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Original Article

Inherent Availability of Protection and Control Systems in a 500 kV Transmission Line Bay: A Case Study in Colombia

Disponibilidad inherente de los sistemas de protección y control en una bahía de línea de 500 kV: estudio de caso en Colombia

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Abstrac

Introduction: The availability of protection and control systems in 500 kV transmission line bays is a key factor in ensuring operational continuity and the security of the National Transmission System.
Objective: To evaluate the inherent availability of protection and control systems in a 500 kV transmission line bay arranged in a breaker-and-half configuration by comparing nominal reliability parameters provided by manufacturers with historical failure and repair data.
Methodology: A series-parallel model based on Reliability Block Diagrams (RBDs) was developed in MATLAB to represent 13 Level 1 and Level 2 components of the protection and control system, including protective relays, bay controllers, and communication switches with LAN A/LAN B redundancy under IEC 61850. Nominal reliability parameters supplied by Siemens® and GE® were compared with a historical database equivalent to 287 devices operating over a 12-year period, with 81 recorded failures.
Results: The total availability calculated using historical data from the protection and control systems of the transmission line under study was 99.8408%, compared with the manufacturer-estimated availability of 99.9977%.
Conclusions: Catalog-based data significantly overestimate the actual performance of protection and control systems. Furthermore, real repair times are considerably higher than those assumed by manufacturers, highlighting the need to incorporate historical operating data into availability assessments, maintenance planning, and asset management strategies for extra-high-voltage substations.

Keywords: Inherent availability; Protection and control systems; Extrahigh-voltage substations; Intelligent electronic devices; IEC 61850; Reliability block diagram.

Resumen

Introducción: La disponibilidad de los sistemas de protección y control en bahías de línea de 500 kV es un factor determinante para garantizar la continuidad operativa y la seguridad del Sistema de Transmisión Nacional.
Objetivo: Evaluar la disponibilidad inherente de los sistemas de protección y control de una bahía de línea de 500 kV en configuración interruptor y medio, mediante la comparación entre parámetros nominales de confiabilidad suministrados por fabricantes y datos históricos de falla y reparación.
Metodología: Se desarrolló en MATLAB un modelo serie-paralelo basado en Diagramas de Bloques de Confiabilidad (RBD) para representar 13 componentes de los niveles 1 y 2 del sistema de protección y control, incluyendo relés de protección, controladores de bahía y switches de comunicación con redundancia LAN A/LAN B bajo IEC 61850. Los parámetros nominales proporcionados por Siemens® y GE® fueron comparados con una base histórica equivalente a 287 equipos en operación durante 12 años, con 81 fallas registradas.
Resultados: La disponibilidad total calculada con datos históricos provenientes de los sistemas de control y protección de la línea que se estudio fue de 99.8408%, en contraste con la información del fabricante que indicaba la disponibilidad sería del 99,9977 %.
Conclusiones: Los datos de catálogo sobrestiman significativamente el desempeño real de los sistemas de protección y control. Asimismo, los tiempos reales de reparación son considerablemente superiores a los asumidos por los fabricantes, evidenciando la necesidad de incorporar datos históricos de operación en los estudios de disponibilidad, la planificación del mantenimiento y la gestión de activos en subestaciones de extra alta tensión.

Palabras clave: NDisponibilidad inherente; Sistemas de protección y control; Subestaciones de extra alta tensión; Dispositivos electrónicos inteligentes; IEC 61850; Diagrama de bloques de confiabilidad.

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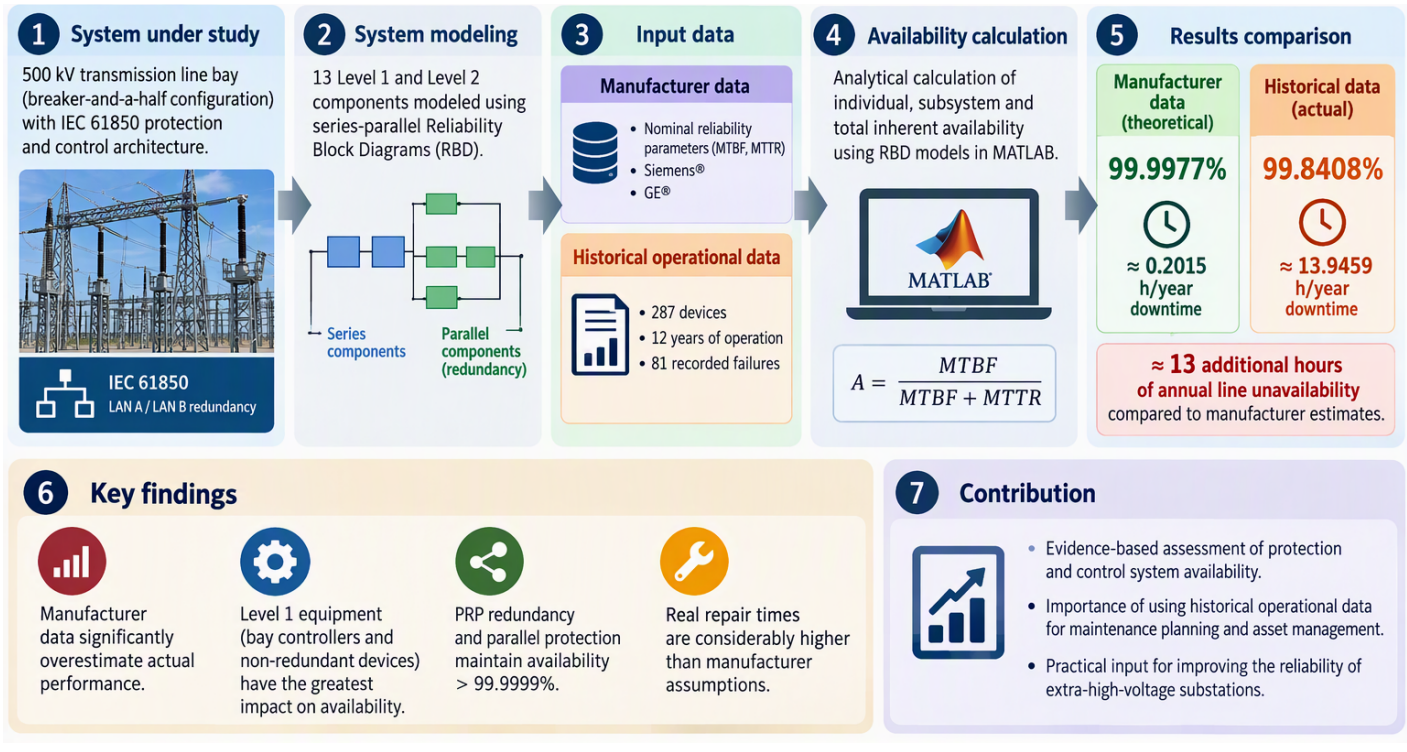
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Why was the study conducted?
This study evaluated the inherent availability of IEC 61850-based protection and control systems in a 500 kV transmission line bay. It compared availability estimates obtained from manufacturer reliability data with those calculated using historical operational and maintenance records.

What were the key findings?
Availability was 99.9977% when calculated using manufacturer data and 99.8408% when historical data were used. This difference represents approximately 13 additional hours of annual downtime. Level 1 devices showed the greatest impact on overall system availability.

What do these findings contribute?
The findings show that manufacturer reliability data may overestimate actual system availability. They highlight the importance of incorporating historical failure and repair records into availability assessments, maintenance planning, and asset management processes.

Graphical Abstract



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Introduction

Extra-high-voltage (EHV) substations constitute critical nodes for long-distance electric power transmission and for maintaining the operational security of the National Transmission System (NTS) (1). In particular, 500 kV substations configured in a breaker-and-a-half arrangement play a crucial role when associated with long transmission lines, as this topology provides operational flexibility, service continuity, and the capability to maintain operation during contingencies and maintenance activities (2). In this context, the performance of protection and control systems is essential, since the timely detection of faults, selective protection operation, and secure supervision of the transmission line bay depend directly on these systems (3).

In modern substations, protection, control, and monitoring functions are primarily implemented through Intelligent Electronic Devices (IEDs) interconnected via digital communication networks based on the IEC 61850 standard (4). This standard establishes a common framework for automation function modeling, data naming conventions, system configuration, and information exchange among devices from different manufacturers, thereby promoting interoperability and functional integration across the process, bay, and station levels (5). Furthermore, IEC 61850 incorporates communication services with different time-critical requirements, including MMS (Manufacturing Message Specification) for supervisory and client-server communications, GOOSE (Generic Object-Oriented Substation Event) for event-driven high-speed messaging, and Sampled Values for the digital transmission of analog process signals (6). As a result, substation automation systems have evolved from heavily hardwired architectures toward more flexible, configurable, and scalable distributed solutions (7).

However, the increasing dependence on communication infrastructures has also introduced new challenges for reliability and availability assessment (8). In this regard, one of the most widely adopted mechanisms for enhancing service continuity is the Parallel Redundancy Protocol (PRP), defined in IEC 62439-3 and extensively implemented in IEC 61850-based substations (9), as illustrated in Figure 1. PRP employs two independent active Ethernet networks, allowing each device to simultaneously transmit identical copies of every frame over both Local Area Networks (LANs). The receiving node processes the first frame received and discards the duplicate, thereby eliminating switchover times in the event of a communication path failure (10). From an availability perspective, this architecture reduces vulnerability to single network failures and enhances the continuity of critical functions supported by IEDs, although it does not completely eliminate common-cause failures or unavailability associated with the terminal equipment itself (11). In this study, inherent availability is defined as the probability that a system remains operational considering only its failure and repair rates, typically represented by the Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR) (12).

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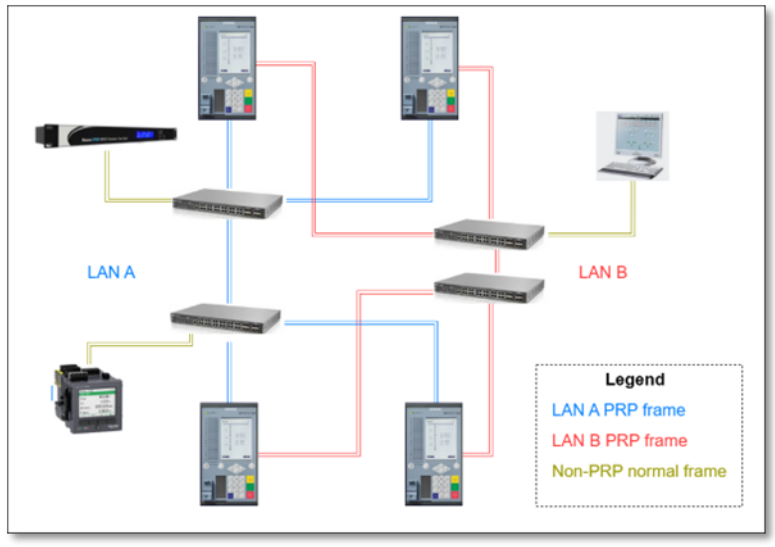


Figure 1. General IEC 61850-based substation automation architecture with PRP redundancy through LAN A and LAN B networks. Source: (10).

From a functional perspective, substation automation is organized into hierarchical levels that structure the interaction among primary equipment, bay-level IEDs, and supervisory systems, as illustrated in Figure 2. Level 0 corresponds to primary yard equipment; Level 1 comprises IEDs responsible for bay-level protection and control functions; Level 2 integrates substation communication and supervisory systems; and Level 3 corresponds to the control center (13), (14). For the evaluation presented in this paper, the analysis focuses on Levels 1 and 2, since these layers contain the devices and communication links that directly support the functionality of the transmission line bay under study.

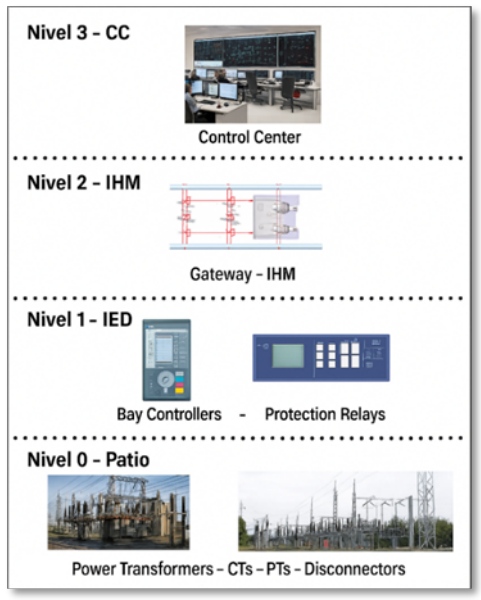


Figure 2. Control and supervision levels in a substation.

Source: Authors' own elaboration.

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Despite the importance of these systems, quantitative availability assessments for 500 kV substations remain limited, particularly when real-world configurations involving multi-vendor IEDs and redundant communication architectures are considered (15). Most studies reported in the literature rely on generic models, idealized assumptions, or manufacturer-provided nominal parameters, which restricts understanding of the actual behavior of protection and control systems in service (16). In particular, a review of the studies reported in (1)-(17) indicates that most investigations focus on IEC 61850 architectures, communication network analyses, and theoretical reliability models, while only a limited number employ real historical failure and repair data to directly compare operational availability with availability estimated from nominal manufacturer parameters. Consequently, a significant knowledge gap persists regarding the actual in-service behavior of these systems.

To address this gap, this paper evaluates the inherent availability of the protection and control systems of a 500 kV transmission line bay configured in a breaker-and-a-half arrangement and associated with a transmission line exceeding 200 km in length through a component-based assessment approach. A series-parallel model based on Reliability Block Diagrams (RBDs) is developed to represent Level 1 and Level 2 components, including protection IEDs, bay controllers, and communication switches interconnected through LAN A/LAN B redundancy in accordance with IEC 61850. The analyzed architecture incorporates equipment manufactured by internationally recognized suppliers widely deployed in substation protection and control applications, namely Siemens® and GE®, thus providing technical representativeness to the case study and supporting the comparison between manufacturer-provided nominal data and historical operational data. Based on this framework, results obtained using manufacturer reliability parameters are compared with those derived from historical failure and repair records from an operating system in Colombia, South America. The objective is to identify discrepancies in estimated availability and provide technical insights for maintenance planning and asset management in extra-high-voltage substations.

The primary contribution of this research is the development and application of an inherent availability model based on Reliability Block Diagrams (RBDs) for the protection and control systems of a 500 kV transmission line bay operating under an IEC 61850 architecture, using both manufacturer-specified nominal parameters and actual historical operational data. Unlike most studies reported in the literature, which rely on theoretical information or generic configurations, this work incorporates historical failure and repair records obtained from a fleet of equipment in service, enabling the quantification of the gap between expected and observed availability. In addition, the study identifies the influence of actual repair times and component functional configurations on overall system availability, providing practical guidance for asset management and maintenance planning in extra-high-voltage substations.

The remainder of this paper is organized as follows. Section 2 describes the analyzed system, with emphasis on the 500 kV substation configuration, the breaker-and-a-half transmission line bay arrangement, and the IEC 61850-based protection and control architecture. Section 3 presents the methodological approach adopted for evaluating inherent availability, including series-parallel

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modeling through Reliability Block Diagrams and the definition of the failure and repair parameters considered. Section 4 introduces the case study and presents the results of the comparative assessment between manufacturer-provided nominal data and historical operational data. Section 5 discusses the findings and identifies the elements with the greatest impact on system availability, as well as their technical implications for maintenance and reliability. Finally, Section 6 summarizes the main conclusions of the study and outlines recommendations for future research.

System Description

General Configuration of the Substation and Transmission Line Bay

The substation selected for the availability assessment operates at a voltage level of 500 kV and adopts a breaker-and-a-half configuration, a topology widely used in highly critical substations due to its ability to maintain service continuity and facilitate maintenance activities without requiring the complete outage of the scheme. The transmission line bay under study is located between Sections 0 and 1 of the substation. In this arrangement, each circuit is functionally associated with two circuit breakers and shares a central breaker with the adjacent bay, thereby increasing operational flexibility while also adding complexity to the protection, control, and supervisory systems (18).

The transmission line associated with the evaluated bay exceeds 200 km in length, requiring the installation of shunt reactors at both terminals to absorb the line's capacitive reactive power, control the voltage profile, and mitigate temporary overvoltages typically encountered in long extra-high-voltage transmission corridors (19). The overall arrangement of the main equipment and the location of the bay within the 500 kV switchyard are illustrated in Figure 3. From an operational perspective, the combination of a high-voltage level, long transmission distance, and reactive power compensation requirements constitutes a highly demanding case study in which the unavailability of secondary systems may significantly affect the security and operability of the transmission corridor (20)

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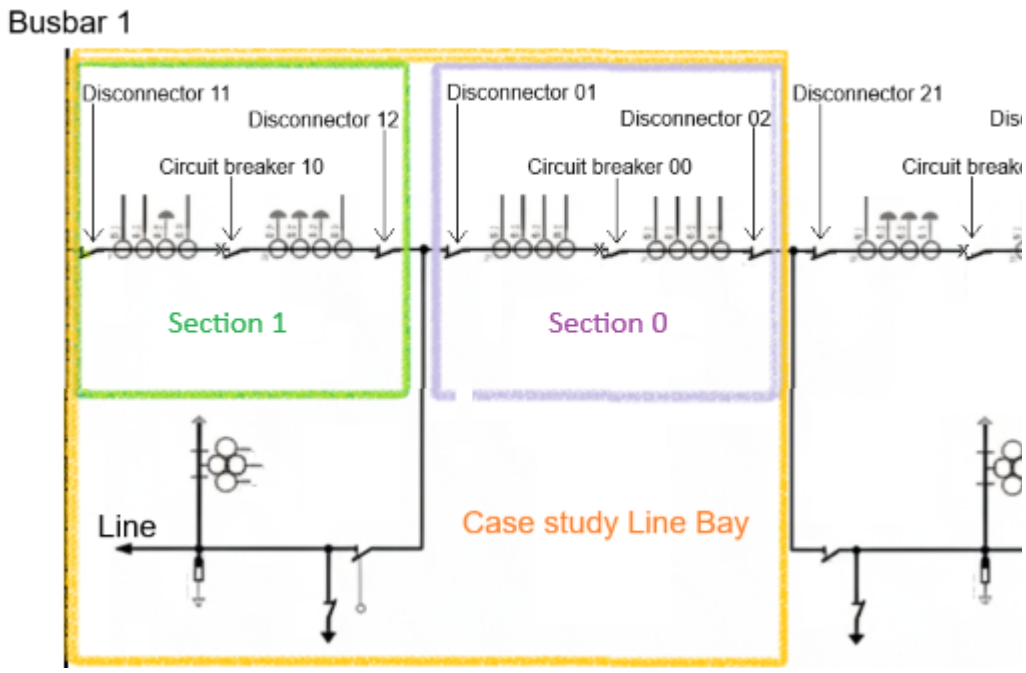


Figure 3. Single-line diagram of the 500 kV transmission line bay in a breaker-and-a-half configuration. Source: Authors' own elaboration.

Protection and Control Architecture of the Bay

The protection and control architecture associated with the transmission line bay comprises equipment belonging to Automation Levels 1 and 2, which are the focus of this investigation. As illustrated in Figure 4, Level 1 encompasses the Intelligent Electronic Devices (IEDs) responsible for bay-level protection and control functions (21).

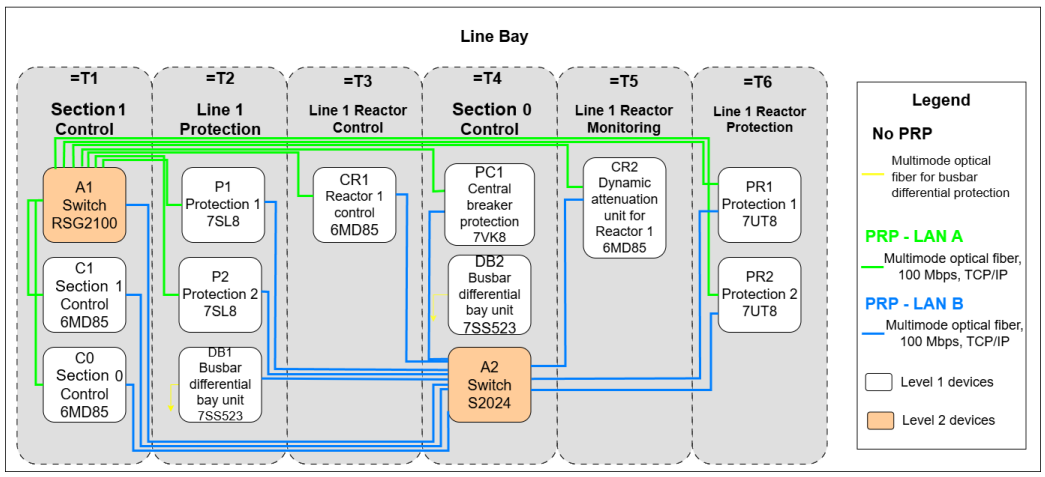


Figure 4. Protection and control architecture of the transmission line bay with IEC 61850 communications and LAN A/LAN B redundancy.

Source: Authors' own elaboration.

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Level 2, in turn, includes the communication and supervisory infrastructure that supports information exchange among these IEDs and higher-level automation systems (22). The architecture is based on the IEC 61850 standard and employs LAN A/LAN B network redundancy, consistent with the communication framework described in the Introduction.

The analyzed bay incorporates equipment manufactured by internationally recognized suppliers with extensive experience in substation protection and control applications, particularly Siemens® and GE®, thereby providing technical representativeness to the case study. However, the objective of this work is not to compare manufacturers, but rather to evaluate the difference between availability estimated using nominal manufacturer reliability parameters and availability derived from historical operational data.

Scope of the Modeled System

For the inherent availability assessment, thirteen components belonging to Levels 1 and 2 were considered due to their direct contribution to the functionality of the transmission line bay. These components include protection relays, bay controllers, and network switching devices. Their general characteristics are summarized in Table 1. The selected components represent those whose failure or unavailability may compromise the local protection, control, and supervisory functions of the bay.

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Table 1. Components Included in the Inherent Availability Model (Levels 1 and 2)

Item	Component	Tag	Model Reference	Level	Main Function	Manufacturer
1	Network Switch 1 (LAN A)	A1	RSG2100	1	LAN A communication management	Siemens®
2	Network Switch 2 (LAN B)	A2	S2024	1	LAN B communication management	GE®
3	Section 1 Bay Controller	C1	6MD85	1	Bay control and supervision, Section 1	Siemens®
4	Section 0 Bay Controller	C0	6MD85	1	Bay control and supervision, Section 0	Siemens®
5	Line Protection 1	P1	7SL8	1	Main Protection 1 for Line 1	Siemens®
6	Line Protection 2	P2	7SL8	2	Main Protection 2 for Line 1	Siemens®
7	Busbar Differential Unit	DB1	7SS523	2	Busbar Differential Protection 1	Siemens®
8	Reactor Controller 1	CR1	6MD85	2	Reactor 1 control and supervision	Siemens®
9	Central Breaker Protection	PC1	7VK8	1	Central breaker protection	Siemens®
10	Busbar Differential Unit	DB2	7SS523	1	Busbar Differential Protection 2	Siemens®
11	Reactor Automation Unit	CR2	6MD85	2	Reactor 2 control and supervision	Siemens®
12	Reactor Protection 1	PR1	7UT8	2	Differential Protection 1 for Reactor 1	Siemens®
13	Reactor Protection 2	PR2	7UT8	2	Differential Protection 2 for Reactor 1	Siemens®

Source: Authors' own elaboration.

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This system boundary was established because the study focuses on the inherent availability of the local secondary architecture of the bay, consisting of the IEDs and communication infrastructure that directly support its operation. Accordingly, the proposed methodology represents the Level 1 and Level 2 components using a series-parallel structure based on the functional dependencies among devices and the communication redundancy architecture illustrated in Figure 4.

Availability Modeling and Methodology

To evaluate the inherent availability of the protection and control system, an analytical approach based on Reliability Block Diagrams (RBDs) was adopted (23). This methodology enables the logical representation of the IEC 61850 system architecture through series and parallel configurations, thereby capturing the functional dependencies among the 13 components identified at Levels 1 and 2 (24).

Mathematical Formulation of Inherent Availability

Inherent availability (A) is defined as the proportion of time during which a component or system remains operational, considering only operating and repair times and excluding logistical or administrative delays. For each component, availability is calculated using Equation (1)(25):

$$A = \frac{MTBF}{MTBF + MTTR} \quad (1)$$

Where:

- A is the inherent availability of the equipment.
- MTTR is the Mean Time to Repair.
- MTBF is the Mean Time Between Failures.

Complementary to this metric, inherent unavailability (U) represents the probability or fraction of time during which a component or system is in a failed or out-of-service state. Mathematically, unavailability is defined as the exact complement of availability, as expressed in Equation (2) (26):

$$U = 1 - A = \frac{MTTR}{MTBF + MTTR} \quad (2)$$

Where:

- U is the inherent unavailability of the equipment.
- A is the inherent availability of the equipment.
- MTTR is the Mean Time to Repair.
- MTBF is the Mean Time Between Failures.

Based on individual component availability, the RBD model determines the equivalent availability of the overall system. For subsystems operating under redundant configurations, such as the LAN A and LAN B networks implemented through the PRP protocol, the availability of the parallel arrangement (Ap) is calculated using Equation (3) (27):

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$$A_P = 1 - \prod_{i=1}^{n}(1 - A_i) = 1 - \prod_{i=1}^{n}(U_i) \quad (3)$$

Where:

- Ai is the inherent availability of component i.
- (1 − Ai) represents the probability of failure of component i.
- Ap is the probability that at least one component remains operational.

Conversely, for critical components whose individual failure interrupts the protection or control function of the bay, a series configuration is employed. The equivalent availability of this arrangement (As) is given by Equation (4) (28):

$$A_s = A_1 * A_2 * \ldots * A_n \quad (4)$$

Where:

- Ai is the inherent availability of component i.
- As is the overall system availability.

Series-Parallel Model Structure

The evaluated system consists of thirteen major components distributed across Levels 1 and 2. The logical architecture and operational dependencies of these devices are represented through a Reliability Block Diagram (RBD), as illustrated in Figure 5. Within this logical framework, Level 1 components whose individual failure directly compromises the protection or control functionality of the bay are modeled using a series configuration

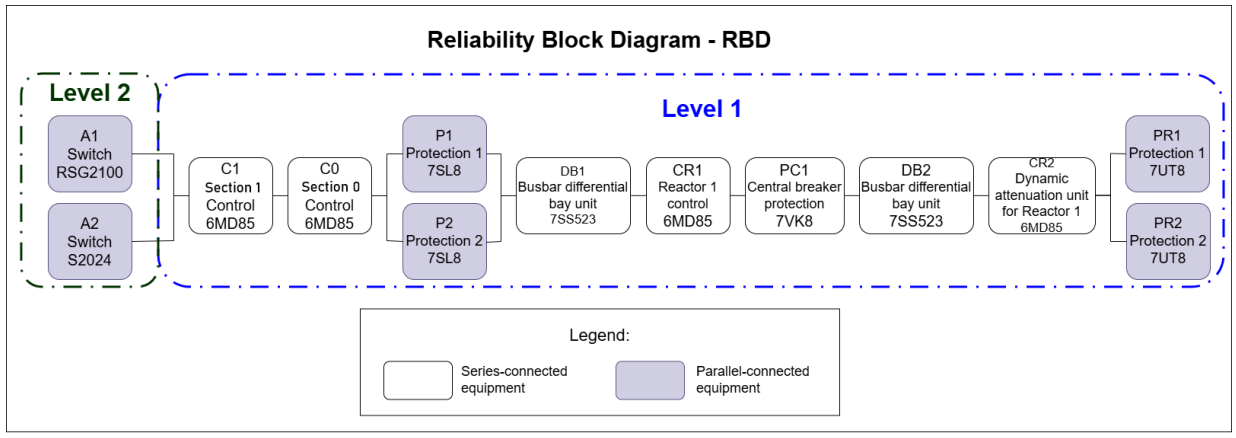


Figure 5. Reliability Block Diagram (RBD) of the Level 1 and Level 2 componen

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These components include Section 1 and Section 0 bay controllers, the Busbar Differential Unit 1, Reactor Controller 1, Central Breaker Protection, Busbar Differential Unit 2, and Reactor Controller 2.

The series arrangement in the RBD model indicates that the simultaneous operation of these devices is strictly required to ensure the execution of critical process-level functions. In addition, active redundancy is provided by the line protection devices P1 and P2 and the reactor protection devices PR1 and PR2, which are modeled as parallel arrangements, as summarized in Table 2. Likewise, the communication infrastructure associated with Level 2 is represented by parallel configurations, reflecting the active redundancy provided by the PRP protocol through the switches connected to the independent LAN A and LAN B networks.

Table 2. Explicit Definition of the RBD Model

Group	Components	Configuration
PRP Network	A1, A2	Parallel
Line Protection	P1, P2	Parallel
Reactor Protection	PR1, PR2	Parallel
Bay Controller	C1	Series
Bay Controller	C0	Series
Busbar Differential Protection	DB1	Series
Reactor Control	CR1	Series
Central Breaker Protection	PC1	Series
Busbar Differential Protection	DB2	Series
Reactor Control	CR2	Series

Source: Authors' own elaboration.

Evaluation Scenarios and Data Sources

To quantify the gap between theoretical design expectations and actual field performance, the RBD model was simulated under two contrasting statistical scenarios.

Theoretical Scenario: Manufacturer Nominal Data

This scenario represents the availability expected during the design stage. Manufacturers of Intelligent Electronic Devices (IEDs), such as Siemens® and GE®, determine the Mean Time to Failure (MTTF) using reliability prediction techniques based on electronic component counts, following standards such as MIL-HDBK-217F, Telcordia SR-332, and IEC TR 62380, as well as Accelerated Life Testing (ALT) procedures (29)–(31). This approach assumes ideal operating conditions and relies on an exponential statistical model that considers a constant failure rate

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(λ) throughout the equipment life cycle, thereby neglecting wear-out mechanisms and early-life manufacturing defects. In this scenario, MTTR values assume ideal logistical conditions and immediate component replacement (32).

Actual Scenario: Historical Operational Data

This scenario represents the empirical behavior of the system based on the analysis of an operational database obtained from a Colombian transmission utility, whose identity is omitted due to confidentiality agreements. The dataset corresponds to approximately 287 devices operating continuously over a twelve-year period (2014-2026), during which 81 confirmed failures were recorded, corresponding to a statistical incidence of approximately 28.2229% of the installed fleet. As an initial reference, a fleet-wide exponential model was employed. This model assumes a constant failure rate over time and provides an aggregate measure of equipment behavior (33). Under this assumption, the estimated MTTF was approximately 32.2608 years. As part of the data-cleaning process, no valid failure events were removed as outliers, since the objective of the study was to characterize the actual operational behavior of the equipment. Only incomplete, inconsistent, or insufficiently documented records were excluded when the time to failure or corresponding failure mode could not be determined.

However, because the historical data demonstrated that failures did not follow a constant-rate pattern, the individual times-to-failure were subsequently fitted using a two-parameter Weibull distribution, a model widely applied in reliability engineering due to its flexibility in representing different stages of equipment life through the shape parameter β (34). The resulting fit yielded a shape parameter of $\beta = 0.7608$, indicating an early-failure or infant-mortality behavior, and a characteristic life of $\eta = 5.5984$ years. Based on these parameters, the estimated MTTF was approximately 6.5884 years. The comparison between the two models is particularly relevant in this context, as the fleet-level exponential model provides a useful average measure for general benchmarking purposes, whereas the Weibull model offers a more realistic representation of the failure observed in service, thereby reducing the risk of overestimating inherent availability.

The Weibull fitting procedure was implemented in MATLAB using all non-zero failure times available in the historical database. The shape parameter (β) and scale parameter (η) were estimated using built-in statistical fitting tools. The choice of the Weibull distribution was motivated by its ability to represent increasing, constant, or decreasing failure-rate behaviors, which cannot be adequately captured through a conventional exponential model.

Analysis of the historical records revealed that hardware-related failures accounted for 80.2% of all observed events. Additional failures were associated with communication loss and software/firmware-related issues. These findings suggest that both hardware degradation mechanisms and certain software-related events contribute to the discrepancy between nominal manufacturer parameters and actual field performance. However, quantifying the individual contribution of each failure mechanism is beyond the scope of the present study. Historical records also enabled the estimation of actual MTTR values, demonstrating that each corrective intervention required approximately 15 person-hours of effort from protection and control specialists. This operational burden has a significant impact on Operating Expenditure (OPEX) and is not reflected

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in manufacturer catalog metrics. The reported historical MTTR was calculated from corrective maintenance records associated with the documented failures in the database. For each event, the elapsed time between fault identification and restoration of the equipment to operational condition was considered. The reported value corresponds to the average intervention time observed across all analyzed events.

Computational Implementation

The processing of reliability parameters and the mathematical solution of the RBD model were automated through an algorithm developed in the MATLAB environment. The computational framework was designed to evaluate the system topology in a hierarchical and scalable manner, enabling the analysis of both manufacturer-provided nominal data and historical failure records. The algorithm operates through a sequence of processing stages, the most relevant of which includes the estimation of individual component availability based on failure and repair rates, the identification and reduction of redundant subsystems associated with parallel configurations, and the aggregation of equivalent nodes with critical system components. To ensure the reproducibility of the proposed methodology, a representative portion of the simulation logic is presented in the form of pseudocode below.

Input: Component dataset containing the following fields: (ID, NAME, MTBF, MTTR, LEVEL, CONNECTION_TYPE, PARALLEL_WITH).
Output: Individual availability of each component, availability of parallel subsystem groups, availability by system level, and overall system availability.

Step 1. Import the CSV file containing the component reliability parameters, validate the availability of the required input fields (ID, NAME, MTBF, MTTR, LEVEL, CONNECTION_TYPE, and PARALLEL_WITH), and identify the total number of components to be analyzed.

```
(file, url) = uigetfile('*.csv', 'File components CSV');
If isequal(file, 0)
   Error('Error.');
End
```

Step 2. Calculate the individual availability of each component i:

```
A_i = MTBF_i / (MTBF_i + MTTR_i)
A_ind = zeros(n_comp, 1);
MTTF  = zeros(n_comp, 1);
For i = 1:n_comp
   Mtbf_i = T.MTBF(i);
   Mttr_i = T.MTTR(i);
   MTTF(i) = mtbf_i - mttr_i;
   If MTTF(i) <= 0
      Warning('MTTF <= 0 para %s. Se usa MTTF = MTBF.', T.NOMBRE{i});
      MTTF(i) = mtbf_i;
   End
```

Step 3. Identify parallel groups by separating the components according to their respective system levels. For each component within a given level, verify whether CONNECTION_TYPE = Parallel. If

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so, locate the associated component specified in the PARALLEL_WITH field and group all mutually related components into a single redundant subsystem.

The equivalent availability of each parallel group is then calculated as:

A_par = 1 - ∏(1 - A_i)

```
Function grupos = identify_parallel_groups (T, idx_nivel, A_ind)
N = length(idx_nivel);
   Asignado = false(n, 1);
   Grupos = {};
   For i = 1:n
      If asignado(i)
         Continue;
      End
      Fi     = idx_nivel(i);
      Id_fi  = T.COMPONENTE{fi};
      Tipo_i = T.TIPO_CONEXION(fi);
      If tipo_i == 2
         Grupo_local = i;   % indices DENTRO de idx_nivel
```

Store each identified parallel group as an equivalent block.

Step 4. Calculate Availability by System Level. For each system level, consider all equivalent blocks resulting from the previous stage, including both the reduced parallel groups and the individual components connected in series. The availability of each level is then computed as the product of the availabilities of all constituent blocks:

A_nivel = ∏ A_j

```
A_nivel1 = 1.0;
A_nivel2 = 1.0;
For nivel = 1:2
   Idx_nivel = find(T.NIVEL == nivel);
   For k = 1:length(A_serie_list)
      Fprintf('  %-45s | %18.10f\n', nombres_serie{k}, A_serie_list(k)*100);
   End
   Fprintf('  %s\n', repmat('-',1,68));
   If isempty(A_serie_list)
      A_nivel = 1.0;
   Else
      A_nivel = prod(A_serie_list);
   End
```

Step 5. Determine the overall availability of the protection and control system by considering that Level 1 and Level 2 are connected in series within the RBD structure

A_total = A_nivel1 × A_nivel2

```
A_sistema       = A_nivel1 * A_nivel2;
Fprintf('##   TOTAL SYSTEM AVAILABILITY \n');
Fprintf('##   A_TOTAL = A_Nivel1 x A_Nivel2\n');
```

Step 6. Calculate the Total System Unavailability

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U_total = 1 - A_total

Calculate the annual downtime in hours and minutes:

Annual_Downtime_Hours = U_total × 8760

Unavailable_Minutes = Horas_no_disponibles × 60

Step 7. Report Results

Print a table containing the calculated availability values.

Figure 6 illustrates the overall methodological workflow implemented for the evaluation of inherent availability. The procedure begins with the collection and preprocessing of the historical failure database, followed by the estimation of reliability parameters, the development of the Reliability Block Diagram (RBD) model, and the calculation of both individual and equivalent availabilities. The methodology concludes with a comparative assessment of the results obtained from historical operational data and those derived from manufacturer-provided nominal reliability parameters.

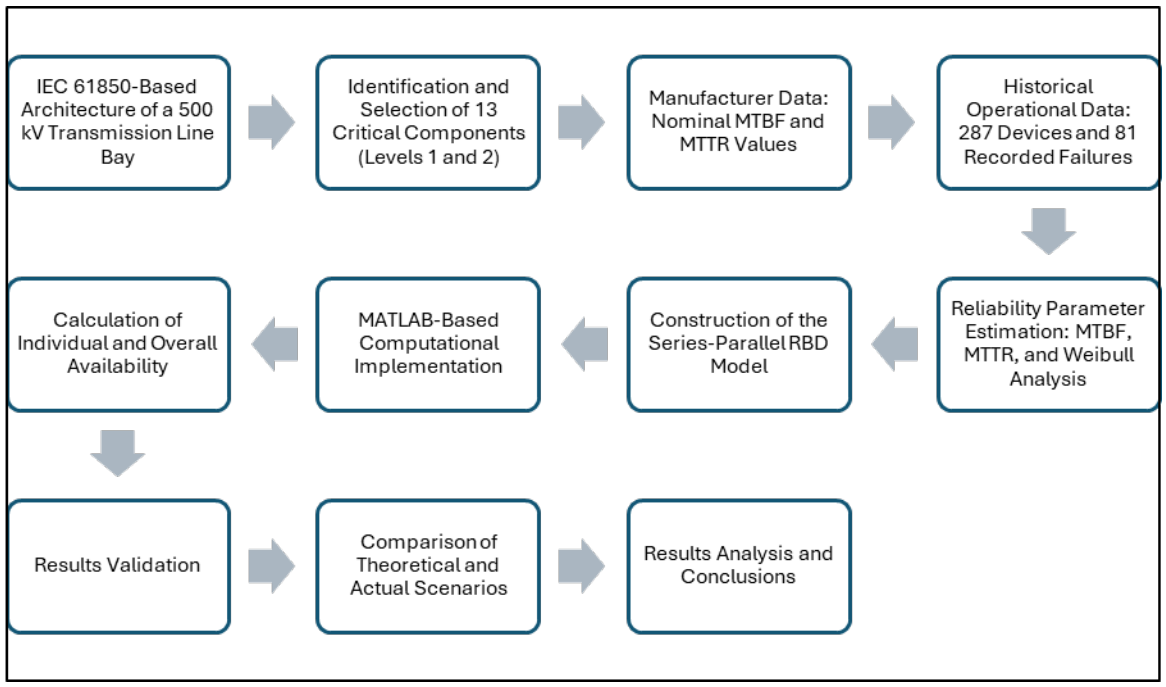


Figure 6. Methodological workflow employed for the evaluation of system inherent availability.

Source: Authors' own elaboration.

The results obtained using MATLAB were cross validated against independent calculations performed in Microsoft Excel®. The verification process included the computation of individual component availabilities, the aggregation of parallel subsystems, and the determination of the equivalent system availability through series configurations. The results exhibited discrepancies below the numerical rounding error threshold, thereby confirming the correct implementation of the availability equations and computational procedures employed in this study.

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Results and Discussion

To evaluate the performance of the protection and control system architecture, the inherent availability of both the individual components and the overall system was determined under two distinct scenarios: (i) a theoretical scenario based on manufacturer catalog data and (ii) an actual operational scenario derived from the utility's historical failure records. The calculations were performed by implementing the Reliability Block Diagram (RBD) mathematical model in MATLAB. To ensure consistency in the presentation of results throughout the paper and considering that the observed variations may occur in the order of thousandths, all numerical values are reported with four decimal places.

Evaluation of the Theoretical Scenario

The MTBF values used for the protection and control relays were obtained from technical documentation provided by GE® and Siemens® (29)–(31). These references correspond to manufacturer technical reports and product documentation and were therefore considered primary sources of catalog reliability data. In this study, such information was used exclusively for the parameterization of the availability model and for the representation of the theoretical operating scenario based on nominal manufacturer specifications.

In the theoretical scenario, the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) values represent ideal operating conditions as defined by the equipment manufacturers. Table 3 summarizes the reliability parameters and the calculated individual availability of the 13 critical components included in the analysis. Under these assumptions, the parallel redundancy implemented within architecture increases the availability of the corresponding subsystems to values exceeding 99.9999%. The equivalent availability of Level 1 was calculated as 99.9977%, while Level 2 achieved an availability of 99.9999%. Consequently, the overall theoretical availability of the protection and control system was determined to be 99.9977%, corresponding to an annual unavailability of only 0.2015 hours per year, or approximately 12.0900 minutes of downtime per year.

Table 3. Individual Availability (Theoretical Scenario)

ID	NAME	MTBF (h)	MTTR (h)	MTTF (h)	LEVEL	TYPE	AVAILAB. (%)
1	A1_RSG2100	397506	1,5000	397504,5000	2	Paralelo	99,9996
2	A2_S2024	388068	1,5000	388066,5000	2	Paralelo	99,9996
3	C1_6MD85	407905	1,5000	407903,5000	1	Serie	99,9996
4	C0_6MD85	407905	1,5000	407903,5000	1	Serie	99,9996
5	P1_7SL8	407905	1,5000	407903,5000	1	Paralelo	99,9996
6	P2_7SL8	407905	1,5000	407903,5000	1	Paralelo	99,9996
7	DB1_7SS523	438000	1,5000	437998,5000	1	Serie	99,9996
8	CR1_6MD85	613200	1,5000	613198,5000	1	Serie	99,9997
9	PC1_7VK8	407905	1,5000	407903,5000	1	Serie	99,9996
10	DB2_7SS523	438000	1,5000	437998,5000	1	Serie	99,9996
11	CR2_6MD85	613200	1,5000	613198,5000	1	Serie	99,9997
12	PR1_7UT8	407905	1,5000	407903,5000	1	Paralelo	99,9996
13	PR2_7UT8	407905	1,5000	407903,5000	1	Paralelo	99,9996

Source: Authors' own elaboration.

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Evaluation of the Actual Operational Scenario

The analysis of the actual operational scenario incorporates the empirical behavior of equipment operating under real environmental, electrical, and maintenance conditions within the Colombian transmission system context. In this scenario, the MTTR increases significantly, from 1.5 h to 15 h, primarily due to maintenance logistics, travel times, and the diagnostic and restoration activities required in 500 kV substations. Furthermore, the MTBF values exhibit substantial reductions for the Level 1 IEDs. The resulting reliability parameters and individual component availabilities are presented in Table 4. When the mathematical model is applied to these empirical data, the equivalent availability of Level 1 decreases to 99.8408%, whereas Level 2 maintains a robust availability of 99.9999% owing to the effective redundant configuration of the communication equipment. Consequently, the overall inherent availability of the system under actual operating conditions is calculated as 99.8408%.

Table 4. Individual Availability (Actual Operational Scenario)

ID	NAME	MTBF (h)	MTTR (h)	MTTF (h)	LEVEL	TYPE	AVAILAB. (%)
1	A1_RSG2100	57754	15	57739	2	Paralelo	99,9740
2	A2_S2024	388068	15	388053	2	Paralelo	99,9961
3	C1_6MD85	57754	15	57739	1	Serie	99,9740
4	C0_6MD85	57754	15	57739	1	Serie	99,9740
5	P1_7SL8	57754	15	57739	1	Paralelo	99,9740
6	P2_7SL8	57754	15	57739	1	Paralelo	99,9740
7	DB1_7SS523	57754	15	57739	1	Serie	99,9740
8	CR1_6MD85	57754	15	57739	1	Serie	99,9740
9	PC1_7VK8	57754	15	57739	1	Serie	99,9740
10	DB2_7SS523	438000	15	437985	1	Serie	99,9965
11	CR2_6MD85	57754	15	57739	1	Serie	99,9740
12	PR1_7UT8	57754	15	57739	1	Paralelo	99,9740
13	PR2_7UT8	57754	15	57739	1	Paralelo	99,9740

Source: Authors' own elaboration.

Discussion and Comparative Analysis

The comparison between the two scenarios reveals a critical discrepancy with direct implications for asset management. As presented in Table 5, the comparative availability and unavailability results highlight a substantial difference between the theoretical scenario and the actual operational scenario. While the theoretical model predicts a nearly negligible annual downtime of 0.2015 h/year, the historical operational data indicate an annual unavailability of 13.9459 h/year. This difference, exceeding 13 hours of additional downtime per year, can be primarily attributed to two factors. First, the degradation of MTBF at Level 1: Protection and control devices operating under field conditions exhibit empirical failure rates significantly higher than those reported in manufacturer specifications. This discrepancy may be associated with adverse environmental conditions, electromagnetic transients inherent to 500 kV transmission systems, and accelerated

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aging mechanisms that are not fully represented in nominal reliability estimates. Second, the logistical impact on MTTR: Manufacturer data assumes ideal repair conditions, corresponding to a repair time of approximately 1.5 h. However, these estimates do not account for fault detection activities, the deployment of maintenance crews to remote substations, spare-part availability, diagnostic procedures, and switching or isolation protocols required for safe intervention. Under actual operating conditions, these factors increase the average repair time to approximately 15 h.

Table 5. Comparison of Inherent Availability Results Under Theoretical and Actual Operational Scenarios

Availability Metric	Theoretical Scenario	Actual Operational Scenario
Level 1	99.9977%	99.8408%
Level 2	99.9999%	99.9999%
Transmission Line Bay	99.9977%	99.8408%

Source: Authors' own elaboration.

Despite the reduction in the individual reliability of the equipment, the analysis demonstrates the effectiveness of PRP redundancy (IEC 62439-3) and the parallel configuration of the primary protection schemes (P1/P2 and PR1/PR2). Even with an MTTR of 15 h, these parallel subsystems maintain availability levels exceeding 99.9999%, thereby preventing a complete loss of the protection function. However, components configured in series, particularly the bay controllers C1_6MD85 and C0_6MD85, emerge as the primary reliability bottlenecks. As a result, they constitute the main contributors to the reduction in overall system availability to 99.8408%.

These findings highlight the need for transmission system operators to avoid relying exclusively on manufacturer catalog data when developing maintenance strategies and reliability assessments. Instead, maintenance planning should be supported by historical operational data that more accurately reflects actual equipment performance under field conditions. In particular, the implementation of predictive maintenance strategies and the optimization of spare-parts inventories for critical Level 1 series-connected components are recommended, as these devices exert the greatest influence on overall system availability. Such measures would contribute to reducing repair times, mitigating the impact of failures, and narrowing the gap between the theoretical performance expected during the design phase and the availability effectively achieved in service.

Conclusions

Overestimation of Theoretical Availability: A critical discrepancy was identified between the availability projected using manufacturer catalog data (99.9977%) and the actual availability observed under field operating conditions (99.8408%). This difference, which translates into an increase in annual downtime from approximately 0.2015 h/year to 13.9459 h/year, demonstrates that models based solely on nominal reliability parameters substantially underestimate both the

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operational effort required to maintain system functionality and the actual risk of unavailability within the National Transmission System (NTS).

Impact of Logistics on MTTR: The primary factor contributing to the reduction in actual availability is the variability of the Mean Time to Repair (MTTR). While manufacturers assume standardized repair times of approximately 1.5 h, the operational reality of extra-high-voltage substations in Colombia, South America, results in an average MTTR of 15 h. This increase is primarily attributable to maintenance crew mobilization to remote sites, on-site fault diagnosis, spare-parts availability, and equipment isolation and clearance procedures required prior to maintenance activities. Consequently, repair logistics emerge as a critical determinant of overall system availability and must be explicitly considered in reliability assessments and maintenance planning processes.

Effectiveness of Redundant Architectures (IEC 61850 and PRP): Despite the overall degradation of reliability parameters under actual operating conditions, the mathematical model confirmed the high effectiveness of parallel redundancy schemes, including the dual primary protection functions (Protection 1 and Protection 2) and the LAN A/LAN B communication networks operating under the PRP protocol. These redundant subsystems-maintained availability levels exceeding 99.9999% even under real-world conditions, thereby preventing the functional collapse of the protection and control system in the presence of single-point failures.

Series-Connected Components as Reliability Bottlenecks: The Reliability Block Diagram (RBD) analysis identified the series-connected devices, particularly the Level 1 bay controllers, as the weakest elements within the protection and control architecture. Owing to the absence of active redundancy, the failure of any of these devices directly compromises system functionality and immediately affects overall availability. Consequently, these components constitute the dominant contributors to system unavailability and are primarily responsible for the reduction in overall availability to 99.8408%.

Implications for Asset Management: The findings of this study provide a valuable quantitative framework for transmission system operators and asset managers. The results indicate that maintenance strategies should not rely exclusively on manufacturer-reported MTBF values but rather incorporate local historical failure and repair data to more accurately reflect actual operating conditions. Accordingly, the adoption of predictive maintenance strategies and the optimization of spare-parts supply chains for critical Level 1 series-connected components are strongly recommended. Such measures would help mitigate the impact of MTTR on system availability, improve service continuity, and support more effective asset lifecycle management in extra-high-voltage substations.

During the development of this research, one of the main challenges was the collection, validation, and preprocessing of actual failure and repair data, highlighting the critical importance of maintaining reliable historical records for availability assessments. The results obtained should not be interpreted as a limitation of Siemens® technology or the SIPROTEC 5 family of devices, since the discrepancies observed between theoretical and operational data varied among equipment references and were strongly influenced by specific operating, maintenance, and support conditions. Furthermore, at the beginning of the analysis period, several of these devices had been

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only recently introduced into the market, a factor that may have influenced both their in-service performance and the level of operational experience associated with their deployment. Finally, the case study demonstrates that, within the Colombian context, geographical conditions, the limited accessibility of certain substations, and organizational processes related to the procurement of spare parts or replacement equipment contribute significantly to extended repair times.

Recommendations

Implementation of Strategic Spare Parts Inventories: The results demonstrate that MTTR is the factor with the greatest impact on the actual availability of the system. Reducing the MTTR from 36 h, which represents the worst-case scenario in the absence of locally available spare parts, to 15 h, corresponding to a scenario with strategically distributed inventories at the national level, constitutes the improvement measure with the highest return in terms of operational availability. Therefore, it is recommended that the transmission system operator establish and maintain strategic inventories of critical spare parts at geographically distributed locations with nationwide coverage, prioritizing the series-connected components identified in the RBD analysis. Such an approach would significantly reduce restoration times following failures, improve service continuity, and mitigate the adverse impact of logistics-related delays on the availability of protection and control systems in extra-high-voltage substations.

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Statement of authorship contribution credits

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Conflict of Interest

Not applicable.

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