Using Multi-terminal DC Networks to Improve the Hosting Capacity of Distribution Networks

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Main challenges facing distribution networks

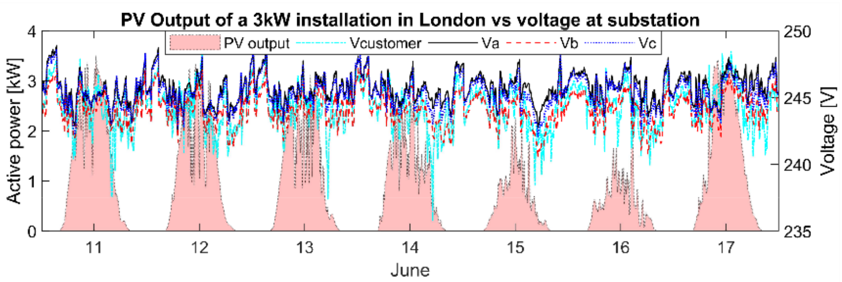
A growing number of distributed generation (DG) and electric vehicles (EVs)

Impacts of DG

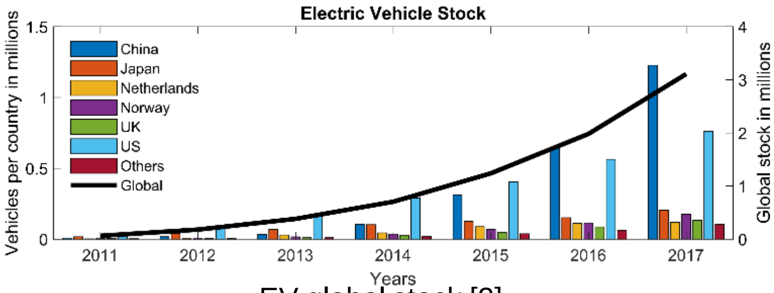
- Voltage rise above limits
- Premature ageing of voltage regulation devices
- Increased energy losses

Impacts of EVs

- Voltage drops in low-voltage (LV) feeders
- Thermal limits violations
- Congestion of the network



PV output of 3kW installation in London [1]

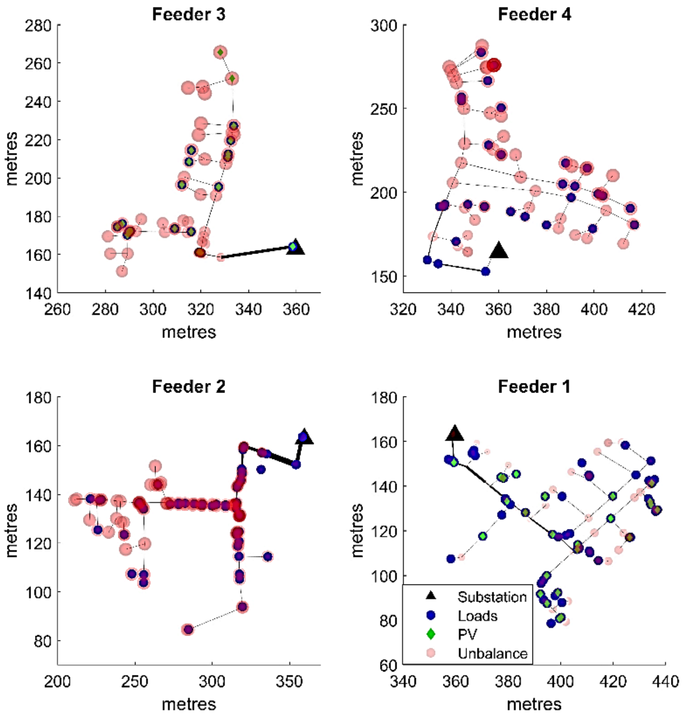


EV global stock [2]

Main challenges facing distribution networks

Typical characteristics of distribution networks:

- Radial operation
- Network **reconfiguration only in case of faults**
- **Uneven distribution of the load/generation** between feeders and phases
- Majority of **DG and EVs are connected to a single phase**
- Line currents and voltages are **unbalanced**



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Main challenges facing distribution networks

Different ways to increase the hosting capacity:

- Network reinforcement ✘
- Energy storage ✓
- Demand response ✓

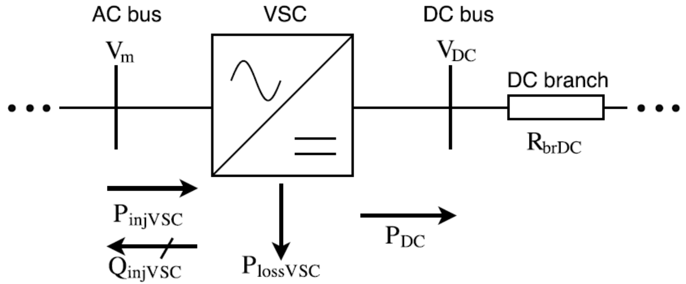
But, how do we **use the existing infrastructure more efficiently?**

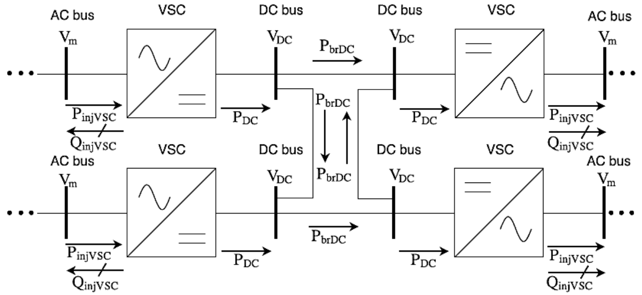
- **Using power electronics ?**

Hybrid AC/DC networks

Using distributed power-electronics devices to mesh distribution networks and increase their hosting capacity:

- **Voltage source converters (VSCs)** allow the **transfer of power to and from individual feeders** and the **injection of reactive power**
- Incremental escalation to form **Multi-terminal DC (MTDC)** networks
- **Active management** and distribution of power flows
- The set points of the VSCs are **calculated through an Optimal Power Flow**





Hybrid AC/DC networks

AC/DC OPF formulation for balanced and unbalanced networks, using the power flow equations in polar form and the current injection method [3], respectively:

$$
\begin{aligned}
\min_{X} \quad & f(x) = \sum_{i=1}^{M} (P_{g,i} - P_{d,i}) \\
\text{s.t.} \quad & P_{g,i} - P_{d,i} - P_i(V,\theta) - P_{injVSC,i} = 0, \\
& Q_{g,i} - Q_{d,i} - Q_i(V,\theta) - Q_{injVSC,i} = 0, \\
& P_{injVSC,i} - P_{lossVSC,i} - P_{DC,i} = 0, \\
& P_{g,i}^{min} \leq P_{g,i} \leq P_{g,i}^{max}, \\
& Q_{g,i}^{min} \leq Q_{g,i} \leq Q_{g,i}^{max},
\end{aligned}
$$

$$P_i(V,\theta) = V_i \sum_{k=1}^{M} V_k [G_{i,k} \cos(\theta_i - \theta_k) + B_{i,k} \sin(\theta_i - \theta_k)]$$

$$Q_i(V,\theta) = V_i \sum_{k=1}^{M} V_k [G_{i,k} \sin(\theta_i - \theta_k) - B_{i,k} \cos(\theta_i - \theta_k)]$$

$$
\begin{aligned}
\min_{X} \quad & f(x) = \sum_{i=1}^{n} \sum_{j=1}^{n} G(i,j)[(V_{Rei} - V_{Rej})^2 + (V_{Imi} - V_{Imj})^2] \\
\text{s.t.} \quad & I_{Rek}^{shunt} - I_{Rek}^{series} = 0, \\
& I_{Imk}^{shunt} - I_{Imk}^{series} = 0, \\
& V_{min}^2 \leq V_{Rei}^2 + V_{Imi}^2 \leq V_{max}^2, \\
& \theta_{min} \leq \tan^{-1}\left(\frac{V_{Imi}}{V_{Rei}}\right) \leq \theta_{max}
\end{aligned}
$$

$$\Delta I_k^s = \frac{(P_k^{sp})^s - j(Q_k^{sp})^s}{(E_k^s)^*} - \sum_{i \in \Omega_k} \sum_{t \in \alpha_{ph}} Y_{ki}^{st} E_i^t$$

Hybrid AC/DC networks

Incorporating the characteristics of the converters into the AC/DC OPF formulation for both balanced and unbalanced networks

- Active power balance for each converter:

$$P_{injVSC,i} - P_{lossVSC,i} - P_{DC,i} = 0$$

- Power losses of the converter as a quadratic expression, representing the no-load, switching and conduction losses of the converter [4]:

$$P_{lossVSCi} = a_i + b_i I_k + c_i I_k^2$$

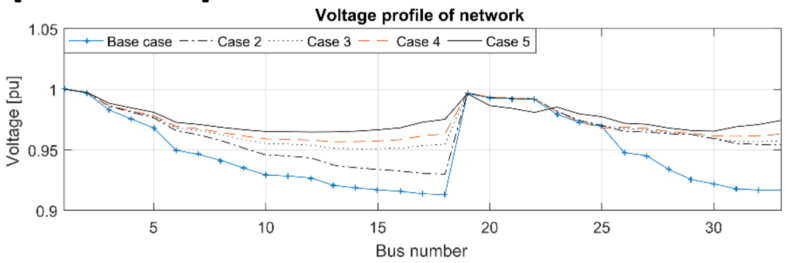
- Power flow in DC lines of MTDC network:

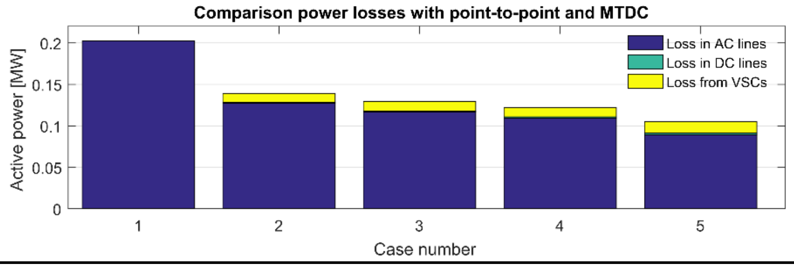
$$P_{DC,i} = V_{DC,i} \sum_{j=1}^{N} V_{DC,j} [G_{DC,i,j}]$$

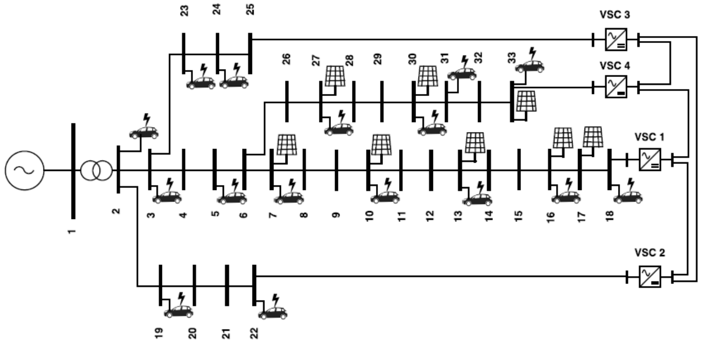
Case studies

Case 33-bus Network [5] – Balanced single-phase equivalent

- MTDC configuration results in **a smoother voltage profile and lower power losses**
- **Losses of the converters and DC lines are small** compared to the overall losses of the network





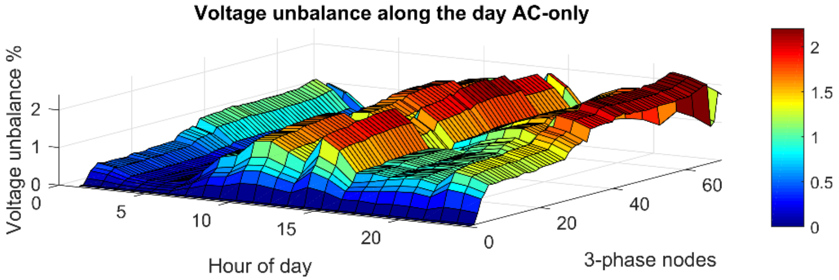


Case	1	2	3	4	5
Description	Base	2 VSCs point to point	4 VSCs point to point	4 VSCs MTDC	4 VSCs MTDC end points

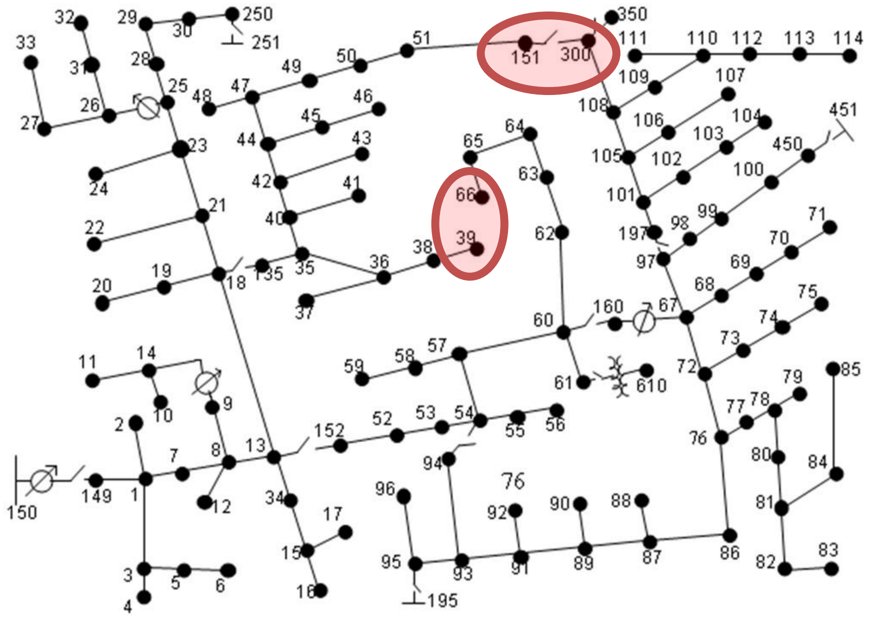
Case studies

Case IEEE 123 Node Test Feeder [6] – Unbalanced three-phase network

- The inclusion of **DG and EVs results in voltage unbalance**, especially at peak hours (noon/evening)



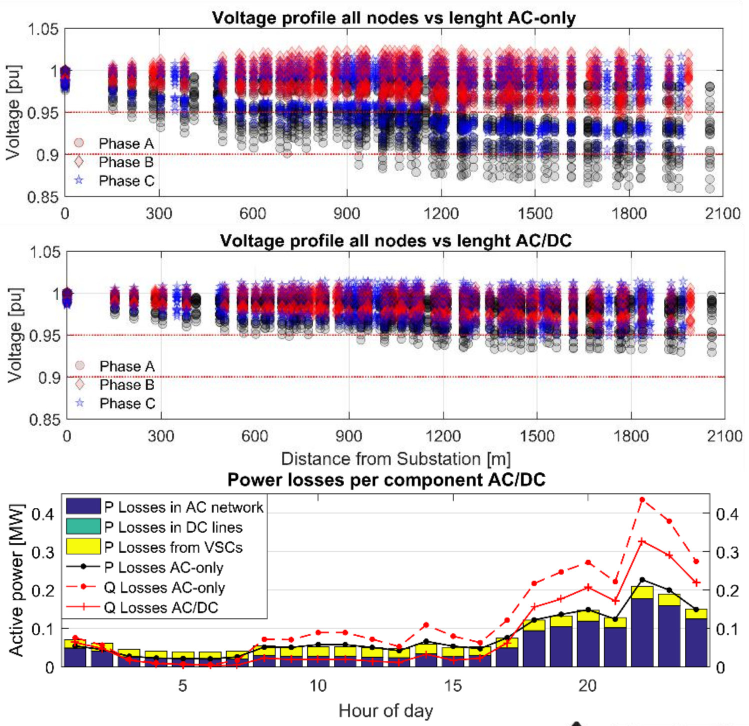
- VSCs will be used to connect the network where buses are close to each other (151-300, 39-66)



Case studies

Case IEEE 123 Node Test Feeder [6] – Unbalanced three-phase network

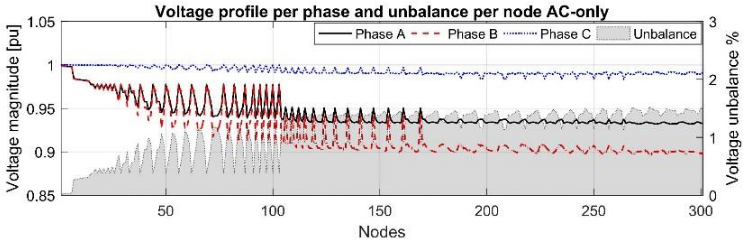
- The redistribution of the power between different buses, and also between different phases, **helps reduce the voltage unbalance factor (VUF)**
- **More uniform voltage profile**
- The incorporation of the converters and the MTDC network results in a **decline in the overall power losses**
- **Lower utilisation** of the main transformer

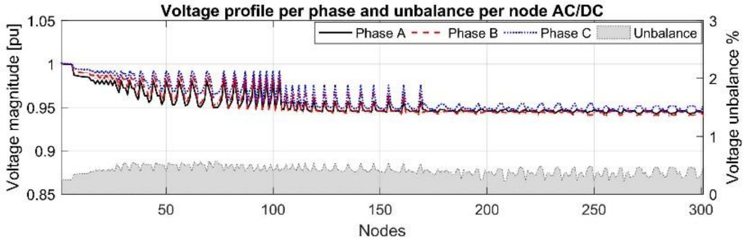


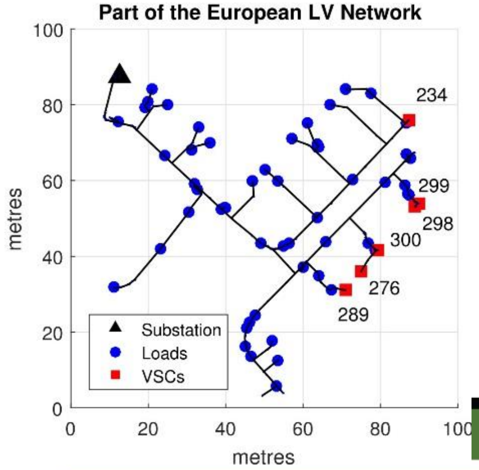
Case studies

Case European LV network [6] – Unbalanced three-phase network

- Model of a **real LV network in the UK** with uneven load distribution
- The incorporation of the MTDC resulted in a **voltage profile with less VUF**
- Overall **lower power losses** and **lower utilisation of the main transformer**







	Base case	MTDC A (234-299-300)	MTDC B (276-289-298)
Transformer loading	112%	105.7%	106.1%
Losses [MW]	0.0213	0.0175	0.0179

Conclusions

- Given the characteristics of DG and EVs, **distribution networks will become saturated with** congestion concentrating **in particular substations and feeders**
- **Active management of the power flows** will become essential
- **VSCs and MTDC networks** can allow a **more efficient distribution of the power** between feeders/substations
- The **power losses of the VSCs and DC lines are small compared to the overall losses** of the network
- A **more balanced distribution between phases** can be achieved, **lowering the VUF**
- Leading to **a significant reduction in the power losses**, **enhancement of the voltage profile** and a **reduced utilisation of the main transformer**
- Ultimately, **increasing the hosting capacity** of distribution networks and **deferring the need for reinforcements**

References and acknowledgments

- [1] UKPN, “Validation of Photovoltaic (PV) Connection Assessment Tool - Closedown Report," Report, March 2015.
- [2] IEA, “Global EV outlook 2017," 2017.
- [3] P. A. N. Garcia, J. L. R. Pereira, S. Carneiro, V. M. d. Costa, and N. Martins, “Three-phase power flow calculations using the current injection method," IEEE Transactions on Power Systems, vol. 15, no. 2, pp.508-514, 2000.
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- [5] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing," IEEE Power Engineering Review, vol. 9, no. 4, pp. 101-102, 1989.
- [6] IEEE PES Distribution System Analysis Subcommittee's Distribution Test Feeder WG, “Distribution test feeders," 2017.

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Thank you for your attention

Questions?