

# Technical Study Guide for Local Flexibility Services in Distribution Networks

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# 1 Introduction

## Objectives of the Study

The objective of this document is to serve as a comprehensive technical guide for the preparation of a research-oriented interview at **RSE – Ricerca sul Sistema Energetico**, focusing on the position “*Simulation and experimentation of schemes for local flexibility services*” (Ref. *TGM7-2025-RAC*).

The document consolidates theoretical foundations, computational methods, and practical insights spanning distribution network modeling, power flow analysis, flexibility mechanisms, and control theory. It is designed to enable a deep and structured understanding of the multi-disciplinary topics relevant to this research area, bridging electrical engineering, optimization, and automation.

The final goal is to achieve:

- A solid grasp of the physical and mathematical models underlying distribution networks.
- The ability to simulate and analyze power flow and flexibility activation using numerical tools.
- Understanding of the regulatory and market context for local flexibility in Europe and Italy.
- The capability to apply control and optimization methods to power system operation problems.

## Position Requirements Overview

According to RSE’s call for applications (Ref. *TGM7-2025-RAC*, 2025), the role requires a multidisciplinary background including:

- Modeling and simulation of electrical distribution networks, including *Power Flow* and *Optimal Power Flow (OPF)* analysis.
- Understanding of electricity markets and regulatory frameworks, particularly concerning DSOs and ancillary services.
- Knowledge of optimization and control techniques for energy systems.
- Familiarity with scientific programming environments (MATLAB, Python, Julia).

Preferred qualifications also include experience in:

- Research projects funded by national or European programs (e.g., Horizon, PNRR).
- Advanced control (predictive, optimal, robust) and optimization techniques.
- Simulation tools such as DlgSILENT PowerFactory, OpenDSS, or MATPOWER.

The skills covered in this document align with these requirements, providing both theoretical explanations and practical examples to support technical discussion during the interview.

## How This Document Is Structured

The document follows a progressive learning structure, starting from fundamental principles and advancing toward complex interdisciplinary applications:

1. **Fundamentals of Distribution Networks** – topology, components, and per-unit modeling.
2. **Power Flow and Optimal Power Flow** – steady-state analysis and optimization.
3. **Flexibility in Distribution Networks** – modeling, classification, and quantification.
4. **Electricity Markets and Regulation** – European and Italian frameworks for local flexibility.
5. **Optimization Techniques** – from convex to mixed-integer and stochastic methods.
6. **Control Theory and Automation** – predictive and hierarchical control for smart grids.
7. **Simulation Tools and Programming** – Python, MATLAB, and power system simulators.
8. **Research Methodology and Project Participation** – good practices in scientific collaboration.

Each section concludes with key concepts, equations, and references to primary sources such as:

- IEEE standards and textbooks on power systems and control.
- ENTSO-E and ARERA regulatory documents.
- RSE and EU project reports on local flexibility and grid automation.

This document aims to be self-contained yet rigorous, serving as both a study manual and a future technical reference for applied research in electrical energy systems.

## 2 Fundamentals of Distribution Networks

### 2.1 Structure and Components

A power distribution network is the final stage in the electrical power system, delivering electricity from transmission substations to end-users. Its structure reflects the transition from high-voltage (HV) transmission systems to medium-voltage (MV) and low-voltage (LV) grids.

- **Transmission network:** typically operates above 110 kV, designed for long-distance bulk power transfer.
- **Primary distribution (MV):** ranges from 1 kV to 35 kV, connecting substations to local feeders.
- **Secondary distribution (LV):** below 1 kV, supplying residential, commercial, and industrial loads.

The main components of a distribution network are:

- **Transformers** – step-down voltage levels between stages (HV/MV/LV).

- **Feeders and laterals** – overhead or underground conductors that deliver power to customers.
- **Switches, circuit breakers, and protection devices** – ensure safe operation and fault isolation.
- **Distributed Energy Resources (DERs)** – local generators (e.g., PV, wind), storage, and demand-side resources.
- **Smart meters and sensors** – provide data for monitoring, automation, and flexibility services.

Modern distribution systems are evolving toward **active distribution networks (ADNs)**, in which distributed resources and controllable loads participate in voltage regulation, congestion management, and flexibility provision [1, 2].

## 2.2 Radial vs. Meshed Networks

Traditionally, distribution networks have been designed as **radial systems**, where power flows unidirectionally from the substation to the end users. In a radial feeder, each load is supplied by a single path, which simplifies protection coordination and reduces system cost.

However, the increasing penetration of distributed generation (DG) and storage has motivated the development of **meshed or looped topologies**, providing multiple paths for power flow and improved reliability. These configurations, though more complex to control, enable bidirectional power exchange and facilitate flexibility activation.

The network topology can be characterized by its *graph representation*:

$$\mathcal{G} = (\mathcal{N}, \mathcal{E})$$

where  $\mathcal{N}$  is the set of buses (nodes) and  $\mathcal{E}$  is the set of lines (edges). For radial networks,  $|\mathcal{E}| = |\mathcal{N}| - 1$ , while meshed systems contain additional loops, i.e.  $|\mathcal{E}| > |\mathcal{N}| - 1$ .

## 2.3 Per Unit System and Base Values

To simplify power system analysis, electrical quantities are often expressed in the **per unit (p.u.) system**. This normalization makes equations dimensionless and allows easy comparison across different voltage levels.

For a given system base:

$$S_{\text{base}} = \text{apparent power base (MVA)}, \quad V_{\text{base}} = \text{voltage base (kV)}$$

the derived quantities are:

$$I_{\text{base}} = \frac{S_{\text{base}}}{\sqrt{3}V_{\text{base}}}, \quad Z_{\text{base}} = \frac{V_{\text{base}}^2}{S_{\text{base}}}$$

Then any quantity  $X$  (voltage, current, impedance, power) can be expressed as:

$$X_{pu} = \frac{X_{\text{actual}}}{X_{\text{base}}}$$

This approach simplifies multi-voltage network calculations, especially when transformers are involved, since all elements can be converted to a common base [3, 4].

## 2.4 Load Models and Profiles

Load modeling is a key aspect of distribution network studies. Different load models capture how demand responds to voltage and frequency variations, influencing voltage stability and flexibility assessments.

## Static load models

Static models relate real and reactive power to voltage magnitude:

$$P = P_0 \left( \frac{V}{V_0} \right)^\alpha, \quad Q = Q_0 \left( \frac{V}{V_0} \right)^\beta$$

where  $\alpha$  and  $\beta$  define the voltage dependence:

- Constant power load:  $\alpha = \beta = 0$
- Constant current load:  $\alpha = \beta = 1$
- Constant impedance load:  $\alpha = \beta = 2$

## Dynamic load models

Dynamic models consider time-dependent behavior, including thermostatically controlled loads, electric vehicles (EVs), and heat pumps. These loads introduce temporal flexibility, allowing demand shifting or curtailment during grid operation.

## Load profiles

Typical LV or MV load profiles vary by consumer type:

- **Residential:** peak in the evening (18–22 h).
- **Commercial:** peak during daytime hours.
- **Industrial:** relatively constant demand.

Profiles are often normalized and derived from measurement campaigns or standard datasets (e.g., ENTSO-E, Terna, EDSO). In flexibility studies, load profiles are crucial for estimating baseline consumption and available flexibility.

## Summary

This section has introduced the structure, modeling, and representation of distribution networks, providing the foundation for subsequent analysis such as Power Flow and Optimal Power Flow (OPF). The next section will build on these concepts, describing the mathematical formulation of power flow equations and optimization-based extensions.

# 3 Power Flow and Optimal Power Flow

## 3.1 AC and DC Power Flow

The **Power Flow Problem** (also known as *Load Flow*) is a fundamental tool in power system analysis. It determines the steady-state operating condition of a network, i.e. bus voltages, line currents, and power flows, given a specified load and generation scenario.

A power system can be represented as a network of buses connected by transmission or distribution lines. At each bus  $i$ , the complex power injection is given by:

$$S_i = P_i + jQ_i = V_i I_i^*$$

where  $V_i$  is the complex bus voltage and  $I_i^*$  is the conjugate of the injected current.

By applying Kirchhoff's Current Law (KCL) and using the network admittance matrix  $Y_{bus}$ , the relationship becomes:

$$I_i = \sum_{j=1}^N Y_{ij} V_j$$

Substituting, we obtain the nonlinear power flow equations:

$$S_i = V_i \sum_{j=1}^N Y_{ij}^* V_j^*$$

or, separating into real and reactive power components:

$$P_i = \sum_{j=1}^N |V_i| |V_j| (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$

$$Q_i = \sum_{j=1}^N |V_i| |V_j| (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$

where:

- $G_{ij}$  and  $B_{ij}$  are the conductance and susceptance between buses  $i$  and  $j$ ,
- $\theta_{ij} = \delta_i - \delta_j$  is the phase angle difference.

Solving these nonlinear equations provides:

- Bus voltage magnitudes and angles;
- Real and reactive power flows on each line;
- System losses.

## Bus types

To solve the power flow problem, bus types must be defined:

- **Slack (reference) bus:**  $V$  and  $\delta$  known;  $P$ ,  $Q$  computed.
- **PV bus:**  $P$  and  $|V|$  known;  $\delta$ ,  $Q$  computed.
- **PQ bus:**  $P$ ,  $Q$  known;  $|V|$ ,  $\delta$  computed.

## Numerical solution methods

The most common iterative techniques are:

- **Gauss-Seidel** — simple but slow convergence.
- **Newton-Raphson (NR)** — quadratic convergence; standard for large systems.
- **Fast-Decoupled Load Flow (FDLF)** — approximated NR using decoupled  $P$ - $\theta$  and  $Q$ - $V$  subproblems.

In MATLAB or Python environments, these are implemented in tools such as **MATPOWER** [5] and **pandapower**.

## DC Power Flow Approximation

The DC power flow is a linearized approximation valid under:

1. Small angle differences ( $\sin \theta \approx \theta$ ).
2. Voltage magnitudes near 1 p.u. ( $|V| = 1$ ).
3. Negligible line resistance ( $R \ll X$ ).

Under these assumptions:

$$P_i = \sum_j B_{ij}(\delta_i - \delta_j)$$

This simplification allows very fast computation, suitable for market clearing, contingency screening, and optimization problems such as OPF or flexibility dispatch.

## 3.2 Optimal Power Flow (OPF): Introduction

The **Optimal Power Flow** (OPF) problem extends the traditional power flow by optimizing a given objective function (e.g., minimizing cost or losses), while satisfying physical and operational constraints.

The generic OPF formulation is:

$$\begin{aligned} \min_{x,u} \quad & f(x, u) \\ \text{s.t.} \quad & g(x, u) = 0 \quad (\text{power flow equations}) \\ & h(x, u) \leq 0 \quad (\text{operational constraints}) \end{aligned}$$

where:

- $x$  = state variables (voltages, angles),
- $u$  = control variables (generator outputs, tap changers, flexible loads),
- $f(x, u)$  = objective function (e.g., generation cost, losses, voltage deviation).

### Common objectives:

- $\min \sum_i C_i(P_{G_i})$  — generation cost minimization;
- $\min \sum_{(i,j)} r_{ij} I_{ij}^2$  — loss minimization;
- $\min \sum_i |V_i - V_{ref}|^2$  — voltage regulation;
- max renewable utilization or flexibility activation.

### Typical constraints:

$$\begin{aligned} P_i^G - P_i^D &= \sum_j |V_i||V_j|(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i^G - Q_i^D &= \sum_j |V_i||V_j|(G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \\ V_i^{\min} &\leq |V_i| \leq V_i^{\max} \\ P_i^{G,\min} &\leq P_i^G \leq P_i^{G,\max} \\ S_{ij} &\leq S_{ij}^{\max} \end{aligned}$$



### 3.3 Solving OPF: Convex Relaxations and Algorithms

The AC-OPF is a **nonconvex, nonlinear** optimization problem (due to quadratic equality constraints). Several relaxation and approximation methods exist to improve computational tractability:

- **DC-OPF:** linearization assuming flat voltage magnitude and small angle differences.
- **Quadratic Programming (QP)** or **Linear Programming (LP)** for convex cost functions.
- **Second-Order Cone Programming (SOCP)** relaxation — convex approximation preserving voltage and current limits.
- **Semidefinite Programming (SDP)** relaxation — globally optimal under certain network conditions [6].

Common solvers include:

- IPOPT, CPLEX, GUROBI, MOSEK (general-purpose);
- MATPOWER, PYPower, pandapower, and Julia/JuMP for OPF modeling.

### 3.4 Applications in Flexibility Analysis

In the context of distribution networks, OPF can be extended to model the participation of flexible resources, such as demand response or distributed storage, in local markets.

**Examples of flexibility-oriented objectives:**

- Minimizing voltage violations via demand curtailment;
- Minimizing DSO operational cost subject to network limits;
- Maximizing offered flexibility from DERs to resolve contingencies.

The optimization can include binary variables representing activation decisions (mixed-integer OPF), or stochastic components to account for renewable uncertainty.

Mathematically, flexibility activation can be formulated as:

$$\min_{P_G, P_{flex}} C(P_G) + C_{flex}(P_{flex})$$

subject to power balance and operational constraints, where  $P_{flex}$  represents controllable flexibility provision (positive or negative power modulation).

### 3.5 Tools: MATPOWER, OpenDSS, PowerFactory (Overview)

**MATPOWER** [5] is an open-source MATLAB toolbox for steady-state power flow and OPF analysis. It supports both AC and DC formulations and is widely used in academia.

**OpenDSS** (Open Distribution System Simulator) is developed by EPRI for distribution-level studies. It includes time-series simulations, integration with Python, and support for smart grid applications such as voltage control and storage management.

**DigSILENT PowerFactory** is a commercial-grade simulator offering advanced capabilities (dynamic studies, protection, market modeling). It is often used in research projects and by DSOs for system planning and flexibility analysis.

## Summary

Power flow and OPF methods form the analytical foundation for evaluating flexibility in modern distribution systems. While AC power flow provides the physical representation of network behavior, OPF integrates economic and operational optimization — essential for designing and analyzing local flexibility markets.

## 4 Flexibility in Distribution Networks

### 4.1 Definition and Importance

**Flexibility** in power systems refers to the ability of the electricity network and connected resources to adapt generation or consumption patterns in response to internal or external signals, such as market prices, grid constraints, or renewable generation variability.

Formally, flexibility can be defined as:

$$F(t) = \frac{dP(t)}{dt}$$

representing the rate at which the net power exchange at a node (or network area) can be modified within technical and operational limits.

Flexibility enables several key objectives:

- Maintaining balance between generation and demand in real time;
- Mitigating voltage or thermal limit violations in distribution grids;
- Integrating variable renewable generation (solar, wind);
- Supporting congestion management and system restoration;
- Providing local ancillary services to the DSO.

In the context of active distribution networks (ADNs), the DSO becomes an active system operator, coordinating local flexibility from distributed energy resources (DERs) to enhance system efficiency and reliability [7, 8].

### 4.2 Types of Flexible Resources

Flexibility can originate from different technologies and actors. The main classes are listed below.

#### Energy Storage Systems (ESS)

Storage systems such as batteries or thermal reservoirs can shift energy temporally, providing both upward (discharging) and downward (charging) flexibility. Their main constraints are energy capacity ( $E_{\max}$ ), power limits ( $P_{\max}$ ), and state of charge (SOC):

$$SOC(t+1) = SOC(t) + \eta_c P_{\text{ch}}(t) \Delta t - \frac{1}{\eta_d} P_{\text{dis}}(t) \Delta t$$

with  $0 \leq SOC(t) \leq E_{\max}$ .

## Demand Response (DR)

Demand-side flexibility comes from modulating consumption according to price signals or direct control commands. DR can be:

- **Implicit (price-based):** customers react voluntarily to dynamic tariffs;
- **Explicit (contract-based):** aggregators or DSOs activate loads in exchange for payments.

Examples include HVAC systems, electric vehicles, or industrial processes with schedulable loads.

## Renewable Generation (Variable RES)

Photovoltaic (PV) and wind plants can provide downward flexibility by curtailing production. Some inverter-based units also offer upward flexibility via reactive power control or temporary overproduction within rated limits.

## Virtual Power Plants (VPPs)

A **Virtual Power Plant** aggregates multiple DERs (generation, storage, flexible loads) and operates them as a coordinated entity. The VPP can participate in markets and provide local services to the DSO while ensuring that network constraints are not violated [9].

## Energy Communities and Local Aggregators

**Renewable Energy Communities (RECs)** and **Citizen Energy Communities (CECs)** represent collective actors who manage distributed flexibility across prosumers. Their aggregated potential can be used for peak shaving, congestion management, and energy self-sufficiency at the local level.

## 4.3 Activation Mechanisms and Signals

The activation of flexibility can occur through various control and market-based mechanisms.

- **Direct control:** the DSO or aggregator sends activation commands (e.g., load reduction of 50 kW for 15 minutes).
- **Price signals:** variable energy prices incentivize consumers to adjust demand autonomously.
- **Market-based dispatch:** flexibility bids/offers are submitted to a local market platform and cleared through an optimization (e.g., OPF or auction).
- **Emergency activation:** used in contingency situations, where system operators request immediate support.

The response can be characterized by:

- **Activation time ( $t_{\text{act}}$ ):** delay between request and actual power change;
- **Duration ( $T_{\text{flex}}$ ):** period for which the flexibility can be sustained;
- **Recovery time ( $t_{\text{rec}}$ ):** period before the resource returns to its baseline state.

These parameters are crucial for defining flexibility products and evaluating the reliability of flexible resources.

#### 4.4 Flexibility Potential Estimation

Estimating the *potential* of flexibility in a distribution network involves assessing how much power variation ( $\Delta P$ ,  $\Delta Q$ ) can be achieved at each node or feeder, considering technical and network limits.

Mathematically, the flexibility envelope at bus  $i$  can be formulated as:

$$\mathcal{F}_i = \{(\Delta P_i, \Delta Q_i) \mid V_i^{\min} \leq V_i \leq V_i^{\max}, S_{ij} \leq S_{ij}^{\max}\}$$

The total system flexibility can then be aggregated as:

$$F_{\text{sys}}(t) = \sum_i \Delta P_i(t)$$

subject to network constraints derived from an OPF model.

##### Approaches for estimation:

- **Analytical methods:** linearized power flow sensitivities (Jacobian-based).
- **Optimization-based:** solving multiple OPF instances to derive upper/lower flexibility bounds.
- **Data-driven approaches:** regression or machine learning models trained on simulation data or historical measurements.

These methods can quantify not only the total available flexibility but also its **spatial** and **temporal** distribution, which are essential for DSO decision-making and local market design.

#### 4.5 Multi-Energy Systems and Sector Coupling

Future flexibility solutions will increasingly rely on **multi-energy systems**, where electricity, heat, and gas sectors interact to provide cross-sector flexibility.

Examples include:

- Using **heat pumps** and **thermal storage** to shift electrical demand through heat buffering.
- Employing **Power-to-Gas (P2G)** and **Power-to-Heat (P2H)** technologies to absorb surplus renewable energy.
- Integrating **electric vehicles (EVs)** as mobile storage units.

This concept is referred to as **sector coupling**, enabling additional degrees of flexibility across the energy system and supporting decarbonization goals [10].

#### Summary

Flexibility in distribution networks is a cornerstone of the energy transition. It bridges technical control and economic optimization, enabling distributed energy resources and consumers to actively participate in system operation. Understanding how to model, quantify, and activate flexibility — both from the network and market perspectives — is central to research roles such as the one at RSE.

## 5 Electricity Markets and Regulation

### 5.1 Introduction

Electricity markets provide the economic framework within which generation, consumption, and flexibility interact. They ensure that energy is produced, transported, and consumed efficiently while maintaining system reliability and promoting competition. In Europe, the market structure has evolved to integrate renewable sources and decentralized actors, leading to the emergence of new products such as local flexibility and ancillary services.

This section introduces the fundamental market architecture, key regulatory principles, and the evolving role of Distribution System Operators (DSOs) and aggregators.

### 5.2 Market Structure Overview

The European power market is organized into multiple temporal and spatial layers, as illustrated in Figure ???. Each layer corresponds to a specific time horizon and operational objective.

- **Forward / Futures Market:** contracts for months or years ahead; used for hedging price risks.
- **Day-Ahead Market (DAM):** determines the energy schedule for each hour of the next day through a market coupling algorithm (EUPHEMIA).
- **Intraday Market (IDM):** enables trading closer to real time to adjust for forecast errors.
- **Balancing Market (BM):** operated by the Transmission System Operator (TSO) to correct imbalances in real time.
- **Local Flexibility Markets (LFM):** emerging platforms where DSOs procure flexibility to solve local constraints.

$$\text{Time Horizon: Years} \rightarrow \text{Day-Ahead} \rightarrow \text{Intraday} \rightarrow \text{Real-Time} \quad (1)$$

### 5.3 Day-Ahead Market (DAM)

The DAM is a *centralized auction* where market participants submit energy bids/offers for each hour of the next day. The market operator (in Italy: **GME – Gestore dei Mercati Energetici**) clears the market by solving a welfare-maximizing optimization:

$$\max_{P_i} \sum_i (p_i^{\text{bid}} - c_i) P_i$$

subject to:

$$\sum_i P_i = 0 \quad (\text{supply-demand balance})$$

and network constraints modeled through zonal coupling.

The output is the **Market Clearing Price (MCP)** for each zone and hour, and the accepted quantities  $P_i^*$  for each participant.

## 5.4 Balancing and Ancillary Services

Real-time balance is maintained by the TSO (in Italy: **Terna**) through the activation of **balancing resources**. These services include:

- **Frequency Containment Reserve (FCR)**: automatic, local control within seconds;
- **Frequency Restoration Reserve (FRR)**: manual or automatic correction within minutes;
- **Replacement Reserve (RR)**: slower resources to restore reserves after activation.

Flexibility providers (generators, storage, demand response) can participate if they meet technical requirements such as response time, controllability, and metering accuracy.

The activation price is typically determined through a *pay-as-bid* or *marginal pricing* mechanism.

## 5.5 Role of the DSO and Local Flexibility Markets

Traditionally, the DSO was a passive infrastructure operator focused on reliability and voltage quality. With increasing distributed generation, DSOs now face:

- Congestion in medium- and low-voltage networks;
- Voltage rise issues due to PV infeed;
- Bidirectional power flows;
- Need for local congestion management instead of costly reinforcements.

To address these issues, the concept of **Local Flexibility Markets (LFMs)** has emerged. In an LFM, the DSO can procure active or reactive power flexibility from local actors to:

- Relieve congestion on specific feeders;
- Maintain voltage profiles within statutory limits;
- Support TSO-DSO coordination mechanisms.

The market clearing is often formulated as a **local optimal power flow** problem:

$$\min_{P_i, Q_i} C_{\text{flex}}(P_i, Q_i) \quad \text{s.t.} \quad \mathbf{f}(V, \theta, P, Q) = 0, \quad V^{\min} \leq V \leq V^{\max}, \quad S_{ij} \leq S_{ij}^{\max}$$

Flexibility can be offered by prosumers, storage, or aggregators. This approach aligns technical needs (DSO constraints) with economic incentives (market payments).

## 5.6 Regulatory Framework in the European Union

The evolution of electricity markets in Europe is guided by the **EU Clean Energy Package (CEP)** and associated directives, particularly:

- **Directive (EU) 2019/944**: establishes common rules for the internal electricity market and the role of active consumers and aggregators;
- **Regulation (EU) 2019/943**: focuses on market integration, transparency, and capacity allocation;
- **Network Codes and Guidelines**: specify technical rules for grid connection, balancing, and operation.

Key principles include:

1. **Non-discriminatory access:** all qualified actors can participate in markets.
2. **Unbundling:** separation of market operation, network ownership, and generation activities.
3. **Consumer empowerment:** enabling self-consumption and collective participation.
4. **TSO–DSO cooperation:** to ensure efficient coordination of flexibility resources.

## 5.7 Italian Context (ARERA and Pilot Projects)

In Italy, the regulatory authority **ARERA** (Autorità di Regolazione per Energia Reti e Ambiente) oversees the implementation of European principles through national regulations.

Relevant initiatives include:

- **ARERA Deliberation 352/2021/R/eel:** introduces experimentation of local flexibility markets;
- **TERNA Pilot Projects (UVAM, UVAP):** enable aggregation of distributed resources for balancing services;
- **DSO Demonstrations:** projects by e-distribuzione, Areti, and others testing flexibility procurement at MV/LV levels.

These pilots aim to evaluate the technical and economic feasibility of flexibility activation in distribution networks. RSE plays an important role in analyzing the results of these pilots, developing models, and designing the future market architecture.

## 5.8 Emerging Trends and Challenges

Current research and regulatory discussions focus on:

- Interoperability and standardized communication between TSO, DSO, and aggregators;
- Locational marginal pricing (LMP) extensions to distribution grids;
- Integration of peer-to-peer (P2P) trading and energy communities;
- Cybersecurity and data privacy for market participation;
- Fair remuneration for distributed flexibility.

Ultimately, the goal is a **coordinated, hierarchical system** where both transmission and distribution levels actively contribute to the secure and efficient operation of the power system.

## Summary

Electricity markets are evolving from centralized, generation-dominated systems toward decentralized, flexible ecosystems. Understanding the economic mechanisms, regulatory frameworks, and the roles of each actor is fundamental for engineers involved in flexibility modeling and control. For RSE's research topics, this knowledge connects directly to:

- Simulation of market mechanisms integrated into network operation models;
- Analysis of DSO–TSO coordination strategies;
- Quantification of technical–economic flexibility potential.

## 6 Optimization Techniques

### 6.1 Mathematical Optimization Basics

Optimization is the process of finding the best solution (minimizing or maximizing an objective function) subject to a set of constraints. A general optimization problem can be written as:

$$\begin{aligned} \min_x \quad & f(x) \\ \text{s.t.} \quad & g_i(x) \leq 0, \quad i = 1, \dots, m \\ & h_j(x) = 0, \quad j = 1, \dots, p \end{aligned}$$

where:

- $x \in \mathbb{R}^n$  is the vector of decision variables;
- $f(x)$  is the **objective function**;
- $g_i(x)$  and  $h_j(x)$  represent inequality and equality constraints.

Common concepts:

- **Feasible region:** the set of all  $x$  satisfying constraints;
- **Global optimum:** the best feasible solution minimizing  $f(x)$ ;
- **Local optimum:** a solution optimal only within a neighborhood;
- **Lagrange multipliers:** indicate sensitivity of the objective to constraints;
- **Duality:** relates the original problem (primal) and its dual, often simplifying analysis.

Optimization in power systems is used for:

- economic dispatch and unit commitment,
- power flow and optimal power flow,
- flexibility procurement and market clearing,
- scheduling of storage and demand response.

### 6.2 Convex Optimization

A problem is **convex** if both the feasible region and the objective function are convex:

$$f(\lambda x_1 + (1 - \lambda)x_2) \leq \lambda f(x_1) + (1 - \lambda)f(x_2)$$

for all  $\lambda \in [0, 1]$ .

Convex problems are desirable because:

- any local minimum is also a global minimum;
- efficient solvers (interior-point, gradient descent) can find solutions reliably;
- duality theory guarantees strong results (KKT conditions).

Examples:

- Linear Programming (LP): linear  $f$ , linear constraints;
- Quadratic Programming (QP): quadratic  $f$ , linear constraints;



- Second-Order Cone Programming (SOCP);
- Semidefinite Programming (SDP): used in convex relaxations of OPF.

The **KKT conditions** (Karush–Kuhn–Tucker) are necessary and sufficient for optimality in convex problems:

$$\nabla f(x^*) + \sum_i \lambda_i \nabla g_i(x^*) + \sum_j \mu_j \nabla h_j(x^*) = 0$$

subject to feasibility and complementary slackness.

In the context of power systems:

- AC OPF is non-convex (due to power flow equations);
- DC OPF is convex (linear approximation);
- Convex relaxations (SOCP, SDP) are used to approximate the AC OPF while preserving tractability.

### 6.3 Mixed-Integer Linear/Nonlinear Programming

**Mixed-Integer Linear Programming (MILP)** adds discrete decision variables ( $x_i \in \{0, 1\}$ ) to linear optimization, enabling modeling of on/off devices, unit commitment, or topology re-configuration.

A general MILP problem:

$$\begin{aligned} \min_{x,y} \quad & c^T x + d^T y \\ \text{s.t.} \quad & Ax + By \leq b, \quad y \in \{0, 1\}^n \end{aligned}$$

Examples of applications:

- switching operations in distribution networks,
- activation of discrete flexibility resources,
- investment and planning under network constraints.

When nonlinearities are present (e.g., AC power flow equations), the problem becomes **MINLP** — Mixed-Integer Nonlinear Programming — which is NP-hard. Solvers use relaxation, branch-and-bound, or decomposition techniques (e.g., Benders decomposition) to find approximate or exact solutions.

### 6.4 Stochastic and Robust Optimization

Uncertainty plays a major role in distribution networks, due to renewable generation and demand variability. Two main paradigms are used to handle uncertainty:

**1. Stochastic Optimization** Uncertainty is represented via a set of scenarios  $\omega \in \Omega$ , each with probability  $p_\omega$ :

$$\min_x \mathbb{E}_\omega[f(x, \omega)] = \sum_\omega p_\omega f(x, \omega)$$

It seeks the decision minimizing the expected cost (e.g., average system performance).

Example:

$$\min_x \sum_\omega p_\omega (c^T x_\omega) \quad \text{s.t.} \quad A_\omega x_\omega \leq b_\omega$$

Applications:

- day-ahead scheduling of storage under renewable uncertainty;
- flexibility bidding with uncertain activation;
- planning of network reinforcements with probabilistic loads.

**2. Robust Optimization** Here, uncertainty is represented by a bounded set  $\mathcal{U}$  (no probabilities assumed):

$$\min_x \max_{u \in \mathcal{U}} f(x, u)$$

The goal is to find decisions that perform well under the worst-case realization.

Applications:

- ensuring voltage limits under uncertain injections,
- guaranteeing flexibility delivery despite uncertainty,
- defining robust local flexibility offers.

**Trade-off:** Stochastic methods optimize average performance, while robust methods ensure guaranteed feasibility.

## 6.5 Flexibility Procurement as Optimization Problem

The DSO flexibility procurement problem can be formulated as an OPF-based optimization:

$$\begin{aligned} \min_{P_i, Q_i, \Delta P_i} \quad & C_{\text{grid}}(P_i, Q_i) + C_{\text{flex}}(\Delta P_i) \\ \text{s.t.} \quad & P_i^{\min} \leq P_i + \Delta P_i \leq P_i^{\max} \\ & Q_i^{\min} \leq Q_i \leq Q_i^{\max} \\ & \text{Network constraints: } f(V, \theta, P, Q) = 0 \end{aligned}$$

where:

- $C_{\text{grid}}$  = grid operational cost (losses, voltage deviations);
- $C_{\text{flex}}$  = cost of activating flexibility resources;
- $\Delta P_i$  = power deviation offered by resource  $i$ .

Variants:

- **Centralized optimization:** DSO collects all bids and solves one large OPF;
- **Decentralized optimization:** each agent solves local problems with price coordination (ADMM, dual decomposition);
- **Multi-objective optimization:** combines technical (voltage, congestion) and economic (cost, fairness) objectives.

## 6.6 Tools: CVXPY, Pyomo, MATLAB, Julia/JuMP

Several open-source tools can be used to formulate and solve optimization problems relevant to distribution networks:

**CVXPY (Python)** A high-level library for convex optimization. Supports LP, QP, SOCP, SDP problems. Example:

```
import cvxpy as cp
x = cp.Variable()
y = cp.Variable()
objective = cp.Minimize(x + y)
constraints = [x + 2*y >= 1, x >= 0, y >= 0]
prob = cp.Problem(objective, constraints)
prob.solve()
```

**Pyomo (Python)** More general — supports MILP, MINLP, and stochastic optimization via interfaces with solvers such as GLPK, CBC, and IPOPT.

**MATLAB Optimization Toolbox** Useful for prototyping, includes linear, quadratic, non-linear, and mixed-integer solvers. Also integrates with Simulink for closed-loop control optimization.

**Julia/JuMP** High-performance modeling language for optimization. Supports linear, nonlinear, and mixed-integer programming with clean syntax:

```
using JuMP, HiGHS
model = Model(HiGHS.Optimizer)
@variable(model, x >= 0)
@variable(model, y >= 0)
@objective(model, Min, x + y)
@constraint(model, x + 2y >= 1)
optimize!(model)
```

JuMP is particularly suited for large-scale OPF and flexibility problems due to its efficiency and compatibility with `PowerModels.jl` and `InfrastructureModels.jl`.

## Summary

Optimization provides the mathematical foundation for analyzing and managing flexibility in distribution networks. It allows DSOs and aggregators to:

- quantify flexibility potential,
- determine cost-optimal activation,
- ensure secure operation under uncertainty.

A solid understanding of convexity, duality, and mixed-integer formulations is essential to interpret OPF-based flexibility results and design control or market mechanisms.

## 7 Control Theory and Automation

### 7.1 Fundamentals of Control Systems

Control theory deals with the design of systems that regulate their own behavior to achieve desired objectives. A control system consists of:

- a **plant** (the physical process to be controlled),
- a **controller** (computes corrective actions),
- **actuators** (apply control actions),
- **sensors** (measure system outputs).

**Feedback Control** Feedback involves measuring the system output and using this information to correct deviations from the reference. A basic continuous-time feedback loop is:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

where  $e(t) = r(t) - y(t)$  is the error between the reference  $r$  and output  $y$ . This is the classical **PID controller**.

### Block Diagram Representation

$$r(t) \longrightarrow [\text{Controller}] \longrightarrow [\text{Plant}] \longrightarrow y(t)$$

The closed-loop transfer function is:

$$T(s) = \frac{C(s)G(s)}{1 + C(s)G(s)}$$

where  $G(s)$  is the plant transfer function and  $C(s)$  is the controller.

**Performance Criteria** Design goals usually involve:

- **Stability:** output remains bounded for bounded inputs (BIBO stability);
- **Accuracy:** small steady-state error;
- **Speed:** short settling and rise times;
- **Robustness:** tolerance to model uncertainty and disturbances.

Classical design methods include Root Locus, Bode plots, and Nyquist analysis.

## 7.2 Predictive, Robust and Adaptive Control

As power systems become more complex and dynamic, advanced control techniques are used to handle constraints, uncertainties, and multivariable interactions.

**Model Predictive Control (MPC)** MPC optimizes control actions over a finite prediction horizon, using a dynamic model of the system:

$$\begin{aligned} \min_{u_0, \dots, u_{N-1}} \quad & \sum_{k=0}^{N-1} \ell(x_k, u_k) + \ell_f(x_N) \\ \text{s.t.} \quad & x_{k+1} = f(x_k, u_k) \\ & x_k \in \mathcal{X}, u_k \in \mathcal{U} \end{aligned}$$

At each time step, the first control action  $u_0$  is applied, and the optimization is repeated in a receding horizon fashion.

Advantages:

- explicit handling of input and state constraints,
- anticipatory control (predictive behavior),
- multi-variable coordination (e.g., voltage and reactive power).

In flexibility management, MPC can coordinate energy storage and controllable loads to mitigate network constraints or follow market signals.

**Robust Control** Robust control aims to guarantee performance under model uncertainty or disturbances. Let the true plant be:

$$G(s) = G_0(s)(1 + \Delta(s))$$

where  $\Delta(s)$  represents uncertainty. Robust design ensures stability for all  $\Delta(s)$  within a bounded set.

Common methods:

- $H_\infty$  control — minimizes the worst-case gain from disturbance to output:

$$\min_K \|T_{zw}(s)\|_\infty$$

- $\mu$ -synthesis — structured uncertainty analysis.

Applications include voltage regulation under uncertain grid impedance or renewable generation fluctuations.

**Adaptive Control** Adaptive control updates controller parameters online in response to changing system dynamics. Common approaches:

- Model Reference Adaptive Control (MRAC);
- Self-tuning regulators;
- Gain scheduling (for nonlinear systems).

For distributed energy resources (DERs), adaptive control enables maintaining performance despite varying operational conditions (e.g., PV output or battery SoC).

### 7.3 Applications in Power Systems

Control theory is crucial for ensuring secure, stable, and optimal operation of electric networks. Applications include:

- **Voltage and reactive power control:** using OLTCs, capacitor banks, and inverters;
- **Frequency regulation:** balancing generation and demand through primary, secondary, tertiary control;
- **Microgrid control:** hierarchical management of distributed generators and loads;
- **Storage control:** maintaining SoC and providing fast frequency response;
- **Demand response:** automatic load modulation in response to price or control signals.

The control hierarchy is typically:

$$\text{Primary (local)} \rightarrow \text{Secondary (area)} \rightarrow \text{Tertiary (system)}$$

Each level has distinct time scales (from milliseconds to hours).

**Voltage Control Example** A distributed voltage controller can adjust reactive power of inverters:

$$Q_i = K_v(V_i^{\text{ref}} - V_i)$$

where  $K_v$  is a droop coefficient. These local controllers are simple yet effective, while coordinated MPC or OPF can optimize global objectives.

## 7.4 Decentralized and Hierarchical Control in Smart Grids

Future smart grids integrate thousands of controllable devices. Centralized control becomes computationally and communicatively impractical, motivating decentralized and hierarchical architectures.

**Decentralized Control** Each agent (e.g., PV inverter, battery) makes decisions based on local measurements and limited communication. Common methods:

- droop control,
- consensus algorithms,
- distributed optimization (e.g., ADMM).

Advantages:

- scalability,
- resilience to failures,
- privacy preservation.

**Hierarchical Control** Hierarchical control divides the grid into control layers:

- **Primary:** fast local regulation (droop, PLLs);
- **Secondary:** restore nominal values (voltage, frequency);
- **Tertiary:** economic optimization (e.g., OPF, market clearing).

In flexibility markets, tertiary control can involve activation signals from DSOs or aggregators that trigger local secondary control loops.

## Summary

Control theory provides the operational backbone of flexibility management. Optimization determines *what* actions to take (planning and scheduling), while control determines *how* to execute them in real time. The integration of MPC, robust, and adaptive control allows flexible resources to participate reliably in local markets while maintaining grid stability.

# 8 Simulation Tools and Programming

## 8.1 Python for Power System Analysis

Python has become a standard tool in power system research due to its open-source ecosystem and strong libraries for optimization, simulation, and data analysis. It is ideal for flexibility studies, OPF modeling, and integration with data-driven or control algorithms.

**Key Packages:**

- **NumPy, SciPy:** numerical computation, linear algebra, and optimization;
- **pandas:** time-series and data manipulation;
- **matplotlib, Plotly:** visualization;
- **pandapower:** user-friendly power system analysis library built on PYPOWER and pandas;
- **CVXPY, Pyomo:** optimization modeling for OPF and flexibility procurement;
- **OpenDSSDirect.py:** Python interface for OpenDSS simulation engine;
- **GridCal, PyPSA:** open-source environments for planning, OPF, and flexibility modeling.

**Example: Power Flow using pandapower**

```
import pandapower as pp

net = pp.create_empty_network()

# Buses
b1 = pp.create_bus(net, vn_kv=20.)
b2 = pp.create_bus(net, vn_kv=0.4)

# Transformer
pp.create_transformer_from_parameters(net, hv_bus=b1, lv_bus=b2,
sn_mva=0.4, vn_hv_kv=20, vn_lv_kv=0.4, vk_percent=4, vkr_percent=1)

# Loads and generation
pp.create_load(net, b2, p_mw=0.05)
pp.create_sgen(net, b2, p_mw=0.02)

# Run power flow
pp.runpp(net)
print(net.res_bus)
```

This script sets up a simple MV/LV network and computes steady-state bus voltages. Such models can be expanded to simulate demand response, flexibility activation, and voltage control strategies.

**Advantages of Python:**

- Integration of simulation, optimization, and data analysis;
- Reproducible research (Jupyter Notebooks, open-source tools);
- Easy coupling with machine learning (TensorFlow, PyTorch);
- Ideal for automation and batch simulation of flexibility scenarios.

## 8.2 MATLAB/Simulink for Grid Modeling

MATLAB and Simulink are standard in academia and industry for control and system-level simulations. They are particularly useful for:

- small-signal and dynamic stability analysis,
- implementation of control algorithms (PID, MPC),
- closed-loop simulation of DERs and grid components.

### Simulink Workflow

1. Define the network model (buses, lines, loads, sources);
2. Add control loops (voltage regulators, frequency control, droop);
3. Include disturbance or flexibility signals;
4. Run time-domain simulations to observe dynamic response.

**Example: MPC for Battery Control** An MPC controller can manage a battery’s charge/discharge to minimize operational cost and maintain SoC limits:

$$\min_{P_b(t)} \sum_t c(t)P_b(t) \quad \text{s.t.} \quad E_{t+1} = E_t + \eta P_b(t)\Delta t, \quad E_{\min} \leq E_t \leq E_{\max}$$

Simulink provides blocks such as “Model Predictive Controller” for direct implementation. Integration with MATLAB scripts allows parameter tuning, Monte Carlo simulation, and data analysis.

### Toolboxes of Interest:

- Simscape Electrical,
- Optimization Toolbox,
- Control System Toolbox,
- Model Predictive Control Toolbox.

## 8.3 Power System Simulators: OpenDSS, DIgSILENT PowerFactory

**OpenDSS (Open Distribution System Simulator)** Developed by EPRI, OpenDSS is an open-source tool for steady-state and time-series analysis of distribution systems. It supports:

- AC power flow and fault studies,
- PV, storage, and demand response modeling,
- co-simulation with external controllers (Python, MATLAB),
- dynamic and probabilistic studies.

**Integration Example:** Using the `OpenDSSDirect.py` interface, one can run simulations and post-process results in Python.



```
import opendssdirect as dss

dss.Basic.Start(0)
dss.Text.Command("Redirect network_model.dss")
dss.Solution.Solve()
voltages = dss.Circuit.AllBusVmagPu()
```

OpenDSS is widely used in flexibility and market simulation projects across Europe (including RSE) because of its transparency and scripting capability.

**DIgSILENT PowerFactory** A commercial, high-fidelity simulation environment widely adopted by DSOs and TSOs. Features include:

- advanced load flow, short-circuit, and dynamic analysis;
- scripting with DPL or Python;
- model libraries for DERs, protection, and control;
- co-simulation with MATLAB/Simulink.

In research contexts, PowerFactory is used to validate algorithms developed in Python or MATLAB on realistic grid models.

## 8.4 Numerical Experiment Design

A rigorous research workflow involves:

1. **Model definition:** choose system (IEEE 33-bus, LV feeder, etc.);
2. **Scenario creation:** define time-series for demand, PV, and flexibility;
3. **Simulation:** perform power flow or dynamic simulations;
4. **Post-processing:** compute voltage deviations, losses, and flexibility activation;
5. **Visualization:** use plots to highlight the impact of control or market actions.

To ensure reproducibility:

- document all assumptions and parameters,
- version-control your scripts (e.g., Git),
- structure results in dataframes (time-indexed for easy analysis).

**Sensitivity Analysis:** Vary model parameters (e.g., PV penetration, flexibility bids) to assess robustness. Combine deterministic and stochastic simulations to evaluate uncertainty effects.

## 8.5 Example: Simulating Flexibility Activation

Below is a simplified workflow to simulate flexibility activation in a low-voltage feeder:

1. Load an IEEE 33-bus network in **pandapower**;
2. Define flexibility offers from storage or controllable loads:

$$\Delta P_i^{\max}, C_i(\Delta P_i)$$

3. Run a baseline power flow to identify overloaded branches;
4. Formulate and solve an OPF including flexibility variables:

$$\min_{\Delta P_i} \sum_i C_i(\Delta P_i) \quad \text{s.t.} \quad V_{\min} \leq V_i \leq V_{\max}$$

5. Apply flexibility actions to the model and re-run power flow;
6. Compare results: voltage profile, losses, cost.

Visualization of voltage profiles before and after flexibility activation:

```
import matplotlib.pyplot as plt

plt.plot(net.res_bus.vm_pu, label="Before")
plt.plot(net.flex.res_bus.vm_pu, label="After")
plt.xlabel("Bus index")
plt.ylabel("Voltage [p.u.]")
plt.legend()
plt.show()
```

This workflow illustrates the connection between modeling, optimization, and simulation — exactly the integrated approach expected in RSE’s projects on local flexibility.

## Summary

Simulation tools enable testing and validation of control and optimization strategies in realistic network conditions. Python and OpenDSS are favored for open, flexible research workflows; MATLAB/Simulink and PowerFactory are essential for high-fidelity validation and control prototyping. A skilled researcher should be able to switch between them depending on the study’s objective.

## 9 Research Methodology and Project Participation

### 9.1 Scientific Method in Engineering Research

### 9.2 EU and National Projects: Horizon, PNRR, etc.

### 9.3 Writing Reports and Presenting Results

### 9.4 Collaboration and Communication in Research Teams

## 10 Appendices

### 10.1 Glossary of Terms

### 10.2 Useful Links and References

### 10.3 LaTeX Tips for Technical Writing

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