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Quantitative comparison of cascading failure models for power system analysis

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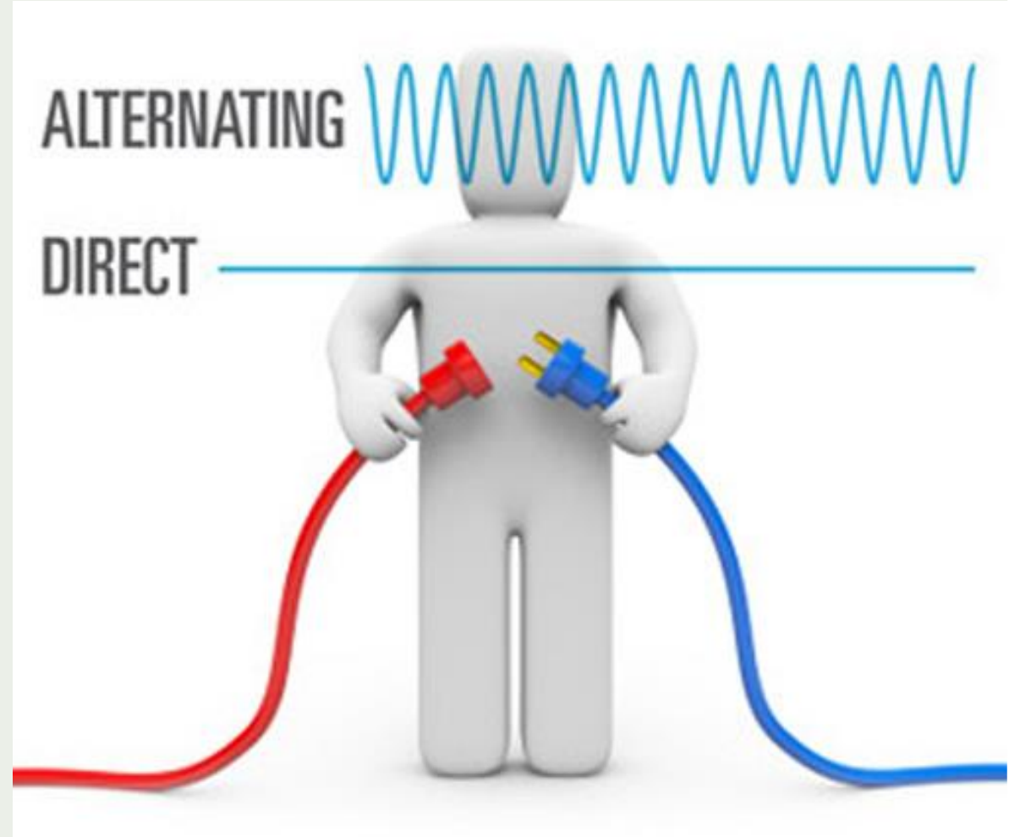
Introduction & Motivation

- Accurate computer models crucial, e.g. for transmission system operators, to ensure a stable and reliable supply of energy to customers and prevent component overloads or even blackouts
- Computational cost of power flow simulations increasing with increasing model complexity, but always using the best modelling method available might not be necessary under certain circumstances
- Comparison of the AC OPF-based Manchester model with the less accurate, but also less computationally intensive DC OPF-based OPA model to determine if and when it is worth choosing the more detailed approach



THE “DC“ POWER FLOW APPROXIMATION

- neglect reactive power
- assume all voltages are ~1 p.u.
- disregard active power losses

→ This converts the originally non-linear AC power flow problem into a set of linear equations, which can be solved directly

Power system modeling

Both the Manchester model and the OPA model support cascading failure analysis and were modified to incorporate external influencing factors, i.e.,

- variable demand (by multiplying all bus loads by a factor f)
- temperature dependent transmission line capacities (dynamic line rating)

Dynamic line rating

Dynamic line rating is determined as a function of solar irradiance q, ambient temperature T_{amb} and maximum tolerable line temperature T_{line}^{max}. Using the equation of thermal equilibrium the highest possible current flow through a conductor at reference conditions can be computed:

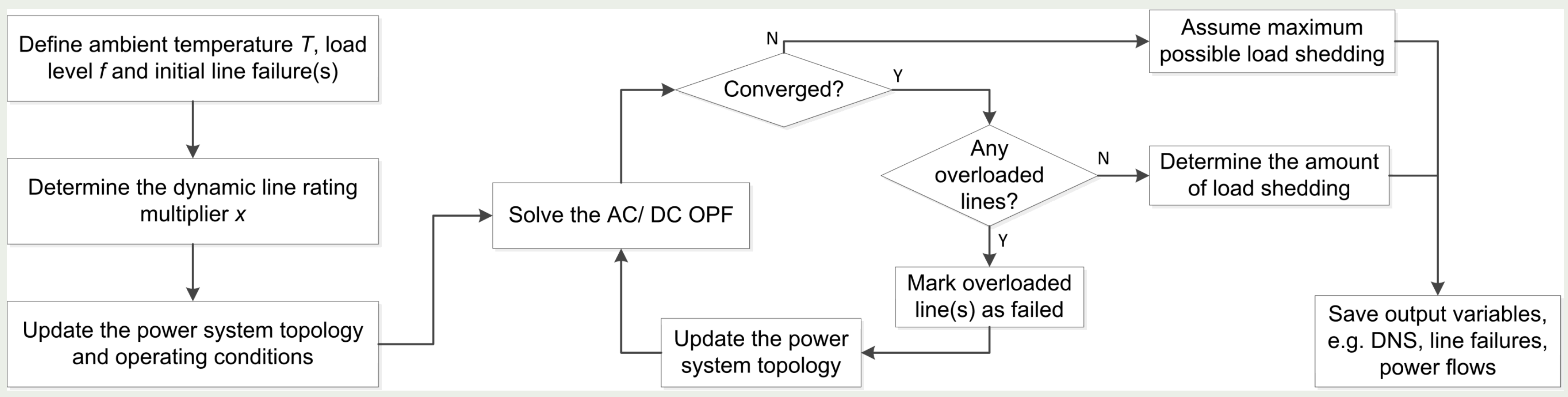
$$I\left(T_{ref}\right)^2 = \frac{\overbrace{P_{conv}\left(T_{ref}, T_{line}^{max}\right)}^{\text{natural convective cooling}} + \overbrace{P_{rad}\left(T_{ref}, T_{line}^{max}\right)}^{\text{radiative cooling}} - \overbrace{P_{sun}\left(q_{ref}\right)}^{\text{solar heating}}}{\underbrace{R\left(T_{ref}\right)}_{\text{resistivity of the conductor at reference temperature}}}$$

$$T_{ref} = 20°C \qquad T_{line}^{max} = 80°C \qquad q_{ref} = 900\,\frac{W}{m^2}$$

The relative decrease or increase in ampacity w.r.t. the reference conditions is then computed by the ratio $\boldsymbol{x = I(T_{amb})/I\left(T_{ref}\right)}$.

Cascading failure analysis

In each simulation the following sequence of actions is carried out:


Define ambient temperature *T*, load level *f* and initial line failure(s)
Determine the dynamic line rating multiplier *x*
Update the power system topology and operating conditions
Solve the AC/ DC OPF
Converged?
N
Assume maximum possible load shedding
Y
Any overloaded lines?
N
Determine the amount of load shedding
Y
Mark overloaded line(s) as failed
Update the power system topology
Save output variables, e.g. DNS, line failures, power flows

Case study

The model comparison is performed based on power flow simulations of the 24 Bus IEEE Reliability Test System (RTS) for a variety of different operating points:

parameter		min	max	
ambient temperature	$T\ [°C]$	-10	40	in 2°C steps
bus load (w.r.t. base load)	$f\ [\%]$	90	180	in 2% steps

To obtain a comprehensive understanding of the differences and similarities of the Manchester and the OPA model test series with and without random initial transmission line failures were conducted.

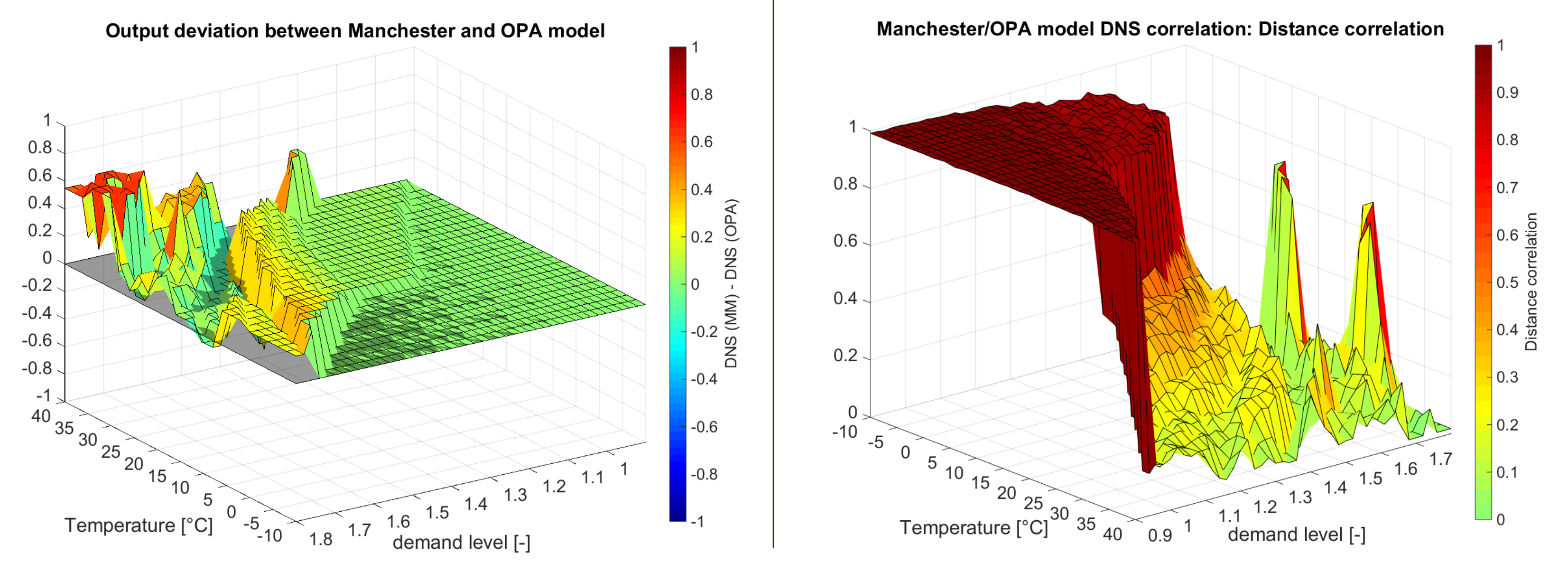
Monte Carlo analysis

- triggering of cascades by sampling independent initial line failures with a probability of 0.033 (to have at least one outage per simulation run on average)
- 1000 repetitions at every operating point, i.e., 26 · 46 · 1000 = 1’196’000 simulation runs for each model

Comparison results

Demand not served (DNS)

Distance correlation


without random initial failures

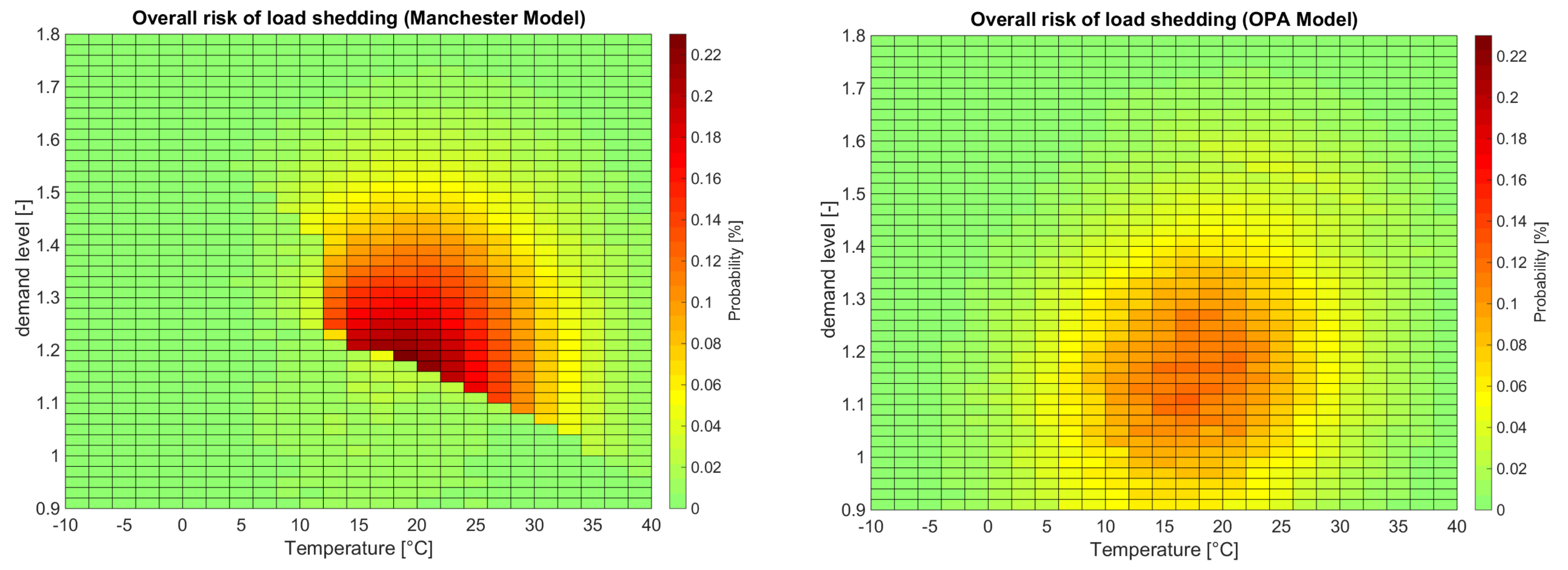
with random initial failures

- similar results below the diagonal from (–10°, 1.8) to (+40°, 0.9)
- large deviations at medium/ high loads, especially in conjunction with high temperatures

→ Manchester model better suited for power flow studies at medium-to-high temperature and load levels

Overall risk of operation

- Computed by multiplying the probability $P(T,f)$ of a certain ambient temperature T and demand level f coinciding with the probability $P_{T,f}(DNS > 0)$ of greater than zero load shedding under these conditions
- $P(T,f)$ determined by means of a multivariate normal distribution based on historic data



- identified area of elevated risk similar above the diagonal from (–10°, 1.8) to (+40°, 0.9)
- OPA model noticeably more pessimistic below this diagonal

→ OPA model results sufficient when it comes to determining areas of elevated risk

Line Criticality

most frequently failed lines (by ID) immediately after an initial failure

Rank	1	2	3	4	5	6	7	8	9	10
Manchester Model	10	11	23	28	18	17	12	5	7	6
OPA Model	11	23	28	10	18	3	17	36	37	29
Overlap *(indep. of rank)*	***100%***					***20%***				

- perfect overlap in the five most vulnerable lines (if the actual ranks are neglected)
- conformity rapidly decreasing beyond that

→ OPA model sufficient to identify the most critical branches

Conclusions

- Substantial deviations between Manchester and OPA model at elevated temperature and demand levels
- Depending on the type of and degree of accuracy required by a particular investigation, as well as the imposed boundary conditions, utilizing the less computationally expensive OPA model can be sufficient