MAX PLANCK INSTITUTE
FOR DYNAMICS OF COMPLEX
TECHNICAL SYSTEMS
MAGDEBURG

# Computing a global optimal solution for energy supply and storage of the future The reason reduced models are unavoidable

Power Web Conference

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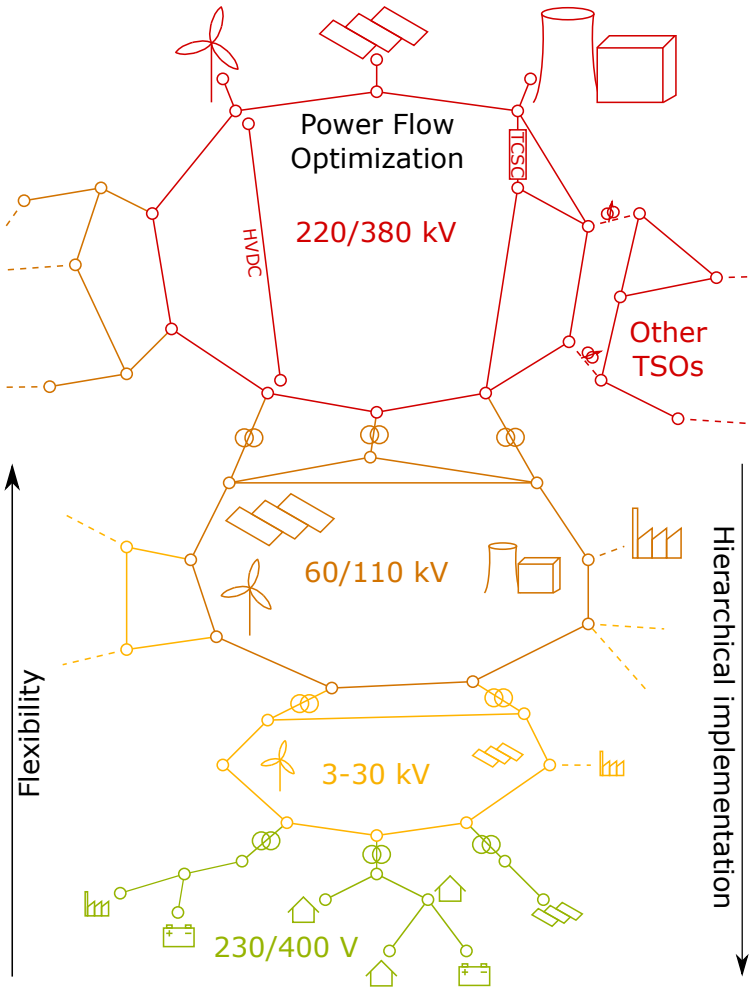
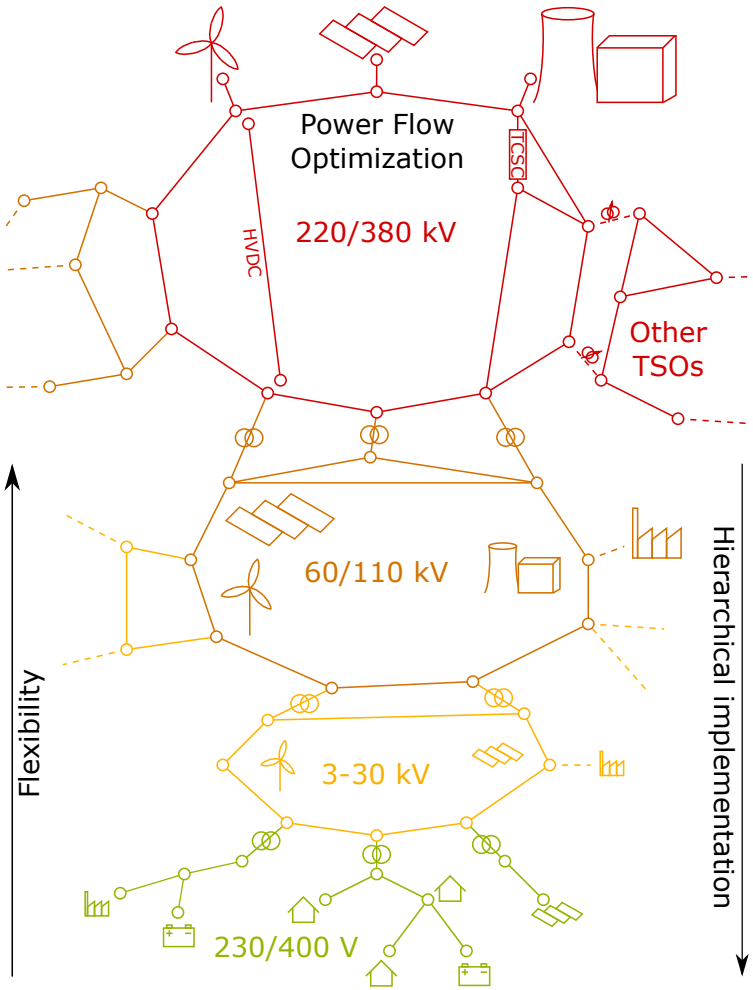
June,17 2021

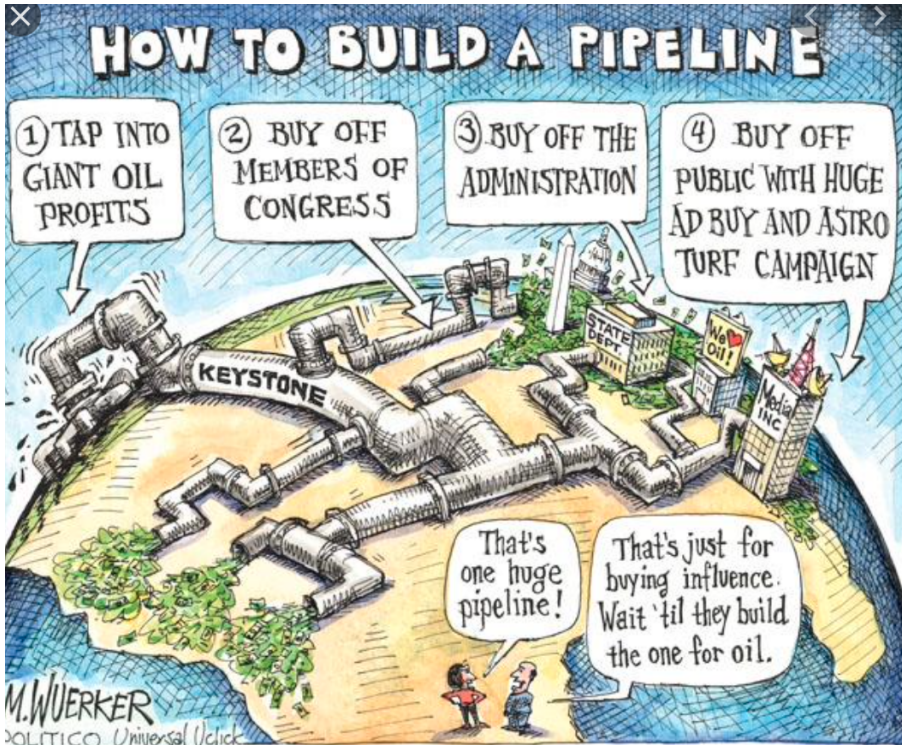
# Motivation




- different voltage
- transmission system operator's main concern is **stability** and **security** of the system in case of contingencies
- the distribution system operator aims to exploit inherent **flexibilities**
- make the flexibility from the distribution grid available within the whole network
- don't neglect the dynamics

# Motivation


Flexibility
230/400 V
3-30 kV
60/110 kV
HVDC
220/380 kV
Power Flow
Optimization
TCSC
Other
TSOs
Hierarchical implementation


HOW TO BUILD A PIPELINE
1 TAP INTO GIANT OIL PROFITS
2 BUY OFF MEMBERS OF CONGRESS
3 BUY OFF THE ADMINISTRATION
4 BUY OFF PUBLIC WITH HUGE AD BUY AND ASTRO TURF CAMPAIGN
KEYSTONE
STATE DEPT
We ♥ Oil!
Media INC
That's one huge pipeline!
That's just for buying influence. Wait 'til they build the one for oil.
M.WUERKER

# What I do and what I don't do


- Simulation of Energy
- Projects that develop new mathematics
- application in power and gas
- Modeling, Simulation and Optimization
- no software, no lab experiments, no financial markets expert
- however regulatory settings should be considered in the modeling

# Acknowledgments and Collaborations

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für Bildung
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# Overview

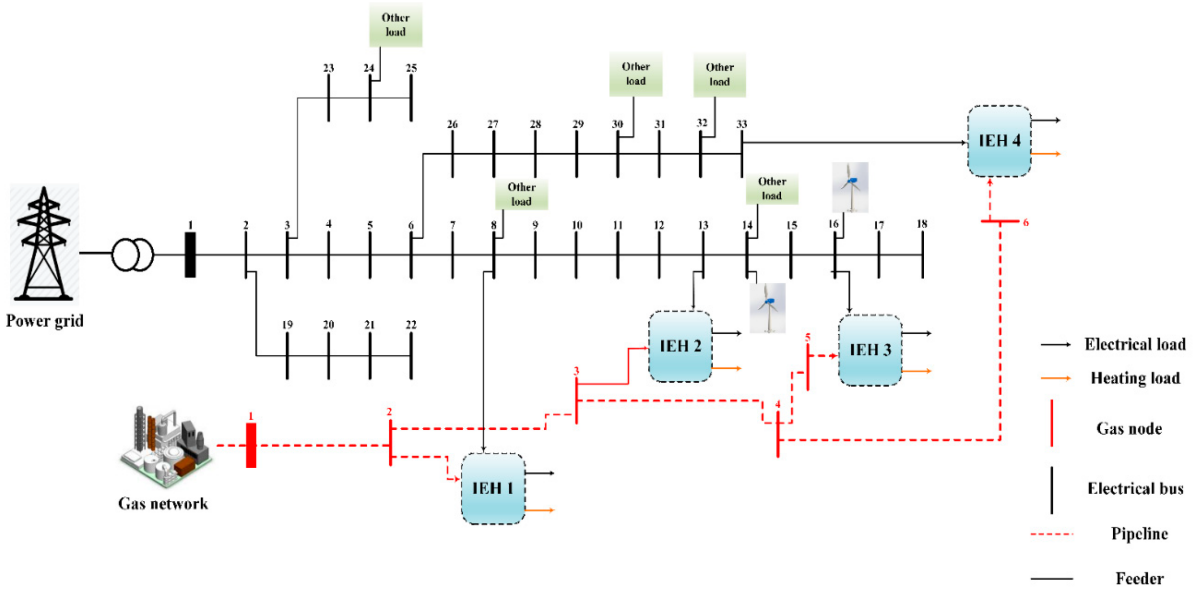
1. Global Point of View
2. Power flow equation
3. Optimization problem
4. Numerical simulations

# Optimization and Optimal Control

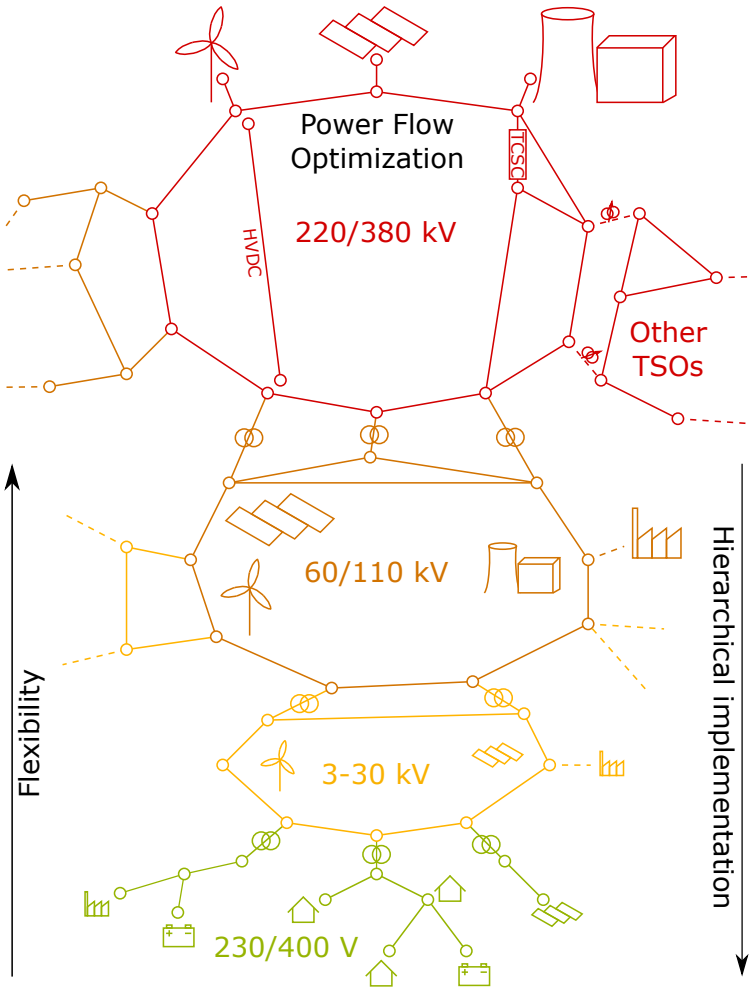
## Global Optimal Solution needs an objective function $f(x)$

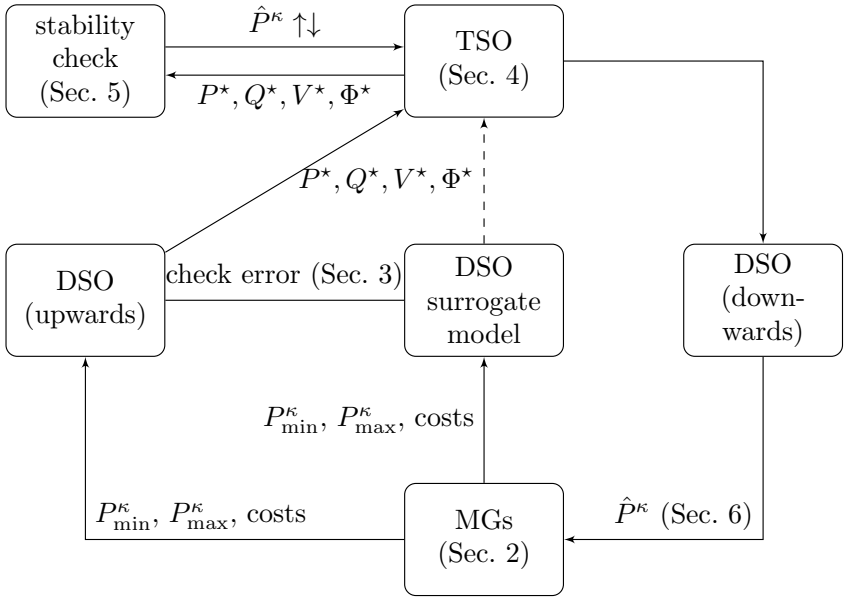
- Monetary cost
- Environmental impact
- Societal impact

What is $x$ and what are the constraints on $x$?

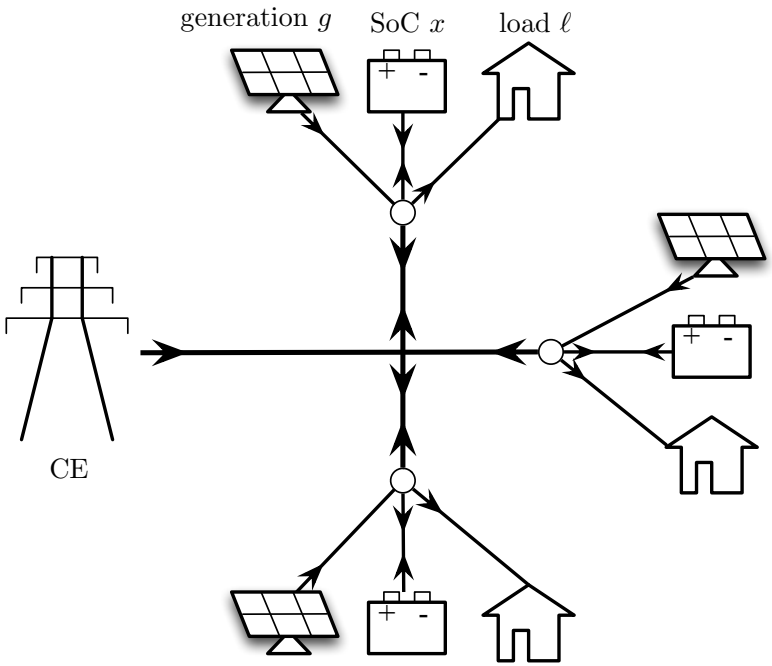


# Optimal Battery Control in the Hierarchical Power Grid



# Microgrid Level




- time discrete system
- battery control (charging and discharging)
- only active power demand is considered
- peak shaving could be one optimization goal
- time horizon is important

# Surrogate Model

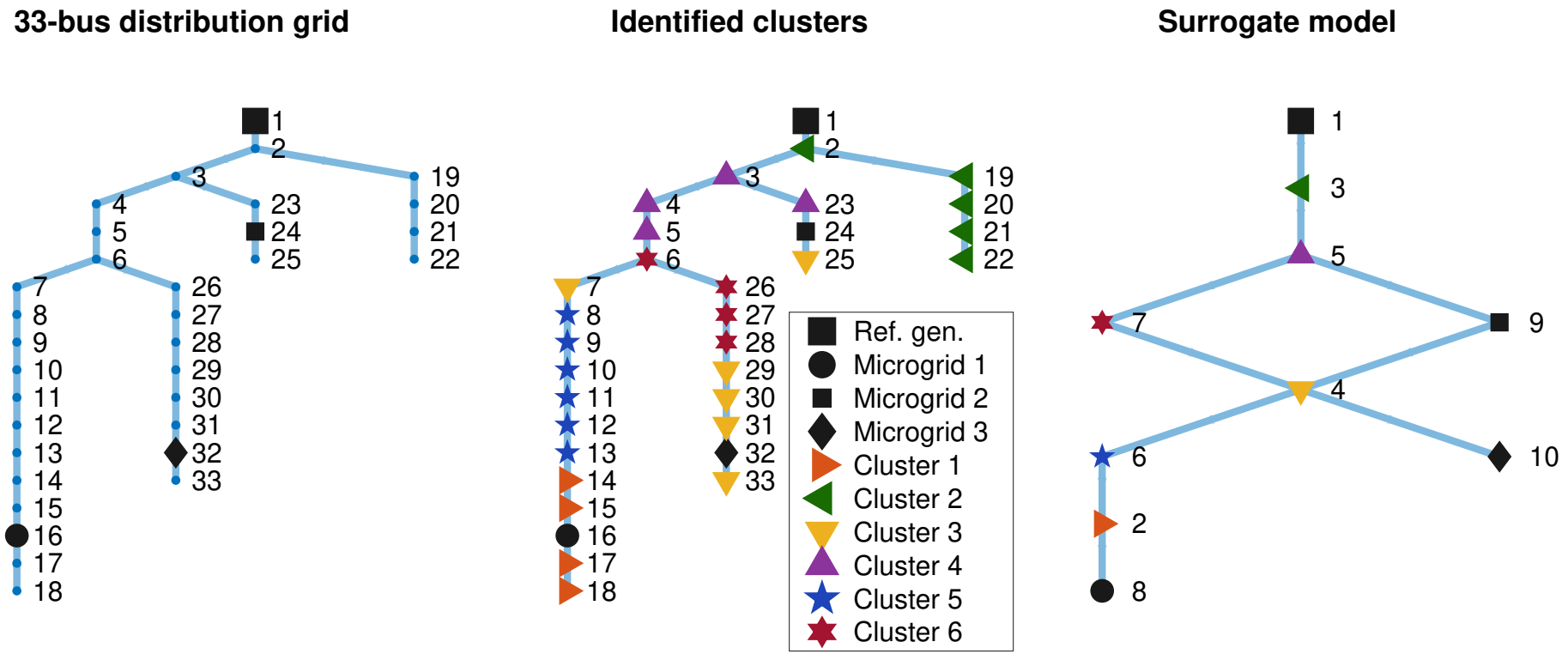



Figure: The 33-bus distribution grid used as test instance (left), the identified load node clusters (middle), and the surrogate model (right) obtained with the identified clustering.

Two purposes: faster computation and secure communication

[1] Mlinarić, P., Ishizaki, T., Chakrabortty, A., Grundel, S., Benner, P., Imura, J. I. (2018, June). Synchronization and aggregation of nonlinear power systems with consideration of bus

# Battery control

- Batteriesteuerung (laden/entladen)
- "peak shaving" als Optimierungsziel
- MPC - Zeithorizont!

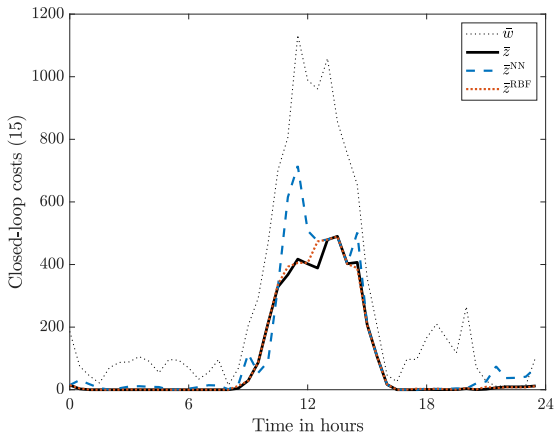
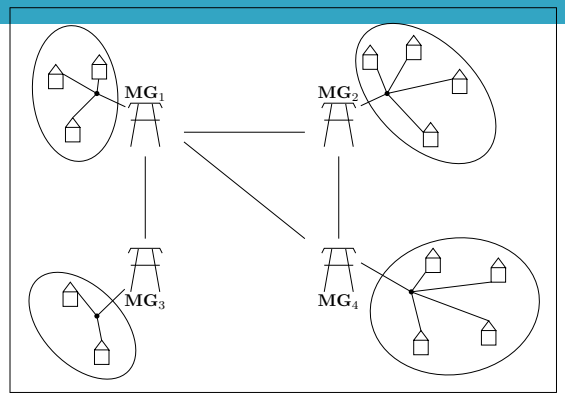



Figure: Impact of mapping error (top) and approximation via RBF and NN (bottom) on the closed-loop performance within 48 consecutive time steps.




| | cost | runtime[ms] |
|---|---|---|
| no contr | 12,2 | — |
| ADMM | 4,4 | 2.5 |
| RBFs | 4,5 | 1.2 |
| NNs | 5,6 | 0.05 |

Table: Comparison of the summed MPC closed-loop performance cost and runtime (per call): ADMM vs. RBFs vs. NNs.

[2] M Baumann, S Grundel, P Sauerteig, K Worthmann Surrogate models in bidirectional optimization of coupled microgrids at-Automatisierungstechnik 67 (12), 1035-1046, 2019

# Overview

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# Network Structure

**Tree as graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with nodes $\mathcal{V}$ and edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$**

- nodes are referred to as buses, edges represent transmission lines
- low-voltage subnet is rooted at a transformer station (the slack 0)

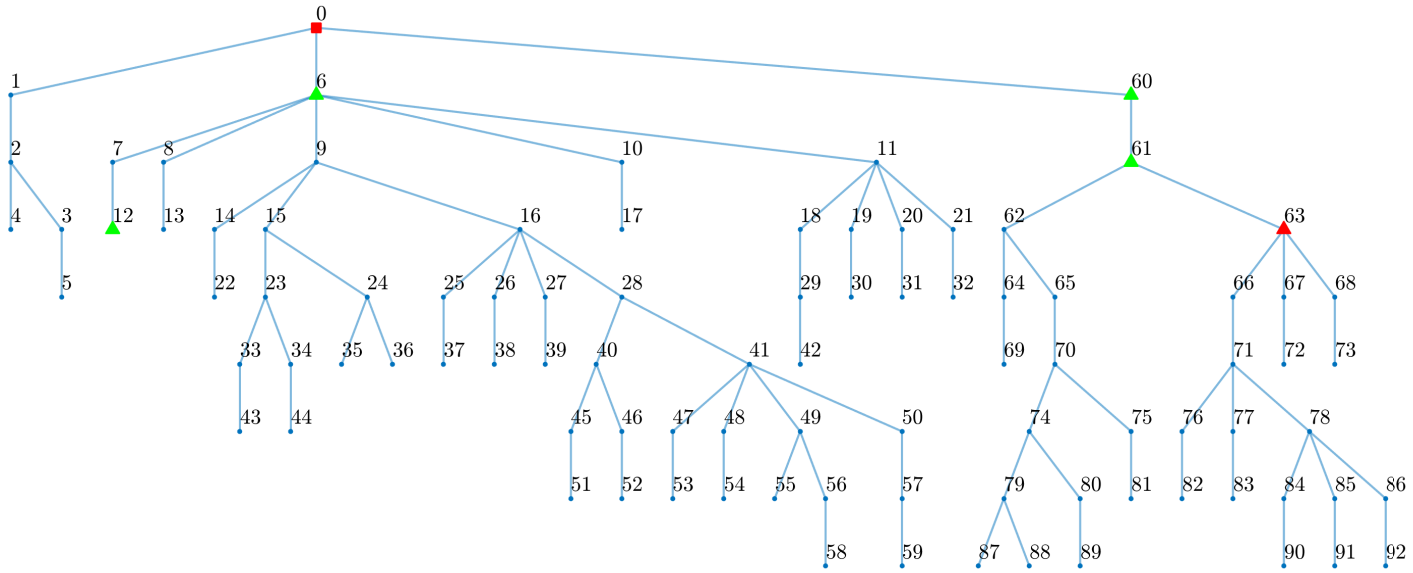



Figure: Tree-structured graph with slack node 0 (red square) and 92 (following) nodes.

# Quantities of Interest

Each bus $i \in \mathcal{V}$,

- incorporates an active power demand $P_i$ in kW,
- a reactive power demand $Q_i$ in kvar,
- and a complex voltage $V_i = |V_i| \mathrm{e}^{\mathrm{j}\delta_i}$, where $|V_i|$ and $\delta_i$ denote the voltage magnitude and angle, respectively.

Typically,

- the voltage $V_0 = |V_0| \, \mathrm{e}^{\mathrm{j}\delta_0}$ at the slack node is given.
- For $i > 0$, we assume that the active power demand is known in advance.
- Given the power factor $\tan(\varphi_i)$ the reactive power demand is determined by

$$Q_i \quad = \quad P_i \cdot \tan(\varphi_i), \tag{1}$$

with $\varphi_i$ from the complex power $S_i = P_i + \mathrm{j}Q_i = |S_i| \, \mathrm{e}^{\mathrm{j}\varphi_i}$.

# Admittance Matrix and Power Flow

$$\begin{bmatrix} P_i - |V_i| \sum_{j=1}^{n} |V_j| (G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})) \\ Q_i - |V_i| \sum_{j=1}^{n} |V_j| (G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})) \end{bmatrix} = 0 \quad \forall\, i \in \mathcal{V}, \tag{2}$$

## Admittance Matrix

(complex) admittance $y_{ij} \in \mathbb{C}$ along the transmission line $(i,j) \in \mathcal{E}$ is encoded via the bus admittance matrix $Y \in \mathbb{R}^{n \times n}$ given by

$$Y_{ij} = \begin{cases} y_i + \sum_{k \in \mathcal{V} \setminus \{i\}} y_{ik}, & \text{if } i = j \\ -y_{ij}, & \text{else.} \end{cases}$$

- the so-called shunt admittance, $y_i$ is omitted.
- $Y = G + \mathrm{j}B$ with matrices $G = (G_{ij}), B = (B_{ij}) \in \mathbb{R}^{n \times n}$, which are parameters of the system.
- (2) consists of $2n$ equations with $4n$ variables namely $(|V_i|, \delta_i, P_i, Q_i)^\top \in \mathbb{R}^4$
- $\delta_{ij} = \delta_i - \delta_j$ denotes the angle difference for $i, j \in \mathcal{V}$.

# Overview

# The objective function

## Line Loss

The transportation of energy comes along with losses depending on the length and material of the line and the amount of the current flow.

$$P_L(I) = 3 \cdot \sum_{l=1}^{n-1} R_l' \ell_l \left| I_l \right|^2 . \tag{3}$$

- $R_l'$ and $\ell_l$ denote the specific resistance in $\Omega$/km and the length in m
- $|I_l|$ represents the magnitude of the complex current along the line
- The factor 3 reflects the fact that the lines consist of three phases.

$$I = \frac{1}{\sqrt{3}} \max\{\left|Y^{\mathrm{f}} \cdot V\right|, \left|Y^{\mathrm{t}} \cdot V\right|\},$$

$|\cdot|$ and max are to be understood component-wise

# Constraints

- active power demand $P_i$ is given.
- $Q_i = P_i \tan(\varphi_i)$ and $\cos(\varphi_i) = \mu_i$

$$\underline{\mu}_i \quad \leq \quad \mu_i \quad \leq \quad \overline{\mu}_i$$

- Note that the power factors can only be set indirectly by manipulating inverters.
- voltages have to stay within some corridors, w

$$\underline{V}_i \quad \leq \quad |V_i| \quad \leq \quad \overline{V}_i$$

- Having the interface to the upper grid level in mind, we assume some bounds on $Q_0$ to be given by the DSO, i.e.

$$\underline{Q}_0 \quad \leq \quad Q_0 \quad \leq \quad \overline{Q}_0$$

# Optimization Problem

$$\min_{\mu_i \in [\underline{\mu}_i, \overline{\mu}_i]} \quad P_L(I) = 3 \cdot \sum_{l=1}^{n-1} R_l' \ell_l \, |I_l|^2 \tag{4a}$$

subject to $\quad \forall\, i \in \mathcal{V}:$

$$\begin{bmatrix} P_i - |V_i| \sum_{j=1}^{n} |V_j| (G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})) \\ P_i \cdot \tan(\varphi_i) - |V_i| \sum_{j=1}^{n} |V_j| (G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})) \end{bmatrix} = 0 \tag{4b}$$

$$I = \frac{1}{\sqrt{3}} \max\{\left|Y^{\mathrm{f}} \cdot V\right|, \left|Y^{\mathrm{t}} \cdot V\right|\} \tag{4c}$$

$$\underline{V}_i \leq |V_i| \leq \overline{V}_i \quad \forall\, i > 0 \tag{4d}$$

$$\mu_i = \cos \varphi_i \quad \forall\, i \in \mathcal{V} \tag{4e}$$

$$|V_0| = 1, \quad \delta_0 = 0 \tag{4f}$$

$$\underline{Q}_0 \leq P_0 \tan(\varphi_0) \leq \overline{Q}_0 \tag{4g}$$

Due to constraint (4b) the problem becomes non-convex.

# Overview

# Details on implementation

- $R'_l$, $\ell_l$ and the grid topology were provided by our industrial partner.
- $P_i$ from Gaussian distribution with $\mathbb{E}(P) = 2.5$ kW, $\sigma(P) = 0.5$ kW.

| | | | | | |
|---|---|---|---|---|---|
| $\underline{\mu}_i$ | 0.9 | $\underline{V}_i$ | 0.9 [p.u.] | $\underline{Q}_0$ | $-\infty$ |
| $\overline{\mu}_i$ | 1 | $\overline{V}_i$ | 1.1 [p.u.] | $\overline{Q}_0$ | $-100$ [kvar] |

Table: Parameters used in the implementation.

We use the `MATLAB` package `matpower` to solve the PFEand `MATLAB`s `fmincon` to solve the optimization. The `fmincon` setting is displayed in Table below.
For the computation of $Y$, $Y^{\mathrm{f}}$ and $Y^{\mathrm{t}}$ we use the open-source software `PandaPower`.

| option | setting |
|---|---|
| `Algorithm` | `interior-point` |
| `MaxFunctionEvaluations` | `1e5` |
| `StepTolerance` | `1e-16` |

Table: `fmincon` setting.

# Scenarios

We distinguish three scenarios with respect to controllability of the power factors:

1. $\cos(\varphi_i) = 0.9$ for all $i > 0$ (no optimization)
2. $\cos(\varphi_i) = \mu^*$ for all $i > 0$ (1-dimensional optimization)
3. $\cos(\varphi_i) = \mu_i^*$ for all $i > 0$ ($n$-dimensional optimization).

The corresponding objective function value is denoted by $P_L^{\mathrm{ref}}$, $P_L^{1\mathrm{D}}$, and $P_L^{n\mathrm{D}}$, respectively.

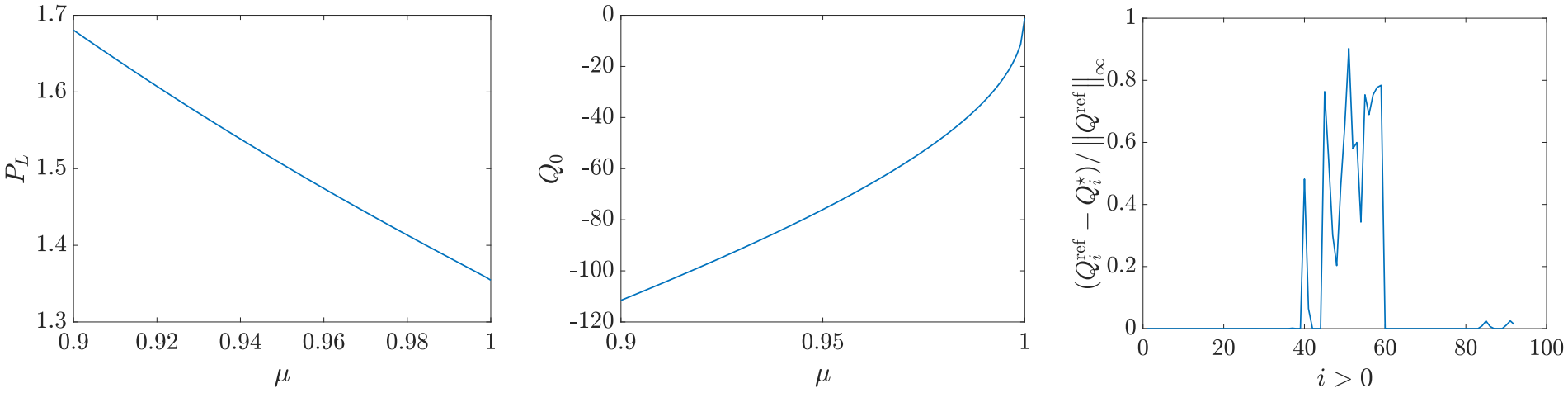



Figure: Impact of the choice of $\mu$ on $P_L$ (left) and $Q_0$ (middle) for the 1-dimensional unconstraint optimization problem and comparison of reactive power $Q_i^{\mathrm{ref}}$ of the reference scenario and $Q_i^{\star}$ of the solution of the $n$-dimensional problem.

# Change in active Power at a single node

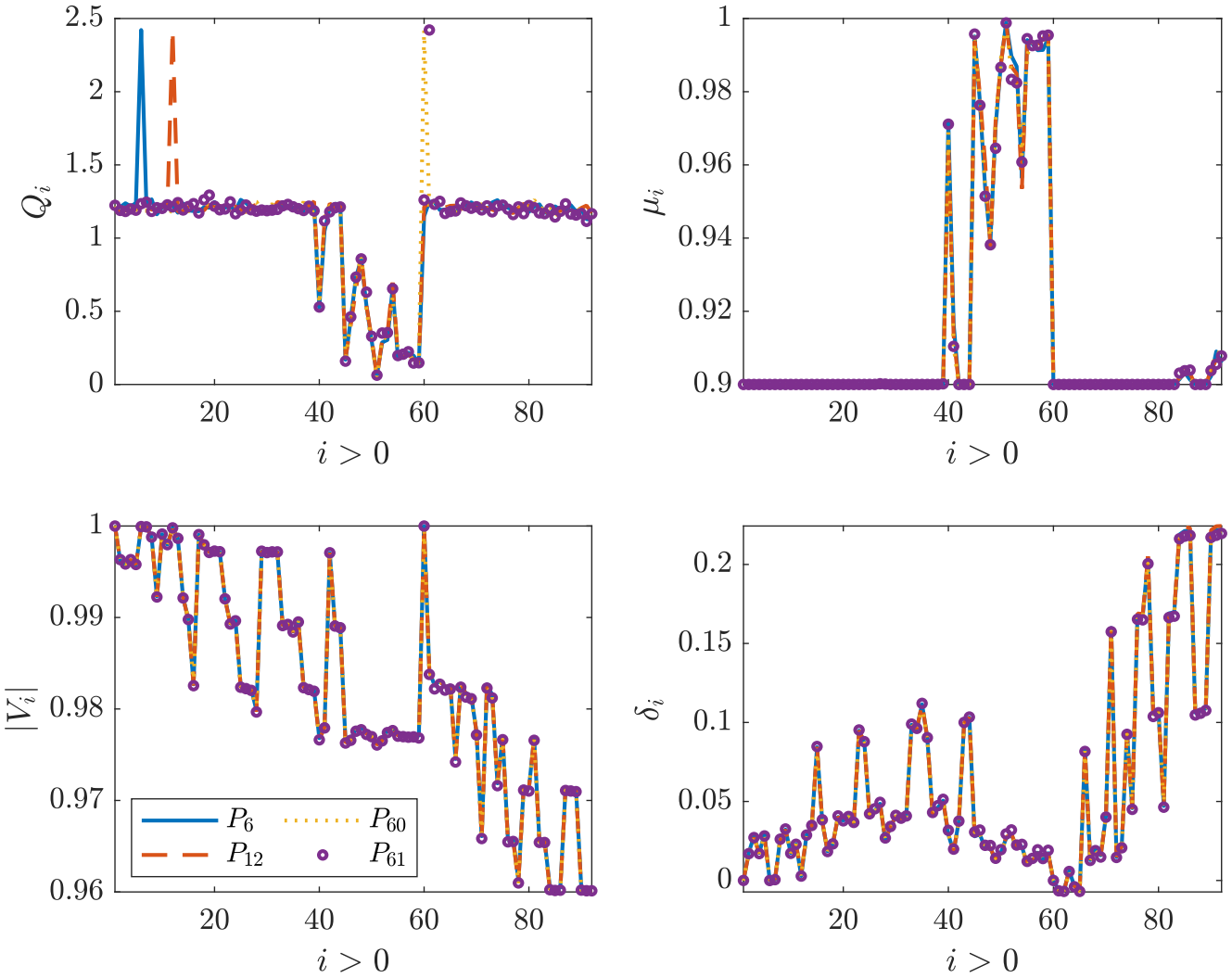



Figure: Impact of changing the active power at one node $i$ to $P_i = 5$ kW.

# Impact of manipulation

| setting | $P_L^{\mathrm{ref}}$ | $P_L^{1\mathrm{D}}$ | $P_L^{n\mathrm{D}}$ |
|---|---|---|---|
| no manipulation | 1.72 | 1.65 | 1.62 |
| $P_6 = 5$ | 1.75 | 1.67 | 1.64 |
| $P_{12} = 5$ | 1.76 | 1.68 | 1.65 |
| $P_{60} = 5$ | 1.72 | 1.64 | 1.61 |
| $P_{61} = 5$ | 1.74 | 1.66 | 1.63 |
| $P_{63} = 5$ | 1.73 | 1.66 | 1.63 |
| $P_{63} = 10$ | 1.76 | 1.68 | 1.64 |
| $P_{63} = 20$ | 1.87 | 1.75 | 1.71 |
| $P_{63} = 50$ | 2.16 | 1.96 | 1.93 |
| $\mathrm{std} = 1$ | 1.74 | 1.67 | 1.64 |
| $\mathrm{std} = 2$ | 1.79 | 1.71 | 1.68 |
| $\mathrm{std} = 4$ | 1.82 | 1.73 | 1.69 |
| $\mathrm{std} = 8$ | 1.88 | 1.78 | 1.73 |

Table: Impact of manipulating the active power at a single bus or increasing the variance of the active power within the whole grid on the objective function value. All values are given in kW.

# Strong disturbance at bus 63

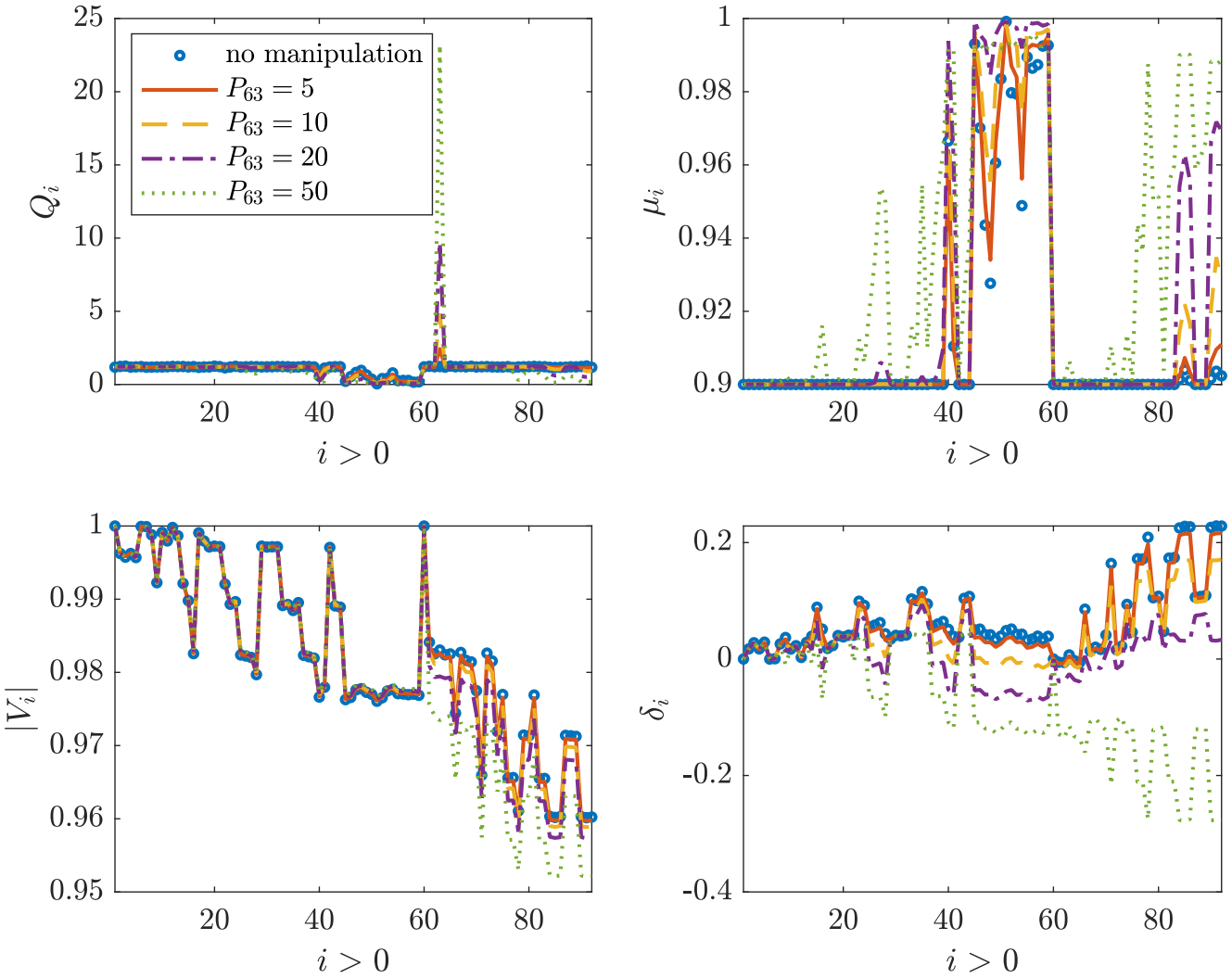
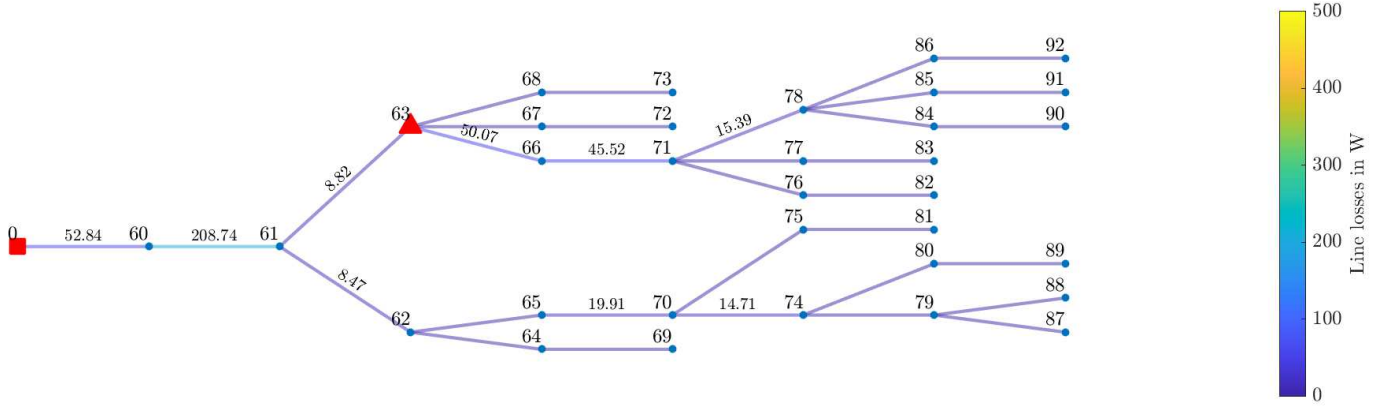
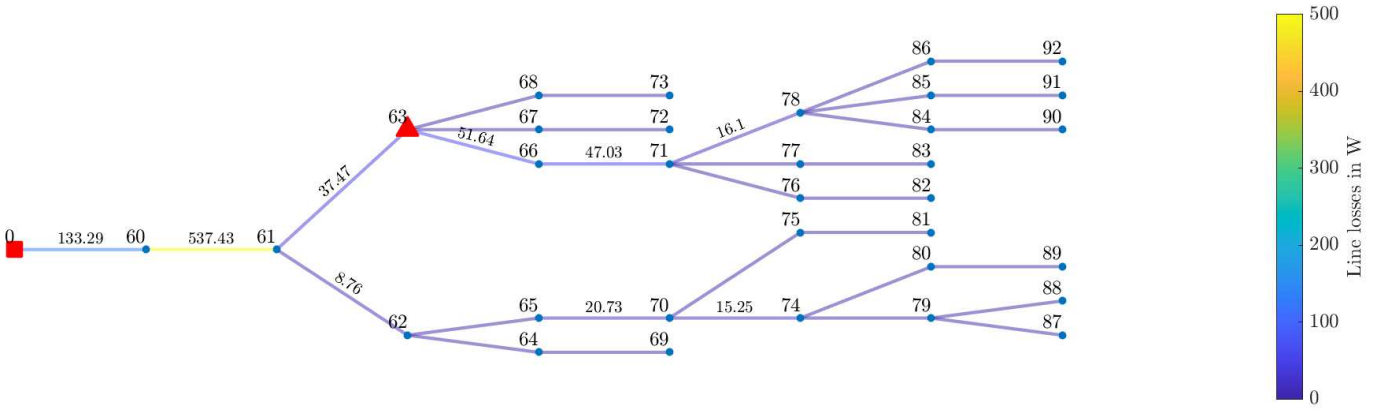



Figure: Impact of changing the active power $P_i$ at one node $i$ (major disturbance).

# Line Losses




(a) Reference scenario without disturbance.




(b) Reference scenario with $P_{63} = 50$.

# Line Losses

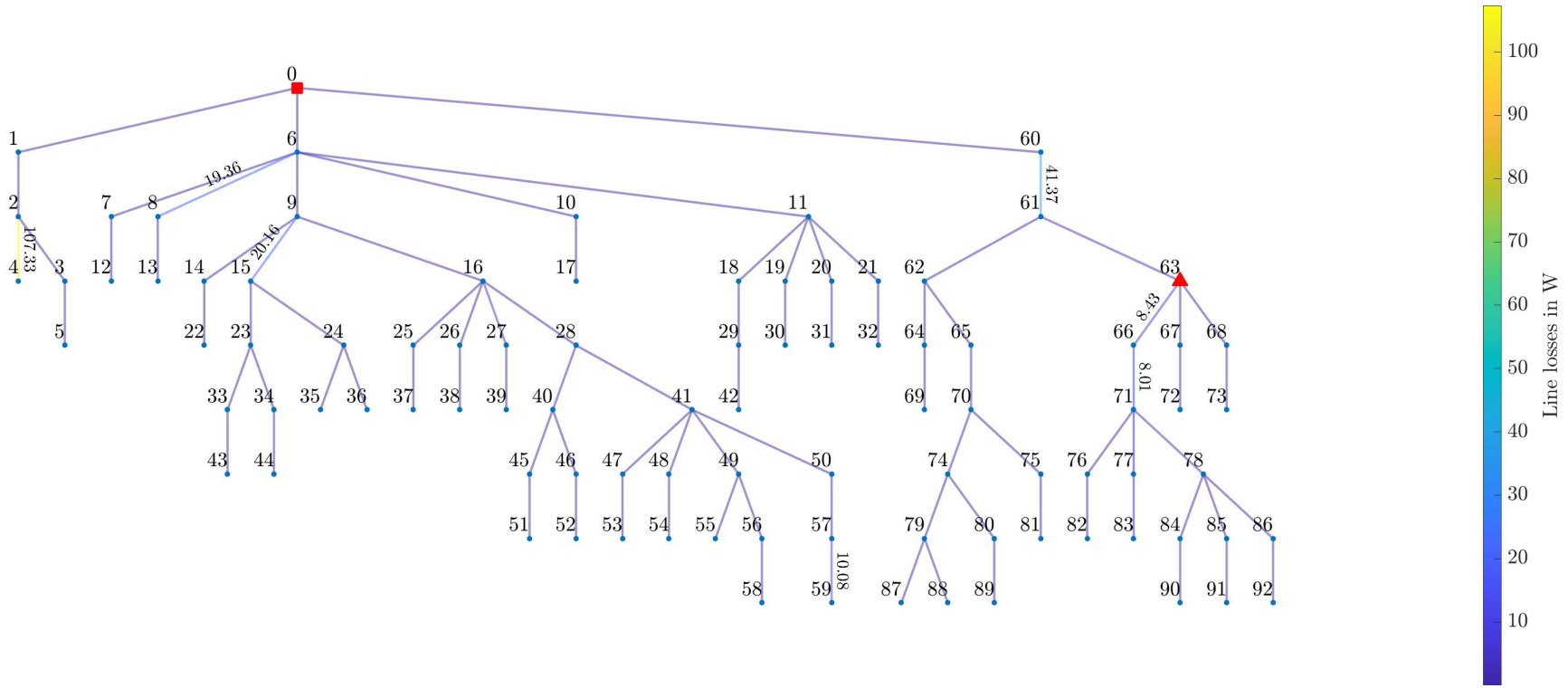



Figure: Difference between line losses before and after ($n$-dimensional) optimization with $P_{63} = 50$ kW.

# Changes with increased variance

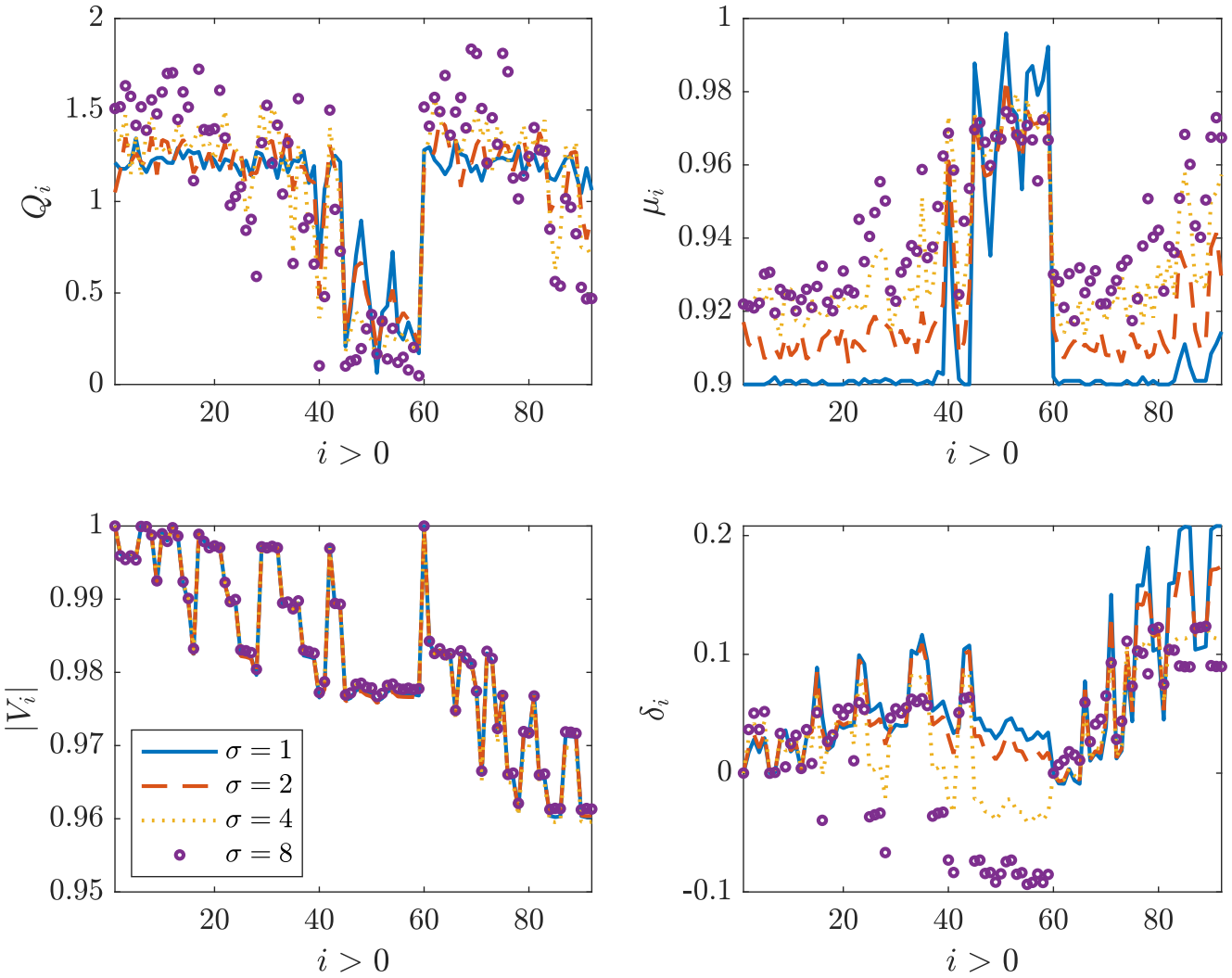



Figure: Impact of increasing the variation of the $P_i$.

# Summary

- Modeling is a crucial part of solving the problem
- Different optimization problems everywhere
- Models are complex and need to be communicated $\Rightarrow$ Surrogate Models aka reduced models
- There are hidden controls that can be used.

## Thank you for your attention!


1. P. Sauerteig, M. Baumann, J. Dickert, S. Grundel, K. Worthmann *Reducing transmission losses via reactive power control* to appear
2. P. Benner, S. Grundel, P. Mlinarić *Clustering-Based Model Order Reduction for Nonlinear Network Systems* P Benner, S Grundel, P Mlinarić arXiv preprint arXiv:2003.06952
3. M Baumann, S Grundel, P Sauerteig, K Worthmann *Surrogate models in bidirectional optimization of coupled microgrids* at-Automatisierungstechnik 67 (12), 1035-1046, 2019