

Article

Comparative Reliability Analysis of Transformer and Power-Router-Based Configuration in Double-Fed Power System

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Abstract

This study aims to quantify and compare the reliability of two alternative power system architectures: a conventional configuration based on traditional elements and a future envisioned architecture, where multi-port power converters operate as network nodes. The objective is to evaluate how these two approaches perform relative to each other in terms of reliability, and to determine whether the emerging converter-based structure represents an improvement or a drawback compared with the conventional design. To simplify the analysis and the comparison results, the analysis is presented for a double-fed power system. Both systems were modeled using two-state components characterized by constant failure and re-pair rates. Reliability assessment was carried out using a continuous-time Markov chain (CTMC) approach to derive the key adequacy indices. To validate the analytical results, a non-sequential Monte Carlo Simulation (MCS) was also performed, allowing a direct comparison between stochastic sampling and analytical modeling. The results show that the transformer-based configuration achieves a reliability of 0.9972 compared with 0.9960 for the power-router-based configuration, while also exhibiting lower LOLE and EENS, indicating a modest reliability advantage for the conventional architecture under the adopted assumptions.

Keywords: power system reliability; multi-port power converters; converter-dominated power systems; Markov processes; Monte Carlo simulations



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1. Introduction

The reliability of power systems is a fundamental requirement for ensuring a secure, continuous, and efficient supply of electricity to end-users. The increasing integration of renewable energy sources (RES), energy storage systems (ESS), and power electronic interfaces has significantly transformed the architecture of electrical grids across the world. Although these technologies enhance flexibility and facilitate decarbonization, they also introduce new uncertainties and vulnerabilities due to stochastic generation profiles, converter failures, and complex interdependencies among system components. Consequently, adequate reliability assessment techniques are required to accurately capture the operational characteristics of the emerging system configurations. In addition, although multi-

port power converters significantly enhance the flexibility and controllability of power systems, they introduce challenges in terms of reliability that must be accurately addressed.

Among the available approaches, Markov Chain model, particularly the CTMC, provides a rigorous framework for quantifying reliability. By explicitly modeling component failure and repair processes, the CTMC allows for the derivation of adequacy indices such as LOLP, LOLE, EENS, and reliability. In addition, because the number of transition rate matrix dimensions of the CTMC is dependent on the number of components considered, the complexity increases. Therefore, the MCS technique was used to validate the analytical method.

Undoubtedly, the increasing integration of RES and power electronic interface devices will affect the reliability of future power systems. This study acknowledges these developments and aims to evaluate the impact of such system transformations. Specifically, this study presents a comparative analysis of the reliability of the current power system and a future envisioned system. Therefore, a double-fed power system under two configurations is considered: a conventional design using transformers and a modernized configuration employing multi-port power converters, also referred to as power routers. The analysis assumes constant failure and repair rates, with the associated limitations discussed in Section 3; economic feasibility is out of this study scope. Both systems were evaluated considering their operating conditions to enable a fair comparison of their performances. Reliability is assessed using a CTMC-based analytical framework, and the results are validated through a Monte Carlo simulation, thereby combining the efficiency of analytical modeling with the robustness of stochastic sampling.

The key contributions of this study are as follows.

- Development of a CTMC-based reliability model for both conventional and power-router-based double-fed system configurations, explicitly incorporating component failure and repair processes.
- Comparative evaluation of critical reliability metrics (LOLP, LOLE, EENS, and reliability index) for traditional transformer-based grids and modern multi-port converter architectures.
- Validation of analytical results through Monte Carlo simulation, highlighting the consistency and limitations of CTMC-based modeling when applied to complex system topologies.

Through this dual-method approach, this study provides insights into the reliability implications of replacing traditional components with advanced power electronic devices and demonstrates the role of the MCS as a validation tool for CTMC-based reliability assessment.

This study aims to quantify and compare adequacy metrics (LOLP, LOLE, EENS, and reliability) for two alternative double-fed architectures: a conventional transformer-based grid and a prospective converter-centric system in which multi-port power converters serve as network nodes. This comparison is emphasized because future power systems are expected to rely extensively on power electronics for controllability and flexibility; however, few reliability assessments explicitly examine converter-dominated configurations. A rigorous, quantitative reliability comparison is therefore needed to guide engineering choices and to frame the operational trade-offs associated with large-scale converter deployment.

The remainder of this paper is organized as follows: Section II provides a literature review of reliability assessment methods, with a particular focus on Markov-based and Monte Carlo approaches. Section III delineates the methodology, encompassing system modeling, the Markov Chain framework, and the formulation of reliability indices. Section IV presents a discussion of the results derived from the case studies, emphasizing the

influence of various components and configurations on the reliability performance. Finally, Section V presents the principal conclusions and suggests directions for future research.

2. Literature Review

The reliability assessment of modern power systems integrating RES, ESS, electric vehicles (EVs), and power electronic converters has increasingly relied on Markov Chain-based models, owing to their ability to capture stochastic system behavior. In modern power systems, advanced power electronic interface configurations, such as multi-port power converters, have attracted considerable attention for their potential contributions to power system operation. Multi-port converter topologies, sometimes referred to as “power routers” (or “energy routers”), offer a promising way to interconnect multiple sources and loads while actively regulating power flows [1–3]. By enabling simultaneous bidirectional power exchange across several ports, these converters reduce the need for many single-port converters and support centralized control strategies, thereby improving system flexibility, coordination, and overall power flow management [4–6]. Consequently, power routers derive their flexibility and reconfiguration capability from the multi-port structure, which allows the interconnection of multiple sources and loads while actively regulating power exchange among ports. In this study, these features are treated as inherent operational characteristics of the architecture, whereas the quantitative comparison is focused on the adequacy performance.

Numerous studies have applied continuous- and discrete-time Markov models, including semi-Markov and higher-order variations, to evaluate component- and system-level reliability. To enhance confidence in these analytical models, MCS methods are widely employed as validation tools that capture the uncertainties and dynamic operating conditions. This hybrid approach ensures both analytical precision and practical robustness in the modeling of complex and evolving power system architectures.

2.1. Markov Chain-Based Approaches

The Markov process method operates based on given failure and repair rates, which may be time-dependent or constant. It is a widely used stochastic modeling approach for reliability evaluation in power systems and other engineering applications. By capturing the time-dependent behaviors of component failures and repairs, Markov processes enable the assessment of system reliability, availability, and maintainability.

A Markov process is a stochastic process that satisfies the Markov property—the future state of the system depends only on its present state, not on the sequence of past states. Formally, let $\{X_n, n = 0, 1, 2, \dots\}$ be a stochastic process that takes a finite or countable set of values, typically denoted by non-negative integers $\{0, 1, 2, \dots\}$. If $X_n = i$, then the process is in state i at time n . We assume that whenever the process is in state i , there is a fixed probability P_{ij} that it will next be in state j , such that

$$P\{X_{n+1} = j \mid X_n = i, X_{n-1} = i_{n-1}, \dots, X_0 = i_0\} = P_{ij} \quad (1)$$

for all possible states $i_0, i_1, \dots, i_{n-1}, i, j$ and all $n \geq 0$ [7].

If the state space X is discrete (finite or countably infinite), the Markov process is referred to as a Markov chain. When the parameter space T is also discrete, the model is called a discrete-time Markov chain (DTMC) [8]. Conversely, if transitions between states can occur at any instant in continuous time, the model is a CTMC [9].

In power system reliability studies, the Markov Chain method is popular owing to its simplicity and flexibility. However, its practicality diminishes as the system complexity or the number of components increases due to the rapid growth of the state space [10].

2.2. Markov Chain Applications in Power System Reliability

Markov Chain models have been widely employed to assess the reliability of modern power systems, particularly with the increasing integration of RES, distributed energy resources (DERs), ESS, power electronic devices, and EVs. The studies in [11,12] applied Markov chain modeling to assess the reliability of power systems, with a particular focus on microgrid architecture. Ref. [11] utilizes Markov Chains alongside Hardware-in-the-Loop simulation to compare centralized and decentralized microgrid control, revealing that eliminating the central controller, a single point of failure, markedly enhances the reliability of the system as the microgrid grows. Although decentralized configurations are more resilient, they pose challenges in terms of synchronization and cyber security. In ref. [12], a continuous-time Markov chain models the behavior of 16 state components of a distribution system over two decades, showing a notable decrease in reliability from 99% to 77.66% due to critical component failures such as bus-bars and transformers. Similarly, studies in [13–15] investigated the impact of solar photovoltaic (PV) power plants on the reliability of power systems using various forms of Markov chain models. Ref. [13] employs a discrete-time Markov chain to model the stochastic nature of solar irradiance and battery state, demonstrating that energy storage can raise system reliability from 0.173 to over 0.96, though the model's assumptions of ideal battery behavior and static load reduce its real-world applicability. Ref. [14] integrates a Markov-based dynamic Bayesian network to analyze PV systems under intermittent faults, revealing that multi-string configurations offer higher reliability than centralized ones, but the method is limited by incomplete or low-quality component failure data. In Ref. [15], a higher-order Markov chain was applied to probabilistic power flow, incorporating spatiotemporal dependencies via copula functions and improving both accuracy and computational efficiency; however, challenges were faced in modeling complex joint distributions and relying heavily on historical data.

In addition, the studies [16,17] evaluated the impact of wind farms on the reliability of power systems using Markov-based methods. Ref. [16] utilizes a discrete convolution-based method that incorporates Markov modeling to assess how wind intermittency and low inertia affect frequency stability, finding that increased wind penetration reduces system reliability, although energy storage offers partial mitigation. Ref. [17] introduces a Semi-Markov Stochastic Process (SMSP) model to analyze hybrid AC/DC systems with integrated wind farms, capturing arbitrary state durations for more accurate reliability estimation in complex systems. The following reviews analyzed the impact of hybrid and energy storage systems on power system reliability using various methods based on the Markov chain. In Ref. [18], a Markov model and frequency-duration technique were used to evaluate a stand-alone hybrid PV/battery/diesel system for a rural healthcare center, showing that this configuration offers superior reliability performance, although the results are constrained by system-specific assumptions. Ref. [19] employs a Markov chain framework to evaluate distribution systems with Mobile Battery Energy Storage Systems (MBESSs), finding that MBESSs significantly improve reliability and fault resilience, but model assumptions such as radial topologies and exclusion of simultaneous faults limit broader applicability. Ref. [20] integrates a two-state Markov ESS model with a multi-state PV model using FMEA to analyze the reliability of hybrid systems, revealing that optimal component sizing and placement can significantly improve indices such as SAIFI and SAIDI, albeit with limitations due to simplified models and reliance on historical solar data. Furthermore, ref. [21] presented a multilevel Markov-based framework that includes converter degradation, showing that converter wear-out, particularly in HVDC systems, decreases reliability under high renewable penetration; however, this approach is computationally intensive and relies on uniform aging assumptions. In Ref. [22], a multi-state Markov model evaluated the integration of photovoltaic, wind, and storage into distribu-

tion networks, reporting substantial improvements in the SAIFI, SAIDI, EENS, and ECOST indices, although it assumed idealized resource availability and component behavior.

2.3. Monte Carlo Simulation for Validation and Hybrid Modeling

The MCS is a probabilistic technique widely applied in power system reliability assessments, offering statistical estimations of performance indices through repeated random sampling of the system states. Its two primary variants are the non-sequential approach, which samples random system states based on steady-state probabilities, and the sequential approach, which simulates the chronological sequence of component failures and repairs, thereby capturing temporal dependencies and outage statistics [23,24]. In addition to its role as a primary reliability estimation method, the MCS is extensively employed as a validation tool for analytical probabilistic approaches, particularly for Markov-based methods.

Recent studies have highlighted the integration of MCS with analytical techniques to enhance the modeling accuracy. For instance, ref. [25] developed a hybrid framework that combined sequential MCS with Markov models to represent stochastic component behaviors and dynamic system responses in distributed power systems. Similarly, ref. [26] employed a hybrid Markov chain–MCS model for distribution network reliability, demonstrating improved precision in accounting for temporal dependencies and operational uncertainties. In another study, ref. [27] applied a Dynamic Hidden Markov Model integrated with MCS to capture the probabilistic influence of electric vehicle charging patterns, revealing reliability degradation under increased EV penetration. Additionally, ref. [28] utilized a quasi-sequential MCS combined with a Continuous Time Markov Chain to assess the reliability of coupled power and transportation systems under bidirectional EV charging strategies. In the context of hybrid AC/DC microgrids, ref. [29] proposed a probabilistic framework that integrates sequential MCS with power flow analysis, enabling an accurate reliability index evaluation for resilient planning.

Recent developments in power system planning and power flow analysis have increased the attention paid to power electronic interfaces, including multi-port power converters, which are sometimes referred to as power or energy routers. For instance, ref. [4] proposed a novel grid concept based on power routers and demonstrated that it could be more efficient than traditional grids. In ref. [3], the authors addressed reliability concerns by introducing an adjustable droop regulator that can compensate for faulty lines by providing a different path to the load. This approach also establishes an energy-based operational mode for the power router grid (PRG) to minimize the steady-state dispatch errors induced by droop control and enhance system resilience without diminishing the tracking performance of the individual PR units. Although new technologies such as power electronics, specifically multi-port power converters, and RES have received significant attention from academia and engineering bodies regarding their integration and operational issues, they require more attention in terms of reliability evaluation to validate and increase their potential for use in engineering applications. Thus, the impact of these new technologies on power system reliability must be considered and addressed using suitable assessment methods, such as Markov processes, which capture the operational characteristics of these technologies, such as power routers.

In this context, the main contribution of the present study is the direct, quantitative comparison between a conventional transformer-based architecture and a power-router-based architecture under the same topology and loading conditions. Unlike prior studies that mainly focus on the Markov modeling of individual technologies or general converter reliability, this study applies a CTMC framework to evaluate how replacing transformers with multi-port power routers affects the LOLP, LOLE, EENS, and overall reliability.

The proposed model is further validated through Monte Carlo simulation, providing a baseline benchmark for future studies on converter-dominated grid reliability.

3. Methodology

The overall procedure adopted for the reliability assessment is illustrated in Figure 1. The methodology integrates system modeling, component reliability representation, CTMC formulation, adequacy index evaluation, Monte Carlo validation, and sensitivity analysis to enable a structured and comparative assessment of the considered configurations.

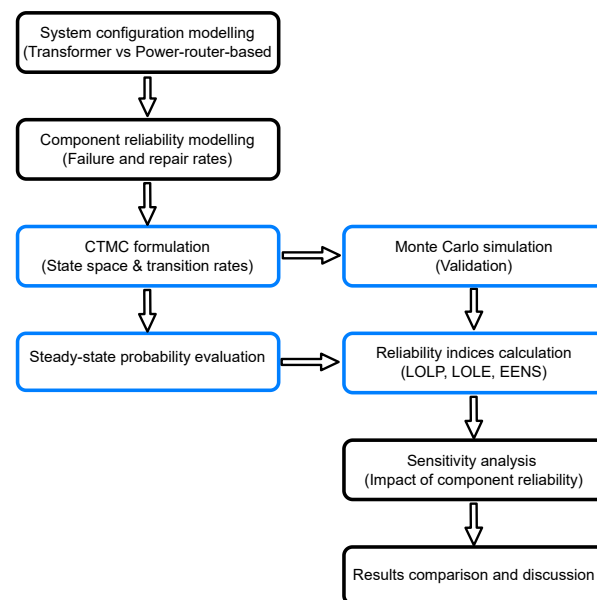


Figure 1. Flowchart of the proposed reliability assessment methodology.

3.1. System Modeling and Requirements

This study considers a conventional and modified double-fed power system that reflects the architecture of a traditional power system, as illustrated in Figure 2 and a modern power grid in Figure 3, integrating multi-port power converters.

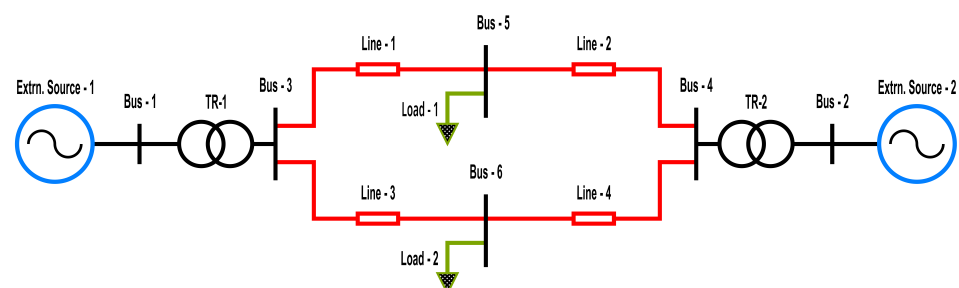


Figure 2. Double-Fed Power System with Transformer.

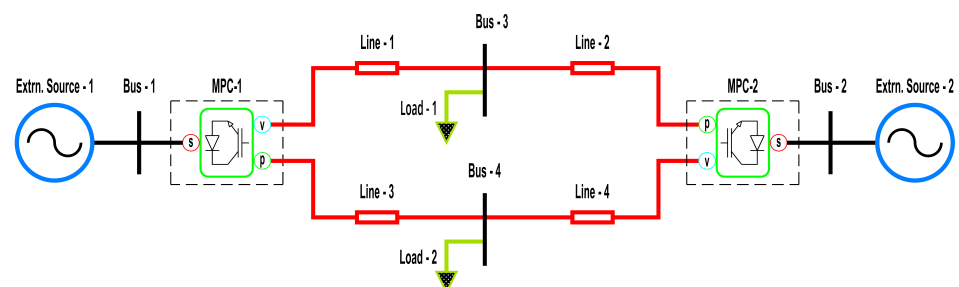


Figure 3. Double-Fed Power System with Power Routers.

In reality, RES exhibit stochastic generation patterns due to the variability in wind speed and solar irradiance, whereas power electronic converters are subject to time-dependent failure processes, typically modeled by the Weibull distribution, which captures infant mortality, random failure, and wear-out phases. These factors introduce significant complexity into the reliability modeling of modern power systems.

To enable a tractable and consistent reliability assessment within the Markov Chain framework, this study adopts the simplifying assumption that all system components, including generators, power transformers, power lines, and power routers, are modeled as two-state elements, either operational or failed. Both failure and repair processes are assumed to follow exponential distributions, characterized by constant failure and repair rates. The study is deliberately designed as a baseline reliability comparison of two alternative double-fed architectures. Assuming two-state components with constant failure and repair rates and independent behavior enables a clear CTMC formulation and direct comparison of the two topologies. The effects, such as common-cause failures, cascading outages, port-level functional dependencies, and aging-related degradation are excluded and deferred to future work using multi-state, semi-Markov, or dependency-aware reliability models. Regarding operational capacities, the following assumptions were considered: load demand was modeled using monthly average loads (see Figure 4), with each month considered constant; and generation sources were represented by two external slack sources (External Source-1 and External Source-2), modeled as ideal slack buses with explicit capacity. Transformers are assumed to have equal transfer capability with the corresponding external source connected, and overload and other limitations are not considered. Power lines are assumed to have sufficient capacity to fully supply the connected load when operational; thermal limits and other constraints are not explicitly considered in this study.

In the modernized architecture shown in Figure 3, the conventional bus interconnections and transformers are replaced by power routers that are modeled as multi-port devices. Each multi-port converter contains at least three ports to ensure normal operating conditions. The correct operation of power routers within the grid requires the following conditions to be satisfied [3,4]:

- Two different ports of each power router must interface with every line.
- Each line must always be connected to only one V-f port.
- Each power router must have one Slack port.
- The power router grid must be interfaced with an external slack grid.

Each port is characterized by its own constant failure and repair rates, and the overall functionality of the router depends on the availability of these ports. Therefore, ports are modeled as availability components; thermal limitations, and other constraints are not considered. The failure of specific ports can isolate buses or loads, thereby affecting the system operation.

The system operational states are defined according to their ability to meet the total load demand and to comply with the operational system conditions. Any state in which the available generation, after accounting for component failures, is insufficient to satisfy the load, is considered a system failure. The configuration was abstracted into a state-space model, which formed the basis for a quantitative reliability analysis using the Markov Chain method.

3.2. Markov Chain Modeling Approach

Markov chains are used to model a sequence of continuous random variables that correspond to a set of system states. State transitions can be mathematically represented by a transition rate matrix. For a system with n discrete states, $S_1, S_2, \dots, S_n$, the element ρ_{ij}

denotes the transition rate from state i to state j (corresponding to the rate of departure from i to j).

In a power system, most components have only two possible states: up or down status. Here, state i represents the upstate and state j represents the downstate. Consequently, the transition ρ_{ij} from the up state (i) to the down state (j) corresponds to the failure rate (λ_{ij}), whereas the transition ρ_{ji} from the down state (j) to the up state (i) corresponds to the repair rate (μ_{ji}). The system states are classified as either up or down, depending on the connectivity and transfer capabilities. The Markov differential equation must then be solved to obtain time-dependent state probabilities. This general form can be written in matrix notation for $i = 1, 2, \dots, n$, as presented in (2):

$$\begin{bmatrix} p'_1(t) \\ p'_2(t) \\ \vdots \\ p'_n(t) \end{bmatrix} = \begin{bmatrix} -\sum_{j=2}^n \rho_{1j} & \cdots & \rho_{n1} \\ \rho_{12} & & \\ j \neq 2^n \rho_{2j} & \cdots & \rho_{n2} \\ \vdots & \ddots & \vdots \\ \rho_{1n} & \cdots & -\sum_{j=1}^{n-1} \rho_{nj} \end{bmatrix} \begin{bmatrix} p_1(t) \\ p_2(t) \\ \vdots \\ p_n(t) \end{bmatrix} \quad (2)$$

Note that the above formulation follows the column-vector convention, where each column of the matrix is summed to zero. This is equivalent to the standard infinitesimal generator (transition rate) matrix Q , which is usually presented in the row-sum-to-zero form; in other words, the matrix in (2) corresponds to Q^T .

The steady-state solution is obtained by setting $p'_i(t) = 0$ for $i = 1, 2, \dots, n$. In this case, the stationary probability vector $\mathbf{P} = [P_1, P_2, \dots, P_n]$ satisfies the equations in (3).

$$\pi Q = 0, \quad \sum_{s=1}^{N_s} \pi_s = 1 \quad (3)$$

Once the steady-state probabilities are determined, the system reliability indices can be calculated, as described in the following subsections. In addition, to realize and reduce the time for the code simulations, the reduction of the system using a reliability block diagram (RBD) was considered by calculating the equivalent failure and repair rates for series and parallel connections based on the RBD principle [30]. The computational procedure of the proposed CTMC-based reliability assessment is summarized in Algorithm 1.

Algorithm 1 CTMC steady-state adequacy indices computation

Require: component failure rates $\{\lambda_i\}$, repair rates $\{\mu_i\}$

Ensure: steady-state probabilities π

- 1: $n \leftarrow$ number of components
 - 2: Number of CTMC states $N_s \leftarrow 2^n$
 - 3: Initialize transition-rate matrix $Q \in \mathbb{R}^{N_s \times N_s}$
 - 4: **for** each state $s = 0, \dots, N_s - 1$ **do**
 - 5: **for** each component $i = 1, \dots, n$ **do**
 - 6: **if** component i is operational in state s **then**
 - 7: add transition to state s' (component i failed) with rate λ_i
 - 8: **else**
 - 9: add transition to state s'' (component i repaired) with rate μ_i
 - 10: **end if**
 - 11: **end for**
 - 12: set diagonal element $Q_{ss} = -\sum_{j \neq s} Q_{sj}$
 - 13: **end for**
 - 14: Solve balance equations $\pi Q = 0$
 - 15: Enforce normalization $\sum_{s=1}^{N_s} \pi_s = 1$
 - 16: Compute reliability indices (LOLP, LOLE, EENS) using π
-

3.3. Monte Carlo Simulations Approach Validation Tool

This study utilized the Non-Sequential Monte Carlo Simulation to evaluate power system reliability for validation purposes. The calculation begins by probabilistically sampling the state of each system component based on its individual availability, A . Each unique combination of component states defines a complete system state based on the number of trials N , which is then analyzed using the network connectivity model and the operational conditions. This model determines the available generation capacity and whether loads can be electrically reached by that generation [24]. For any system state where the load exceeds the available capacity or where loads are isolated, the monthly and annual LOLP, LOLE, EENS and R(reliability) are calculated as presented in (4), (5), and (7).

Algorithm 2 summarizes the non-sequential Monte Carlo procedure used to validate CTMC results and to estimate LOLP, LOLE, and EENS indices.

Algorithm 2 Non-sequential Monte Carlo simulation adequacy indices computation

Require: component availabilities $\{A_i\}$ (or $\{\lambda_i, \mu_i\}$), monthly loads and hours, trials N

- 1: Initialize $N_f(m) \leftarrow 0$, EENS_acc(m) $\leftarrow 0$ for all months m
- 2: **for** $k = 1$ to N **do** ▸ each trial independent (non-sequential) Sample each component as operational with A_i , otherwise failed
- 3: Evaluate supplied energy and compute monthly deficits Δ_m
- 4: **for** each month m **do**
- 5: **if** $\Delta_m > 0$ **then** $N_f(m) += 1$; EENS_acc(m) $+= \Delta_m \times \text{hours}_m$
- 6: **end if**
- 7: **end for**
- 8: **end for**
- 9: **for** each month m **do**
- 10: $\text{LOLP}_m \leftarrow N_f(m)/N$, $\text{LOLE}_m \leftarrow \text{LOLP}_m \times \text{hours}_m$, $\text{EENS}_m \leftarrow \text{EENS_acc}(m)/N$
- 11: **end for**
- 12: **return** $\text{LOLP}_m, \text{LOLE}_m, \text{EENS}_m$

3.4. Reliability Indices

Several indices have been developed to accurately calculate the system reliability. Reliability indices such as LOLP, LOLE, EENS, and reliability- R are fundamental metrics used to evaluate the performance and adequacy of modern power systems. LOLP quantifies the probability of the load demand exceeding generation, and LOLE quantifies the expected duration during which the system is unable to meet the load demand. LOLE is calculated as expressed in Equations (4) and (5).

$$\text{LOLP} = \sum_{i \in F} P_i \quad (4)$$

$$\text{LOLE} = \sum_{i \in F} P_i \cdot T \quad (5)$$

where P_i is the steady-state probability of failure state i , and T is the total observation period (h/year). Furthermore, the EENS measures the expected magnitude of the not-supplied energy and is given by Equation (7), with L_i representing the not-served load in state i .

In addition, availability, which represents the probability that a system or component is operational, can be defined for two-state models as expressed in (6).

$$A = \frac{\mu}{\lambda + \mu} \quad (6)$$

$$\text{EENS} = \sum_{i \in F} P_i \cdot T \cdot L_i \quad (7)$$

The system reliability is calculated $R = 1 - LOLP$.

where λ and μ are the constant failure and repair rates, respectively, as presented in (6).

These indices are widely used in Markov Chain-based reliability assessments to capture both the frequency and severity of system failures. Furthermore, as emphasized by [30], these indices provide a robust foundation for system adequacy evaluation, whereas recent applications, such as those by [31,32], have extended their use to modern grids with high renewable penetration and policy-driven constraints. From this perspective, these indices are essential for the reliability assessment and evaluation of contemporary power system adequacy.

3.5. System Description

The system under study consists of two power sources integrated through a meshed network, in which the double transmission paths enhance supply reliability and operational flexibility. In the multi-port power converter (MPC)-based configuration (Figure 3), External Source-1 (250 MW) is connected to Bus-1, and External Source-2 (240 MW) is connected to Bus-2. Both sources interface with the grid via the MPC, each comprising a slack port (s), voltage-control port (v) for voltage and frequency control, and power-control port (p) for active and reactive power control. This design enables the coordinated control of the energy sources, power flow, and system stability.

The converters are linked through a meshed network of four transmission lines: Line-1 (Bus-1–Bus-3), Line-2 (Bus-3–Bus-2), Line-3 (Bus-1–Bus-4), and Line-4 (Bus-4–Bus-2). Two aggregated loads are connected: Load-1 at Bus-3 and Load-2 at Bus-4, with the rated power shown in Figure 4. For comparison, the conventional system (Figure 2) replaces the MPCs with transformers (TR-1 and TR-2) while maintaining the same topology, lines, and load distribution as the proposed system. This benchmark allows for the direct evaluation of the benefits of the MPC-based configuration for small-scale power systems in terms of controllability, and reliability. In addition, the two configurations are compared under the same network topology, the same transmission lines, the same external sources, and the same load distribution. The only structural difference is the replacement of the power transformer in the conventional system by multi-port power converters in the modified system.

The reliability of both configurations was assessed using the CTMC method, which models the system states and transitions based on exponentially distributed component failure and repair rates. Key reliability indices, including LOLP, LOLE, EENS, and reliability, were derived from this model. The analytical model was validated using a Monte Carlo simulation with 1,500,000 trials, and the same indices as those in the CTMC were used for calculations. The reliability algorithm was implemented in Python (version 3.12) using an integrated development environment (IDE)-Spyder.

3.6. Input Data: Failure Rates, Repair Rates, Capacities

The reliability assessment relies on input data, including failure rates and repair rates for generators, transformers, transmission lines, and power routers. The failure and repair rates of external sources, such as steam generators, power transformers, and power transmission lines, were obtained from the Electrical Transient Analyzer Program (ETAP) software component database. Regarding the power router ports, each port is considered an independent inverter, including the DC link; thus, the failure and repair rates are obtained from [33], which calculates the equivalent failure and repair rates for each port. In addition, the equivalent failure and repair rates are calculated for the groups External Source-1 & Transformer-1, External Source-2 & Transformer-2, and External Source-1 & Slack Port-1, External Source-2 & Slack Port-2. The determination of the equivalent groups is shown

in Figure 5, which graphically illustrates how two components connected in series can be represented as a single equivalent component. The capacities of the traditional and modified test systems, including the 490 MW total generation and monthly mean load presented in Figure 4, were used to model the system's performance. Table 1 lists the data considered for the reliability assessment of both the systems.

Table 1. Components failure and repair rates.

Component	Capacity (MW)	λ (f/Year)	μ (r/Year)
External Source 1/2	250/240	0.032	37.43
Power Transformers	—	0.013	23.86
Power Router Ports	—	1.000	1752
Power Lines	—	0.024	1095
Source 1/2 + TR	—	0.045	32.14
Source 1/2 + s-Port	—	1.032	722.57

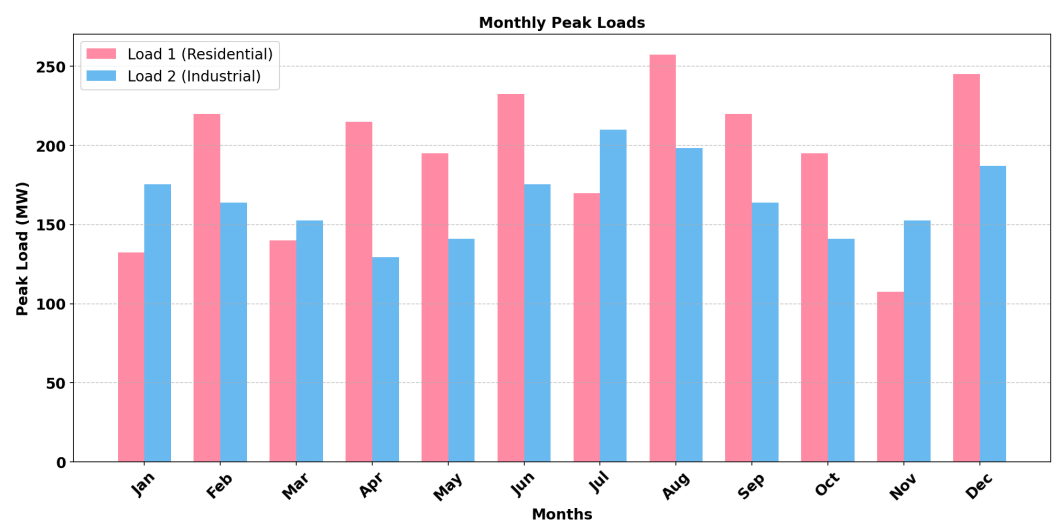


Figure 4. Monthly load power demand.

The power demand is presented through the load curve in Figure 4 for every month of the year, showing a realistic demand, where the peak demand occurs in July.

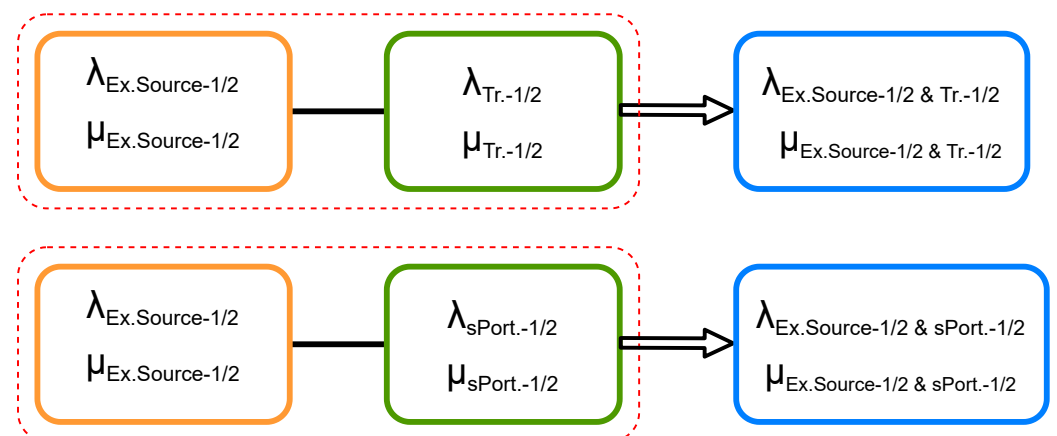


Figure 5. System reduction reliability block-diagram.

4. Results and Discussion

The selected double-fed benchmark was intentionally adopted as a representative test system to evaluate the reliability impact of replacing conventional transformers with power

routers under identical assumptions, thereby enabling a transparent and controlled comparison between the two architectures. In addition, reliability assessment was performed for both the conventional transformer-based configuration and the modernized power-router-based configuration using the CTMC and validated by the MCS with 1,500,000 trials. Table 2 summarizes the annual indices, and Figures 6–10 illustrate the graphical comparison of LOLE and EENS under different modeling approaches. Additionally, Figure 9 presents the system reliability index for each system configuration evaluated based on the CTMC and MCS approaches.

Table 2. Reliability indices for Power Transformer and Power Router.

Topology Method	Power Transformer		Power Router	
	CTMC	MCS	CTMC	MCS
LOLP	0.002794	0.002819	0.004031	0.004066
LOLE (h/yr)	24.48	24.70	35.31	35.62
EENS (MWh)	2819.42	2845.30	6363.16	6420.85
Reliability	0.9972	0.9971	0.9960	0.9959

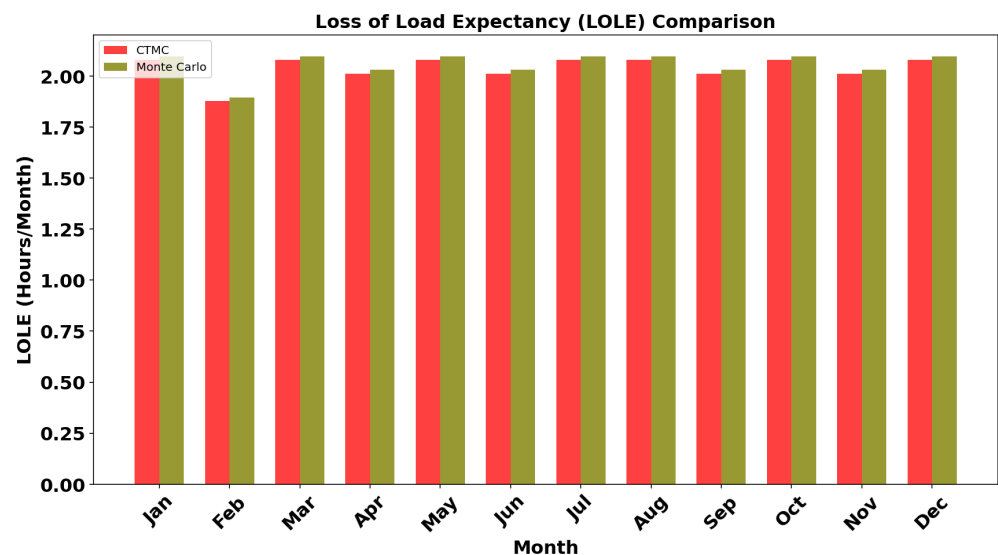


Figure 6. LOLE for the power transformer-based topology assessed by CTMC and MCS.

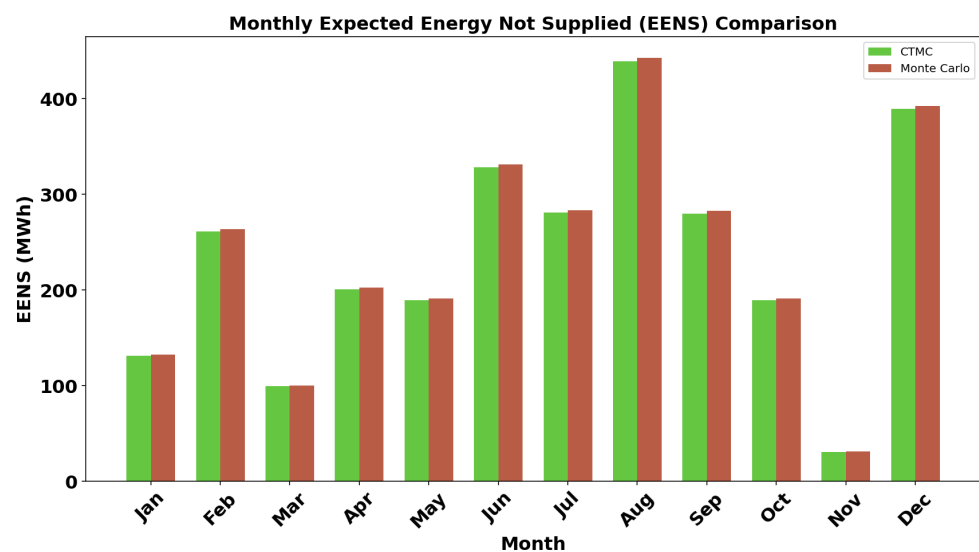


Figure 7. EENS for the power transformer-based topology assessed by CTMC and MCS.

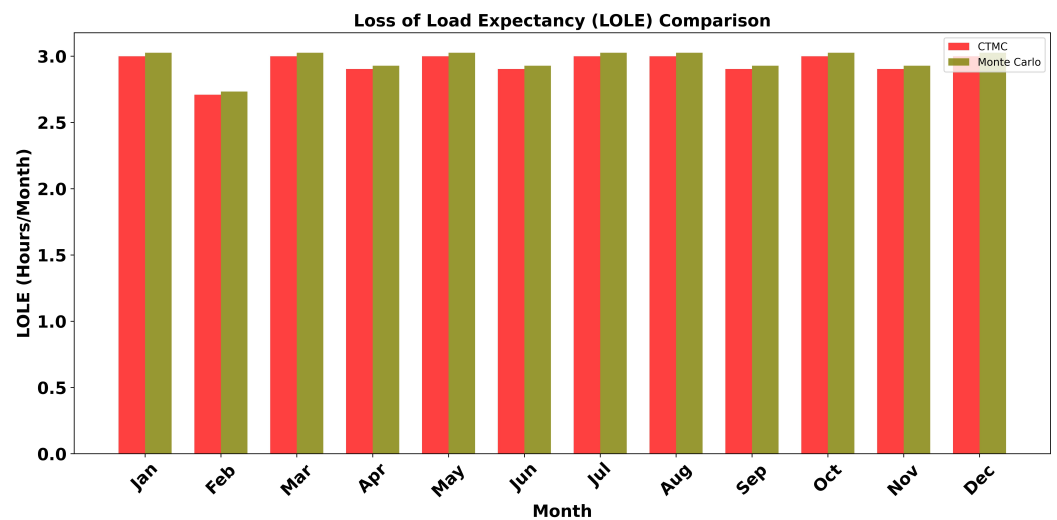


Figure 8. LOLE for the power router-based topology assessed by CTMC and MCS.

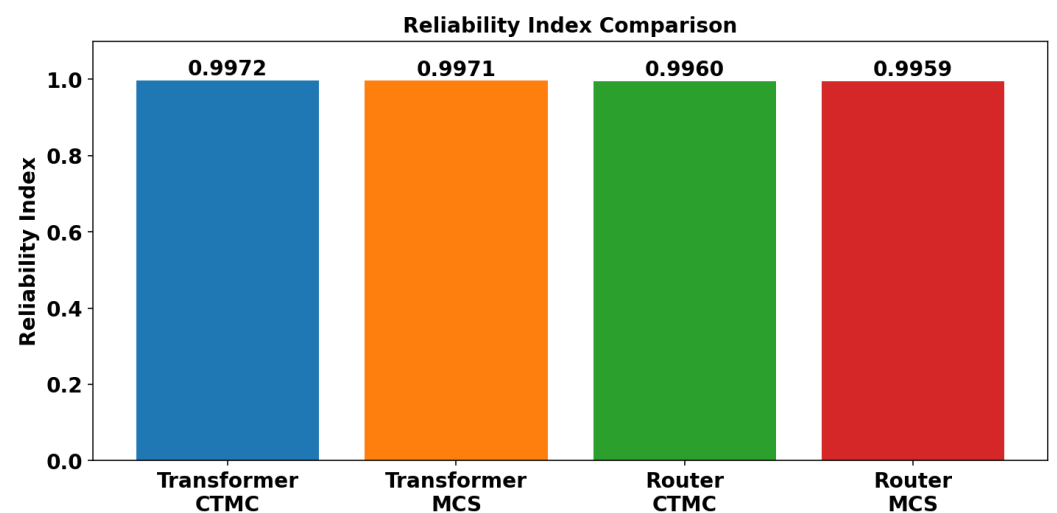


Figure 9. Reliability index for the power transformer and power router-based topology assessed by CTMC and MCS.

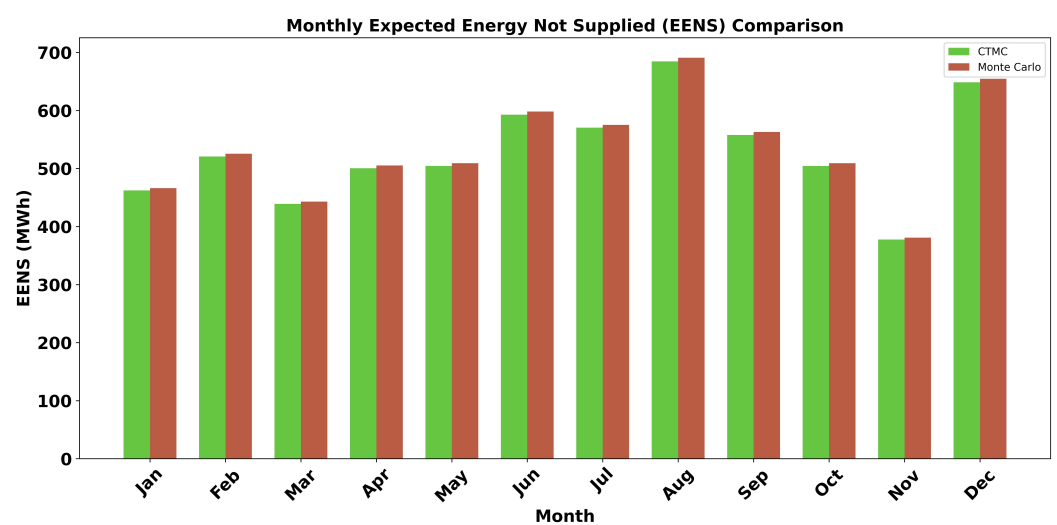


Figure 10. EENS for the power router-based topology assessed by CTMC and MCS.

For the transformer-based configuration, the LOLP was estimated to be approximately 0.002794, with a corresponding LOLE of approximately 24.48 h/year, and an EENS of

2819.42 MWh/year. In contrast, the router-based system exhibited slightly higher LOLP of 0.004031, LOLE of 35.31 h/year, and EENS of 6363.16 MWh/year. These results indicate that the integration of multi-port power converters decreases system reliability (from 99.72% to 99.60%) and increases both the frequency and severity of supply interruptions.

Despite the higher reliability indices of the conventional system, the power-router-based configuration offers enhanced operational flexibility as stated in Section 2, particularly in terms of renewable energy integration and controllability. The increase in the LOLE and EENS can be attributed to the additional failure modes introduced by the ports of the multi-port converters, which act as critical points in the topology. Furthermore, regarding the computational methods, the discrepancy between the CTMC and MCS results remained within 1%, confirming the robustness of the analytical framework and the consistency of the stochastic validation. In addition, the proposed CTMC-non-sequential MCS framework represents a compromise between modeling fidelity and computational tractability. CTMC methods become computationally demanding for large-scale systems due to state-space explosion, whereas both CTMC and non-sequential MCS are not naturally suited to time-dependent degradation mechanisms associated with component aging and wear-out behavior. Although sequential MCS can capture these phenomena, its computational burden increases significantly with the system size. Furthermore, this study focuses exclusively on reliability performance and does not consider techno-economic aspects, such as investment costs, maintenance strategies, replacement policies, or life-cycle economics. Therefore, scalable reliability assessment methods capable of incorporating time-dependent failures, together with integrated techno-economic evaluations, remain important areas for future research.

The findings emphasize that although power routers introduce reliability penalties under constant failure/repair assumptions, their ability to reconfigure networks and support renewable penetration provides a functional advantage that outweighs the observed reliability trade-offs. Thus, their adoption must be coupled with appropriate redundancy strategies, such as port reassignment during failures, to mitigate risks and enhance the adequacy of future power grids.

Based on the modeling assumptions (two-state components with constant failure and repair rates), the transformer-based configuration achieved better adequacy metrics than the power router arrangement, exhibiting lower LOLP and LOLE, and a markedly lower EENS. The main source of the reliability disparity is the extra port-level failure modes of multi-port converters, which increase the number of system-failure states; also, the failure and repair rate value is higher than that of the transformer (see Table 1).

5. Conclusions and Future Research

This study developed and verified a CTMC-based framework for the reliability evaluation of two alternative double-fed system configurations: a conventional transformer-based arrangement and a multi-port converter topology. The framework was validated via Monte Carlo simulations, which confirmed that it provides stable reliability metrics suitable for systematic comparative analyses. To make the problem more tractable, the analysis used two-state models with constant failure and repair rates and assumed statistically independent failures.

Therefore, this study establishes a transparent reference point for examining the reliability trade-offs arising from the deployment of multi-port power converters in a small-scale network versus conventional system deployment. Furthermore, although multi-port converters enhance the operational flexibility and control capabilities of power systems, their integration into power system architectures is expected to exhibit lower reliability because of the power valve elements. Indeed, individual ports have substantially higher

failure rates and are much more sensitive to faults than robust devices, such as transformers. Nevertheless, although this general idea is intrinsically correct, this study offers distinctive quantitative evidence indicating that, given the assumptions adopted, the actual increase in failure ratios is moderate and the converter-based option remains viable from a reliability perspective. These findings open new discussion pathways, wherein converters provide operational advantages and, with targeted redundancy or port-reassignment strategies, can be deemed acceptable from an adequacy standpoint. This analysis does not account for deployment costs, maintenance strategies, or life-cycle expenses, all of which remain crucial subjects for future investigation.

It is worth noting that the proposed model provides a tractable benchmark rather than a complete representation of all failure interactions in meshed converter-based systems. Therefore, the present results should be interpreted as a comparative baseline under identical assumptions. At the same time, future work is foreseen to extend the framework to include common-mode failures, cascading effects, and non-exponential degradation processes, including Weibull-based sensitivity analyses, enabling evaluation of the reliability impact of converter-based architectures under more realistic operating conditions based on multi-state, semi-Markov, or dependency-aware reliability models.

In this perspective, future research, extending the current baseline, should prioritize several main directions:

- Incorporating models with non-exponential lifetime distributions to represent aging and wear-out effects more precisely;
- Investigating dependent and common-mode failures affecting ports and transmission lines;
- Assessing scalability on extensive, meshed benchmark grids under renewable and load fluctuations;
- Evaluating the impact of redundancy and dynamic reconfiguration (such as port reassignment) on adequacy metrics.
- Integrating deployment, maintenance, and life-cycle costs to support a comprehensive techno-economic evaluation.

Collectively, these efforts will enhance applicability and provide practical insights for implementing multi-port power converter technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

CTMC	Continuous-Time Markov Chain
MCS	Monte Carlo Simulation
RES	Renewable Energy Sources
ESS	Energy Storage Systems

EVs	Electric Vehicles
DER	Distributed Energy Resources
DTMC	Discrete-Time Markov Chain
SMSP	Semi-Markov Stochastic Process
PV	Photovoltaic
MBESS	Mobile Battery Energy Storage Systems
FMEA	Failure Modes and Effects Analysis
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
ECOST	Energy Cost Index
MPC	Multi-Port Power Converter
ETAP	Electrical Transient Analyzer Program
IDE	Integrated Development Environment
RBD	Reliability Block Diagram
LOLP	Loss of Load Probability
LOLE	Loss of Load Expectation
EENS	Expected Energy Not Supplied
HVDC	High-Voltage Direct Current
LCC-VSC	Line-Commutated Converter–Voltage Source Converter
PRG	Power Router Grid
AC/DC	Alternating Current/Direct Current
MW	Megawatt
MWh	Megawatt-hour

References

1. Bhattacharjee, A.K.; Kutkut, N.; Batarseh, I. Review of Multiport Converters for Solar and Energy Storage Integration. *IEEE Trans. Power Electron.* **2019**, *34*, 1431–1445. [\[CrossRef\]](#)
2. Rodriguez-Bernuz, J.M.; Prieto-Araujo, E.; Girbau-Llistuella, F.; Sumper, A.; Villafila-Robles, R.; Vidal-Clos, J.A. Experimental validation of a single phase Intelligent Power Router. *Sustain. Energy Grids Netw.* **2015**, *4*, 1–15. [\[CrossRef\]](#)
3. Rodriguez-Bernuz, J.M.; Gadelha, V.; Bullich-Massagué, E.; Sumper, A. Droop-based power routers for enhanced resilience in networked grids. *Electr. Power Syst. Res.* **2025**, *243*, 111475. [\[CrossRef\]](#)
4. Gadelha, V.; Sumper, A.; Bullich-Massagué, E.; Aragüés-Peñalba, M. Electrical grids based on power routers: Definition, architecture and modeling. *IEEE Access* **2023**, *11*, 10004–10017. [\[CrossRef\]](#)
5. Gadelha, V.; Bullich-Massagué, E.; Sumper, A. Optimal Power Flow in electrical grids based on power routers. *Electr. Power Syst. Res.* **2024**, *234*, 110581. [\[CrossRef\]](#)
6. Gevorkov, L.; Dominguez-Garcia, J.L.; Romero, L.T.; Martinez, A.F. Modern multiport converter technologies: A systematic review. *Appl. Sci.* **2023**, *13*, 2579. [\[CrossRef\]](#)
7. Ross, S.M. *Introduction to Probability Models*; Academic Press: Cambridge, MA, USA, 2014.
8. Trivedi, K.S., Discrete-Time Markov Chains. In *Probability and Statistics with Reliability, Queuing and Computer Science Applications*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2016; Chapter 7, pp. 351–419. [\[CrossRef\]](#)
9. Trivedi, K.S., Continuous-Time Markov Chains. In *Probability and Statistics with Reliability, Queuing and Computer Science Applications*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2016; Chapter 8, pp. 421–576. [\[CrossRef\]](#)
10. Yadav, A.; Nandal, N.; Malik, S.; Malik, S. Markov approach for reliability-availability-maintainability analysis of a three unit repairable system. *Opsearch* **2023**, *60*, 1731–1756. [\[CrossRef\]](#)
11. Bani-Ahmed, A.; Rashidi, M.; Nasiri, A.; Hosseini, H. Reliability analysis of a decentralized microgrid control architecture. *IEEE Trans. Smart Grid* **2018**, *10*, 3910–3918. [\[CrossRef\]](#)
12. Taher, M.A.; Iqbal, H.; Roy, S.; Tufail, S.; Tariq, M.; Sarwat, A.I. Continuous Markov-based reliability analysis of underground vault in distribution power systems. In *Proceedings of the 2024 IEEE Texas Power and Energy Conference (TPEC)*; IEEE: Piscataway, NJ, USA, 2024; pp. 1–6.
13. Wu, L.; Wen, C.; Ren, H. Reliability evaluation of the solar power system based on the Markov chain method. *Int. J. Energy Res.* **2017**, *41*, 2509–2516. [\[CrossRef\]](#)
14. Cai, B.; Liu, Y.; Ma, Y.; Huang, L.; Liu, Z. A framework for the reliability evaluation of grid-connected photovoltaic systems in the presence of intermittent faults. *Energy* **2015**, *93*, 1308–1320. [\[CrossRef\]](#)

15. Liu, M.; Xiong, Y.; Li, Q.; Murad, M.A.A.; Zhong, W. Higher-Order Markov Chain-Based Probabilistic Power Flow Calculation Method Considering Spatio-Temporal Correlations. *Energies* **2025**, *18*, 1058. [\[CrossRef\]](#)
16. Nguyen, N.; Mitra, J. Reliability of power system with high wind penetration under frequency stability constraint. *IEEE Trans. Power Syst.* **2017**, *33*, 985–994. [\[CrossRef\]](#)
17. Bo, Y.; Bao, M.; Yang, B.; Ding, Y.; Huang, Y. A semi-markov stochastic model for operational reliability assessment of hybrid AC and LCC-VSC-based DC system with remote wind farms. *IEEE Trans. Power Syst.* **2024**, *39*, 6154–6167. [\[CrossRef\]](#)
18. Raghuwanshi, S.S.; Arya, R. Reliability evaluation of stand-alone hybrid photovoltaic energy system for rural healthcare centre. *Sustain. Energy Technol. Assessments* **2020**, *37*, 100624. [\[CrossRef\]](#)
19. Chen, Y.; Zheng, Y.; Luo, F.; Wen, J.; Xu, Z. Reliability evaluation of distribution systems with mobile energy storage systems. *IET Renew. Power Gener.* **2016**, *10*, 1562–1569. [\[CrossRef\]](#)
20. Ostovar, S.; Esmaeili-Nezhad, A.; Moeini-Aghtaie, M.; Fotuhi-Firuzabad, M. Reliability assessment of distribution system with the integration of photovoltaic and energy storage systems. *Sustain. Energy Grids Netw.* **2021**, *28*, 100554. [\[CrossRef\]](#)
21. Peyghami, S.; Blaabjerg, F.; Palensky, P. Incorporating power electronic converters reliability into modern power system reliability analysis. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *9*, 1668–1681. [\[CrossRef\]](#)
22. Adefarati, T.; Bansal, R. Reliability assessment of distribution system with the integration of renewable distributed generation. *Appl. Energy* **2017**, *185*, 158–171. [\[CrossRef\]](#)
23. Allan, R.; Jebril, Y.; Saboury, A.; Roman, J. Monte Carlo simulation applied to power system reliability evaluation. In *Proceedings of the 10th Advances in Reliability Technology Symposium*; Springer: Berlin/Heidelberg, Germany, 1988; pp. 149–162.
24. Li, W.; Billinton, R. *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.
25. Guimarães, I.O.; da Silva, A.M.L.; Nascimento, L.C.; Fotuhi-Firuzabad, M. Reliability assessment of distribution grids with DG via quasi-sequential Monte Carlo simulation. *Electr. Power Syst. Res.* **2024**, *229*, 110122. [\[CrossRef\]](#)
26. Hampannavar, S.; Longe, O.M.; Himabindu, N.; Deepa, B.; Swapna, M. Reliability modeling and assessment of a community microgrid with electric vehicle charging station as a critical load. *E-Prime Electr. Eng. Electron. Energy* **2024**, *8*, 100610. [\[CrossRef\]](#)
27. Anand, M.; Bagen, B.; Rajapakse, A. Probabilistic reliability evaluation of distribution systems considering the spatial and temporal distribution of electric vehicles. *Int. J. Electr. Power Energy Syst.* **2020**, *117*, 105609. [\[CrossRef\]](#)
28. Hou, K.; Xu, X.; Jia, H.; Yu, X.; Jiang, T.; Zhang, K.; Shu, B. A reliability assessment approach for integrated transportation and electrical power systems incorporating electric vehicles. *IEEE Trans. Smart Grid* **2016**, *9*, 88–100. [\[CrossRef\]](#)
29. Xu, W.; Zeng, S.; Du, X.; Zhao, J.; He, Y.; Wu, X. Reliability of active distribution network considering uncertainty of distribution generation and load. *Electronics* **2023**, *12*, 1363. [\[CrossRef\]](#)
30. Allan, R.N.; Billinton, R. *Reliability Evaluation of Power Systems*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.
31. Wang, Y.; Vittal, V.; Abdi-Khorsand, M.; Singh, C. Probabilistic reliability evaluation including adequacy and dynamic security assessment. *IEEE Trans. Power Syst.* **2019**, *35*, 551–559. [\[CrossRef\]](#)
32. Yu, H.H.; Chang, K.H.; Hsu, H.W.; Cuckler, R. A Monte Carlo simulation-based decision support system for reliability analysis of Taiwan's power system: Framework and empirical study. *Energy* **2019**, *178*, 252–262. [\[CrossRef\]](#)
33. Dong, J.; Chen, P. Reliability Evaluation of Multi-terminals VSC-HVDC System. *J. Electr. Syst.* **2015**, *11*, 342–352.

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