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Statistical Failure Analysis and Reliability Indices Estimation in a Medium-Voltage Distribution System

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***Summary* — This paper presents a statistical failure analysis of data obtained from the DISPO system for the purpose of evaluating the reliability and maintainability of a medium-voltage distribution network. Failure occurrences and outage durations are analyzed using statistical methods to model reliability behavior and downtime characteristics. Based on the processed data, key reliability and maintainability indicators are determined. Emphasis is placed on maintainability assessment through the evaluation of repair times and their influence on system availability. Standard distribution system performance indices are calculated, including the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), Mean Time Between Failures (MTBF), and Mean Time To Repair (MTTR). These indicators enable the identification of critical components and network sections with the greatest impact on overall system performance. The obtained results support condition-based maintenance planning and targeted reliability improvement measures. The proposed approach demonstrates how historical outage records can be systematically utilized to enhance operational decision-making and improve the reliability performance of distribution systems.**

***Keywords* — Failure statistics, Reliability assessment, Distribution network performance, Maintainability modeling.**

I. Introduction

Ensuring high reliability of electric power distribution networks is a central objective of modern power system planning and operation, as interruptions at distribution level directly affect end-users and the wider economy. Regulatory frameworks in many countries explicitly link utility performance incentives or penalties to continuity of supply, which is monitored through standardized reliability metrics [2]. At the same time, increasing integration of dispersed generation, aging infrastructure, and evolving customer expectations are making distribution networks more complex to operate and more exposed to stochastic failure mechanisms. In thiscontext, quantitative assessment of reliability is essential not only for regulatory reporting, but also for asset management, network planning, and optimization of maintenance strategies in medium-voltage (MV) distribution systems.

Distribution system reliability is commonly evaluated using continuity indices such as the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI). However, to obtain unbiased and statistically meaningful reliability indices, utilities must rely on structured, complete and consistently coded outage data collected over several years. This requires dedicated information systems that integrate operational event recording with network topology and customer data, as implemented for example in the Croatian DISPO (DIStribucijska POuzdanost) - Information System for Identification and Monitoring of Distribution Reliability.

A substantial body of literature addresses statistical analysis of failures and estimation of reliability indices in MV distribution networks using historical outage databases [3], [4], [5], [6]. Many early and contemporary works focus on calculating SAIDI, SAIFI and related indices from recorded outages to characterize performance of specific feeders or substations, often in the form of case studies on real distribution utilities [7], [8]. These studies typically classify outages by cause and voltage level, and then compute annual customer- and load-oriented indices to identify critical feeders or regions with systematically poor reliability. More recent contributions emphasize statistical modeling of failure processes and restoration-related times in MV networks, moving beyond simple index calculation. Clavijo-Blanco et al. provide a detailed statistical characterization of key reliability parameters such as time between failures, time to locate the fault, switching time and repair time, using MV outage data from a European distribution system operator and fitting appropriate probability distributions to each parameter [3]. Building on this, a later work by the same research group introduces an integrated Monte Carlo-based algorithm for statistical characterization of reliability indices in real MV networks, explicitly accounting for the probabilistic distribution of SAIDI and SAIFI and their economic implications via penalty-based schemes [4]. Other authors propose methodologies to estimate component failure rates for overhead lines, underground cables and transformers directly from large incident databases, showing that utilityspecific failure rates can significantly deviate from generic handbook values and thereby improve prediction of future interruptions and reliability indices [9]. Recent analyses of MV and LV distribution grids highlight that adverse weather conditions, equipment faults and operational interventions are major contributors to unplanned outages and to the deterioration of SAIDI and SAIFI [10].

In the Croatian setting, works presented at HRO CIGRE and HO-CIRED have used DISPO-based outage statistics to compare reliability performance across different distribution areas, dem-

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onstrating significant differences in SAIDI and SAIFI levels and pointing to the impact of planned outages and maintenance practices on overall continuity of supply [11]-[13]. Authors in [1] discuss distribution reliability and quality of supply in Croatia, with emphasis on continuity indices, regulatory requirements and use of operator databases for reliability monitoring and planning.

II. Dataset Description

The dataset used in this study originates from the DISPO information system, which is employed for recording, monitoring, and analyzing operational events in Croatian power distribution networks. DISPO represents a centralized outage management and reliability tracking platform integrating event logging, classification, and performance indicator calculation within a unified relational database environment. Operational events are entered manually into the system by authorized personnel following the occurrence or completion of an outage. The accuracy and consistency of the dataset therefore depend on standardized reporting procedures and predefined classification catalogues embedded within the system. Each recorded event is uniquely labeled and associated with detailed technical and operational descriptors, enabling traceability and structured analysis. Outages are categorized according to predefined event types. The classification of outage types used in this study is summarized in Table I, where planned outages (Type A) and forced outages (Type B) are distinguished. This categorization allows separate evaluation of reliability and maintainability indicators in accordance with established power system reliability assessment methodologies. The system architecture supports hierarchical aggregation across organizational units, plants, voltage levels, feeders, and components, enabling multi-level performance analysis.

The analyzed dataset consists of approximately 57,000 recorded events covering the period from 2006. to 2024. The records span multiple voltage levels and organizational units within the distribution system.

Each dataset entry contains the following attributes:

- Label – unique event identifier
- Organizational Unit – responsible operational entity
- Plant – substation or supply facility
- Field – network section identifier
- Type – outage classification
- Voltage – operating voltage level
- Start – outage start timestamp
- Duration (min) – interruption duration in minutes
- Pmax (kW) – maximum interrupted power
- ENS (kWh) – Energy Not Supplied
- Affected Customers – number of impacted customers
- Customer Minutes – aggregated outage duration across all affected customers
- Description – textual event description
- Cause – categorized failure cause
- Fault – fault type classification
- Fault Location – specific equipment location
- Unit – operational unit designation
- Component – affected network component
- Feeder Type – feeder classification
- Entry Date – data entry timestamp

A schematic representation of the dataset structure and parameter interrelations is presented in Fig. 1.

Raw data showed trailing commas in the final row and string types with comma decimals; these were fixed by artifact removal, comma-to-dot replacement, and type conversion (float/int for numerics). Sustained outages (>3 min) were filtered, preparing data for reliable index estimation and statistical analysis.

A specific subset of records associated with so-called EKVI fields was excluded from the analysis. EKVI fields were used in the early stages of DISPO implementation, when measurement points were not yet properly linked to individual low-voltage (LV) feeders within medium-voltage/low-voltage (MV/LV) substations. At that time, the total number of customers was distributed across substations and feeders proportionally according to installed transformer power, in order to approximate customer allocation. Consequently, customer counts associated with EKVI records represent estimated rather than actual values, introducing significant uncertainty in SAIDI and SAIFI calculations. Following the introduction of the Informator system and subsequently the SAP Informator platform, measurement points were progressively linked to specific and accurately defined LV feeders. As a result, feederlevel customer counts are now largely accurate. Remaining discrepancies are primarily due to incomplete or inaccurate customer address data and represent an estimated error margin below 5%. A small number of measurement points remain unassigned, but their impact on aggregated reliability indicators is negligible. Due to the inherent uncertainty of EKVIbased allocation, approximately 12,000 records (±20% of the original dataset) were removed from the analysis to ensure statistical consistency. A total of 151 records (less than 0.3% of the dataset) were removed due to corrupted CSV formatting or encoding-related anomalies.

TABLE I:
DISPO Fault Types

Code	Type	Description
A1	Planned	Elimination of fault consequences
A2	Planned	Regular maintenance
A3	Planned	Construction of facilities/network
A4	Planned	Construction of facilities/connections
A5	Planned	Fault consequences (force majeure)
A6	Planned	Fault consequences (third parties)
A7	Planned	Maintenance of third-party facilities
A8	Planned	Construction third-party network
A9	Planned	Construction third-party connections
A10	Planned	Supply network
B11	Forced	Distribution generator
B10	Forced	Supply network
B14	Forced	Malfunction
C13	Outage by order	By NDC (OPS) order
C12	Outage by order	By Supply order

III. Methodology

The simplified architecture of the Distribution System is presented in Fig. 2. The methodological framework adopted in this study consists of data preprocessing, event filtering, location-based aggregation, and reliability index computation. For reliability and availability assessment, only Type B outages are considered, as

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	Label	Organizational Unit	Plant	Field	Type	Voltage	Start	Duration (min)	Pmax (kW)	ENS (kWh)
0	2264/25	ELEKTRA BJELOVAR-POGONSKI URED VELIKI GRĐEVAC	TS 10/0.4 kV DONJA KOVAČICA	1-DRAŽICA	B11	0.4	2025-11-02 17:16:00	82.0	4.0	5.24
1	2262/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 20/0.4 kV MALE SREDICE	2-BREZOVAC	B11	0.4	2025-11-02 08:47:00	71.0	8.0	9.08
2	2261/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 10/0.4 kV PRESPA - CIGLENA	2-PRESPA-ZIDANA	B14	0.4	2025-11-01 07:26:00	56.0	4.0	3.58
3	2260/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 10/0.4 kV BJELOVAR 1	10-M. BOGOVIĆA	B11	0.4	2025-10-31 19:43:00	40.0	4.0	2.56
4	2258/25	ELEKTRA BJELOVAR-POGONSKI URED VELIKI GRĐEVAC	TS 10/0.4 kV BEDENIK 1	1-PREMA BEDENIKU 2	B14	0.4	2025-10-31 17:28:00	65.0	4.0	4.16
5	2259/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 10/0.4 kV PREDAVAC - CENTAR	4-PREDAVAC 2	B11	0.4	2025-10-31 16:22:00	198.0	4.0	12.66
6	2257/25	ELEKTRA BJELOVAR-POGON KRIŽEVCI	TS 10/0.4 kV MARINOVAC 2	2-PREMA KLETIMA	B11	0.4	2025-10-31 13:16:00	143.0	4.0	9.14
7	2256/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 10/0.4 kV DONJA NARTA	1-GORNJA NARTA	B14	0.4	2025-10-31 11:50:00	52.0	8.0	6.65
8	2255/25	ELEKTRA BJELOVAR-SJEDIŠTE	TS 20/0.4 kV TAD 1	TP-TRAFO POLJE	A2	20.0	2025-10-31 09:15:00	65.0	173.0	178.15
9	2253/25	ELEKTRA BJELOVAR-POGON KRIŽEVCI	TS 10/0.4 kV ZRINŠĆINA	EKVITP-EKVITP	A2	10.0	2025-10-31 09:05:00	66.0	35.0	36.18

	Affected Customers	Customer Minutes	Description	Cause	Fault	Fault Location	Unit	Component	Feeder Type	Entry Date
0	1.0	82.0	NEMA FAZE	-	-	-	-	-	N	2025-11-02 18:56:00
1	1.0	71.0	NEMA FAZE	-	-	-	-	-	K	2025-11-02 10:01:00
2	1.0	56.0	NEMA STRUJE.	TU6-prolazan kvar	NVO OO 25A U KPMO-U.	zračna dionica - priključak (priključni vod, t...	ZD	PRKV	N	2025-11-01 08:21:00
3	1.0	40.0	NEMA FAZE	-	-	-	-	-	K	2025-10-31 20:23:00
4	1.0	65.0	ZASTOJ NA OMM: 0600602425 - nema jedne faze	TU5-preopterećenje	zamjenjen nvo 00 25a u kpmou	zračna dionica - priključak (priključni vod, t...	ZD	PRKV	N	2025-10-31 18:34:00
5	1.0	198.0	NEMA STRUJE	-	-	-	-	-	N	2025-10-31 19:40:00
6	1.0	143.0	NEMA FAZE	-	-	-	-	-	N	2025-10-31 15:39:00
7	10.0	520.0	NEMA STRUJE	TU6-prolazan kvar	ZAMJENJEN VU 50A U SEKCIJSKOM PANCERU.	zračna dionica - selektivni osigurač	ZD	SOSG	N	2025-10-31 12:42:00
8	33.0	2145.0	MAJERIĆ, UGRADNJA SUMARNOG BROJILA	-	-	-	-	-	K	2025-10-31 09:15:00
9	56.0	3696.0	VRANEŠIĆ, UGRADNJA SUMARNOG BROJILA	-	-	-	-	-	N	2025-10-31 09:05:00

Fig. 1. Sample DISPO dataset.

they represent stochastic failure events. Maintainability assessment includes both Type A and Type B events. Fig.3 shows the distribution of fault types.

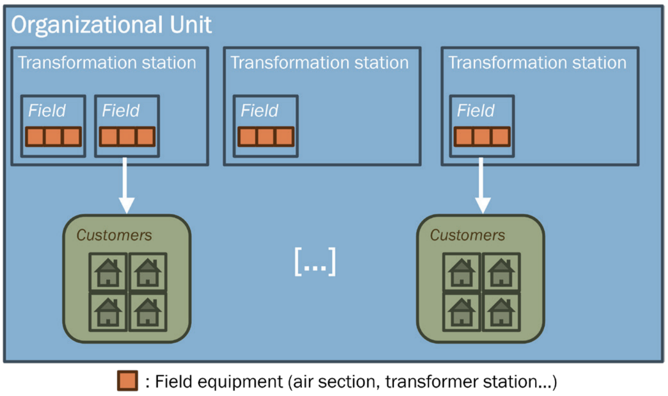

Fig. 2. System architecture of power distribution.

A. Fault Location and Field Analysis

1) Most Frequent Failure Locations: The identification of the most frequent locations of unplanned interruptions represents a primary step in reliability assessment. Failure locations were analyzed primarily according to the attribute Field. In the majority of cases, the field name contains the designation of a street, settlement, or geographically identifiable area, enabling spatial grouping of events at a meaningful operational level. This approach allows aggregation of interruptions by geographically coherent network segments and facilitates the identification of critical areas contributing most significantly to system reliability degradation.

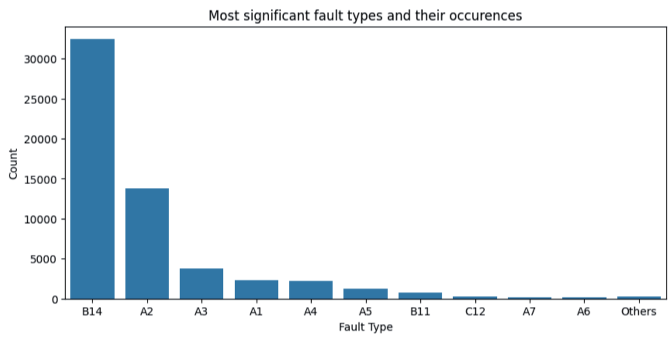

Fig. 3: Distribution of fault types (A: Planned, B: Forced, C: By order) in DISPO dataset (N=57k records).

2) Equipment Distribution per Location: Since each location comprises multiple components, it is necessary to examine the failure frequency of individual elements within the most critical locations. If a single component dominates failure occurrences at a given site, corrective actions such as equipment replacement, enhanced monitoring, or intensified preventive maintenance should be considered to improve operational performance.

B. Reliability Analysis

Reliability evaluation requires the exclusive consideration of forced outages (Type B faults), as these represent unplanned disruptions directly affecting system performance. Two standard performance indicators are used: the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). A high SAIDI combined with low SAIFI indicates infrequent but long-lasting outages, suggesting repair inefficiencies. Conversely, low SAIDI with high SAIFI reflects frequent but short interruptions, implying good repair capability but poor reliability. Simultaneously high SAIDI and SAIFI values indicate inadequate system reliability and maintainability.

1) SAIDI: SAIDI represents the average outage duration experienced by a customer:

$$SAIDI = \frac{\sum_{i=1}^{N} U_i \cdot N_i}{N_{\text{tot}}} \quad (1)$$

where U_i is the duration of the interruption event i [min], N_i is the number of customers affected by the interruption i, N_{tot} is the total number of customers in the observed system, and N is the total number of interruption events in the observed period.

2) SAIFI: SAIFI represents the average interruption frequency per customer:

$$SAIFI = \frac{\sum_{i=1}^{N} N_i}{N_{\text{tot}}} \quad (2)$$

where N_i is the number of customers affected by the interruption i, N_{tot} is the total number of customers, and N is the total number of interruption events.

C. Maintainability Analysis

Maintainability analysis includes both planned (Type A) and unplanned (Type B) outages. Two key indicators are evaluated: Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR).

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1) MTBF: MTBF represents the average operational time between consecutive failures:

$$MTBF = \frac{T_{\mathrm{op}}}{N_f} \tag{3}$$

where T_{op} is the total system operating time during the observation period [h], and N_f is the total number of forced outages (failures). If constant failure rate is assumed:

$$\lambda = \frac{1}{MTBF} \tag{4}$$

2) MTTR: MTTR represents the average repair duration per failure:

$$MTTR = \frac{T_{\mathrm{rep}}}{N_f} \tag{5}$$

where T_{rep} represents the total repair time associated with failures [h].

IV. Results and Discussion

A. Faults Analysis

The spatial distribution of recorded failures is presented in Fig. 4, which illustrates the number of outages aggregated by settlement (based on the Field attribute). Since field names typically correspond to street names or residential areas, this aggregation provides a geographically meaningful representation of failure concentration within the observed distribution network.

The results indicate a non-uniform distribution of failures across settlements. A limited number of locations account for a disproportionately large share of total interruptions, suggesting localized reliability weaknesses. Such concentration may be attributed to aging infrastructure, environmental exposure, network topology characteristics, or higher load density.

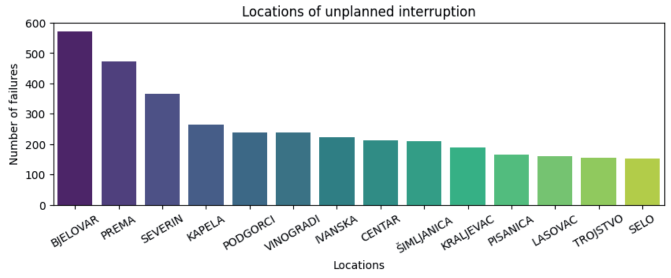

Fig. 4. Most common fault locations.

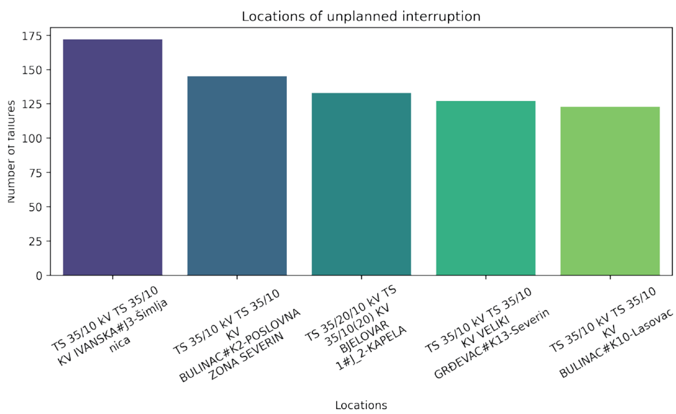

Fig. 5. Most common fault Fields.

To further refine the analysis, Fig. 5 presents the three fields with the highest number of recorded failures over the observed period. These locations represent the most critical network segments from a reliability perspective. The dominance of these fields in total outage count confirms the need for targeted maintenance and potential infrastructure reinforcement in these areas.

Equipment with the most failures in three locations is presented in Fig. 6.

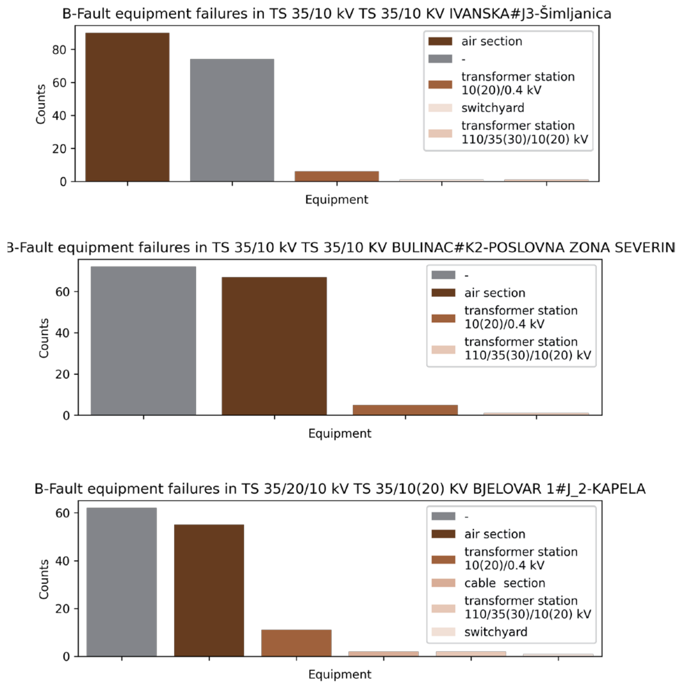

Fig. 6. Most common equipment failure.

The identified critical fields were subsequently analyzed in terms of their contribution to global reliability indices.

B. Reliability Indices

The temporal evolution of failures is shown in Fig. 7, where outages are aggregated by year and month. The results reveal seasonal variations in interruption frequency, with noticeable peaks during specific periods. These peaks may be associated with adverse weather conditions, increased loading, or operational stress factors typical for distribution systems.

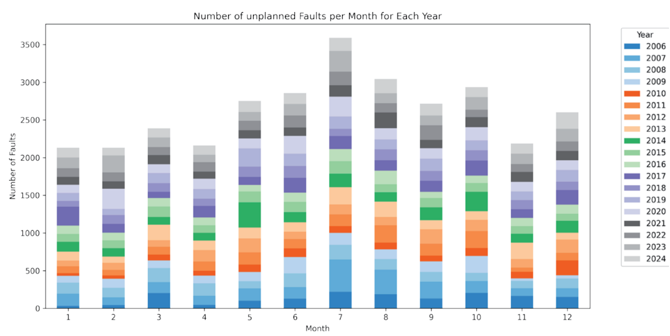

Fig. 7. Failures per month.

It can be observed that the majority of failures occur during the summer months. This seasonal concentration may be associated with the predominant failure mechanisms identified in the dataset.

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In particular, air sections represent one of the most frequent fault locations, which suggests a possible correlation with elevated ambient temperatures and associated thermal stress. Higher temperatures can increase conductor sag, mechanical stress, and the likelihood of insulation degradation, thereby contributing to a higher interruption rate during summer periods. The reduced number of failures during the winter period is primarily driven by climatic factors, such as a lower frequency of atmospheric overvoltages and vegetation dormancy, concurrently accompanied by a decrease in construction activities and general operational workloads during the winter months. The distribution infrastructure of Croatia is exposed to highly diverse environmental stressors due to its distinct climate zones. The continental interior—encompassing the Bjelovar distribution area—is characterized by a moderate continental climate. In this zone, the primary meteorological threats to overhead line reliability include seasonal lightning activity, severe summer windstorms, and winter ice loading events.

The calculated system-wide SAIDI and SAIFI are presented in Fig. 8 and Fig. 9. It can be observed from the temporal analysis of the reliability indices that both SAIFI and SAIDI exhibit a general decreasing trend over the analyzed years. This trend indicates an overall improvement in the continuity of supply and reliability performance of the distribution network. Such positive development can be attributed to systematic investments in network modernization, enhanced maintenance planning, replacement of aging infrastructure, and the implementation of condition-based maintenance practices that resulted from the structured reliability assessment enabled by the DISPO system. Among the concrete measures implemented, the transition to a 20 kV operating voltage is particularly prominent. Consequently, as part of the preparation and retrofitting of the network for 20 kV operation, obsolete equipment is systematically replaced, thereby minimizing the long-term duration and frequency of electricity supply interruptions [14].

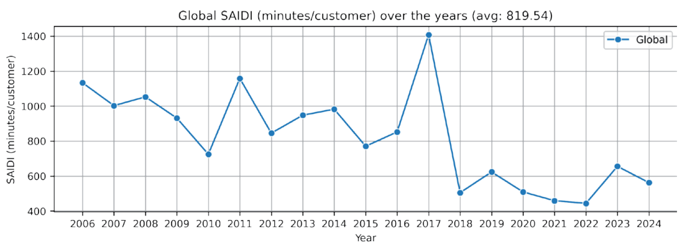


Fig. 8. System wide SAIDI evolution.

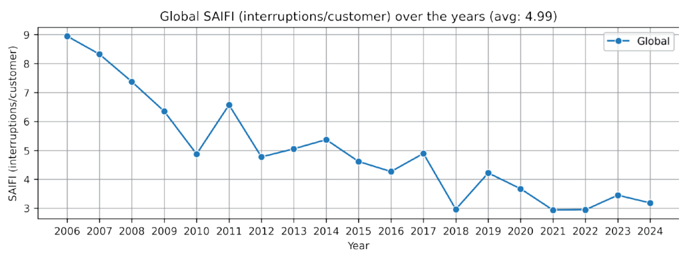
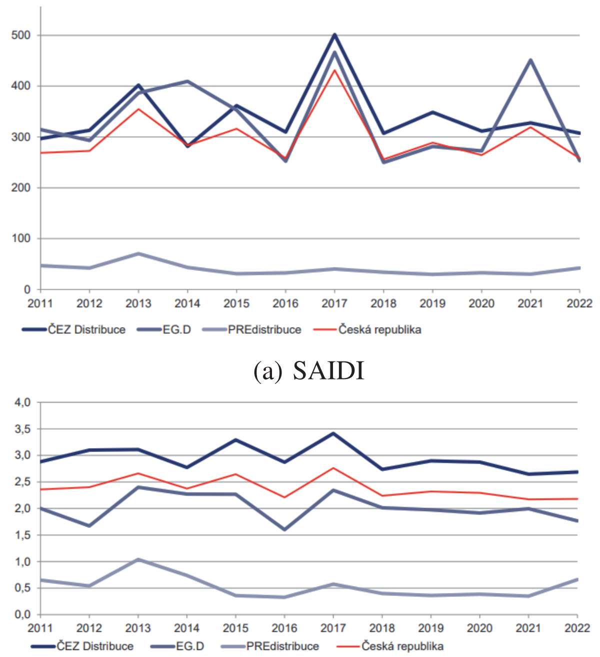


Fig. 9. System wide SAIFI evolution.

A notable exception to this trend occurred in 2017, where both SAIFI and SAIDI values show an elevated deviation relative to the surrounding years. This anomaly corresponds to an exceptionally warm summer in Croatia, which has been climatologically characterized as extremely warm with seasonal temperature anomalies reaching up to approximately 4.0 °C above the long-term average at several monitoring stations, including Bjelovar [15].

To facilitate a benchmarking evaluation, Fig. 10a and 10b display the historical reliability trends of the Czech distribution grid via SAIDI and SAIFI metrics.



(a) SAIDI

(b) SAIFI

Fig. 10. SAIDI and SAIFI for the Czech DSO [16].

The comparative analysis highlights the steady-state nature and high stability of the Czech power system. Concurrently, data from the Bjelovar distribution area demonstrate a pronounced trend of technological and operational advancement, characterized by a steady reduction in both interruption duration and frequency. The projection of this observed trend suggests an imminent performance convergence of the Bjelovar grid with the reference Czech indicators, thereby validating the efficacy of the implemented network modernization measures.

C. Maintainability Indicators

For the three locations with the highest number of faults, the annual MTTR and MTBF were calculated. The results are presented in Fig 11 and Fig 12, illustrating the comparative reliability and maintenance performance at the selected sites.

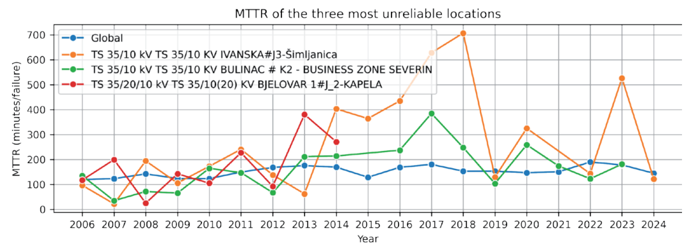


Fig. 11. Annual MTTR for the three locations with the highest number of faults.

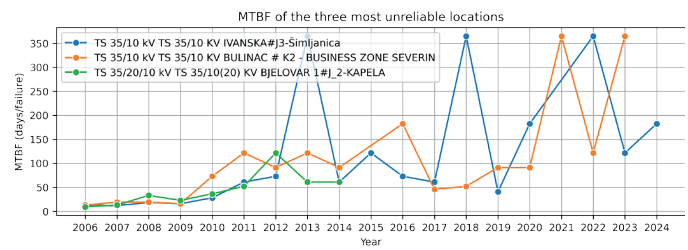


Fig. 12. Annual MTBF for the three locations with the highest number of faults.

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Fig 13 shows the distribution of faults and maintenance activities across the months of the year.

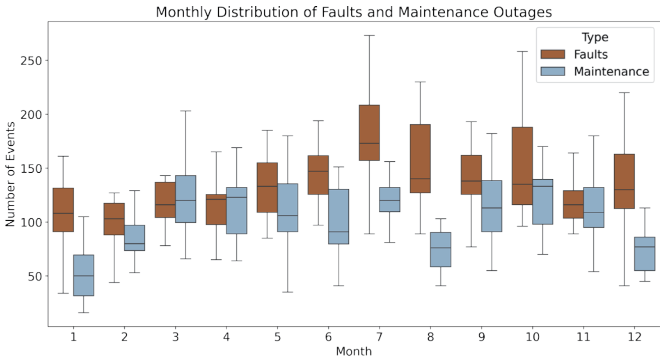

Fig. 13. Distribution of faults and maintenance activities per month.

As can be seen, the highest number of faults occurs during the summer months, while maintenance activities are reduced in August, likely due to annual holidays. Lower maintenance levels are also noticeable in winter, which can be attributed to both public holidays and adverse weather conditions. The box plot representation highlights the variability, median, and outliers for each month, providing insight into seasonal trends in network reliability and maintenance workload.

V. Conclusion and Future Work

Although the analyzed dataset exhibits certain limitations—such as historical gaps due to asset renaming during network revitalization, a 20% omission rate in manual records resulting from equivalence grouping, and a high proportion of unclassified fault causes designated as null values—it nevertheless provides a statistically sound foundation for validating grid performance. The empirical trends established over the analyzed period demonstrate a positive trajectory, characterized by a continuous increase in the Mean Time Between Failures and a concurrent reduction in both SAIDI and SAIFI indices, thereby confirming a measurable improvement in overall system reliability. Furthermore, the spatial-temporal distribution of recurring faults has successfully isolated specific grid segments requiring prioritized capital investment and infrastructure revitalization. Concurrently, preliminary evaluations reveal correlations between localized meteorological stressors and fault occurrences. To build upon these findings, substantial scope remains for future research, particularly regarding the quantification of Energy Not Served (ENS) and the evaluation of associated macroeconomic losses. While data-driven methodologies are increasingly vital for modern distribution systems, the fidelity of the generated insights remains inherently constrained by data quality. Consequently, integrating automated data acquisition pipelines with multi-dimensional operational parameters—such as realtime weather telemetry and advanced asset health metrics—is imperative to enhance the robustness of predictive analytics. Ultimately, this study demonstrates that even in the presence of partial data constraints, structured reliability monitoring yields highly actionable insights that effectively guide targeted investments, optimize maintenance scheduling, and enhance grid performance.

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