A Monte Carlo Method for Reliability Evaluation of a System Integrity Protection Scheme in the Chilean System

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***Abstract*— This paper discusses a Monte Carlo based method for evaluating the reliability of a new System Integrity Protection Scheme (SIPS) to be deployed in the Chilean Central Interconnected System (SIC). This SIPS is being implemented with the objective of detecting the occurrence of extreme contingencies and generating control actions to avoid a collapse of the electric system. Due to its criticality, ensuring its security and proper operation makes necessary to find methods to describe its future behavior and to evaluate its reliability under different operating conditions. This paper describes an effort to develop a method to obtain reliability indices for the SIPS and evaluate the impact of its components on its overall reliability and functionality, detailing requirements, limitations and criticalities to consider. The analysis uses Monte Carlo simulation which, unlike some analytical reliability techniques, allows incorporation of different operating conditions and allows to model different failure distribution functions.**

***Index Terms*-- Availability, Monte Carlo methods, Power system protection, Reliability.**

I. Introduction

The growing complexity of electric power systems, coupled with the need to ensure their reliable operation, has driven the development of new technologies to safeguard their security and integrity. One of the most promising technologies to detect and correct situations that may lead to system instability and its collapse are *System Integrity Protection Schemes* (SIPS). SIPS, also known as *Special Protection Schemes* (SPS) or *Remedial Action Schemes* (RAS), are used to protect the integrity of a power system. Their main function is to maintain system stability during and after a major contingency or perturbation, keeping maximum connectivity and avoiding damage to equipment and sub-systems [5-7].

Due their critical function, it is vital for SIPS designers to ensure proper operation when the contingencies the SIPS were designed to mitigate are detected, as it is also vital to avoid them acting when not needed. As SIPS are made of multiple components and communication links, analyzing SIPS' reliability and understanding the impact their reliability might have on system operation can be a daunting task.

This paper discusses a joint applied research effort between university and industry to evaluate the reliability analysis of a SIPS to be installed in the Chilean Central Interconnected System (*Sistema Interconectado Central*, SIC). The SIPS, denominated *Defense Plan against Extreme Contingencies – Phase 1* (DPAEC-P1), will detect the occurrence of certain critical contingencies that may lead to a system blackout and will act enforce some remedial actions to restore the system to a stable operation point. We will present a simulation based method to obtain reliability indices for the SIPS and to evaluate how different components affect its overall reliability and functionality, detailing requirements, limitations and criticalities to consider.

This paper is structured as follows: Section II describes the SIC and comments how the SIPS to be implemented will contribute to the system security. Section III provides an overview of SIPS and their reliability, with emphasis on the SIPS to be implemented on the SIC. Section IV describes the parameters and assumptions of the Monte Carlo method used to evaluate the SIPS' reliability, while Section V presents simulation results. Finally, Section VI presents the conclusions of this work.

II. Challenges in the SIC

The Central Interconnected System (*Sistema Interconectado Central, SIC*) is the largest Chilean interconnected system, with a total installed capacity of about 12.4 [GW] in 2011.

Power system stability depends on the balance between load (demand) and generation (supply). Whenever a misbalance happens, it is important to restore the balance by shedding load or disconnecting generation. The SIC Independent System Operator (known as *Centro de Despacho Económico de Carga,* CDEC-SIC) coordinates the actions of generation and transmission companies and large customers in order to comply with standards of security, stability and quality of service. To this end, the CDEC-SIC has incorporated SIPS such as load shedding, generation rejection, and generation runback schemes that can trip either load or generation in order to permit the operation of certain transmission corridors above their “N-1” limit, allowing for a more economic operation of the system while maintaining system security at acceptable levels.

Several systemic stability studies have been performed in the SIC in order to evaluate the impact of specific contingencies. These studies have detected that here still persist problems such as transient stability issues, overloading of conductors, and voltage regulation problems [1].

In order to avoid and/or minimize these problems and to increase the capacity of the main transmission corridors it would be necessary to build new transmission lines. However, securing the land rights and obtaining the necessary permits has become increasingly difficult, making it more expensive and delaying new builds. These issues have made the use of SIPS, which present several advantages in terms of lower costs and more rapid deployment, a real and gradually more attractive alternative to increase the transmission capacity of existing transmission corridors, while maintaining acceptable security levels [2], [3].

III. Reliability of SIPS

A. *Overview of SIPS*

SIPS are used to protect the integrity of a power system and avoid its collapse. They should be able to detect major contingencies or perturbations, and then take some remedial actions to maintain system stability and to keep maximum connectivity while avoiding damage to equipment and sub-systems [4]-[6]. SIPS are being increasingly used around the world due to their flexibility facing contingencies [7], [8], as many industry experiences show [9].

Generally speaking, SIPS have a series of subsystems in charge of acquiring, communicating and processing power system information with the purpose of generating actions that will relieve the system after a contingency or anomalous operating condition is detected. These subsystems are composed of sensors, metering instruments, logical actuation units, among others, all connected through communication protocols specific to the industry [10], [11].

Even though SIPS allow protecting electric power systems in the face of critical events or contingencies, blind dependence on them may result in increased risk. Furthermore, coordination of multiple SIPS may result in increased operational complexity as a result of constant evaluations and coordination among all of them, difficulting implementation and maintenance and negatively affecting security [12]-[14].

Therefore, it becomes necessary to develop methodologies that will allow estimating before deployment of the SIPS values such as outage rates, times to failure and to anticipate abnormal conditions during its eventual operation.

B. *Reliability evaluation of SIPS*

Failure to operate of a SIPS or a false positive leading to improper operation can have catastrophic consequences on power system security As proper operation of SIPS can be quite critical to the security of the system, development of methods to adequately evaluate their reliability are of utmost importance. However, in the case of the SIPS no specific industry standard exists to obtain reliability metrics associated to their operation. Nevertheless, different standards make reference to tools for evaluating reliability and security focused on the process control industry [15]-[20], and some of their concepts can be extended to SIPS reliability. Although analytical tools such as RBD, Simplified Equations, FTA, Cut-Sets, and Markov chains can be convenient to conceptualize the problem due to their graphical nature and to obtain a first reliability estimate due to their simplicity, they have severe limitations when implemented for real systems with a high degree of complexity, as their required assumptions tend to oversimplify the systems they try to model. For example, they cannot model straightforwardly time dependences, simultaneous events occurrence and they have limits in terms of the failure probability distributions to be used [21]-[27].

An alternative to analytical methods is Monte Carlo simulation. This technique is used in different applications for obtaining reliability metrics such as availability or time to failure in complex systems [28]-[32]. The flexibility of running Monte Carlo simulation with different parameters allows the user, among others, to define maintenance protocols, model different types of failures with different degrees of severity, evaluate the impact of redundancy in critical components, and consider different configurations of the system. All these characteristics make Monte Carlo methods suitable for reliability studies of complex systems such as SIPS.

C. *DPAEC-P1 characteristics*

Fig. 1 shows a scheme of the SIPS to be implemented in Chile. It has 9 cells and 9 communication links, and each of them is treated in the reliability evaluation as a component. The SIPS whose reliability is being evaluated will be located in a strategic SIC transmission corridor with the objective of detecting the occurrence of extreme contingencies and generating the control actions to avoid a collapse of the system. Besides communication links, the SIPS has operational blocks (cells) with different purposes:

- *Measurement blocks*: Their purpose is to acquire and deliver real time information regarding power flow measurements, temperature and status of the circuit.
- *Control blocks*: Their purpose is to act on the system tripping generation and/or shedding load with the purpose of stabilizing the power system.

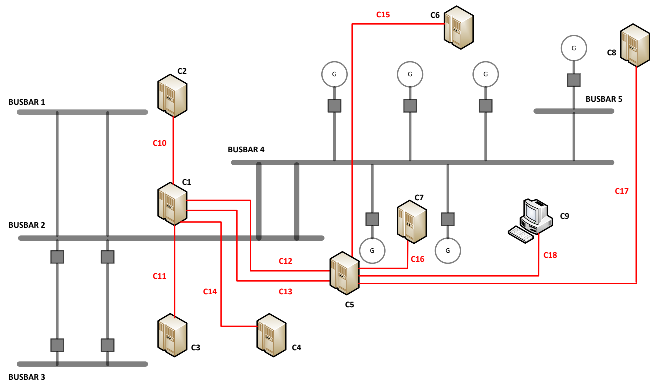

Figure 1. Scheme of the DPAEC-P1

Different components have different levels of criticality, that is, failure of the individual component will have a different effect on the overall performance of the SIPS. Table 1 shows the criticality of each component, and was elaborated based on operational criteria and an analysis of circuit topology. While failure of some components will have little or no effect in SIPS operation in case of an extreme contingency, failure of some other may allow partial operation, and failure in some of the most critical components will impede proper operation and put the system at risk.

TABLE 1
CRITICALITY OF SIPS COMPONENTS

Component criticality	SIPS operational status in case of component failure	Components
High	Unable to operate	C1, C5
Medium	Partial operation	C4, C6, C7, C8, C14, C15, C16, C17
Low	Normal operation	C2, C3, C9, C10, C11, C12, C13, C18

IV. MONTE CARLO SIMULATION FOR RELIABILITY EVALUATION OF THE SIPS

A. *Parameters and assumptions*

Table 2 shows the *Mean Time to Failure* (MTTF) and the *Mean Time to Repair* (MTTR) for each of the components of the SIPS. The MTTF of each component is estimated from reliability data provided by the cell parts' manufacturers, and the MTTR is an estimation of the time it takes to repair/replace it after it fails. However, the reliability data provided by manufacturers is very limited and do not provide any information about the type of underlying failure time distributions. In order to evaluate the sensitivity of the modeling to the sampling distributions, components' time to failures in the Monte Carlo scheme were sampled from both exponential and Weibull distributions.

The time-to-repair values are sampled from a uniform distribution whose extreme values correspond to: 1) the minimum time needed to repair/replace the component and 2) the estimated maximum time that the repair could take. Each component of the SIPS counts with a self-diagnostic scheme that will detect whether the component operates properly and immediately communicate the operator the need to repair/replace it. Thus, the MTTR in Table 2 considers only the time to repair/replace the component and not the time to detect the component's failure. As more SIPS gets installed around the world, it would be desirable that industry organizations get together and collected failure data, similarly to what is being done by CIGRE with reliability data for HVDC lines [33], [34]. This would allow users to count with field reliability data for SIPS' standard components and would permit making better estimates.

TABLE 2
PARAMETERS OF THE COMPONENTS

Comp	MTTF [h]	MTTR [h]	Comp	MTTF [h]	MTTR [h]
C1	200.000	72	C10	1.000.000	240
C2	200.000	48	C11	1.000.000	240
C3	200.000	48	C12	1.000.000	240
C4	200.000	48	C13	1.000.000	240
C5	200.000	72	C14	1.000.000	240
C6	200.000	48	C15	1.000.000	240
C7	200.000	48	C16	1.000.000	240
C8	200.000	48	C17	1.000.000	240
C9	200.000	48	C18	1.000.000	240

B. *Monte Carlo scheme*

The Monte Carlo scheme implemented to evaluate the SIPS reliability consists of repeatedly simulating its operation and randomly generating failures on the SIPS components sampled from probability distributions with the MTTF values and time to repair values as indicated in Table 2. Each of the 20,000 iterations simulated the SIPS operation during 50 years, and from that simulation we obtained availability and outage rate of the SIPS. During the iterations, component's failures are simulated in such a way that once the component is repaired is considered 'as new', that is, its hazard rate goes back to its initial value after repair.

The study does not consider cascading failures or stochastic dependency between failures, or failure probability changing with the power system operating conditions. Although these features could be included in the model, we do not count at this point with sufficient information to model failure probability distributions for this kind of events.

V. SIMULATION RESULTS

A. *Convergence*

Convergence of the Monte Carlo scheme is presented in Fig. 2 and Fig. 3. Both the availability and the outage rate are calculated as the cumulative average of the iterations. In general, we observed convergence for both the availability and the outage rate after 10,000 iterations, meaning that after 10,000 iterations no significant changes in the reliability values could be observed.

B. *Sensitivity to time-to-failure distribution*

Using exponential distribution the availability of the SIPS is estimated to be close to 99.93%, while its outage rate is estimated at 1e-5 failures per hour. This is equivalent to 1 high criticality failure every 100,000 of operation.

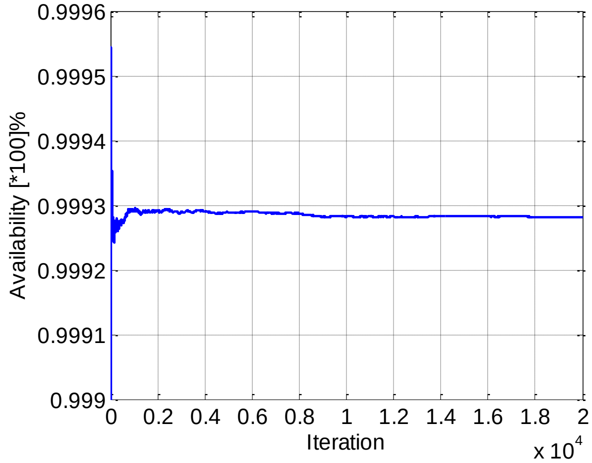

Figure 2. Convergence of SIPS availability (exponential distribution)

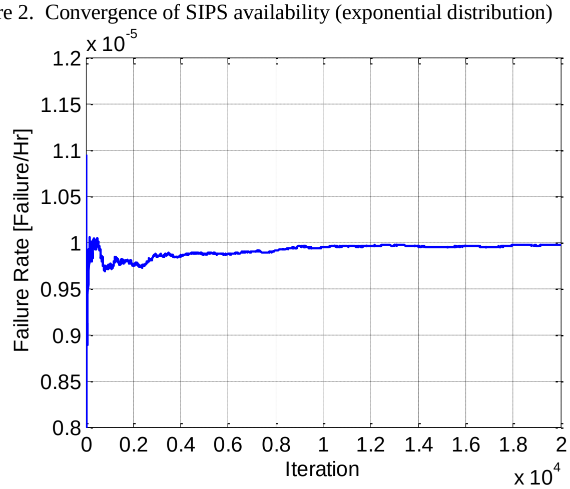

Figure 3. Convergence of SIPS outage rate (exponential distribution)

TABLE 3
COMPARISON OF RESULTS WITH DIFFERENT DISTRIBUTIONS

Reliability metric	Assumed distribution	
	Exponential	Weibull
Availability [%]	99,93	99,985
Outage rate [failures/hour]	1e-5	2,1e-6

TABLE 4
DISTRIBUTION OF FAILURES OF DIFFERENT CRITICALITY

Distribution	Criticality		
	High	Medium	Low
Exponential	19%	44%	37%
Weibull	22%	44%	33%

However, the exponential distribution is sometimes criticized as it considers a constant hazard rate, meaning that disregards ageing of the components. In consequence, we decided to also evaluate the SIPS reliability sampling the time-to-failure for each component from a Weibull distribution with the same MTTF than the exponential distribution. However, unlike the exponential distribution we chose the shape parameter of the Weibull distribution so that it has an increasing hazard rate. This implies that, while at the beginning the Weibull distribution will have a lower hazard rate, as time passes its hazard rate will increase and will eventually be higher than the hazard rate for the exponential distribution. The results of the comparative analysis are presented in Table 3. The results show that using a Weibull distribution the availability increases and the outage rate decreases, despite both time-to-failure distributions with the same MTTF. This happens because despite the Weibull distribution having an increasing hazard rate, before 500,000 hours its hazard rate is smaller. The flexibility of the Monte Carlo method also allowed us to evaluate the reliability of the SIPS for different kinds of failures, as presented in Table 4.

C. *Sensitivity to MTTR and MTTF in critical components*

SIPS designers and system operators can take some measures to improve SIPS reliability, such as including redundancy on some critical components (thus increasing MTTF) and/or reducing the repairing/replacing times of the critical components (thus decreasing MTTR).

For the DPAEC-P1, components 1 and 5 are the most critical, as Table 2 shows. In order to evaluate the sensitivity of the overall reliability to the MTTF and MTTR of components 1 and 5, we rerun the Monte Carlo simulation for different values of MTTF and MTTR, and the results are presented in Table 5 and Table 6 and are also compared to the results in Table 3 (base case). As expected, a higher MTTF increases the availability and decreases the outage rate of the SIPS, and a lower MTTR has the same effect, improving the overall reliability. In fact, duplicating the MTTF in the critical components the outage rate decreases to half its original value. Similarly, decreasing the MTTR of the critical components causes a reduction in the SIPS availability, but does not affect the SIPS outage rate as this value is mostly dependent on the MTTF of the components.

TABLE 5
SENSITIVITY TO CHANGES IN MTTF IN CRITICAL CELLS

Reliability metric	MTTF			
	100% (Base)	200%	50%	25%
Availability	99,93%	99,96%	99,85%	99,72
Outage rate [failures/hour]	1e-5	0,5e-5	2e-5	4e-5

TABLE 6
SENSITIVITY TO CHANGES IN THE MTTR IN CRITICAL CELLS

Reliability metric	MTTR			
	100% (Base)	200%	50%	25%
Availability	99,93%	99,86	99,97	99,98
Outage rate [failures/hour]	1e-5	1e-5	1e-5	1e-5

VI. CONCLUSIONS

SIPS are being implemented in electric power systems around the world as a way to increase operation flexibility by relaxing transmission constraints and by providing a solution to protect power system integrity after major contingencies. Due to their critical function, it is important that they operate properly and therefore evaluating their reliability is paramount before deployment. As SIPS are composed of multiple cells and communication links, analyzing their reliability and how that affects the power system can be quite challenging.

The Monte Carlo simulation scheme implemented in this study proved capable of evaluating reliability of the DPAEC-P1 SIPS to be implemented in the Chilean SIC. The great flexibility and short simulation times of the method allowed designers to test different configurations and assumptions, which contributed to make the reliability evaluation more robust.

One of the most challenging issues faced during this study was the lack of good reliability data for SIPS components. As more SIPS gets installed around the world, it would be desirable that industry organizations get together and collected failure data, similarly to what is being done by CIGRE with reliability data for HVDC lines. This would allow users to count with field reliability data for SIPS' standard components and would permit making better reliability estimates.

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