design which contributes to extended reliability, despite the harsh environment conditions they are subject to.

Table 5 and 6 present the combined results of the MTBF for both architectures, taking into account the individual components reliability, the network topology and the level of functional redundancy achieved. Relatively to the digital SAS design, two borderline cases are presented:

- With no redundancy between merging units, meaning that there are no duplicated inputs and outputs.
- With full redundancy between both merging units of each bay, i.e. fully duplicated inputs and outputs for most critical functions.

Table 5. MTBF indicator for the conventional SAS.

System / condition	Temperature [°C]	Equivalent Failure Rate λ [h^{-1}]	MTBF [h]	MTBF [years]
No redundancy between bay IEDs	25	4,09E-05	24466	2,79
	55	4,95E-05	20222	2,31

Table 6. MTBF indicator for the fully-digital SAS.

System / condition	Temperature [°C]	Equivalent Failure Rate λ [h^{-1}]	MTBF [h]	MTBF [years]
Full redundancy between bay IEDs No redundancy between MUs	25	1,31E-05	76590	8,74
	55	1,65E-05	60717	6,93
Full redundancy between bay IEDs Full redundancy between MUs	25	4,02E-06	248799	28,40
	55	4,70E-06	212915	24,31

The results show that for most cases the reliability of the entire SAS is greatly reduced when compared to the same indicator for individual components. This derives from the fact that, as the number of components in the system increases and an individual failure of some component prevents the execution of some critical function, the MTBF indicator decreases in inverse proportion.

This is the case of the conventional system, where for example a failure of the main protection of a HV line or transformer is identified as a failure of the entire system, since it cannot be replaced by any other component. Although the SAS remains operative for the remaining bays and providing some of the functions (mainly basic protection, besides monitoring and control) in the affected bay, this should be considered as a failure in the SAS and be accounted for in the reliability assessment.

Better results are obtained with the digital SAS, taking advantage of the redundant communication network and of the duplicated functions in distinct bay IEDs. With this system design, an individual failure of a bay IED, assuming that main and critical functions are duplicated, results in no loss of functionality of the entire automation system, which guarantees higher reliability indicators (in average, 2 to 3 times higher MTBF values).

When considering further redundancy in the system by duplicating all I/O signals among distinct process level IEDs in the same bay, further improvements are obtained in the results. With full redundancy (simultaneously at bay and process level) very high reliability indicators are achieved for the entire DSAS. In fact, this is a theoretical result and a best-case scenario, since the architecture was optimized for distribution applications, and so no full redundancy was considered since it could be hardly economically justified.

CONCLUSION AND FUTURE WORK

The authors presented in this work an assessment and a theoretical comparison of the reliability of conventional SAS architectures currently implemented in primary distribution substations and new system designs for DSAS based on process-level technology. The study was exemplified with the application in a real distribution substation in mainland Portugal.

Reliability indicators were calculated using as a base well-established RAM methodology, both for individual components (bay and process IEDs, but also other components, such as network switches) and the global automation system.

The results show that new DSAS architectures can contribute decisively to enhance system reliability if adequate redundancy level is considered in the design of the system. A PRP-based communication network, since it provides two independent networks with all messages duplicated and zero recovery time, is a good option to support high-availability and performant process bus architectures. Care should also be taken with the redundancy of other critical components, such as time synchronization which plays a decisive role in DSAS, avoiding a single point of failure of the protection system of the entire substation.

Besides physical redundancy, the careful functional allocation among the several bay and process-level electronic devices also plays a significant role in system reliability and dependability. Although fully redundant and duplicated systems are not viable in distribution because of the increased cost, some measures were shown to be effective in increasing good reliability indicator while maintaining the total cost of the solution low. In terms of process level, the duplication of the most critical signals, namely the analogue current signals and some binary inputs and circuit breaker commands, hardwired to distinct IEDs, guarantees that most critical functions do not depend on a single point of failure, without increasing too much the total I/O capacity required. At bay level, this new concept also allows new function allocation alternatives, distinct from the past conventional design, because the sampled values needed for a specific function can be subscribed from any merging unit, with adequate configuration of the communication network. This easily enables duplicated function distributed by several devices, thus increasing reliability and dependability of the overall system.

In this work, only hardware failures were considered in the RAM methodology applied. Other sources of failure modes, such as the firmware or communication network constraints, were not accounted for due to the fact they are difficult to measure. In future stages of this work, the authors plan to model this type of failures, in order to measure its impact.

Also, as function allocation plays an utmost role in this type of systems, subsequent studies should go beyond the IED level and further detail its block diagram composed by I/O main modules and software functions inside each device as well as their global interactions. This will enable a more detailed analysis of the system and a more accurate result set between the best-case (fully redundant) and worst-case (conventional design) scenarios, also allowing the evaluation of the impact of different function and I/O allocation strategies in the overall system reliability.

A third line of investigation will be the inclusion of the power system model in the study, accounting for the impact of SAS failures in the availability and operation of the power system itself.

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BIOGRAPHIES

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Rogério Paulo is currently heading the Protection, Automation and Control Products Division within Efacec. Has a background on Strategic Marketing, Global Product Management and R&D in different projects related to Power Systems Automation and Smart Grids. Holds Advanced Management Training, MsC on Industrial Informatics and BsC on Industrial Electronics. Has authored more than 40 peer reviewed papers, articles and reports and received honours from REN (Portuguese TSO) and Minho University. Is involved in standardization activities, being currently an active member of IEC TC57 WG 10 and CIGRE B5.