Modelling the impact of flexible AC transmission systems on the operation of electrical transmission grids

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Agenda

- Motivation
- FACTS overview
- Modelling approach
- Exemplary results
- Conclusion

Motivation

- Increasing electricity demand, fluctuating generation from renewables and the missing, easily controllable generation from conventional power plants represent a great challenge for the German and European transmission grid
- Balance between generation and demand must be maintained at all times without violating voltage, frequency or transmission lines' thermal limits

- Grid expansion: building new transmission lines is necessary and in planning, but the process is expensive and time consuming
- Grid reinforcement: measures that help in utilizing the existing transmission lines to their full potential

- Flexible AC Transmission Systems (FACTS)
  - → Provide reactive power and thus secure voltage stability and help to control power flows
  - → Prevent and resolve congestions in the transmission grid and thus reduce redispatch volumes and costs, renewables curtailment and load shedding.
- Technical possibilities?
- Economic benefits?

Flexible AC Transmission Systems Classification

Parallel FACTS

→ Voltage control

- Static Var Compensator (SVC)
  - Adjustable capacitance and/or inductance connected to a busbar
- Static Synchronous Compensator (STATCOM)
  - Adjustable voltage source connected to a busbar

Serial FACTS

→ Power flow control

- Thyristor Controlled Series Compensator (TCSC)
  - Adjustable capacitance in series with the transmission line
- Static Synchronous Series Compensator (SSSC)
  - Adjustable voltage source in series with the transmission line

- Universal Power Flow Controller (UPFC)
  - Combination of STATCOM and SSSC
  - Parallel and serial voltage impregnation
  - Reactive power feed-in and line power flow control

Optimal powerplant operation

- Optimal power flow: „Find the optimal operating state for an electrical energy network!”

Objective

- Minimize generation/redispatch costs
- Minimize CO_2 emissions
- Minimize losses or renewables curtailment

State variables

- Complex voltages
- Real and reactive power flows
- Pump-storage and battery state of charge

Decision variables

- Generator dispatch/redispatch
- Renewables curtailment
- Operating state of flexible network elements (FACTS, HVDC-converters, PST)
- ESS and pump-storage operation

Constraints

- Power-flow equations
- Thermal branch flow limits
- Generator limits
- Voltage limits
- Components’ technical limits
- Time dependencies

$$\min_{P_g} \sum_{G} c_i(P_{gi})$$

$$\begin{aligned} \text{s.t.} \quad P_{i,g} - P_{i,d} - \sum_{k \in I} P_{ik} &= 0, \\ Q_{i,g} - Q_{i,d} - \sum_{k \in I} Q_{ik} &= 0, \\ \underline{V} \leq V &\leq \overline{V}, \\ F_{ik} &\leq \overline{F}, \\ \underline{P}_g \leq P_g \leq \overline{P}_g, \underline{Q}_g \leq Q_g &\leq \overline{Q}_g \end{aligned}$$

$G:\ Generators, D: Loads,$

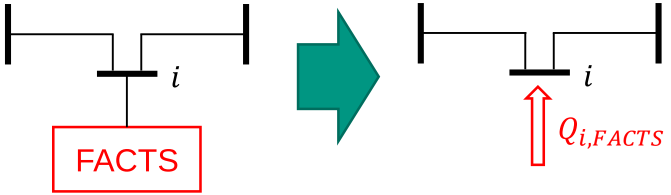
$I, K:\ Buses$

FACTS modelling

- **Power injection model**
  - The impact of the network element is modelled by a power injection (active and reactive) at corresponding bus(es) i (and k)
  - The injected power depends on the elements‘ operating state and the surrounding network status (e.g. bus voltage magnitude and phase angle)

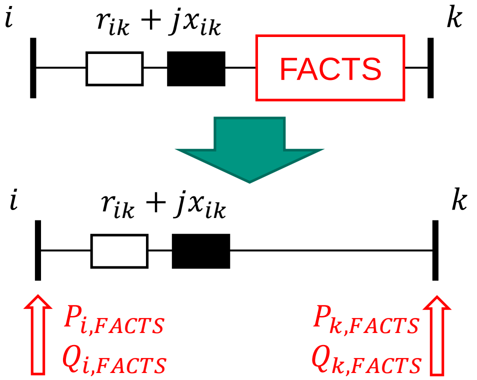
Parallel FACTS

- Reactive power injection at bus i



Serial FACTS

- Active and reactive power injection at bus i and k



SSSC model

- Static Synchronous Series Compensator
- Adjustable voltage source in series to the transmission line
- Power flow control
- Injection model → power injection at the start and end bus of the line
- Steady state condition: $P_{i,SSSC}^t + P_{k,SSSC}^t = 0$

$$P_{i,sssc}^t = V_i^t V_{sssc}^t [G_{ik}\cos(\theta_i^t - \delta_{sssc}^t) + B_{ik}\sin(\theta_i^t - \delta_{sssc}^t)]$$

$$Q_{i,sssc}^t = V_i^t V_{sssc}^t [G_{ik}\sin(\theta_i^t - \delta_{sssc}^t) - B_{ik}\cos(\theta_i^t - \delta_{sssc}^t)]$$

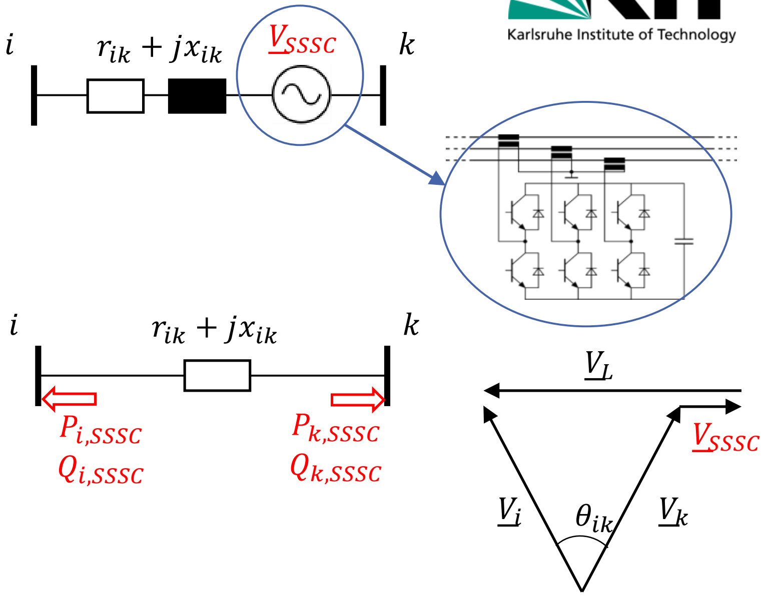
$$P_{k,sssc}^t = -V_k^t V_{sssc}^t [G_{ik}\cos(\theta_k^t - \delta_{sssc}^t) + B_{ik}\sin(\theta_k^t - \delta_{sssc}^t)]$$

$$Q_{k,sssc}^t = -V_k^t V_{sssc}^t [G_{ik}\sin(\theta_k^t - \delta_{sssc}^t) - B_{ik}\cos(\theta_k^t - \delta_{sssc}^t)]$$

$$P_{i,sssc}^t + P_{k,sssc}^t = V_i^t V_{sssc}^t [G_{ik}\cos(\theta_i^t - \delta_{sssc}^t) + B_{ik}\sin(\theta_i^t - \delta_{sssc}^t)] \\ -V_k^t V_{sssc}^t [G_{ik}\cos(\theta_k^t - \delta_{sssc}^t) + B_{ik}\sin(\theta_k^t - \delta_{sssc}^t)] = 0$$

$$\underline{V}_{sssc} \le V_{sssc}^t \le \bar{V}_{sssc}$$

$$\underline{\delta}_{sssc} \le \delta_{sssc}^t \le \bar{\delta}_{sssc}$$

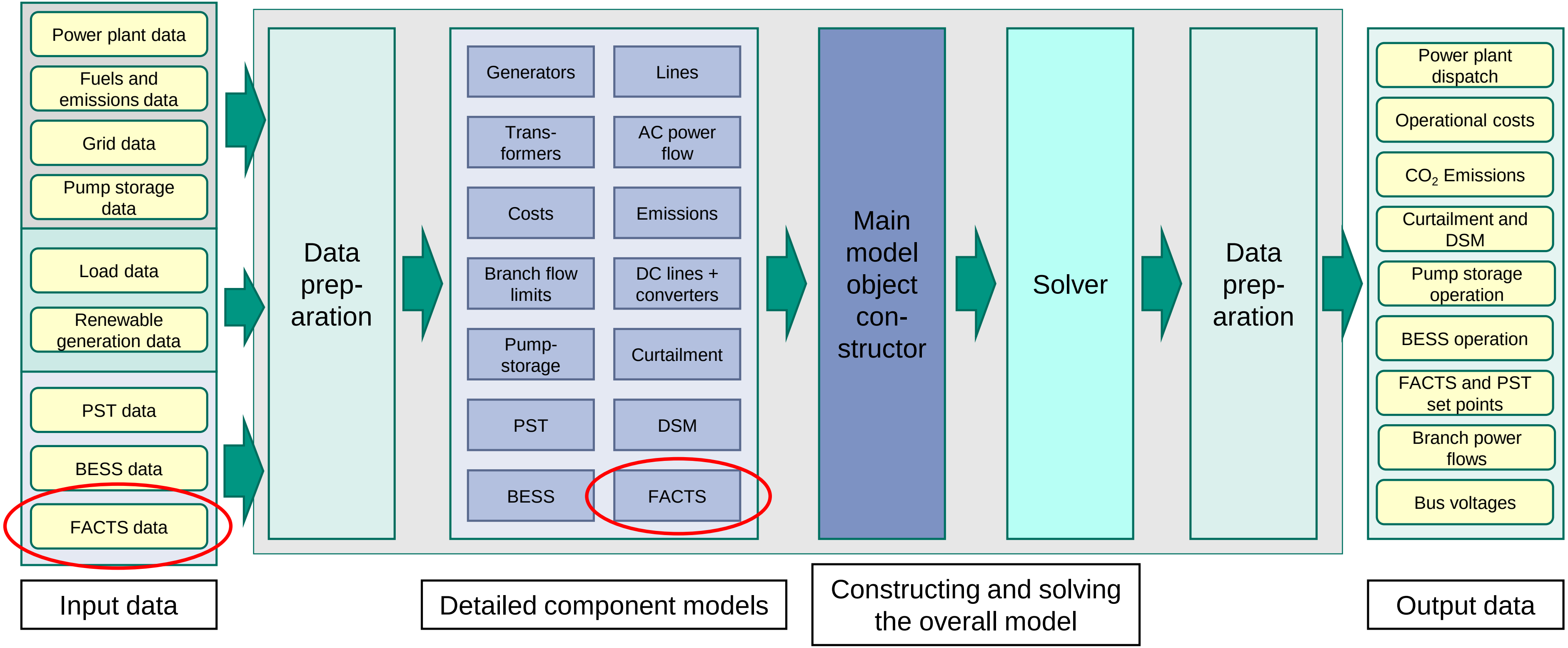


$$P_{i,g} - P_{i,d} - \sum_{k \in I} P_{ik} + P_{i,SSSC} = 0$$

$$Q_{i,g} - Q_{i,d} - \sum_{k \in I} Q_{ik} + Q_{i,SSSC} = 0$$

$$F_{ik} + F_{i,SSSC} \le \overline{F}$$

Overall OPF model overview



Power plant data
Fuels and emissions data
Grid data
Pump storage data
Load data
Renewable generation data
PST data
BESS data
FACTS data

Data prep-aration

Generators
Lines
Trans-formers
AC power flow
Costs
Emissions
Branch flow limits
DC lines + converters
Pump-storage
Curtailment
PST
DSM
BESS
FACTS

Main model object con-structor

Solver

Data prep-aration

Power plant dispatch
Operational costs
CO_2 Emissions
Curtailment and DSM
Pump storage operation
BESS operation
FACTS and PST set points
Branch power flows
Bus voltages

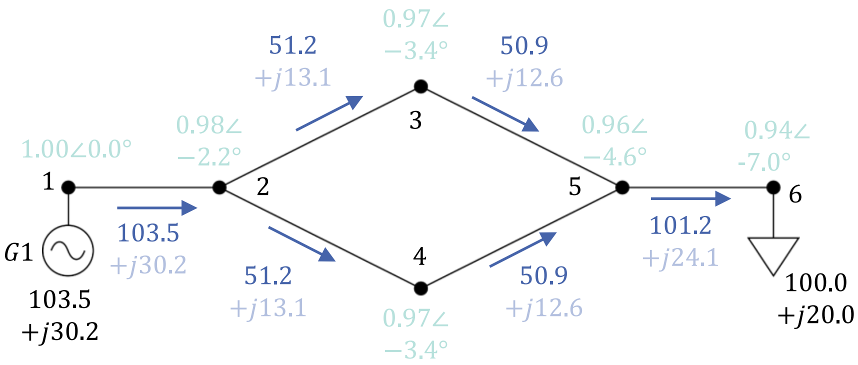
Input data

Detailed component models

Constructing and solving the overall model

Output data

Exemplary results

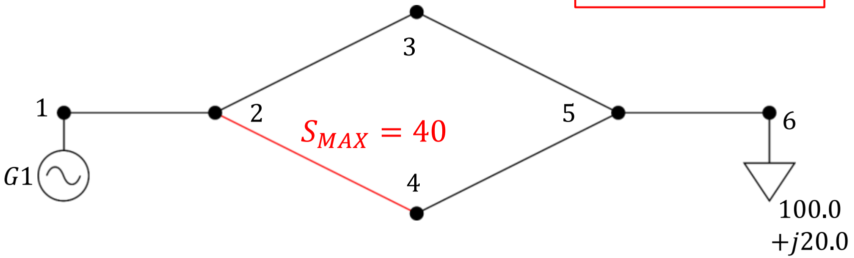


Line parameters:
$r = 0.01$
$x = 0.04$
$b = 0.007$

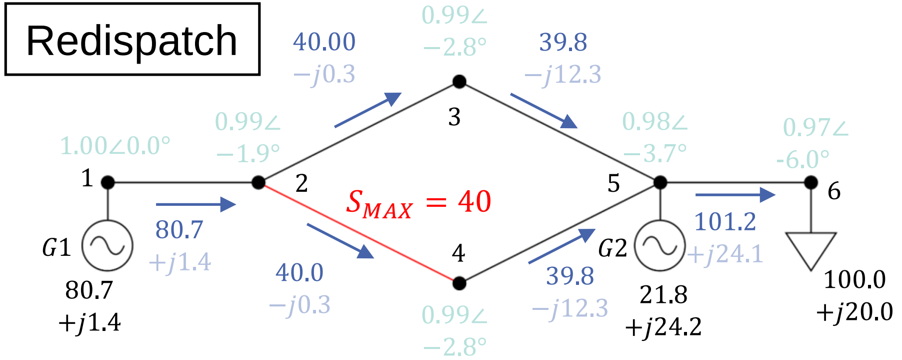
Voltage limits:
$0.9 \leq V \leq 1.1$

No measures

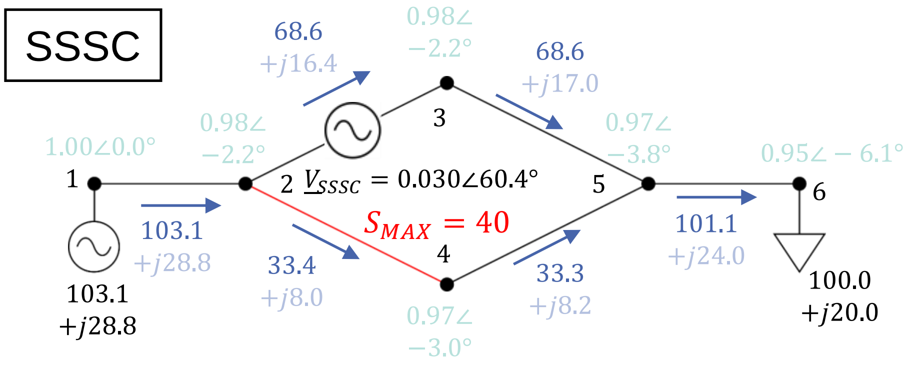
No possible solution

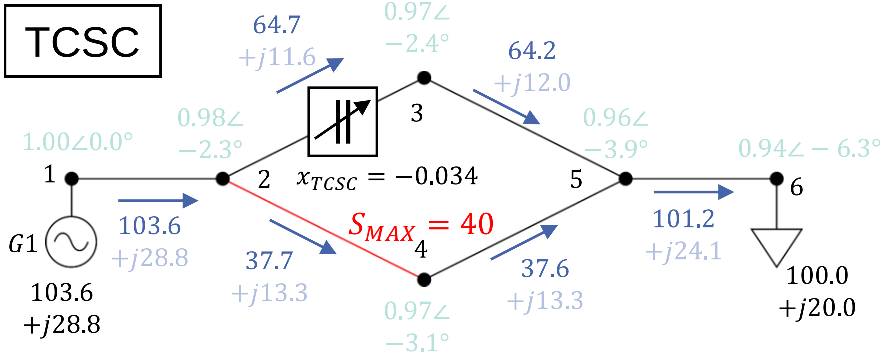


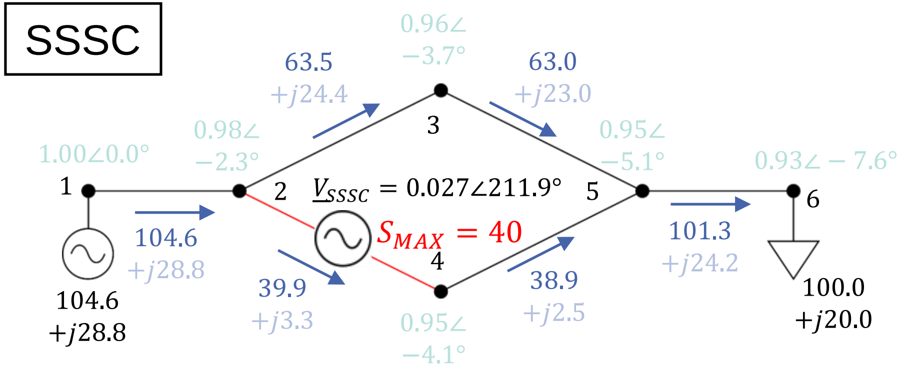
Redispatch

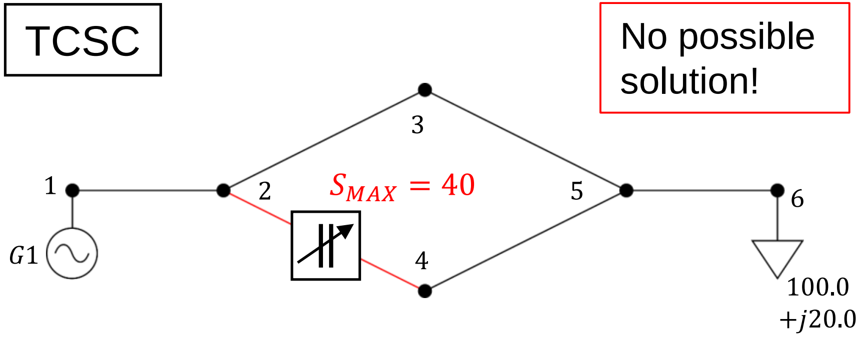


Exemplary results









No possible solution!

Conclusion

Summary

- Models for different types of FACTS with a high level of technical detail have been developed and tested
- Models have been successfully implemented into a large-scale OPF model
- Applied on IEEE test cases and transmission grid of Germany + neighbors

Outlook

- Case studies on a German/European scale
- Placement of new FACTS and other flexible network elements