OPERATIONAL MANAGEMENT OF THE ELECTRICITY DISTRIBUTION SYSTEM IN THE ERA OF DIGITALIZATION AND ARTIFICIAL INTELLIGENCE

MANAGEMENTUL OPERAȚIONAL AL SISTEMULUI DE DISTRIBUȚIE A ENERGIEI ELECTRICE ÎN ERA DIGITALIZĂRII ȘI A INTELIGENȚEI ARTIFICIALE

Valentin DOBRE [1],

Abstract: *The paper presents original contributions on operational management in a distribution network in the context of digitalization and energy transition. The role of artificial intelligence as a support for operators and for increasing network resilience is highlighted. The paper indicates the main functions and objectives of operational management, presents performance indicators and data on a case study related to the Bucharest-Ilfov distribution network. A comparative analysis between SCADA, ADMS and AI-based systems is presented, together with relationships, figures and tables illustrating the evolution of SAIDI/SAIFI indicators, network losses, distributed energy source integration (DER), battery energy storage systems (BESS) and electric vehicle charging infrastructure (EVCS (16)).*

Keywords: Operational management, artificial intelligence (AI), SCADA, ADMS, FLISR, AMI, BESS, DER, electric vehicle charging infrastructure (EVCS), power quality, SAIDI/SAIFI, energy transition.

Rezumat: *În lucrare se prezintă contribuţii originale privind managementul operaţonal într-o reţea de distribuţie în contextul digitalizării şi tranziţei energetice. Este pus în evidenţă rolul inteligenţei artificiale ca suport al operatorilor şi pentru creşterea rezilienţei reţelei. În lucrare sunt indicate principalele funcţiuni şi obiective ale managementului operaţional, sunt prezentaţi indicatorii de performanţă precum şi date privind un studiu de caz relativ la reţeaua de distribuţie Bucureşti-Ilfov. Este prezentată o analiză compartaivă între SCADA, ADMS şi sistemele bazate pe IA, împreună cu relaţii, figuri şi tabele care ilustrează evoluţia indicatorilor SAIDI/SAIFI, pierderile din reţea, integrarea* surselor distribuite de energei (DER), sistemele

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[1] Inginer, România, email: validobre@gmail.com

cu baterii de stocare a energiei (BESS) şi infrastructura pentru încărcarea vehiculleor electrice (EVCS (16)).

Cuvinte cheie: Management operațional, inteligență artificială (AI), SCADA, ADMS, FLISR, AMI, BESS, DER, infrastructură de încărcare a vehiculelor electrice (EVCS), calitatea energiei electrice (power quality), SAIDI/SAIFI, tranziția energetică.

1. Introduction

The operational management of the distribution system (DSO) forms the foundation for the safe and efficient operation of power networks. It ensures the balance between consumption and generation, compliance with power quality standards, and continuity of service.

Key factors currently influencing operational management include:

- the increasing penetration of distributed renewable sources (photovoltaics, wind, cogeneration);
- the emergence of reverse power flows in 20 kV and 0.4 kV networks;
- the development of electric mobility (300–600 kW charging stations for EVs and electric trucks);
- the integration of Battery Energy Storage Systems (BESS) at transformer substations and primary stations;
- digitalization and smart grids (ADMS, IoT, AI) [14].

2. Objectives and functions of operational management

The management of the distribution system plays a key role in ensuring that users receive electrical energy of appropriate quality and under safe operating conditions. In this regard, its objectives and functions are of major importance.

The main objectives include:

a) Operational Safety, as a set of measures, procedures, and technologies aimed at maintaining continuity in the supply of electrical energy;

b) Supply continuity – achieved through the control and monitoring of quality indicators such as SAIDI and SAIFI.

c) Power Quality – Maintaining Voltage and Frequency in Accordance with EN 50160.

d) Economic Optimization – Reduction of Technical and Commercial Losses.

e) Integration of New Technologies – Adapting to Energy Transition Requirements.

The main functions of management include:

- Real-Time Monitoring through SCADA and DMS.
- Operation under Normal Conditions – Voltage Regulation and Load Redistribution.
- Operation under Disturbed Conditions – Fault Isolation and Service Restoration.
- Outage Management – Rapid Fault Location and Field Intervention.
- Power Flow Management – Congestion Avoidance.
- Coordination with the Transmission System Operator (TSO) – Maintaining National Balance.

3. Performance indicators

The main indicators used to assess the performance of the distribution system operator are SAIDI and SAIFI.

SAIDI represents the average outage duration experienced by a consumer over a given period, usually one year.

SAIFI defines the average frequency of long-duration interruptions in the network (system) for a user, expressed as the average number of interruptions experienced by customers connected to the distribution network.

Table 1 presents the values of these indicators determined for the Bucharest–Ilfov area, highlighting the efforts of the distribution system operator to improve the quality of the energy supplied to users in the region.

Table 1 – **Evolution of Performance Indicators**

Year	SAIDI (min/an)	SAIFI (n/an)	ENS (MWh)
2021	180	1.8	12.4
2023	140	1.4	9.6
2024	100	1.0	6.8

4. Modern support technologies

The network operator has at its disposal several digital platforms that support the achievement of its objectives:

- SCADA/DMS – Monitoring and Control.

- ADMS – Integration of GIS, OMS, and DSM.
- FLISR – Fault Location, Isolation, and Service Restoration.
- DERMS – Control of Distributed Energy Resources and BESS.
- AMI – Smart Metering Infrastructure.

Table 2 provides a comparative overview of the main functions of SCADA, ADMS, and AI-based applications.

Table 2 – **Comparison between SCADA, ADMS, and AI**

Characteristic	**SCADA**	**ADMS**	**AI-based Operation**
Monitoring	Real-time monitoring of key network parameters	Integration with GIS and OMS systems for unified network visualization	Predictive monitoring based on machine learning (ML) models
Control	Remote execution of switching operations, manual or scheduled	Partial automation of control and network reconfiguration	Adaptive automation and real-time decision-making optimized by AI
Decision-making	Fully dependent on human operators	Operator-assisted decisions based on predefined rules and scenarios	Autonomous decisions based on artificial intelligence and multi-objective optimization algorithms
DER Integration	Limited integration of distributed energy resources (DERs)	Moderate integration with basic DERMS functionalities	Advanced integration with DERMS platforms and coordinated optimization of distributed resources

The development of artificial intelligence and its specific applications for power systems will play an important role in enhancing their performance.

5. The role of artificial intelligence

5.1. Applications of Artificial Intelligence Used in Operational Management

- **Forecasting – Load and Renewable Energy Forecasting [4]**

In distribution networks, energy consumption forecasting plays a crucial role in resource planning and in defining operational strategies. For example, by employing artificial intelligence algorithms, operators can perform short-term load forecasting for the next 24 hours, which enables optimal power flow management, loss reduction, and the efficient integration of intermittent renewable sources such as photovoltaic and wind generation.

Figure 1 shows the forecasted energy usage curve generated using the AI application, compared with the actual usage level. A strong correlation can be observed between the data provided by the AI application and the real measurements, which is also evident from Table 1.

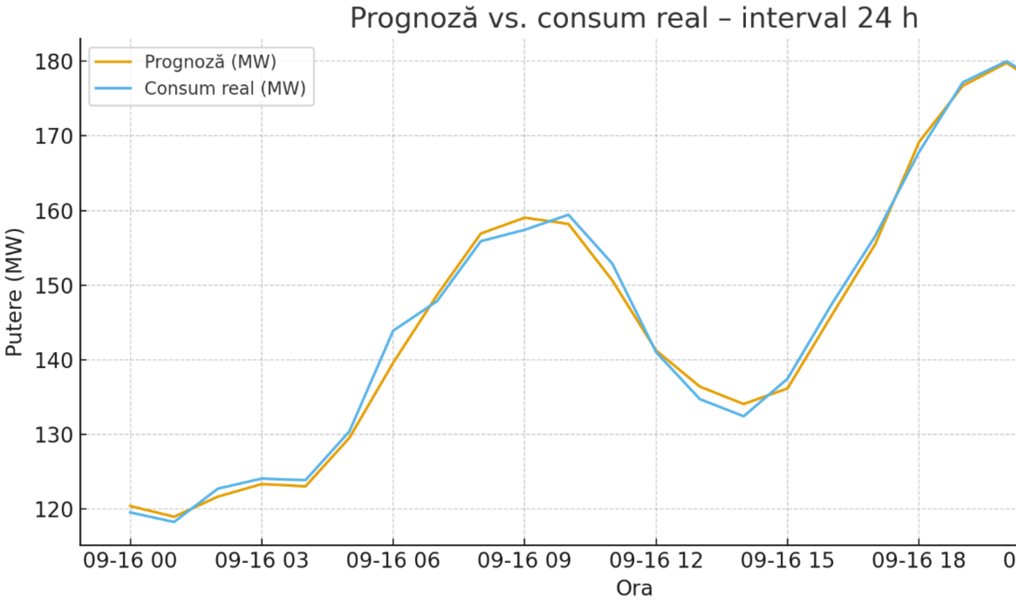

Figure 1. Forecast vs. Actual Consumption

Table 3. Forecast Data vs. Actual Consumption (24h)

Time	Forecast (MW)	Real electricity consumption (MW)	Error (MW)	Error
00:00	120,43	119,57	-0,86	-0,7
01:00	118,99	118,29	-0,7	-0,5
02:00	121,69	122,76	1,07	0,8
03:00	123,37	124,1	0,73	0,5
04:00	123,07	123,9	0,83	0,6
05:00	129,56	130,42	0,86	0,6
06:00	139,62	143,91	4,29	2,9
07:00	148,67	147,86	-0,81	-0,5

08:00	156,92	155,9	-1,02	-0,6
09:00	159,05	157,42	-1,63	-1,0
10:00	158,21	159,44	1,23	0,7
11:00	150,65	152,9	2,25	1,4
12:00	141,26	141,04	-0,22	-0,1
13:00	136,42	134,74	-1,68	-1,2
14:00	134,09	132,45	-1,64	-1,2
15:00	136,18	137,48	1,3	0,9
16:00	145,9	147,39	1,49	1,0
17:00	155,48	156,57	1,09	0,7
18:00	169,16	167,83	-1,33	0,7
19:00	176,71	177,18	0,47	0,2
20:00	179,78	180,01	0,23	0,1
21:00	175,94	176,38	0,44	0,2
22:00	169,51	171,25	1,74	1,0
23:00	156,21	156,65	0,44	0,2

- **Anomaly Detection – Identification of Operational Anomalies in SCADA**

Data Anomaly detection refers to the process of identifying patterns, behaviors, or values that deviate significantly from predefined norms or expectations, indicating potential errors, malfunctions, or critical events. In the context of power networks, anomaly detection enables the early recognition of atypical situations in SCADA/AMI data, such as sudden voltage fluctuations, unusual energy losses, or non-compliant equipment behavior, thus facilitating rapid intervention and preventing incidents.

- **Predictive Maintenance – Transformer Condition Monitoring Using Sensor Data and Machine Learning Algorithms**

Predictive maintenance represents an advanced equipment maintenance strategy that relies on operational data analysis, forecasting algorithms, and artificial intelligence models to anticipate failures before they occur. Unlike traditional preventive maintenance, which is based on predefined time intervals or operating cycles, predictive maintenance focuses on the continuous monitoring of operating parameters (temperature, vibrations, currents, dielectric losses, dissolved gas content in oil, etc.) and on the early detection of deviations from normal operating conditions.

In power networks, predictive maintenance applied to transformers, circuit breakers, and medium- and high-voltage cables enables the optimization of equipment lifetime, reduction of costs associated with unplanned outages, and improvement of supply reliability for consumers.

- **Optimal Power Flow (OPF) – Algorithms for Optimal Power Flow (OPF) are used to reduce technical losses in distribution networks and to optimize load allocation.**

Optimal Power Flow (OPF) is a complex optimization problem applied in power systems to determine the optimal distribution of active and reactive power flows, in order to minimize operational costs and technical losses while respecting system operating and security constraints. In its general formulation, OPF includes an objective function (e.g., minimization of generation cost, Joule losses, or pollutant emissions) and a set of constraints (power flow equations, voltage limits, line capacity, maximum generator output, and N-1 security conditions). The implementation of OPF algorithms [7], [8] in modern transmission and distribution networks enables operators to make optimal decisions regarding unit commitment, voltage control, and renewable integration, thereby improving the efficiency, reliability, and sustainability of the power system.

- **Decision Support – Decision support systems assist distribution network operators in selecting optimal reconfiguration solutions and in using expert systems integrated into ADMS**

Decision support refers to the set of methods, software tools, and information systems designed to aid decision-making in complex and dynamic contexts. These systems integrate operational data, analytical algorithms, and predictive models to provide operators, managers, and decision-makers with structured information, alternative scenarios, and recommendations.

In the energy sector, decision support systems enhance operational management of distribution networks by integrating data from SCADA, AMI, and forecasting platforms. This enables operators to select optimal reconfiguration strategies, reduce losses, and ensure compliance with safety and power quality standards.

More broadly, decision support applies to other critical domains—such as IT, healthcare, or transport—where the analysis of large volumes of data and pattern recognition support faster, evidence-based, and more effective decision-making.

5.2. Benefits of Using Artificial Intelligence in Operational Management

The main benefits generated by artificial intelligence applications in the power system are outlined below.

- **Reduction of Response Time**

The reduction of response time is a key indicator of operational efficiency, defined as the shortening of the interval between the occurrence of an event (fault, deviation, intervention request) and the application of a corrective or preventive action. In power networks, this improvement is made possible through infrastructure digitalization, the integration of artificial intelligence algorithms, and the use of decision support platforms, which allow operators to identify the root causes of incidents more rapidly and restore service in minimal time.

The implementation of FLISR [10] and AI-assisted operational control has reduced incident response times by more than 35% compared to conventional solutions.

- **Increased Decision Accuracy**

Increased decision accuracy refers to the process of reducing uncertainty and improving the technical and economic justification of decisions, by integrating real-time data, forecasting algorithms, and decision support systems. In distribution networks, this leads to optimal selection of reconfiguration actions, appropriate control of power flows, and prioritization of investments based on their impact on system reliability and efficiency. The integration of AI-based decision support platforms has improved the accuracy of decisions concerning automatic network reconfiguration, with a direct impact on reducing SAIDI and SAIFI indices.

- **Flexibility for the Integration of EVCS [16] and DER**

The flexibility of distribution networks in the context of integrating Electric Vehicle Charging Stations (EVCS) and Distributed Energy Resources (DER) refers to the system's ability to adapt safely, efficiently, and sustainably to variations in load and generation. This requires advanced automation solutions, dynamic power flow control, and the use of digital technologies such as artificial intelligence and decision support platforms.

Direct impacts include:

– optimization of existing infrastructure utilization;

– reduction of grid modernization costs;

– higher penetration of EVs and renewables without compromising system stability.

6. Case study – Bucharest–Ilfov

The use of modern command-and-control platforms, together with the implemented measures, has led to an improvement in the performance of the distribution system operator.

a) Modernization Measures

- Conversion of 110 kV overhead lines into underground cables (Fundeni–Afumați, Fundeni–CET Brazi).
- Modernization of the Fundeni–Pipera 110 kV line.
- Automation of 110 kV substations.
- Integration of high-power EV charging stations.
- Implementation of rooftop PV systems contributing to self-consumption in residential and commercial buildings in Voluntari and Otopeni.

b) Implementation of AI and FLISR

- **AI-based Voltage–Reactive Power Control Algorithm**.

AI-driven voltage–reactive power control algorithms allow dynamic adjustment of equipment settings (on-load tap-changing transformers, static compensators, PV inverters), ensuring that voltage remains within permissible limits and optimizing reactive power consumption under variable load conditions and high renewable penetration.

Role and applicability:

- optimization of voltage profiles in distribution and transmission networks;
- minimization of technical losses by controlling reactive power flows;
- management of renewable integration (PV, wind) that causes voltage fluctuations;
- implementation using methods such as Artificial Neural Networks (ANN), genetic algorithms, reinforcement learning, or fuzzy logic.

- **FLISR [10] – 35% Reduction in Restoration Time**

The implementation of FLISR solutions in medium-voltage distribution networks has led to an average reduction of approximately 35% in service restoration time, by automatically locating faults, rapidly isolating the affected section, and re-energizing healthy sections through alternative network configurations.

Direct impacts:

- increased network reliability;
- reduced outage duration for customers;
- lower costs associated with penalties for failing to meet quality indicators (SAIDI/SAIFI).

- **AMI – 23% Reduction in Technical Losses (CPT)**

AMI consists of smart meters, communication systems, and IT platforms that enable real-time collection, transmission, and analysis of consumption and power quality data.

The deployment of smart metering infrastructure (AMI) in distribution networks has resulted in an average 23% reduction in technical losses (CPT), through improved consumption transparency, identification of commercial losses, and network operation optimization.

Benefits of AMI implementation include:

- *reduction of commercial losses by detecting unauthorized consumption and energy theft;*
- *improved accuracy of measurement and billing;*
- *optimization of transformer and network loading through consumption profile analysis;*
- *reduction of technical losses through better grid sizing and reconfiguration.*

c) Results

- **20% Reduction in SAIDI**

Through advanced grid automation and the integration of FLISR functionalities, a 20% reduction in SAIDI was achieved, demonstrating significant improvements in reliability and customer satisfaction.

Direct impacts:

- improved supply continuity;
- reduced costs associated with regulatory penalties;
- alignment with European objectives on distribution service quality.

- **30% Reduction in Voltage Complaints**

The implementation of online power quality monitoring programs, on-load tap-changing transformers, and AI-based voltage–reactive power control algorithms resulted in a 30% reduction in customer complaints regarding voltage levels, demonstrating robust improvements in reliability and consumer satisfaction.

Direct impacts:

- enhanced quality of distribution services;
- fewer costly operational interventions;
- compliance with ANRE regulations and European standards.

7. Comparative analysis

Table 4 and Figures 3 and 4 present the results obtained following the implementation of modern operational management solutions at the analyzed network operator.

Table 4 – **Evolution of Technical Losses (CPT)**

Year	CPT (%)	Reduction compared to 2021
2021	6.2	–
2023	5.5	11%
2024	4.8	23%

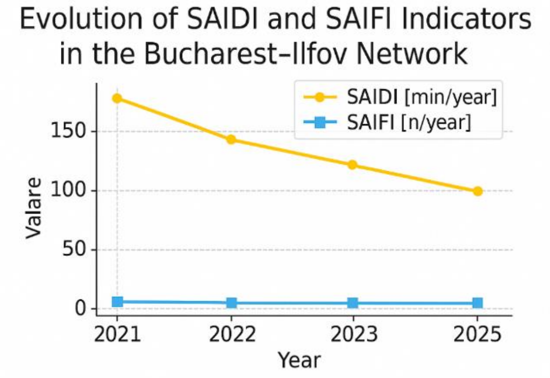

Fig. 3 – Evolution of SAIDI/SAIFI

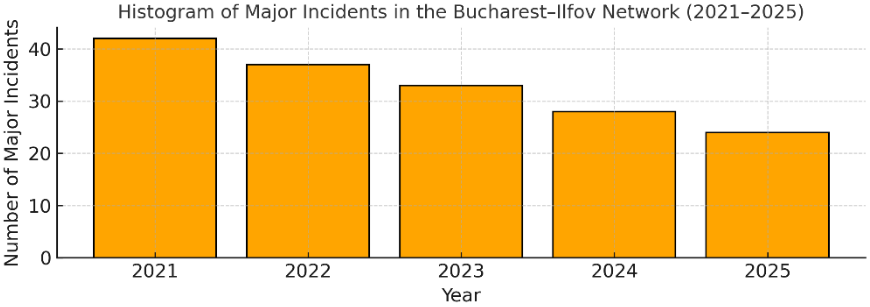

Fig. 4 – Incident Histogram (2021–2025)

8. Challenges and future directions

Of course, the implementation of modern systems within operational management also involves a series of challenges that must be appropriately addressed and resolved.

- **EVs and BESS → Requirement for Load Balancing Algorithms**

The integration of Electric Vehicle (EV) charging stations and Battery Energy Storage Systems (BESS) creates new challenges related to load balancing. When simultaneous demand exceeds the transfer capacity of local distribution networks, advanced algorithms are required to manage energy flows, prioritizing charging according to dynamic criteria (cost, State of Charge – SOC, consumption profile, network availability). Such algorithms can be implemented in smart charging platforms or energy management systems (EMS), ensuring optimized resource utilization and reduced impact on the distribution grid.

- **Cybersecurity Risks in Control Centers**

The increased digitalization of power networks and the transition from SCADA to integrated ADMS (Advanced Distribution Management Systems) heighten the exposure of critical infrastructure to cyberattacks. Control centers, as central hubs of command and monitoring, are particularly sensitive targets for denial-of-service (DoS) attacks, unauthorized access, or manipulation of operational data. Mitigation requires strict cybersecurity policies, continuous monitoring, IT/OT network segmentation, and compliance with international standards such as IEC 62443 and the NIST Cybersecurity Framework.

- **Transition to Autonomous Microgrids with Self-Healing Capabilities**

Autonomous microgrids represent a crucial step in the energy transition, allowing islanded operation in the event of main grid failures and enabling the optimal integration of Distributed Energy Resources (DER). Self-healing capabilities rely on advanced automation technologies, intelligent sensors, and real-time reconfiguration algorithms that detect and isolate faults while restoring service to unaffected consumers. This enhances system resilience, reduces SAIDI/SAIFI indicators, and creates the foundation for more flexible and secure operations.

9. Conclusions

AI-assisted operational management [9] improves the safety, reliability, and flexibility of power networks. The Bucharest–Ilfov case study demonstrates reductions in technical losses (CPT) and in SAIDI/SAIFI indices through the implementation of AI, FLISR [10], and AMI.

The integration of Artificial Intelligence (AI) into operational management of distribution networks marks an essential step in the process of digitalization and the energy transition. By applying machine learning algorithms, predictive models, and real-time analytics, AI enables a proactive approach to distribution system management.

Main benefits include:

- Safety: AI enables rapid anomaly detection, identifies trends leading to potential failures, and supports automated corrective actions, thus reducing the risk of major incidents.
- Reliability: Advanced functionalities such as Fault Location, Isolation and Service Restoration (FLISR) shorten restoration times after outages, thereby lowering SAIDI and SAIFI values.
- Flexibility: By integrating with Advanced Metering Infrastructure (AMI) and with forecasting platforms for demand and distributed generation, AI facilitates network adaptation to dynamic load conditions, increases renewable penetration, and optimizes reactive power flow.

Case Study – Bucharest–Ilfov:

The analysis of the Bucharest–Ilfov metropolitan distribution network highlights the positive impact of digitalization and automation:

- Reduction of Technical Losses (CPT): AMI deployment reduced both commercial and technical losses by ~23%, due to continuous monitoring and rapid detection of unauthorized consumption.
- Improvement of Continuity Indices (SAIDI/SAIFI): The integration of FLISR solutions combined with AI-based decision support reduced outage duration and frequency by ~20–35%, contributing to higher consumer satisfaction.
- Improved Voltage Quality: AI-based voltage–reactive control algorithms and on-load tap-changing transformers led to a ~30% reduction in customer complaints regarding voltage levels outside permissible limits.

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Authors' biographies

Valentin DOBRE graduated in 2001 from the Politehnica University of Bucharest, Faculty of Electrical Engineering, specializing in Metrology and Measurement Systems. In 2004, he completed a master's program at the same faculty, specializing in Intelligent Sensors, Distributed Measurement Systems, and Information Security. Currently, he is a third-year Ph.D. student at the National University of Science and Technology POLITEHNICA Bucharest, within the Doctoral School of Energy Engineering, in the Fundamental Field of Engineering Sciences, specializing in Energy Engineering. He works at Rețele Electrice România, in the Department of Design and Execution of IT, Medium Voltage, and Low Voltage Works for the Muntenia region, where I hold the position of Site Manager.

Email: validobre@gmail.com