Optimisation in electric power systems
Models and applications

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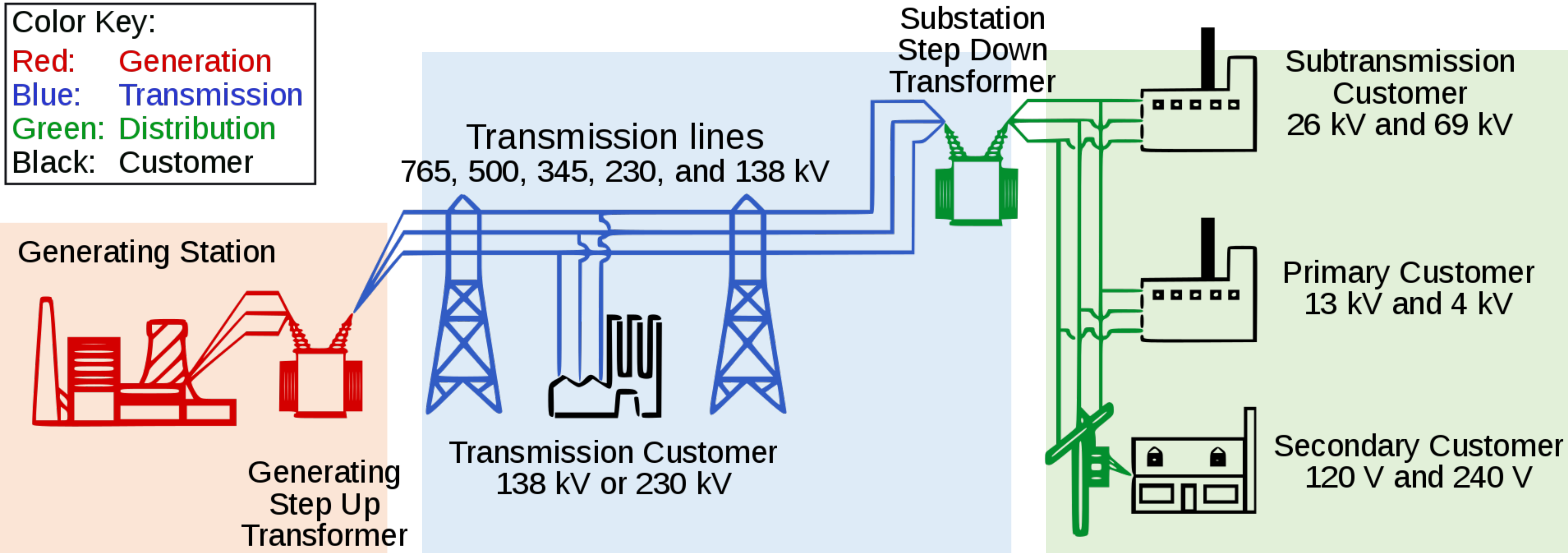
Background-What is an electric power system?

The electricity is transported from the supplies to the end users.



GENERATION UNITS

Converting coal, natural gas, nuclear energy, hydropower, wind, solar energy into electricity.

TRANSMISSION SYSTEM

Moving electricity from generation units to substations.
Such long-distance transmission requires high voltage (> 33 kV).

DISTRIBUTION SYSTEM

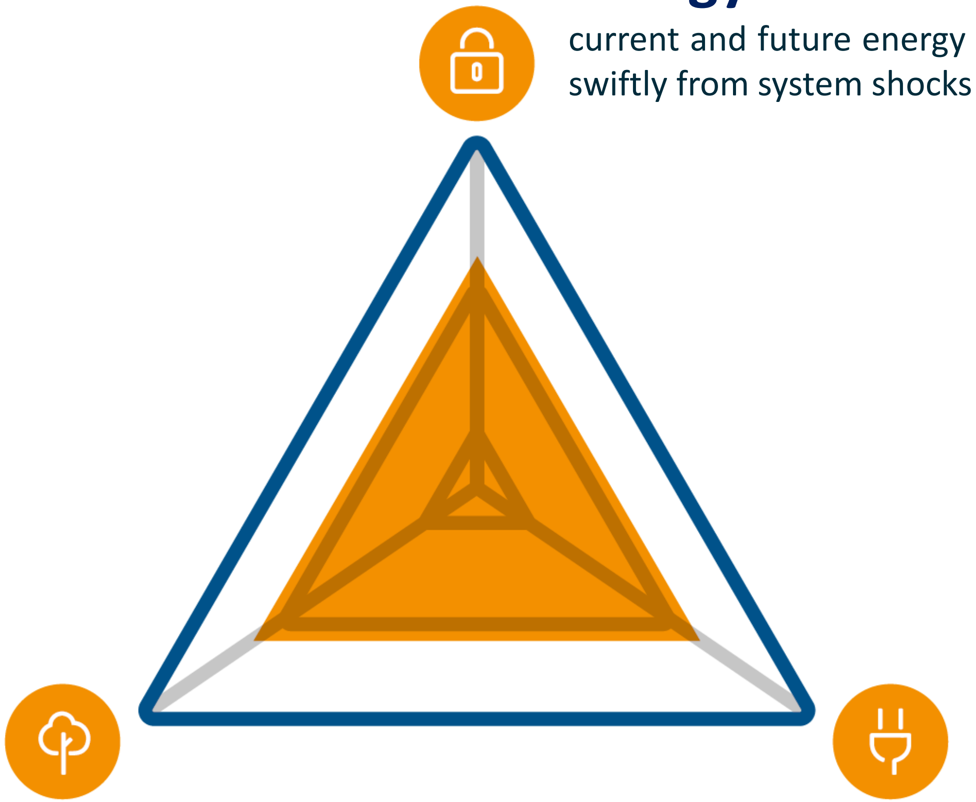
Delivering electricity to local users.
Lower voltage level (2 kV – 33 kV).

Figure source: Final report on the August 14, 2003 blackout in the United States and Canada : causes and recommendations.
https://www.osti.gov/etdeweb/biblio/20461178#:~:text=of%20the%20blackout.-,The%20report%20indicates%20that%20the%20loss%20of%20FirstEnergy's%20overloaded%20Sammis,on%20lines%20in%20adjacent%20areas.

Background-what kind of power system we wish to achieve?

The World Energy Council’s definition of energy sustainability is based on three core dimensions: Energy Security, Energy Equity, and Environmental Sustainability of Energy Systems. Balancing these three goals constitutes a ‘Trilemma’ and balanced systems enable prosperity and competitiveness of individual countries.

Energy Security measures a nation’s capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies.



Energy Equity assesses a country’s ability to provide universal access to reliable, affordable, and abundant energy for domestic and commercial use.

Environmental Sustainability represents the transition of a country’s energy system towards mitigating and avoiding potential environmental harm and climate change impacts

Figure source: World Energy Trilemma Index 2019 Executive Summary. https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2019

Background-what kind of power system we wish to achieve?

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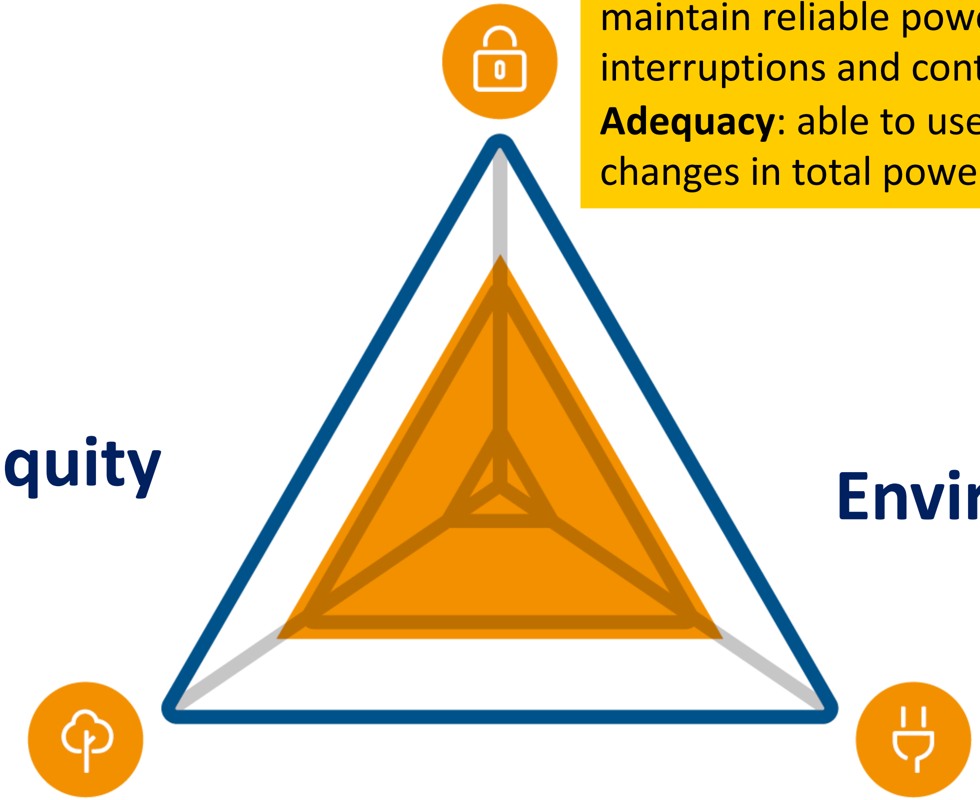
Energy Security

KEEPING THE LIGHTS ON[1]

System security & resilience: able to use the existing resources to maintain reliable power supplies when confronted with interruptions and contingency

Adequacy: able to use the existing and new resources to meet changes in total power requirements in the present and over time



Energy Equity

Everyone has access to reliable and affordable electricity and clean cooking fuels

Promoting policies and infrastructure development that considers different perspectives and disadvantaged communities

Environmental Sustainability

Renewable energy integration: wind, solar, hydropower, etc

Energy efficiency: less energy loses and resource consumption

Carbon emission reduction: cleaner generation technologies, carbon capture and storage, carbon trade

Figure source: World Energy Trilemma Index 2019 Executive Summary. https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2019

[1] Electricity security matters more than ever. https://www.iea.org/reports/power-systems-in-transition/electricity-security-matters-more-than-ever

EPS Optimisation-key technical requirements in power system operation

Load Balancing	Load balancing is to maintain the balance between electric power supply and demand. Load balancing is vital to prevent grid instability, voltage fluctuations, and blackout. It involves increasing the power output of generator/energy storage facilities and reduce the energy demand.
Frequency Control	It ensures that the grid's frequency (e.g., 50 Hz or 60 Hz) remains within a narrow range around the nominal frequency. It involves the continuous adjustment of electrical power generation to match the electrical load (demand) on the power grid.
Voltage Control	Voltage control is the process of regulating and maintaining the voltage levels within acceptable limits It involves adjusting reactive power generation
Grid Reliability & Resilience	Grid reliability refers to the ability of an electrical power system to consistently deliver electricity to consumers without interruption. It involves minimizing power outages, reducing downtime, and ensuring that electricity is available when needed. Grid resilience refers to its ability to withstand and recover from disruptions or disturbances, such as extreme weather events, equipment failures, or cyberattacks.
Reserve Capacity	Reserve capacity refers to the additional power generation capacity available beyond what is required to meet current demand. Reserve capacity is essential for maintaining grid reliability and stability during contingencies

EPS Optimisation 101

Optimisation modeling is a mathematical approach to find the best solution to a problem from a set of possible choices, considering specific constraints and objectives.

OBJECTIVE	Mathematical expressions that define what you want to maximise or minimise	Economic (investment cost, maintenance cost, operation cost, energy trade revenue,…); Technical (voltage deviation,…); Environmental (carbon emission,…)
CONSTRAINTS	The requirements that the solution to the optimisation problem must satisfy	Power flow equations, energy balance equations, cost calculation equations, inequality constraints bounding the operating status, …
DECISION VARIABLES	Variables that you can control or adjust to influence the outcome (subject to certain constraints)	Voltage, power output and on/off status of generation units, the number/capacity of newly-constructed infrastructure, …
INPUT	Known data	Fuel price, electricity price, start-up/shut-down cost of generators, installed capacity of each component, ramping rate limits, reserve requirement,…
OUTPUT	Optimal solutions and optimal values of objective functions	Voltage, power injection and branch flow, power output profiles of generation units, dispatch plan of each component, installed capacity of new infrastructure, …

OPTIMAL POWER FLOW

The Optimal Power Flow (OPF) model determines the dispatch of electric power plants to meet demands at the minimum cost, while satisfying the technical constraints of the system.

$$\min \sum_{i \in S^{\mathrm{GEN}}} f_i^{\mathrm{p}}\left(p_i^{\mathrm{gen}}\right) + f_i^{\mathrm{q}}\left(q_i^{\mathrm{gen}}\right)$$

Objective function: minimise total generation cost

s.t.

$$\sum P^{\mathrm{gen}} - \sum P^{\mathrm{demand}} - \sum P^{\mathrm{loss}} = 0$$

$$\begin{cases} P_i^{\mathrm{gen}} - P_i^{\mathrm{demand}} = U_i \sum_{j=1}^{N_{\mathrm{n}}'} U_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right) \\ Q_i^{\mathrm{gen}} - Q_i^{\mathrm{demand}} = U_i \sum_{j=1}^{N_{\mathrm{n}}'} U_j \left(-B_{ij} \cos\theta_{ij} + G_{ij} \sin\theta_{ij}\right) \end{cases}$$

$$\begin{cases} v_i^{\min} \le v_i \le v_i^{\max} \\ P_i^{\mathrm{gen,min}} \le P_i^{\mathrm{gen}} \le P_i^{\mathrm{gen,max}} \\ Q_i^{\mathrm{gen,min}} \le Q_i^{\mathrm{gen}} \le Q_i^{\mathrm{gen,max}} \\ \theta_{iref} = \theta^{\mathrm{ref}} \end{cases}$$

A day-ahead scheduling model of GB power system incorporating different renewable generation sites

What is the model about:
To find the most economical operation schedule of GB power system by dispatching the generation units including the conventional gas turbines, renewable energy sources, energy storage facilities

Objective function:
The total operation cost of the whole GB power system

Input:
- The constraints representing the GB power system
- The technical specifications of selected renewable energy generation, energy storage
- Wind/radiation/tide data

Output:
- The operation profile of GB power system
  Energy supply mix, the operation scheme of each generation unit, the energy transmission between different regions, ……
- Operation cost, carbon emission, renewable energy curtailment

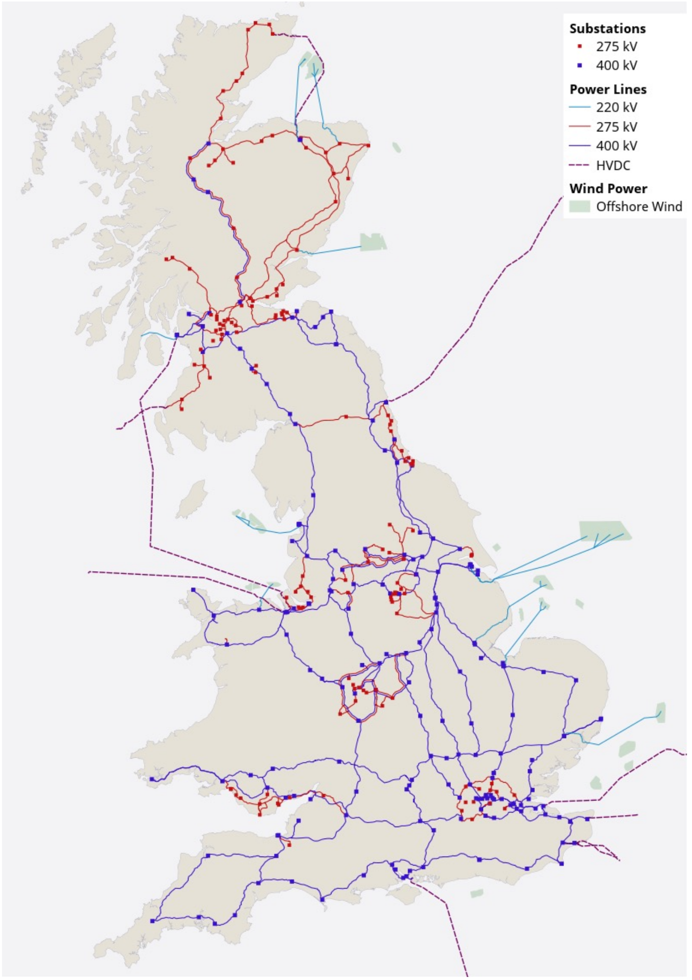


Figure source: https://en.wikipedia.org/wiki/National_Grid_%28Great_Britain%29

Optimisation in EPS

Unit commitment

Electricity & Grid Service Markets

Economic Dispatch

Reliability Optimisation

Voltage/Frequency Control

Resilience Optimisation

Expansion Planning

Restoration

Four other facilities/networks that are the objects of optimisation models:

Microgrid and Distributed Energy Resources (DER)

Renewable Energy generation technologies

Demand Response (DR) / Demand Side Management (DSM)

Energy Storage System

Methodology-Conventional methods

Linear Programming	Objective functions and constraints are in linear forms	• easier to solve, reliable in convergence performance • less accurate than nonlinear power system model
Nonlinear programming	Objective functions and constraints are in linear forms	• accurately reflecting system operation and providing the exact solution • slower in convergence speed; greater computation burden and greater challenges to the solvers
Quadratic Programming	Objective functions are in quadratic forms and constraints are in linear forms	• reflecting quadratic terms in the objective function (e.g., generator's cost function) • no way to simplify a QP
Mixed integer programming	Variables include integer variables	• reflecting the status of key components, e.g., transformer tap ratios, on/off status of generator • super demanding of computation resources (especially MINLP)

Methodology-Conventional methods

Metaheuristic algorithms	Particle Swarm Optimisation, Genetic algorithms, Evolutionary algorithms, …	• **easier to solve, reliable in convergence performance** • **less accurate than nonlinear power system model**
Data-driven methods	Deep reinforcement learning	**Used in decision making and optimal control**
	Data clustering, machine learning, …	**Used in data processing and forecasting forecasting (renewable energy generation, energy demand profiles as the input of optimisation models)**

Methodology-Tools and software

Multiple purposes

MATLAB/Simulink MATPOWER

GAMS (General Algebraic Modeling System)

Python

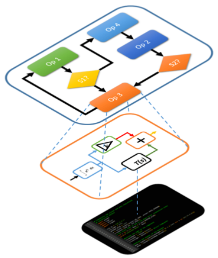
PowerWorld Simulator

DIgSILENT

PSS®

Applied in distribution network or microgrids

HOMER OpenDSS GridLAB-D



Dynamic studies

PSCAD

Important topics in optimisation model-based studies

Uncertainty

Data driven approaches

Renewable energy integration

Cyber security

Smart grid

Flexibility, reliability, resilience

Modelling complexity and computation burden