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RESEARCH ARTICLE

Reliability Assessment of Interconnected Substations Using the Reliability Block Diagram Approach

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Abstract

The reliability of substations plays a crucial role in maintaining the continuity and stability of power supply in transmission systems. This study evaluates the reliability level of two interconnected 150 kV substations using the Reliability Block Diagram (RBD) approach. The RBD model is applied to map the actual component configuration, from major component levels to the system level, based on operational age and component failure rate data. Simulation results show that System1 has a reliability value of 0.907735, while System2 reaches 0.979424. This discrepancy indicates a potential for reliability improvement through component rejuvenation strategies. A scenario simulating the replacement of critical equipment successfully increased the reliability of system1 to 0.980168 and raised the overall reliability of the interconnected system to 0.959989. These findings suggest that a prioritized maintenance or renewal of component strategy targeting critical component can significantly enhance the overall reliability of the transmission system.

Keywords: Reliability Block Diagram, Reliability, Substation, Critical Equipment, Transmission

1. INTRODUCTION

Substations play a vital role in ensuring the reliability and continuity of electricity supply in transmission systems; hence, failures in key components such as circuit breakers, disconnecting switches, current transformers, capacitive voltage transformers, and lightning arresters can have systemic impacts on grid stability. With the growing demand for continuous power supply and operational efficiency, reliability assessment of substations has become increasingly essential. IEEE Std 493-2007 emphasizes the importance of probabilistic approaches in designing industrial and commercial power systems, as well as the need for data-driven analysis of component performance [1]. IEEE Std 3006.2-2016 further provides guidance for evaluating existing systems based on logical configurations and maintenance data [2]. The Reliability Block Diagram (RBD) method is one of the most widely used approaches for modeling and evaluating system reliability due to its ability to represent inter-component relationships and compute system reliability quantitatively [3], [4]. Other journal article addresses reliability assessment using Reliability Block Diagram (RBD) based on failure data and operation time in automotive production processes and indicates that reliability enhancement can be achieved by shortening maintenance durations and incorporating additional redundancy into the system [5]. Applied studies have demonstrated the effectiveness of RBD in various contexts, including power generation systems [6] and isolated smart grids [7]. Moreover, CIGRE technical reports indicate increased failure rates in substation equipment after 25–35 years of operation, particularly in devices with specific design characteristics [8]. This research was conducted by modeling interconnected substation systems and performing reliability analysis using an RBD approach based on historical failure and operational time data, followed by the implementation of a reliability improvement approach through selective equipment replacement, prioritized according to the contribution of each equipment to overall system reliability.

2. Research Methods

This study employs a quantitative approach using Reliability Block Diagram (RBD) analysis to evaluate the reliability of a 150 kV substation system. The RBD method is chosen for its capability to assess both reliability and availability through time-dependent or constant failure and repair probabilities. This approach ensures consistency in modeling subsystems and analyzing the impact of redundancy and failure interactions, particularly in large-scale and interconnected electrical infrastructures such as substations [9]. The flowchart illustrating the methodology of this study is shown in Figure 1.

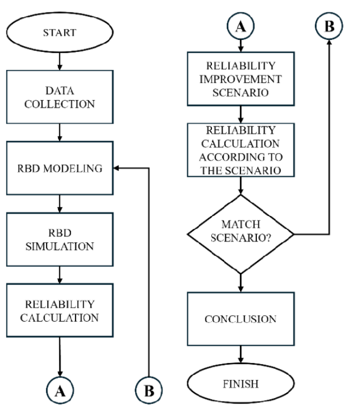

Figure 1. Research Flowchart

The primary subjects of this research are Substation System1 and Substation System2. To facilitate clarity and brevity in subsequent references throughout this paper, these substations will hereafter be denoted as System1 and System2, respectively. System1 dan System2 are operated under a double busbar scheme. Key equipment in each substation includes circuit breakers, disconnecting switches, current transformers, capacitive voltage transformers, and lightning arresters.

Primary data used in the study includes the single-line diagram configuration and equipment operational age since commissioning. Secondary data is sourced from CIGRE technical brochures reporting reliability survey results on substation equipment [8]. Failure rate estimation is based on secondary data, as the equipment in Substation System1 and System2 has experienced very few failures. The distribution type of the secondary data is assumed to follow an exponential distribution; therefore, the reliability of each component is determined using the equation (1).

$$R(t) = \hat{e}(-\lambda t) \tag{1}$$

In Equation (1), R(t) represents the reliability of substation equipment at operation time t. e is the base of the natural logarithm, λ denotes the failure rate of each substation component, and t is the operational time of the equipment in years. The operational time is calculated up to December 31, 2024.

The Reliability Block Diagram (RBD) can model both series and parallel configurations of equipment, as illustrated in Figures 2 and 3, where 'I' denotes the Input and 'O' the Output. In a series configuration, the failure of a single component results in the failure of the entire system. In contrast, in a parallel configuration, the system fails only when all components fail simultaneously. RBD's configuration of series-connected equipment is shown in Figure 2 and RBD's configuration of parallel-connected equipment is shown in Figure 3.

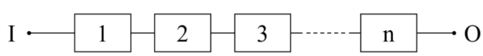

Figure 2. RBD of Series-Connected Equipment

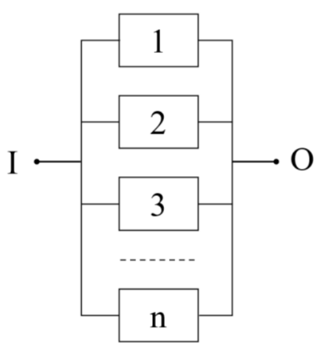

Figure 3. RBD of Parallel-Connected Equipment

The system reliability value (R_s) at time (t) for components connected in series can be calculated using the equation (2).

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \quad (2)$$

The system reliability value (RS) at time (t) for components connected in parallel can be calculated using the equation (3).

$$R_s(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \quad (3)$$

The simulation in this study was conducted using the Reliasoft BlockSim software application [10]. The simulation generates visualizations of the Reliability Block Diagram (RBD) along with system and subsystem reliability equations for the substation. Based on the visual and numerical results— ranging from system-level to individual equipment reliability—the next step is to determine equipment renewal priorities, guided by the sensitivity of each component's reliability to the overall system reliability.

3. Results and Discussion

The case study was conducted on two 150 kV substations (referred to in this study as Substation System1 and Substation System2) located within the operational area of the Semarang Transmission Service Unit. These substations are directly interconnected through the transmission network, both operating under a double bus configuration and equipped with a bay bus coupler. The substations were modeled using the Reliability Block Diagram (RBD) approach, based on actual equipment configurations derived from the single-line diagram. The analysis focused on modeling the equipment configuration and calculating system reliability using actual data and technical references. The RBD configuration in this study is structured across multiple levels: System level (System1, System2), Subsystem Level 1 (Lines A, B, C, D; Bus Coupler System1; Bus Coupler System2; Transformers System1; Transformers System2), Subsystem Level 2 (Line A1, A2, B1, B2, C1, C2, D1, D2; Transformer1 System1, Transformer2 System1, Transformer1 System2, Transformer2 System2), and equipment level. In this study, current transformers (CT) are not included in the calculation and RBD modeling because a failure of the CT does not lead to an operational failure of the substation system. The same applies to lightning arresters (LA). However, based on a survey conducted by CIGRE [8], there are data indicating that LA failures can cause operational failures in the system. Accordingly, LA will be included in the RBD model and its reliability will be evaluated.

3.1 Reliability of Main Substation Equipment

The reliability of each piece of equipment in the substation is calculated using equation (1). The reliability values of each equipment in System1 and System2 are provided in the Table 1–14, where each equipment name is written in the format "EquipmentName_BayName_SystemName" to simplify the identification and labeling of components within the RBD configuration. The abbreviations used in the equipment names are as follows: "LA" stands for Lightning Arrester, "CB" for Circuit Breaker, "DS" for Disconnecting Switch. The calculated reliability values of each equipment in System1 are shown in the Table 1-7. Table 1 shows reliability value of bay line A1, Table 2 shows reliability value of bay line A2, Table 3 shows reliability value of bay line B1, Table 4 shows reliability value of bay line A2, Table 5 shows reliability value of bay transformer 1 in System1, Table 6 shows reliability value of bay transformer 2 in System1, Table 7 shows reliability value of bay bus coupler in System1.

Table 1. Bay Line A1 Substation System1 (A1_SYS1)

Equipment Name	t	λ	R(t)
LA_A1_SYS1	15.798383	0.000450	0.992916
DSLINE_A1_SYS1	34.981938	0.000471	0.983659
CB_A1_SYS1	5.703071	0.005057	0.971571
DSBUS_A1_SYS1	3.141615	0.000471	0.998521
DSBUS2_A_SYS1	0.003590	0.000471	0.999998

Table 2. Bay Line A2 Substation System1 (A2_SYS1)

Equipment Name	t	λ	R(t)
LA_A2_SYS1	15.798383	0.000450	0.992916
DSLINE_A2_SYS1	41.979421	0.000471	0.980422
CB_A2_SYS1	6.732032	0.005057	0.966529
DSBUS1_A2_SYS1	0.003590	0.000471	0.999998
DSBUS2_A2_SYS1	3.141615	0.000471	0.998521

Table 3. Bay Line B1 Substation System1 (B1_SYS1)

Equipment Name	t	λ	R(t)
LA_B1_SYS1	15.571245	0.000450	0.993017
DSLINE_B1_SYS1	15.664290	0.000471	0.992649
CB_B1_SYS1	15.210014	0.005057	0.925967
DSBUS1_B1_SYS1	15.664290	0.000471	0.992649
DSBUS2_B1_SYS1	0.017902	0.000471	0.999992

Table 4. Bay Line B2 Substation System1 (B2_SYS1)

Equipment Name	t	λ	R(t)
LA_B2_SYS1	15.379683	0.000450	0.993103
DSLINE_B2_SYS1	15.664290	0.000471	0.992649
CB_B2_SYS1	15.210014	0.005057	0.925967
DSBUS1_B2_SYS1	0.017902	0.000471	0.999992
DSBUS2_B2_SYS1	15.664290	0.000471	0.992649

Table 5. Bay Transformer 1 Substation System1 (TRF1_SYS1)

Equipment Name	t	λ	R(t)
LA_TRF1_SYS1	41.979421	0.000450	0.981287
CB_TRF1_SYS1	11.729061	0.005057	0.942411
DSBUS1_TRF1_SYS1	2.706496	0.000471	0.998726
DSBUS2_TRF1_SYS1	0.003084	0.000471	0.999999

Table 6. Bay Transformer 2 Substation System1 (TRF2_SYS1)

Equipment Name	t	λ	R(t)
LA_TRF2_SYS1	24.049227	0.007520	0.834560
CB_TRF2_SYS1	24.131325	0.005057	0.885120
DSBUS1_TRF2_SYS1	0.027485	0.000471	0.999987
DSBUS2_TRF2_SYS1	2.692813	0.000471	0.998732

Table 7. Bus Coupler Substation System1 (BUSCOUPLER_SYS1)

Equipment Name	t	λ	R(t)
DSBUS1_BUSCOUPLER_SYS1	15.655339	0.000471	0.992653
DSBUS2_BUSCOUPLER_SYS1	15.655339	0.000471	0.992653
CB_BUSCOUPLER_SYS1	15.201323	0.005057	0.926007

The calculated reliability values of each equipment in System1 are shown in the Table 8-14. Table 8 shows reliability value of bay line C1, Table 9 shows reliability value of bay line C2, Table 10 shows reliability value of bay line D1, Table 11 shows reliability value of bay line D2, Table 12 shows reliability value of bay transformer 1 in System2, Table 13 shows reliability value of bay transformer 2 in System2, Table 14 shows reliability value of bay bus coupler in System2.

Table 8. Bay Line C1 System2 (C1_SYS2)

Equipment Name	t	λ	R(t)
LA_C1_SYS2	3.968068	0.000450	0.998216
DSLINE_C1_SYS2	2.468412	0.000471	0.998838
CB_C1_SYS2	3.177191	0.005057	0.984061
DSBUS1_C1_SYS2	2.468412	0.000471	0.998838
DSBUS2_C1_SYS2	0.002821	0.000471	0.999999

Table 9. Bay Line C2 System2 (C2_SYS2)

Equipment Name	t	λ	R(t)
LA_C2_SYS2	8.135907	0.000450	0.996346
DSLINE_C2_SYS2	3.968068	0.000471	0.998133
CB_C2_SYS2	8.300103	0.005057	0.958895
DSBUS1_C2_SYS2	0.004535	0.000471	0.999998
DSBUS2_C2_SYS2	2.468412	0.000471	0.998838

Table 10. Bay Line D1 System2 (D1_SYS2)

Equipment Name	t	λ	R(t)
LA_D1_SYS2	3.968068	0.000450	0.998216
DSLINE_D1_SYS2	3.163508	0.000471	0.998511
CB_D1_SYS2	3.010258	0.005057	0.984892
DSBUS1_D1_SYS2	2.468412	0.000471	0.998838
DSBUS2_D1_SYS2	0.002821	0.000471	0.999999

Table 11. Bay Line D2 System2 (D2_SYS2)

Equipment Name	t	λ	R(t)
LA_D2_SYS2	3.968068	0.000450	0.998216
DSLINE_D2_SYS2	3.968068	0.000471	0.998133
CB_D2_SYS2	8.010024	0.005057	0.960303
DSBUS1_D2_SYS2	0.002821	0.000471	0.999999
DSBUS2_D2_SYS2	3.968068	0.000471	0.998133

Table 12. Bay Transformer1 System2 (TRF1_SYS2)

Equipment Name	t	λ	R(t)
LA_TRF1_SYS2	2.646291	0.000450	0.998810
CB_TRF1_SYS2	2.728389	0.005057	0.986297
DSBUS1_TRF1_SYS2	2.646291	0.000471	0.998754
DSBUS2_TRF1_SYS2	0.003024	0.000471	0.999999

Table 13. Bay Transformer2 System2 (TRF2_SYS2)

Equipment Name	t	λ	R(t)
LA_TRF2_SYS2	8.218005	0.000450	0.996309
DSLINE_TRF2_SYS2	8.218005	0.000471	0.996137
CB_TRF2_SYS2	8.300103	0.005057	0.958895
DSBUS1_TRF2_SYS2	0.009392	0.000471	0.999996
DSBUS2_TRF2_SYS2	3.968068	0.000471	0.998133

Table 14. Bay Bus Coupler System2 (BUSCOUPLER_SYS2)

Equipment Name	t	λ	R(t)
DSBUS1_BUSCOUPLER_SYS2	3.161700	0.000471	0.998512
DSBUS2_BUSCOUPLER_SYS2	3.161700	0.000471	0.998512
CB_BUSCOUPLER_SYS2	3.968535	0.005057	0.980131

3.2 RBD Modeling and Simulation

Substation System1 and Substation System2 were modeled using a Reliability Block Diagram (RBD) based on the actual equipment configuration derived from the single-line diagram. The modeling was carried out from the equipment level (circuit breaker, disconnecting switch, current transformer, capacitive voltage transformer, lightning arrester), through Subsystem Levels 1 and 2 (each bay within the substation), up to the system level (substation), and finally the integration of both systems.

The single-line diagram of Substation System1 is shown in Figure 4 and single-line diagram of Substation System2 is shown in Figure 5.

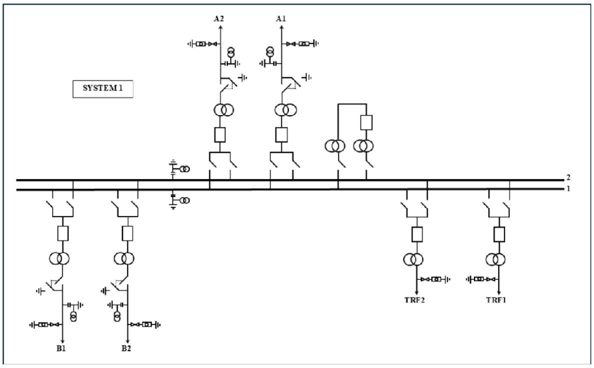

Figure 4. Single line diagram of substation system1

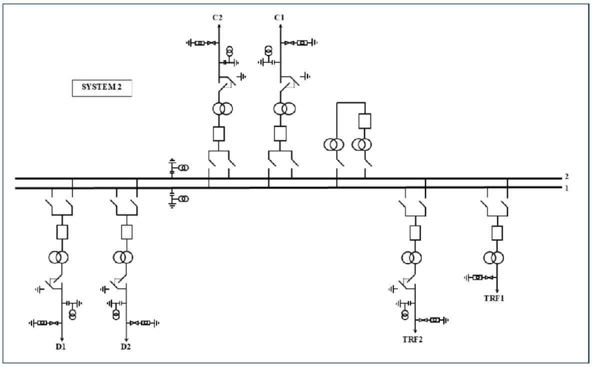

Figure 5. Single line diagram of substation system2

The RBD modeling follows the single-line diagrams. The initial modeling is divided based on each bay within the substation. The RBD visualization in the Figure 6-13 illustrates this modeling approach, which also allows for the derivation of reliability equations at both the subsystem (bay) level and the overall substation system level. The RBD model visualization of bay line (A1, A2, B1, B2) in System1 is shown in the Figure 6.

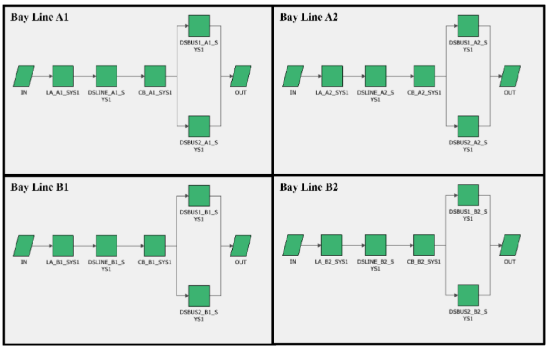

Figure 6. RBD Visualization of Bay Line in System1

Figure 7 shows RBD model Visualization of bay transformer 1 and bay transformer 2 in System1

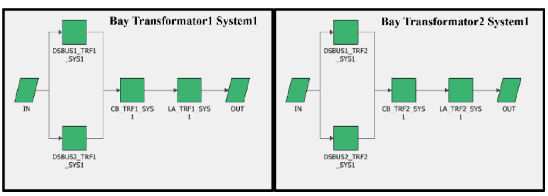

Figure 7. RBD Visualization of Bay Transformer in System1

Figure 8 shows RBD model Visualization of bay bus coupler in System 1

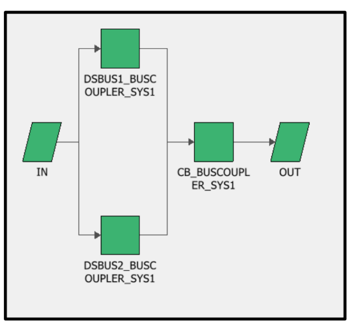

Figure 8. RBD Visualization of Bay Bus Coupler in System1

Figure 9 shows RBD model Visualization of System1

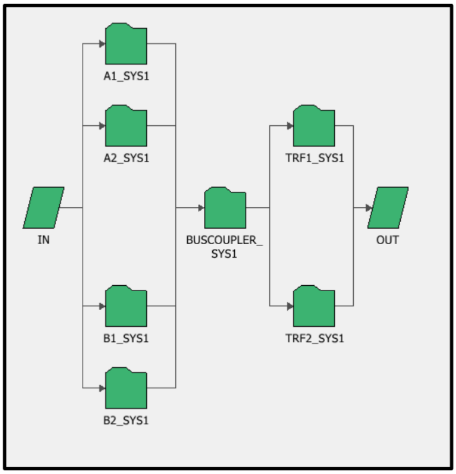

Figure 9. RBD Visualization of System1

From the RBD modeling, the reliability equations for each subsystem level and the overall system of Substation System1 are obtained, as shown in the Table 15.

Table 15. Reliability of System1

Sub System / System Name and RBD Name	Reliability Equation	Reliability Value
Bay Line A1 (A1_SYS1)	RLA_A1_SYS1 × RDSLINE_A1_SYS1 × RCB_A1_SYS1 × (-RDSBUS1_A1_SYS1 × RDSBUS2_A1_SYS1 + RDSBUS1_A1_SYS1 + RDSBUS2_A1_SYS1)	0.948924
Bay Line A2 (A2_SYS1)	RLA_A2_SYS1 × RDSLINE_A2_SYS1 × RCB_A2_SYS1 × (-RDSBUS1_A2_SYS1 × RDSBUS2_A2_SYS1 + RDSBUS1_A2_SYS1 + RDSBUS2_A2_SYS1)	0.940893
Bay Line B1 (B1_SYS1)	RLA_B1_SYS1 × RDSLINE_B1_SYS1 × RCB_B1_SYS1 × (-RDSBUS1_B1_SYS1 × RDSBUS2_B1_SYS1 + RDSBUS1_B1_SYS1 + RDSBUS2_B1_SYS1)	0.912742
Bay Line B2 (B2_SYS1)	RLA_B2_SYS1 × RDSLINE_B2_SYS1 × RCB_B2_SYS1 × (-RDSBUS1_B2_SYS1 × RDSBUS2_B2_SYS1 + RDSBUS1_B2_SYS1 + RDSBUS2_B2_SYS1)	0.912821
Bay Transformer1 (TRF1_SYS1)	RLA_TRF1_SYS1 × RCB_TRF1_SYS1 (-RDSBUS2_TRF1_SYS1 × RDSBUS1_TRF1_SYS1 + RDSBUS2_TRF1_SYS1 + RDSBUS1_TRF1_SYS1)	0.924775

Bay Transformer2 (TRF2_SYS1)	RLA_TRF2_SYS1 × RCB_TRF2_SYS1 × (-RDSBUS2_TRF2_SYS1 × RDSBUS1_TRF2_SYS1 + RDSBUS2_TRF2_SYS1 + RDSBUS1_TRF2_SYS1)	0.738686
Bus Coupler (BUSCOUPLER_ SYS1)	RCB_BUSCOUPLER_SYS1 × (-RDSBUS1_BUSCOUPLER1_SYS1 × RDSBUS2_BUSCOUPLER1_SYS1 + RDSBUS2_BUSCOUPLER1_SYS1 + RDSBUS1_BUSCOUPLER1_SYS1)	0.925957
Sub Station System1 (SYS1)	RBUSCOUPLER_SYS1 × (-RA1_SYS1 × RA2_SYS1 × RB1_SYS1 × RB2_SYS1 + RA1_SYS1 × RA2_SYS1 × RB1_SYS1 + RA1_SYS1 × RA2_SYS1 × RB2_SYS1 + RA1_SYS1 × RB1_SYS1 × RB2_SYS1 + RA2_SYS1 × RB1_SYS1 × RB2_SYS1-RA1_SYS1 × RA2_SYS1 - RA1_SYS1 × RB1_SYS1 - RA1_SYS1 × RB2_SYS1- RA2_SYS1 × RB1_SYS1 - RA2_SYS1 × RB2_SYS1 -RB1_SYS1 × RB2_SYS1 + RA1_SYS1 + RA2_SYS1 + RB1_SYS1 + RB2_SYS1) × (-RTRF1_SYS1 × RTRF2_SYS1+RTRF1_SYS1+RTRF2_SYS1)	0.907735

The RBD model visualization of bay line (C1, C2, D1, D2) in System2 is shown in the Figure 10.

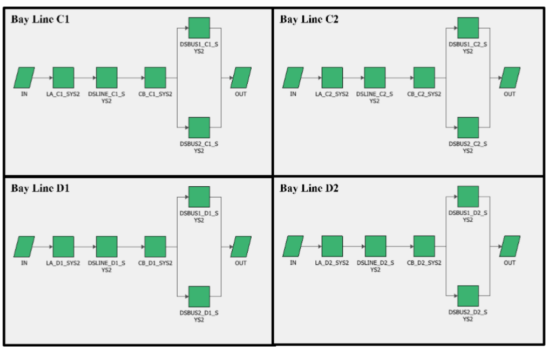

Figure 10. RBD Visualization of Bay Line in System2

Figure 11 shows RBD model Visualization of bay transformer 1 and bay transformer 2 in System2

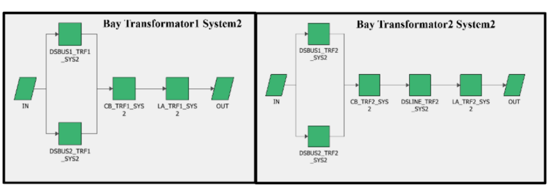

Figure 11. RBD Visualization of Bay Transformer in System2

Figure 12 shows RBD model Visualization of bay bus coupler in System 2

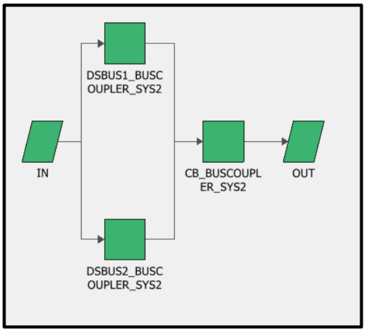

Figure 12. RBD Visualization of Bay Bus Coupler in System2

Figure 13 shows RBD model Visualization of System2

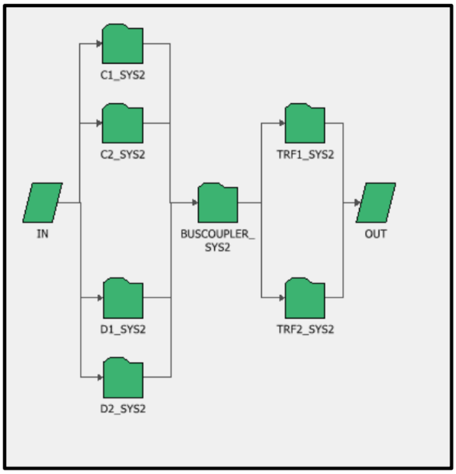

Figure 13. RBD Visualization of System2

From the RBD modeling, the reliability equations for each subsystem level and the overall system of Substation System2 are obtained, as shown in the Table 16.

Table 16. Reliability of System2

Sub System / System Name and RBD Name	Reliability Equation	Reliability Value
Bay Line C1 (C1_SYS2)	RLA_C1_SYS2 × RDSLINE_C1_SYS2 × RCB_C1_SYS2 × (-RDSBUS1_C1_SYS2 × RDSBUS2_C1_SYS2 + RDSBUS1_C1_SYS2 + RDSBUS2_C1_SYS2)	0.981164

Bay Line C2 (C1_SYS2)	RLA_C2_SYS2 × RDSLINE_C2_SYS2 × RCB_C2_SYS2 × (-RDSBUS1_C2_SYS2 × RDSBUS2_C2_SYS2 + RDSBUS1_C2_SYS2+RDSBUS2_C2_SYS2)	0.953607
Bay Line D1 (D1_SYS2)	RLA_D1_SYS2 × RDSLINE_D1_SYS2 × RCB_D1_SYS2 × (- RDSBUS1_D1_SYS2 × RDSBUS2_D1_SYS2 +RDSBUS1_D1_SYS2+RDSBUS2_D1_SYS2)	0.981672
Bay Line D2 (D2_SYS2)	RLA_D2_SYS2 × RDSLINE_D2_SYS2 × RCB_D2_SYS2 × (-RDSBUS1_D2_SYS2 × RDSBUS2_D2_SYS2 + RDSBUS1_D2_SYS2 + RDSBUS2_D2_SYS2)	0.956800
Bay Transformer1 (TRF1_SYS2)	RLA_TRF1_SYS2 × RCB_TRF1_SYS2 × (-RDSBUS2_TRF1_SYS2 × RDSBUS1_TRF1_SYS2 + RDSBUS2_TRF1_SYS2 + RDSBUS1_TRF1_SYS2)	0.985123
Bay Transformer2 (TRF2_SYS2	RLA_TRF2_SYS2 × RDSLINE_TRF2_SYS2 × RCB_TRF2_SYS2 × (-RDSBUS1_TRF2_SYS2 × RDSBUS2_TRF2_SYS2 + RDSBUS1_TRF2_SYS2 + RDSBUS2_TRF2_SYS2)	0.951665
Bus Coupler (BUSCOUPLER_ SY S2)	RCB_BUSCOUPLER_SYS2 × (-RDSBUS1_BUSCOUPLER1_SYS2 × RDSBUS2_BUSCOUPLER1_SYS2 + RDSBUS2_BUSCOUPLER1_SYS2 + RDSBUS1_BUSCOUPLER1_SYS2)	0.980129
Sub Station System2 (SYS2)	RBUSCOUPLER_SYS2 × (-RC1_SYS2 × RC2_SYS2 × RD1_SYS2 × RD2_SYS2 + RC1_SYS2 × RC2_SYS2 × RD1_SYS2 + RC1_SYS2 × RC2_SYS2 × RD2_SYS2 + RC1_SYS2 × RD1_SYS2 × RD2_SYS2 + RC2_SYS2 × RD1_SYS2 × RD2_SYS2 - RC1_SYS2 × RC2_SYS2 - RC1_SYS2 × RD1_SYS2 - RC1_SYS2 × RD2_SYS2 - RC2_SYS2 × RD1_SYS2 - RC2_SYS2 × RD2_SYS2 - RD1_SYS2 × RD2_SYS2 + RC1_SYS2 + RC2_SYS2 + RD1_SYS2 + RD2_SYS2) × (-RTRF1_SYS2 × RTRF2_SYS2 + RTRF1_SYS2 + RTRF2_SYS2)	0.979424

System1 and System2 are interconnected through lines B and C; therefore, the RBD model visualization of the interconnected Substation System1 and System2 is shown in the Figure 14.

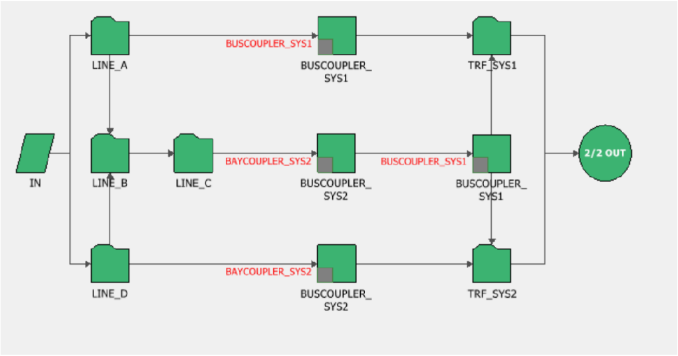

Figure 14. RBD Visualization of the Interconnected System1 and System2

The reliability values of Subsystem Level 1 (bay line A (LINE_A), bay line B (LINE_B), bay line C (LINE_C), bay line D (LINE_D), bay transformer System1 and transformer System2) are obtained through parallel calculations of each subsystem (A1||A2; B1||B2; C1||C2; D1||D2; TRF1_SYS1||TRF2_SYS1; TRF1_SYS2||TRF2_SYS2). Accordingly, the reliability equations for the interconnected System1 and System2 is formulated as (4).

$$\begin{gathered} R_{SYSTEM1andSYSTEM2} = \\ -2R_{TRF_SYS2} \times R_{LINE_D} \times R_{LINE_B} \times R_{TRF_SYS1} \times R_{BUSCOUPLER_SYS1} \times R_{LINE_C} \times \\ R_{BUSCOUPLER_SYS2} \times R_{LINE_A} + R_{TRF_SYS2} \times R_{LINE_D} \times R_{LINE_B} \times R_{TRF_SYS1} \times \\ R_{BUSCOUPLER_SYS1} \times R_{LINE_C} \times R_{BUSCOUPLER_SYS2} + R_{TRF_SYS2} \times R_{LINE_B} \times R_{TRF_SYS1} \times \\ R_{BUSCOUPLER_SYS1} \times R_{LINE_C} \times R_{BUSCOUPLER_SYS2} \times R_{LINE_A} + R_{TRF_SYS2} \times R_{LINE_D} \times \\ R_{TRF_SYS1} \times R_{BUSCOUPLER_SYS1} \times R_{BUSCOUPLER_SYS2} \times R_{LINE_A} \end{gathered} \tag{4}$$

Based on the reliability equation (4), the total reliability value of the interconnected System1 and System2 is calculated to be 0.889045.

3.3 Reliability Improvement

The results obtained from the modeling and simulation indicate that System 1 and System 2 exhibit distinct levels of reliability, with $R_{System1} < R_{System2}$; $R_{System1}$ = 0.907735; $R_{System2}$ = 0.979424.

Based on these findings, a targeted improvement scenario was formulated to enhance the reliability of System1. The scenario is renewal of equipment, where replacement efforts are directed towards the most critical equipment and has biggest impact on system reliability. Therefore, subsystem prioritization was established by identifying and targeting those equipment as shown in Table 17.

Table 17. Subsystem Prioritization

Prioruty Level	Subsystem Name	Reliability Value
Priority 1	BUSCOUPLER_SYS1	0.925957
	TRF1_SYS1 || TRF2_SYS1	0.980343
	LINE_A || LINE_B	0.999977
Priority 2	TRF1_SYS1	0.924775
	TRF2_SYS1	0.738686
	LINE_A	0.996981
	LINE_B	0.992393
Priority 3	LINE_A1	0.948924
	LINE_A2	0.940893
	LINE_B1	0.912742
	LINE_B2	0.912821

Based on Figure 9, the RBD model of System1 constructed from a series configuration of 3 subsystems (BUSCOUPLER_SYS1, TRF1_SYS1 || TRF2_SYS1, LINE_A || LINE_B), these subsystems may also be designated as subsystem level 1. Among the three subsystems, subsystem BUSCOUPLER_SYS1 exhibits the lowest reliability value, with a reliability of R = 0.925957. This subsystem consists of individual component level. Based on figure 8, component DS_BUSCOUPLER_SYS1 becomes the most critical component in the subsystem BUSCOUPLER_SYS1 because it is the because it is the only component without redundancy (serial), whereas the other equipment is connected in parallel (DSBUS1_BUSCOUPLER_SYS1 || DSBUS2_BUSCOUPLER_SYS1). Figure 15 presents the visualization of critical component prioritization as determined by the RBD modeling.

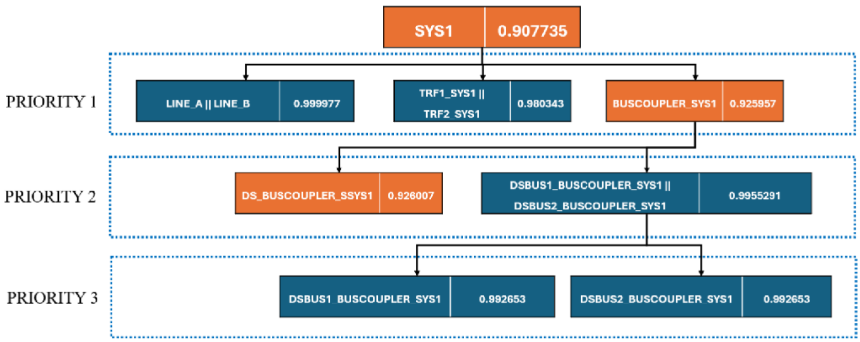

Figure 15. Critical Component Prioritization on System1

Based on Table 7, reliability value of component CB_BUSCOUPLER_SYS1 is 0.926007, which corresponds to the circuit breaker. If this component is replaced with a new one (RCB_BUSCOUPLER_SYS1 = 0.9999), the reliability of System1 would increase to 0.980168, and the total reliability value of the interconnected System1 and System2 would improve to 0.959989. Figure 16 show the reliability versus time plot for conventional approach and RBD approach from 2020-2030.

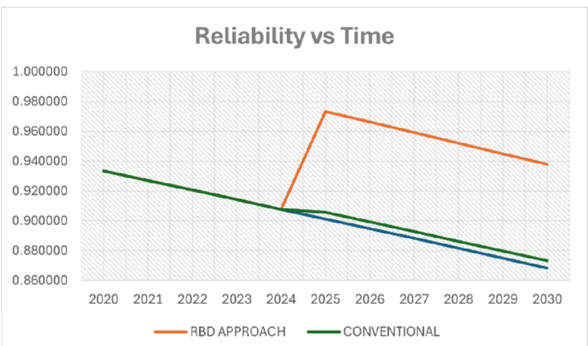

Figure 16. Conventional vs RBD Approach Graph

Figure 16 shows a reliability versus time graph, illustrating the difference of reliability between equipment renewal using the conventional method (based on component age) and the RBD-based approach in System1. The graph represents a scenario of equipment replacement in 2025. The conventional method selects equipment for replacement based on its age, specifically the LA (as shown in Table 5). In contrast, the RBD based approach identifies the CB as the equipment that should be replaced, as shown in Figure 15.

4. Conclusion

The reliability assessment of interconnected substations using the Reliability Block Diagram (RBD) approach reveals a significant disparity in reliability between System1 and System2, where System1 has a reliability value of 0.907735, while System2 reaches 0.979424. This difference is largely influenced by the age of the installed equipment.

When a replacement scenario is implemented targeting the equipment with the highest failure rates based on priority, the system reliability increases significantly. Post replacement RBD simulation results show that System1 can achieve a reliability level of 0.980168 and the interconnected System1 and System2 can achieve a reliability level of 0.959989.

This improvement impacts not only the reliability of individual equipment but also the overall reliability of power flow between substations. Therefore, a selective equipment renewal strategy can serve as an effective solution to enhance transmission system reliability, reduce the risk of systemic failures, and support the continuity of a dependable electricity supply.

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