University of Split
Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture

Active Distribution Network Voltage Profile Optimization Using Mixed Integer Linear Programming

D. Jakus, J. Novakovic, J.Vasilj, N.Grbavac, D.Jolevski
damir.jakus@fesb.hr

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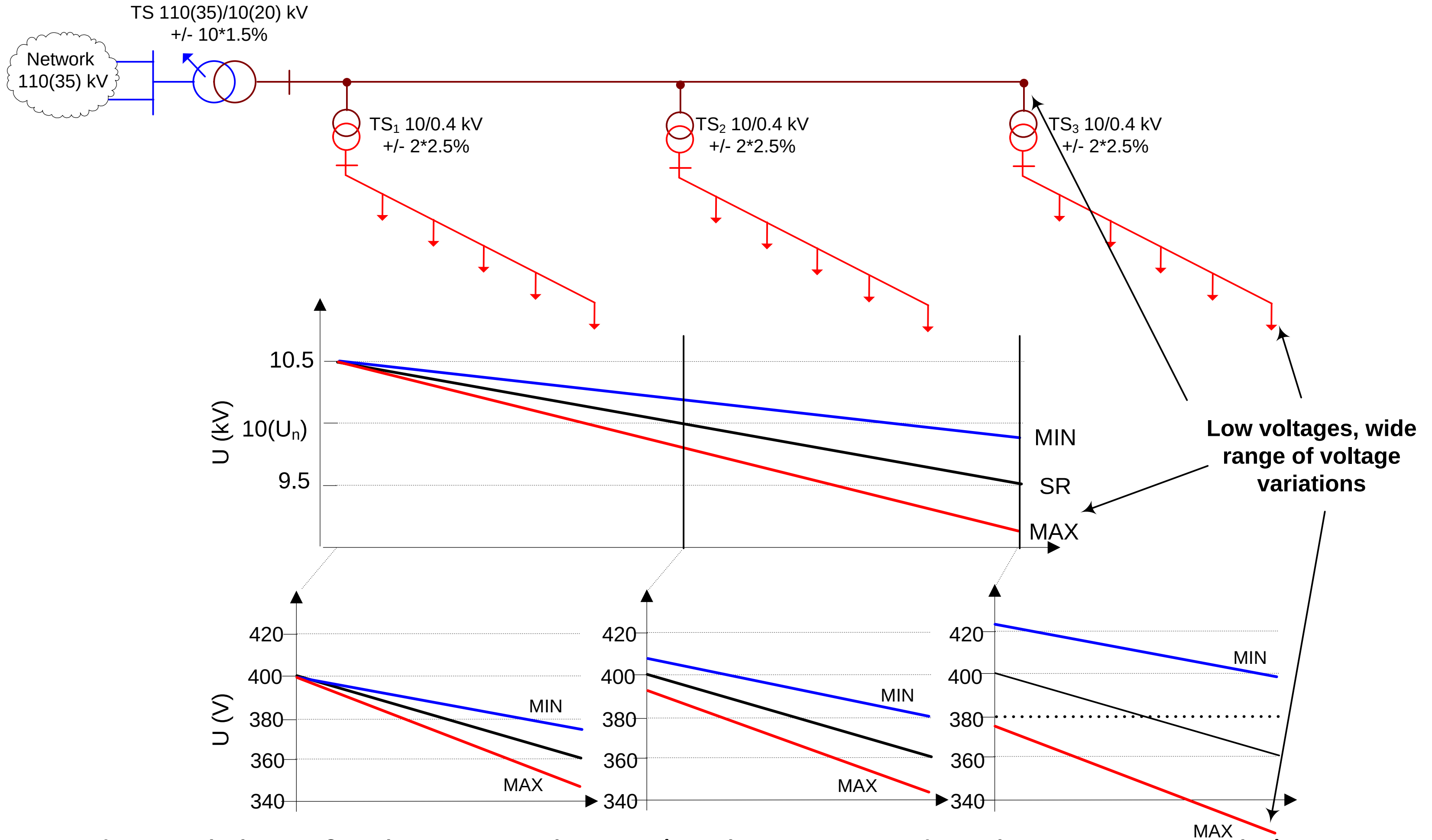
The basic characteristics of passive distribution networks:

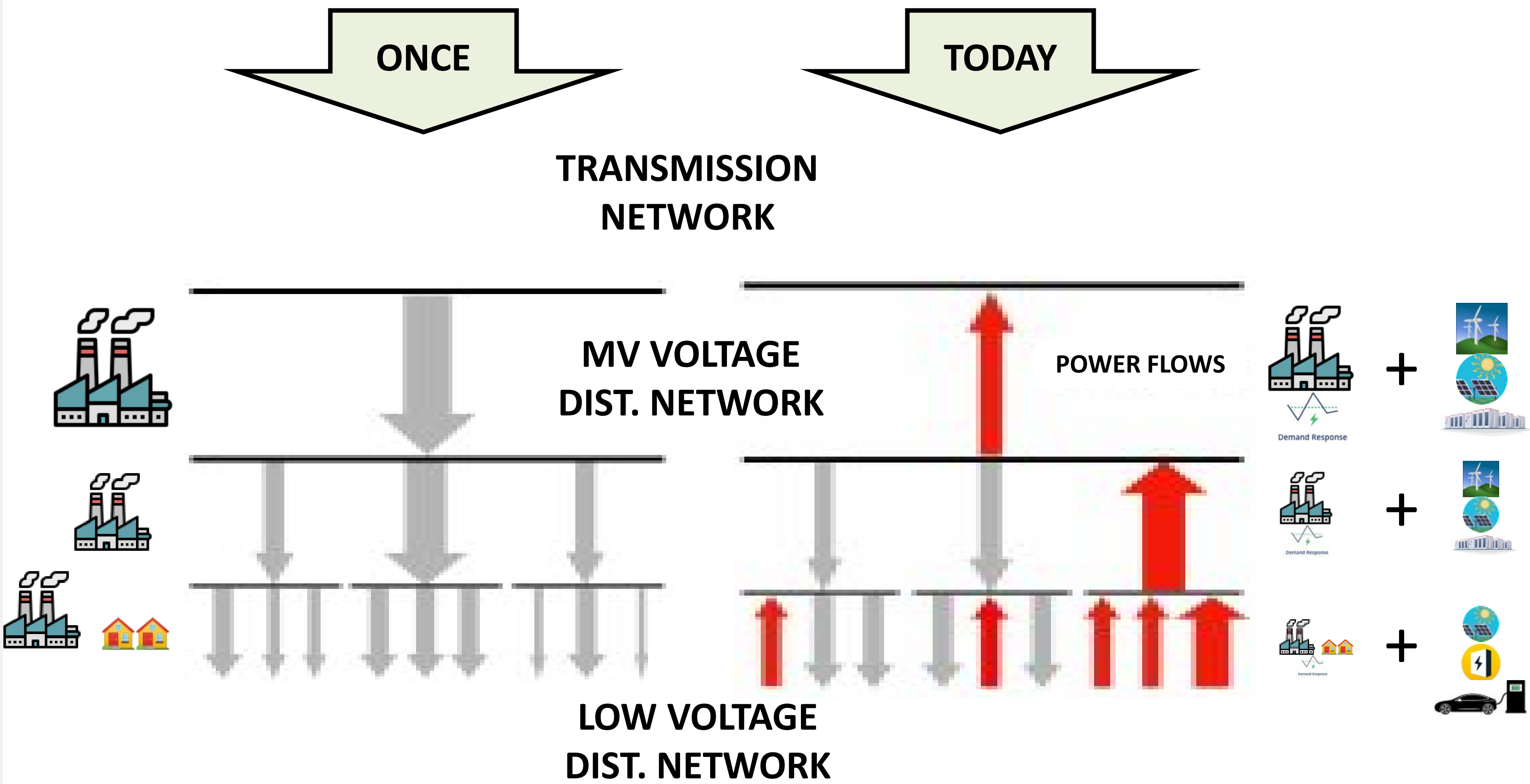


Limited possibility of voltage regulation (in the passive distribution networks):

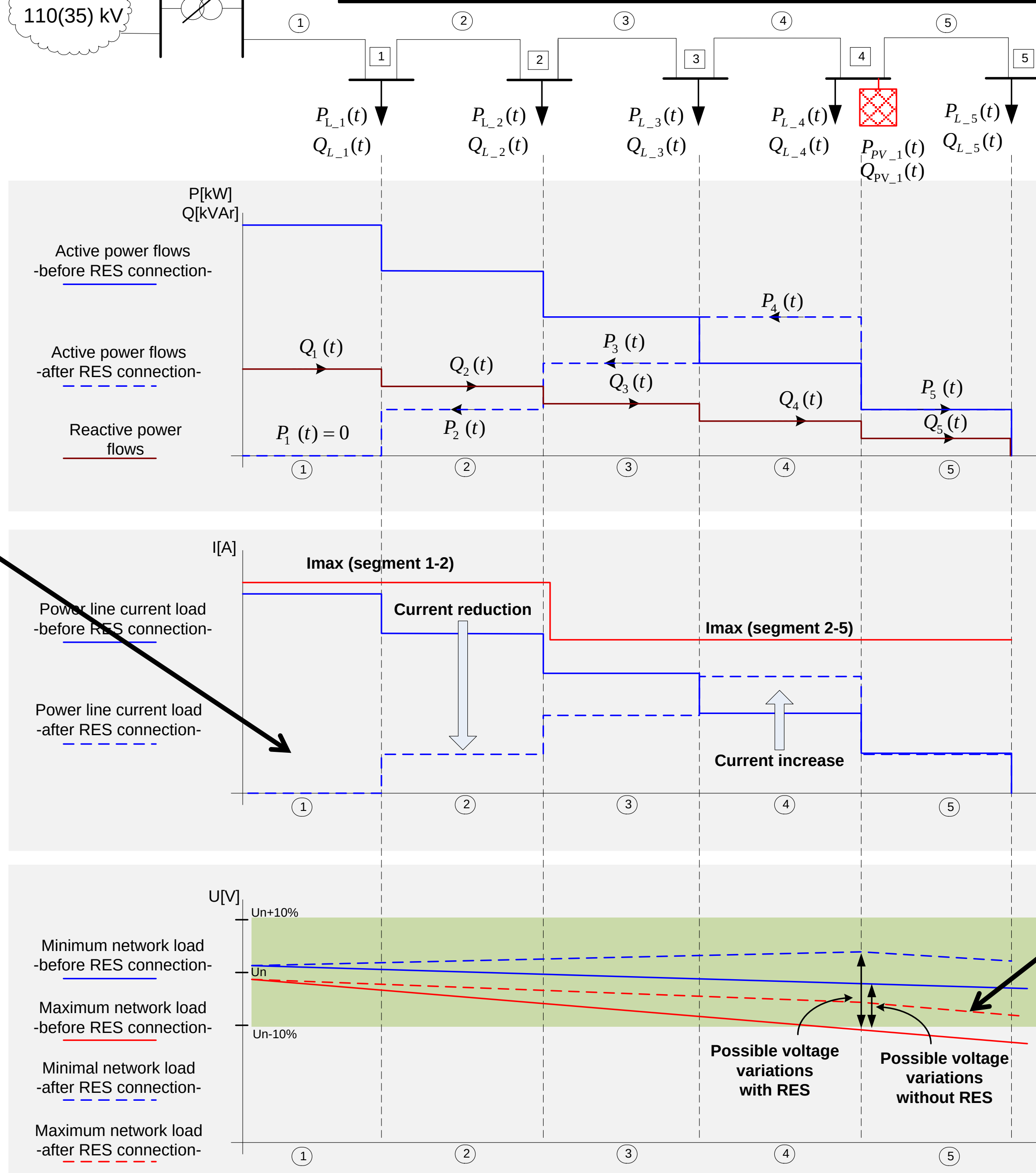
- transformers with on-load tap changers (110 /20(10)kV);
- transformers with off-load tap changers (35/10kV, 20 (10) /0.4 kV);
- capacitor banks

Active/passive distribution network

Unidirectional/bidirectional power flows



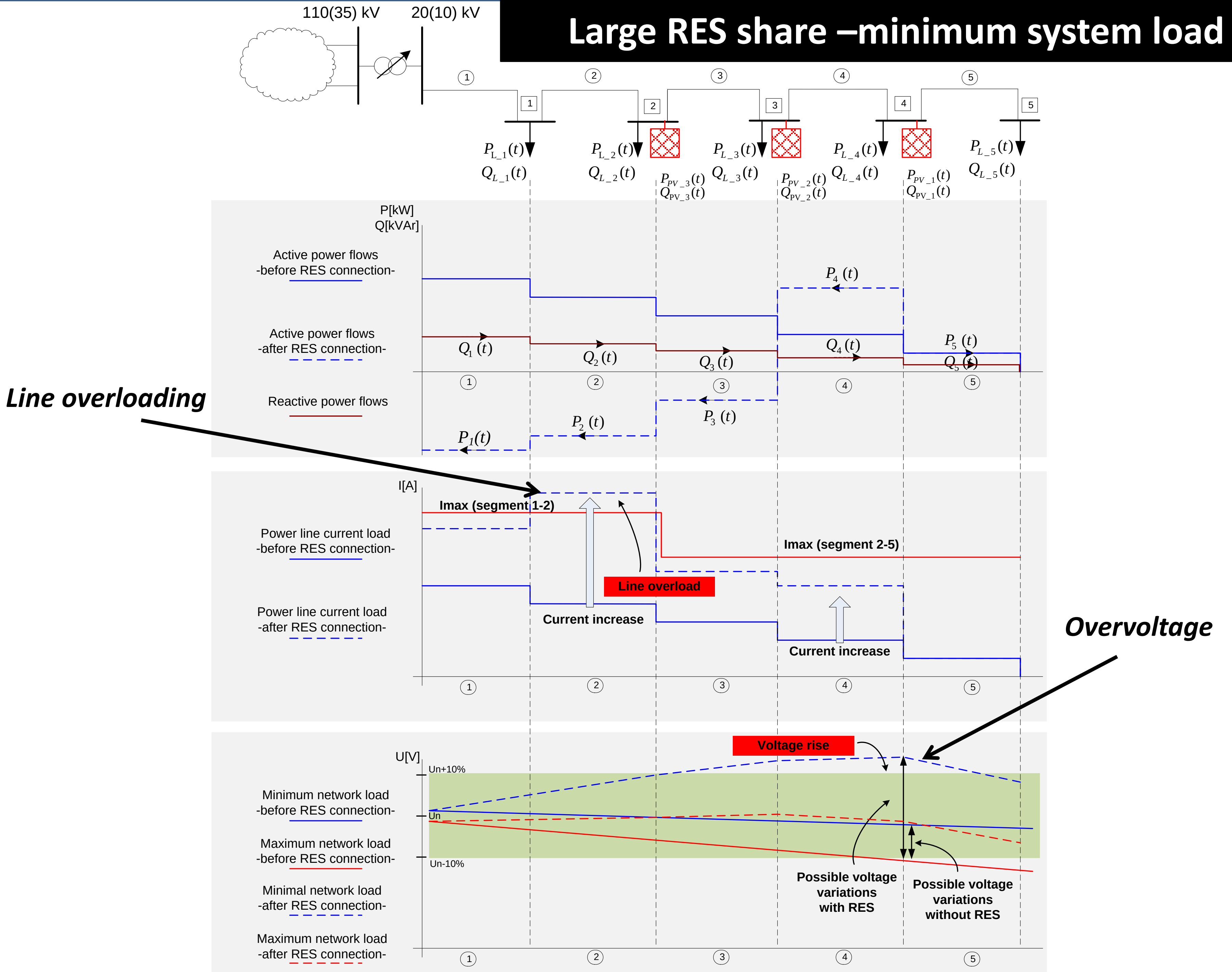
Low/medium share of RES



Increased network capacity - when the RES work

Better voltage conditions - when RES work ???

Large RES share –minimum system load



Voltage regulation mechanisms:

- **<u>Passive distribution network (=> problem with low voltages):</u>**
  - Network reconfiguration
  - Network expansion and reinforcement
  - Transformers with variable number of turns:
    - on-load tap changers (110 / x kV)
    - off-load tap changers (35/10 kV, 10 (20) /0.4 kV, ...)
  - Capacitor banks (binary control, step control, continuous regulation)
- **<u>Active distribution network (=> the problem of too high / too low voltages):</u>**
  - Classic regulatory measures that are used in a passive distribution networks
  - Determination of the optimal network connection
  - The management of distributed electrical sources:
    - Active power regulation => active power curtailment as a measure to reduce network voltages
    - Reactive power control => production / consumption of reactive power as a measure to increase / decrease network voltage
  - Electricity storages
  - Electric Vehicles
  - Demand response,…

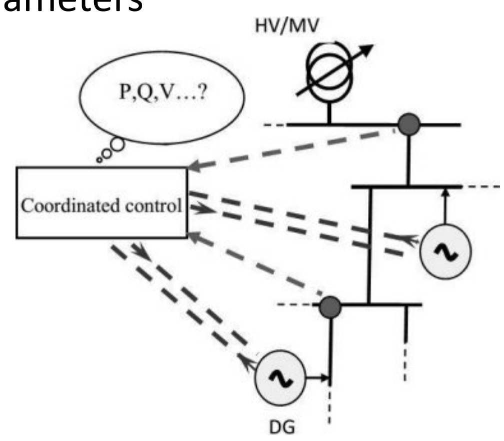
Voltage regulation concepts:

VOLTAGE REGULATION CONCEPTS

COORDINATED CONTROL | **SEMI-COORDINATED CONTROL** | **LOCAL CONTROL**

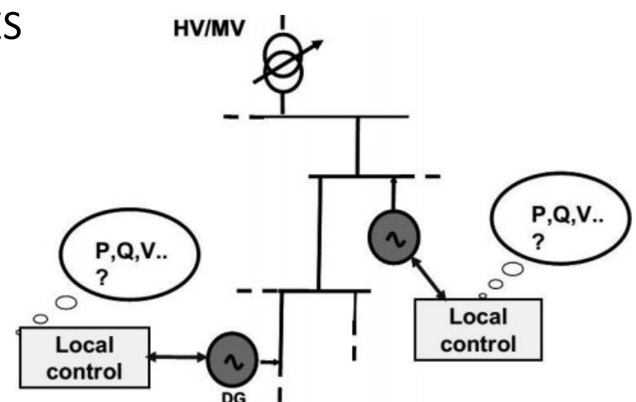
Coordinated control:

- Generally results with better (more optimal) network conditions
- Requires: highly developed IT infrastructure, good measurement coverage along distribution network, data defining network topology and its electrical parameters

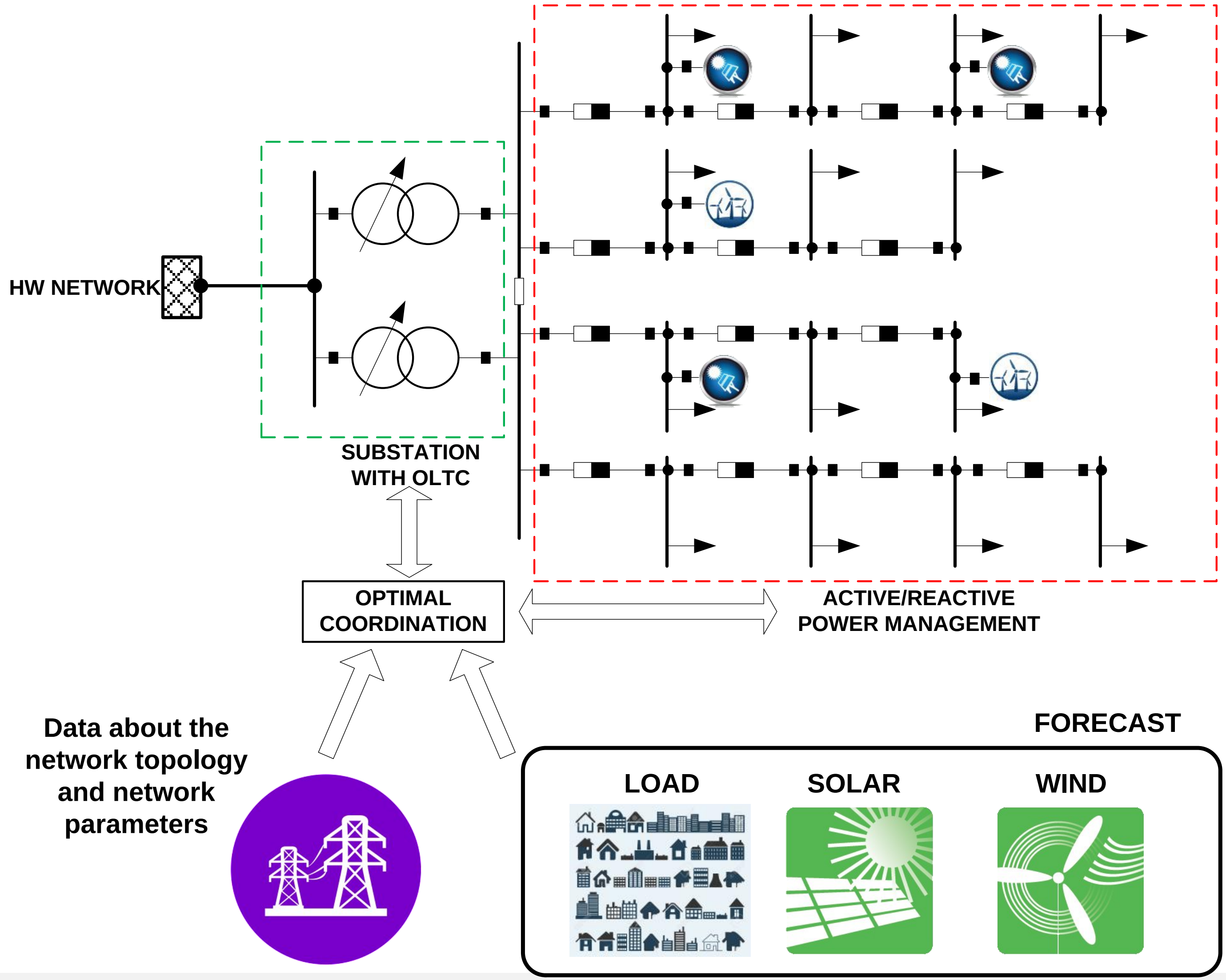


Local control:

- Generally gives poorer results
- No major requirements in terms of IT system;
- Interruptions in the communication system doesn't present threat for the system stability
- It requires only local measurements
- Automatic management at the level of RES



Centralized control of the distribution networks with a high share of renewable energy



Mathematical formulation– MILP

$$\min \sum_{\substack{i\in N\\ t\in T}} \Delta V_{i,t}^2 \Rightarrow \min \sum_{i\in N} \Delta V_i^{max}$$

<= Minimize sum of absolute maximum node deviations

$$\Delta V_i^{max} \geq \Delta V_{i,t}^{pos} \quad \forall i \in N, t \in T$$

$$\Delta V_i^{max} \geq \Delta V_{i,t}^{neg} \quad \forall i \in N, t \in T$$

$$V_{i,t} = 1 + \Delta V_{i,t} \quad \forall i \in N, t \in T$$

$$V_{i',t} = 1 + \Delta V_{i',t} \quad \forall i \in N, t \in T$$

$$\theta_{ij,t} = \theta_{i,t} - \theta_{j,t} \quad \forall i,j \in N, t \in T$$

$$\Delta V_{i,t} = \Delta V_{i,t}^{pos} - \Delta V_{i,t}^{neg} \quad \forall i \in N, t \in T$$

$$\Delta V_{i,t}^{pos} \geq 0 \quad \forall i \in N, t \in T$$

$$\Delta V_{i,t}^{neg} \geq 0 \quad \forall i \in N, t \in T$$

$$V_i^{min} \leq V_{i,t} \leq V_i^{max} \quad \forall i \in N, t \in T$$

$$(V_i^{min} - 1) \leq \Delta V_{i,t} \leq (V_i^{max} - 1) \quad \forall i \in N, t \in T$$

Voltage constraints

$$P_{ij,t} = (\Delta V_{i,t} - \Delta V_{j,t}) g_{ij} - b_{ij}\theta_{ij,t}$$

$$P_{ji,t} = -(\Delta V_{i,t} - \Delta V_{j,t}) g_{ij} + b_{ij}\theta_{ij}$$

$$Q_{ij,t} = -(1 + 2\Delta V_{i,t}) b_{ij0} - (\Delta V_{i,t} - \Delta V_{j,t}) b_{ij} - g_{ij}\theta_{ij,t}$$

$$Q_{ji,t} = -(1 + 2\Delta V_{j,t}) b_{ij0} + (\Delta V_{i,t} - \Delta V_{j,t}) b_{ij} + g_{ij}\theta_{ij,t}$$

$$\left(\sin\left(\frac{360^o l}{n}\right) - \sin\left(\frac{360^o}{n}(l-1)\right)\right) P_{ij,t} +$$

$$-\left(\cos\left(\frac{360^o l}{n}\right) - \cos\left(\frac{360^o}{n}(l-1)\right)\right) Q_{ij,t} +$$

$$-S_{ij}^{\max} \cdot \sin\left(\frac{360^o}{n}\right) \leq 0 \quad \forall (i,j) \in PL, t \in T$$

Active/reactive power flows

$$P_{i,t}^{DG} - P_{i,t}^{L} = \sum_{j\in B} P_{ij,t} \quad \forall i \in N, t \in T$$

$$QP_{i,t}^{DG} - Q_{i,t}^{L} = \sum_{j\in N} Q_{ij,t} \quad \forall i \in N, t \in T$$

Node power balance

$$-Q_{i,t}^{DG\_max} \leq Q_{i,t}^{DG} \leq Q_{i,t}^{DG\_max} \quad \forall DG, t \in T$$

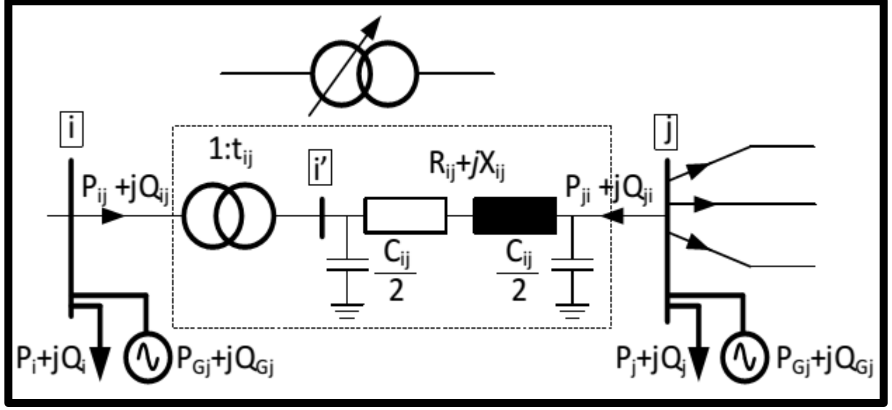
$$Q_{i,t}^{DG\_max} = \tan(\cos^{-1}\varphi_i^{DG}) \cdot P_{i,t}^{DG} \quad \forall DG, t \in T$$

DG reactive power constraints

Mathematical formulation– MILP

transformer modeling

Generalized distribution network branch model



$$V_{i'} = t_{ij} V_i$$

Linear transformer model with binary codification

$$t_{ij} = t_{ij}^{min} + T_{ij} \Delta t_{ij}, 0 \leq T_{ij} \leq K_{ij}$$

$$\Delta t_{ij} = (t_{ij}^{max} - t_{ij}^{min}) / K_{ij}$$

$$t_{ij} = t_{ij}^{min} + \Delta t_{ij} \sum_{n=0}^{N_{ij}} 2^n \lambda_{ij,n}$$

$$\sum_{n=0}^{N_{ij}} 2^n \lambda_{ij,n} \leq K_{ij}$$

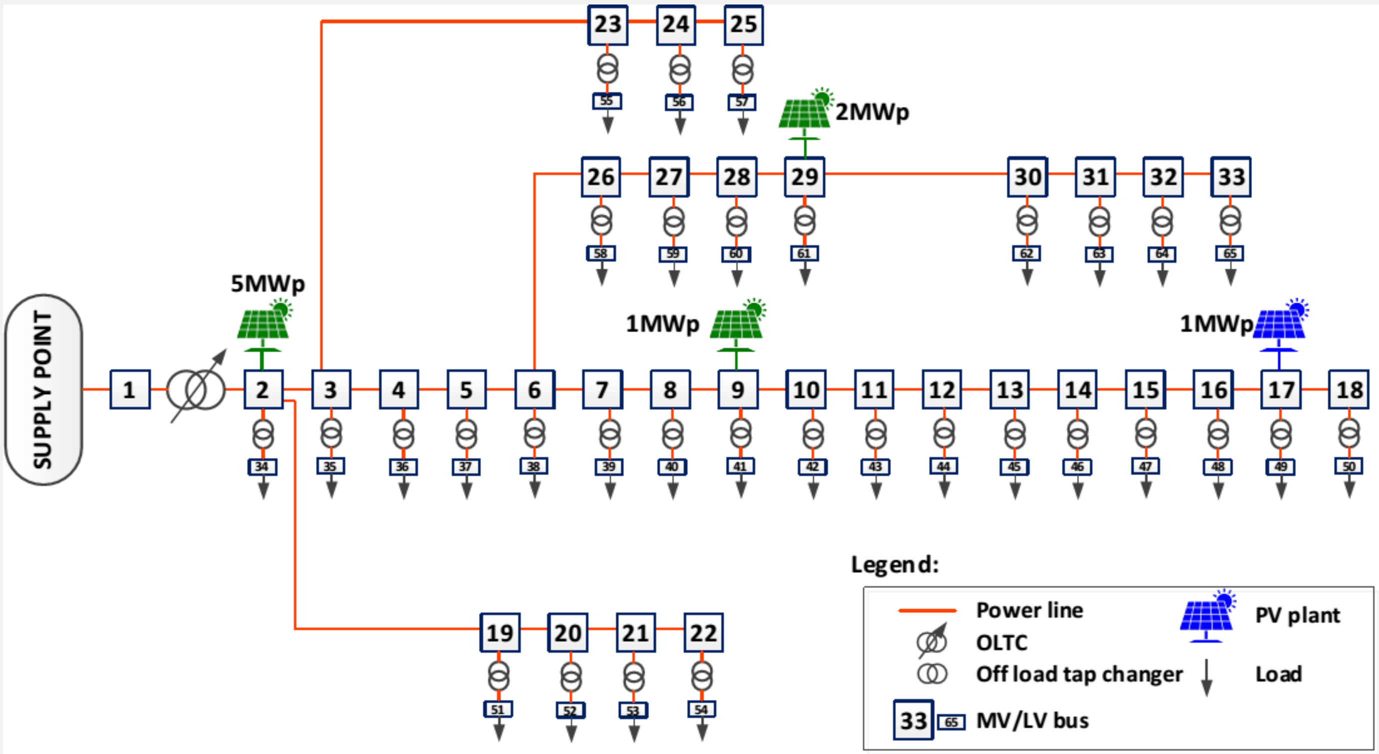
$$V_{i'} = t_{ij} V_i = t_{ij}^{min} V_i + \Delta t_{ij} \sum_{n=0}^{N_{ij}} 2^n x_{ij,n}$$

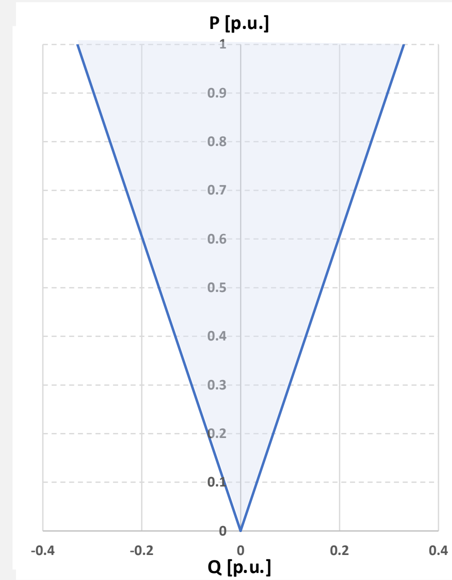
$$x_{ij,n} = \lambda_{ij,n} V_i$$

$$0 \leq V_i - x_{ij,n} \leq (1 - \lambda_{ij,n}) M$$

$$0 \leq x_{ij,n} \leq \lambda_{ij,n} M$$

TEST CASE – modified IEEE 33 bus model





DG reactive capability curve

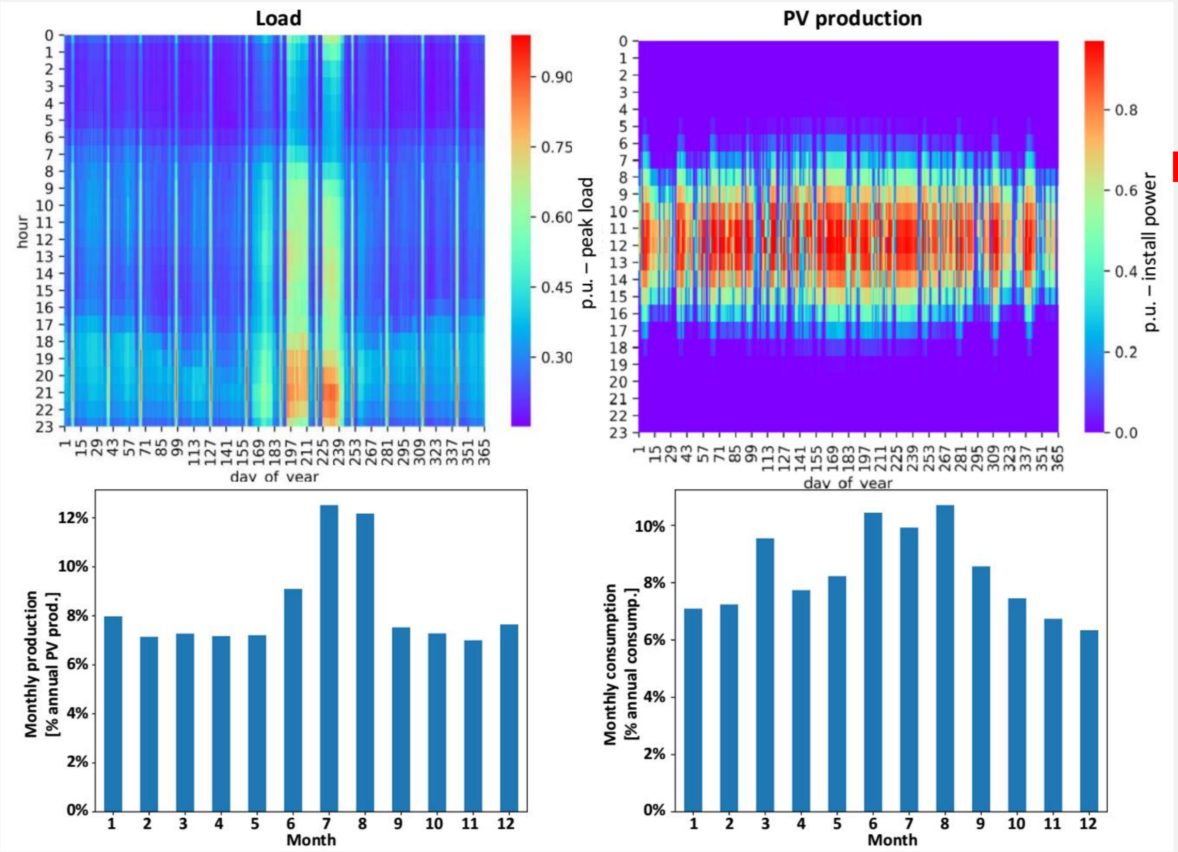
Peak distribution network load:

3.715 MW ; 2.3MVAr

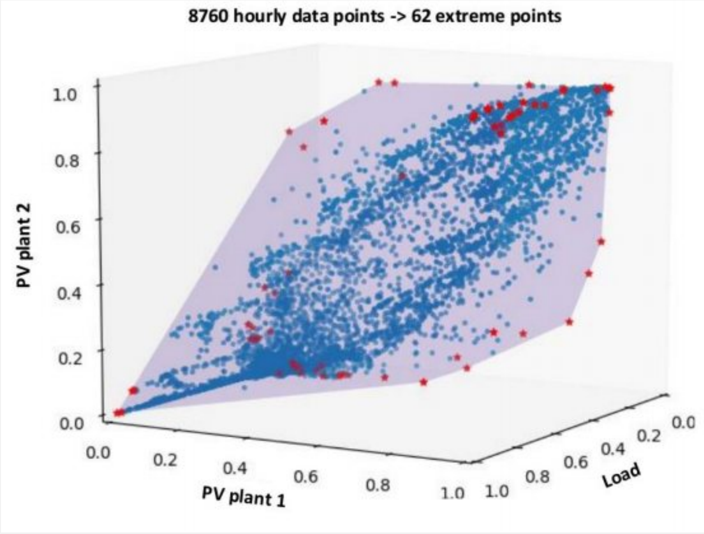
Total PV install power:

9 MWp; max (±2.95MVAr)

Time series of consumption / RES production



Extreme load/PV production scenario selection

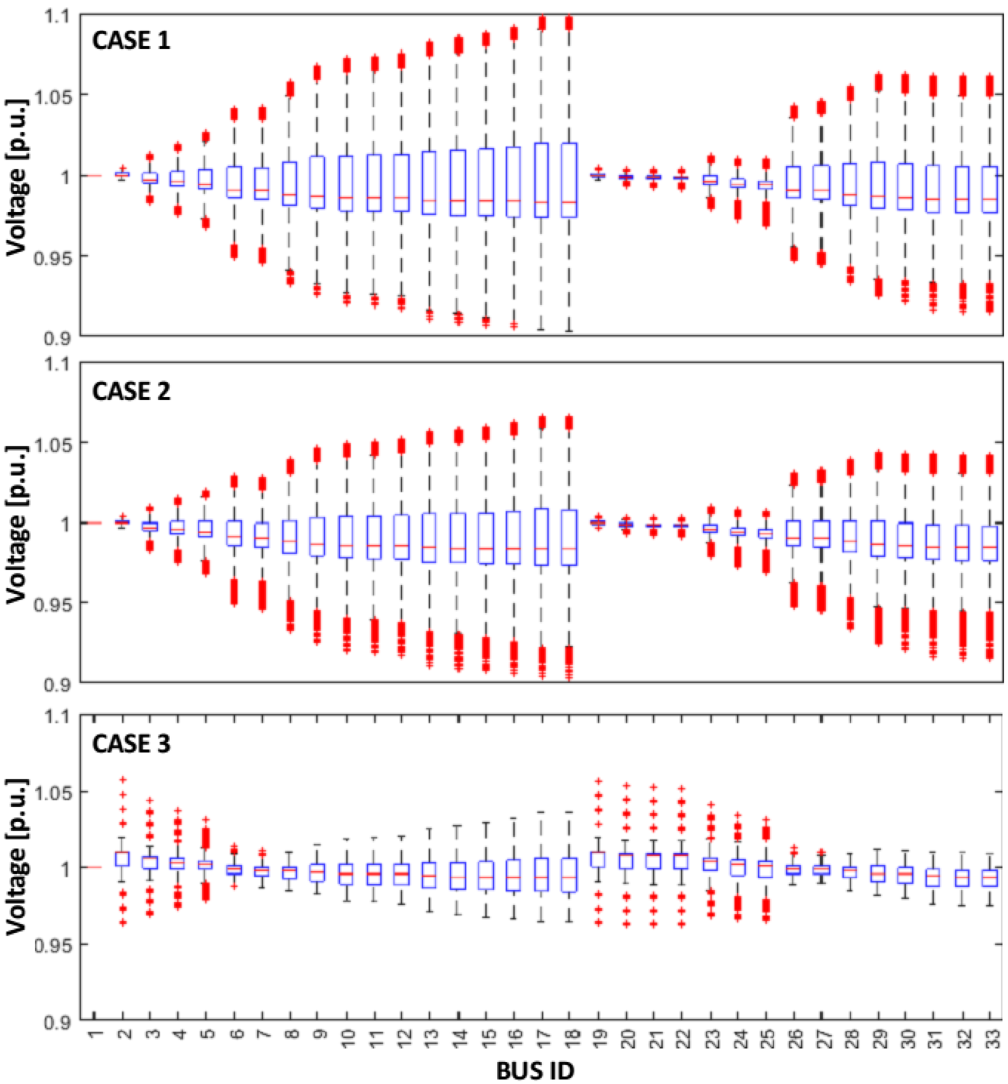


TEST CASES & RESULTS

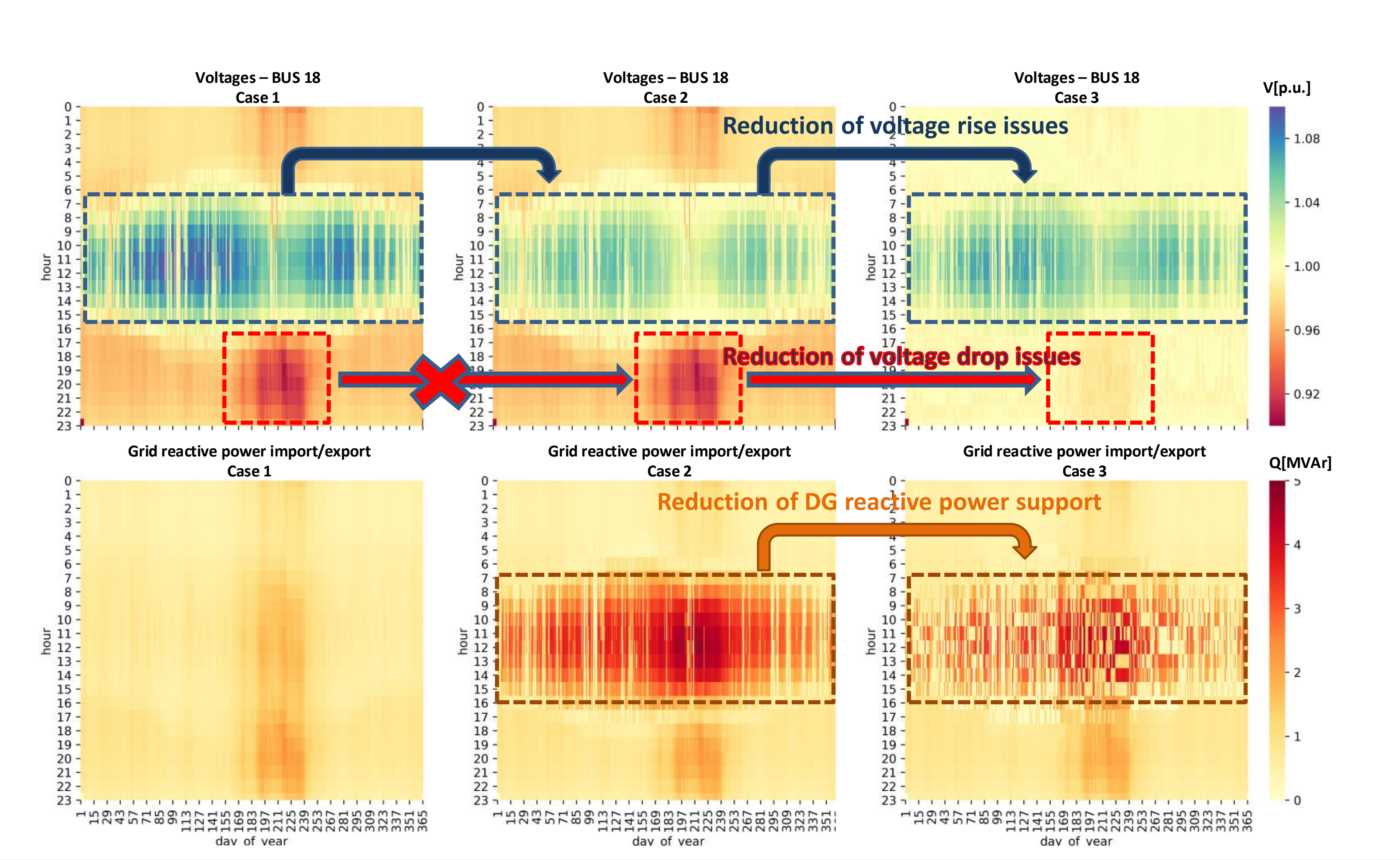
Considered simulation scenarios:

- **Case 1**: both OLTC as well as off-load tap changers are set to a neutral position while PV plants are operating with power factor cosφ=1;
- **Case 2**: both OLTC as well as off-load tap changers are set in a neutral position (nominal turn ratio) while PV production units are operating with a power factor in a range 0.95 cap.<cosφ<0.95 ind. trying to maintain voltages at their point of connection equal to nominal values;
- **Case 3**: OLTC as well as off-load tap changer turn **ratio is optimized together with PV unit power factor** to minimize voltage deviations across the distribution network using the method described in the paper

	Mean voltage [p.u.]	Max voltage/Bus ID [p.u. / ID]	Min voltage/Bus ID [p.u. / ID]	Stand. dev. [p.u.]
CASE 1	0.9946	1.0975 / Bus_17	0.8877 / Bus_62	0.0231
CASE 2	0.9921	1.0661 / Bus_17	0.8877 / Bus_62	0.0182
CASE 3	1.0019	1.0610 / Bus_49	0.9558 / Bus_57	0.0138

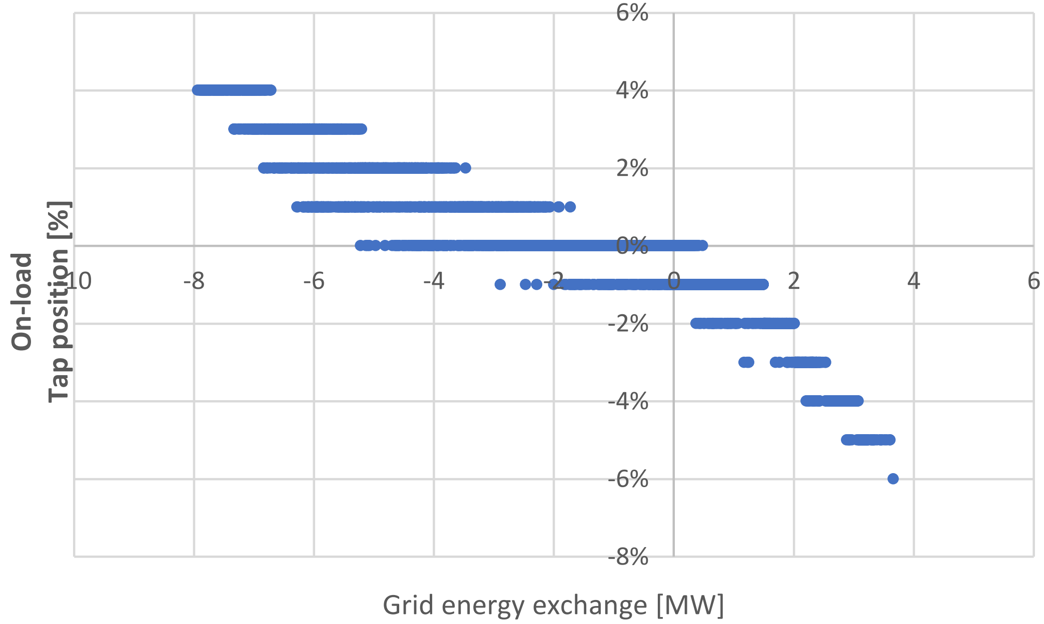


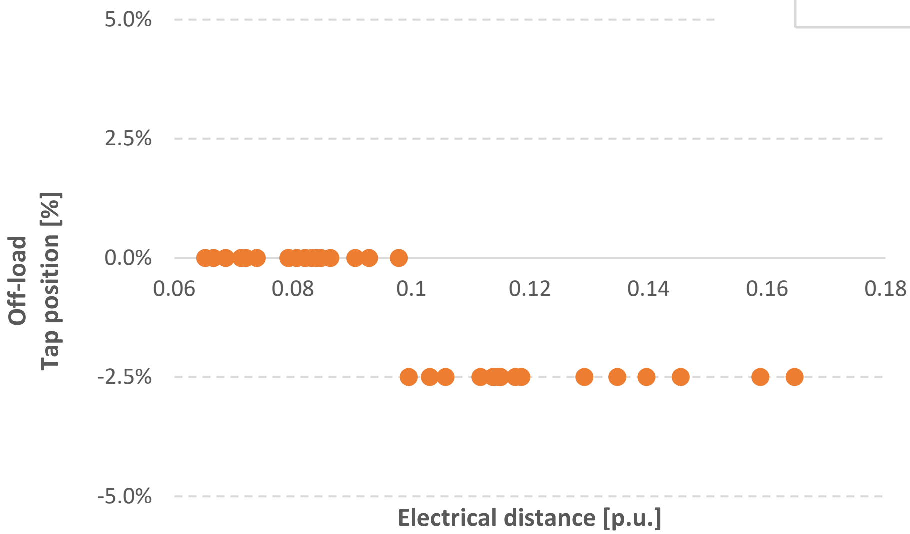
TEST CASES & RESULTS



TEST CASES & RESULTS – Case 3

On-load tap changer operation in relation to grid energy exchage (Load – DG production)





Off-load tap changer settings in relation to bus electrical distances

Thank you for your atention!

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Acknowledgments

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