

random infrastructure networks (of networks)

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1 Conclusions for Power Grid Topologies

Growth Process of (National) Grids

start many small-scale local networks on LV/MV [1, 2]

update 1 if network's capacity becomes a limiting factor MV lines are extended

update 2 HV overlay added, connecting also different local network on lower voltage
[3, p.3]

constraint HV/EHV usually fulfill N-1 criterium [3, p.7]

remark 1 Historically, EHV superseded HV in this role, but they still coexist. [3, p.148]

remark 2 LV network growth driven by amount of load

location HV/MV substations close to load centres [3, p.152]

I hypothesise that it is probably sufficient to model three distinct network levels:

1. low, LV, i.e. connecting all households in a building block to the next higher level
2. middle, MV+HV, the actual distribution backbone in an area
3. high, EHV, connecting different areas over long distances

The low network grows radially from single nodes in the middle network proportional to the load development. The high network consists of long-range connections with high capacity (and is the only one that is meshed ?).

The middle layer is maybe similar road networks [8] in their construction?

Interconnections Between Different Countries/Regions

Power grids are often interconnected via short AC/DC/AC lines and in general at EHV [3, p.6].

Network Structure in General

HV typically built as meshed grid [3, p.15]

- MV
 - operated as radial network (open loops) [3, p.17]
 - mesh another option but more complex to handle [3, p.176]
 - in urban areas, grid follows the road network [3, p.181]
- LV
 - operated/built as radial network (open loops) [3, p.192], i.e. single in-feed from MV
 - length of LV line usually limited to 500m or less [3, p.12]
 - main difference urban/rural [3, p.194ff.], e.g. urban grids are interconnected (proximity)

Choice of Line Type

expected power flow, distance to next substation, type of existing adjacent lines, topography, ?

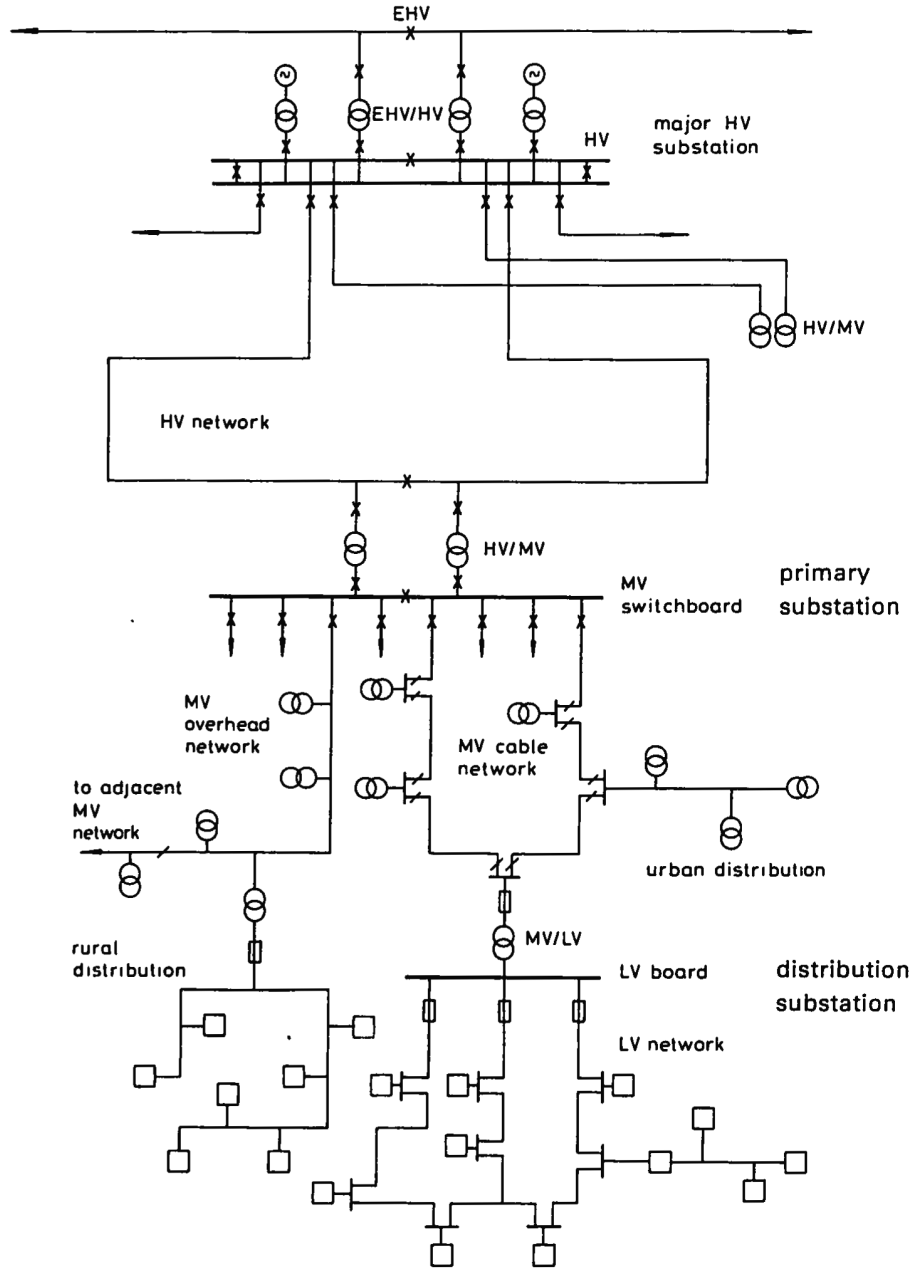


Figure 1.6 EHV/HV/MV/LV network arrangements

⊙ Generator	X Circuit breaker	→ Feeder	□ LV Customer
⊗ Transformer	/ Disconnector	≡ Fuse	

Figure 1: Fig. 1.6 from [3].

2 Literature Summaries

BURN [2]

- In the early days of electricity, energy systems were small and localized → Pearl Street Station in New York City
- From the late 1800s onward, a patchwork of AC and DC grids cropped up across the country → privatization!
- Today's electricity grid – actually three separate grids – is extraordinarily complex as a result.

50Hertz [1]

- Stromversorgung zu Beginn des 20. Jahrhunderts zunächst nur in unmittelbarer Umgebung der Stromerzeugungsstellen möglich
- überwiegend in Stadtgebieten und Ballungsräumen.
- 4040 Unternehmen mit einer installierten Leistung von insgesamt 2096 MW, d.h. durchschnittlich 500 kW je Werk
- Problem: Ausfall eines isolierten Kraftwerks, Schwankende Nachfrage oder extreme Wettersituationen
→ Versorgungssicherheit
- Nach und nach wurden einzelne Kraftwerke im Bereich der Niederspannung verbunden, so dass im ländlichen Bereich weitläufigere Netzstrukturen entstanden
- Diese wurden später an die Mittelspannungsebene angeschlossen, um noch größere Entfernungen überbrücken zu können
- Problem: Zunahme Last+Erzeugung → hohe Lastflüsse → höhere Spannungsebene nötig
- Um 1930 entstand die erste Verbundleitung auf Höchstspannungsebene (220 Kilovolt) für den Stromtransport zwischen Regionalnetzen. → „Reichssammelschiene“
- 1951 im Zusammenschluss der Netze von elf Ländern zum europäischen Verbundnetz UCPTE. Derzeit begann in Deutschland der Ausbau des 380-Kilovolt-Verbundnetzes.

DDR: Zum Ende des Jahres 1975 bestand in der DDR ein Höchstspannungsnetz mit mehr als 7600 km Systemlänge, vorwiegend 220 kV. Bis zur politischen Wende im Jahr 1990 wurde das Verbundnetz der DDR auf eine Systemlänge von 4312 km in 380 kV und 6416 km in 220 kV, ausgebaut. Es bestanden 16 Umspannwerke bzw. Schaltanlagen mit einer Oberspannung von 380 kV und 39 mit 220 kV Oberspannung.

Lakervi and Holmes [3]

chapter 1

- p.3 LV (<1kV), MV (1-36kV), HV (36-300kV), EHV/UHV (>300kV)
- p.6 DC links to former soviet union, scandinavia, UK; i.e. scandinavia is dynamically separated (still true?)
- p.3 higher-voltage systems can be added as overlays when lower levels become too heavily loaded, e.g. UK supergrid 275/400 in the 50's
- p.6 EHV for high power over long distances, country interconnections
- p.7 EHV and HV should be designed to be robust against single-circuit faults (N-1 ?)
- p.7,17 MV and LV in general operated as radial systems (open loops)
 - p.12 length of LV line usually limited to 500m or less
 - p.15 HV typically built as mesh configuration
 - p.17 number of substations connected to feeder is function of: voltage, distance, average demand

chapter 8

- p.148 HV serve as distribution layer primarily, historically they have been superseded by EHV as transmission grids
- p.149 main role to supply HV/MV substations
- p.152 placement of HV/MV substations as close as possible to centre of high load-density area !

chapter 9

- p.166 MV grids exist as an intermediate layer because it's convenient for industrial loads and lines are MUCH cheaper than HV lines, otherwise HV could directly supply LV ...
- p.176 almost always operated radially, although mesh could lead to lower voltage drops and losses, but control would be more complicated
- p.181 in urban areas, MV cables commonly buried along roads -> street network

chapter 10

- p.192 radial design → only a single in-feed
- p.194 average load density in cities can exceed 100 MW/km^2 , rural just 10 kW/km^2
- p.202 in urban areas, LV grids are often close enough to be interconnected, still commonly operated as radial

Rosas-Casals et al. [7]

- data of 33 EU countries
- static robustness, i.e. no load flow redistribution considered !!
- Power grids, having less skewed exponential degree distributions and often without small-world topology, parameter $\gamma \neq$ mean degree
- average nearest neighbor connectivity of a node with the degree k is constant?
- networks grouped in fragile ($\gamma > 1.5$) and robust against intentional attacks
- the application of the N-X contingency-based criteria, though originally intended to avoid interruptions in power service, would difficult the islanding of disturbances
 - the more connected an element is, the easier would be for a disturbance to reach
 - difficulties encountered in preventing perturbations, blackouts or isolating the different power grid elements

Rosas-Casals [6]

UCTE data with coordinates: <http://www.ct.upc.edu/termodinamica/RTEdata>

- spatio-temporal evolution of french grid
- All transmission lines are assumed to be bidirectional; hence the resulting graph is undirected.
- The nodes of the network (i.e., generators, transformers, substations, and so on) are treated as identical, featureless vertices.
- All transmission lines are assumed to be identical (that is, unweighted, with no attributes associated to edges)
- Only the transmission network is considered.
- Fractal spatial distribution of nodes: power grid, being equally geographically constrained, does not follow a fractal pattern until distribution and low voltage grids are considered
- Limited node degree
- Distance-dependence cost of edges
- Trivial clustering-degree correlations

Ravn et al. [5]

assumptions:

- main assumption is that all demand sites and production sites have fixed locations (extra sites cannot be introduced)
- when one cable cannot be used, it should still be possible to redirect the flow through the network, such that all demand is met,
- every site should be connected to at least two other sites
- the network itself should be connected, i.e., it should be possible to reach every site from every other site, only using the selected connections.

method:

- combination of capacity constraints and connectivity constraints, and the possibility of using multiple cables
- voltage levels optimised independently → strong assumption!!
- no (technical?) requirements for inter-level connections
- all demand must be met without storage, i.e. locally, line capacities need to match demand/generation capacity
- simulated annealing (cross-wirings) + load flow calculations in each step
- given: node location and generation/demand capacities
- different kinds of cables, power flow capacity, costs are proportional to length!
- almost impossible to tell if a network design that consists of a lot of nodes can be improved

Strano et al. [8]

- road network evolution typically governed by urbanisation
- continuous expansion and reinforcement of pre-existing structures
- persistent backbone of high-centrality (old) roads
- two elementary processes: densification and exploration, distinguished by edge-betweenness
- densification: low impact on centrality, no dead ends
- exploration: higher impact on centrality, dead ends
- average population per road intersection remains constant over time

- average link length decreases over time
- road networks are planar graphs, cell area distribution follows power law
- homogenisation of cell areas, rectangles become dominant shape

Yang and H. Bell [9]

- mixed NDP : involving simultaneous choice of link addition and capacity improvement which is considered more sensible for road networks
- introduce the network reserve capacity concept for a capacity improvement plan, and raise and clarify some interesting issues relating to NDP and Braess's paradoxes
- The objective is to make an optimal investment decision in order to minimize the total travel cost in the network, while accounting for the route choice behaviour of network users
- travel costs could be equivalent to transport losses, on the one hand we have line losses, on the other hand losses at plants that cannot produce at full capacity
- economic objective function for optimization
- mixed network design problem involving the simultaneous choice of link addition and capacity improvement
- e.g. 4.2.1. Travel cost minimization with fixed demand
- objective function contains travel costs along all links and construction costs (alternatively, they can also be subject to an additional budget constraint)

Liu et al. [4]

- kernel density estimate of a network (nodes/links) to estimate a probable spatial density function
- one parameter, bandwidth of the kernel
- e.g. polynomial, gaussian, ...
- threshold to define cores

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