Appendix B

B Modelling the dynamics and fragmentation of electric power systems

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We have analysed the regular and breakdown dynamics of power grids. In the MANMADE project, we have spent considerable time on formulating a model for this purpose. Such a model should be simple, yet capable of capturing the most fundamental properties of power flow. For the better part of the project, we used the DC load flow model [1]. However, this model turned out to be incapable of taking into account the maximum transmission capacity of power lines correctly. At that point switched to a linear programming model, which proved to be an excellent tool for our investigations. The details of the model is described below in detail.

1 Optimal power flow

We analyzed the load flow problem and studied the cascading breakdown phenomena with linear programming method. The objective function represents the generation and transmission costs that has to be minimized. The set of equality constraints represents the inflow–outflow balances, and the set of inequality constraints represents the generating capacities of power plants and the loadability limits of transmission lines. We can formulate the above mentioned linear programming problem:

$$\text{min:}\ \left(\{P_i \mid i \in V^g\}, \{F_{ij}\}\right) \longmapsto \sum_{i\in V^g} K_i^g \cdot P_i \cdot \Delta t + \sum_{\langle ij\rangle} K_{ij}^t \cdot F_{ij} \cdot \Delta t \quad (1)$$

$$P_i = \sum_{j\in\{\langle ij\rangle\}} F_{ij} \quad (2)$$

$$P_i \leq C_i^g \qquad (i \in V^g) \quad (3)$$

$$|F_{ij}| \leq C_{ij}^t \quad (4)$$

1. P_i denotes the actual power produced/consumed by the power plant/consumer i, measured in MW.

2. F_{ij} is the power flows from i to j, measured in MW.

3. K_i^g is the generation cost of the power plant i (which is element of the set of the power plants V^g), measured in EUR/MWh.

4. K_{ij}^t is the transmission cost. For the sake of simplicity we choose it to depend only the transmission line length l_{ij}, so $K_{ij}^t = K^t \cdot l_{ij}$ (the unit of K^t is EUR/MWh·km).

5. C_i^g is the nominal capacity of power plant i, measured in MW.

6. C_{ij}^t is the line loadability, measured in MW.

The advantage of the application of linear programming technique described above is that it takes into account economic considerations under given physical constraints. Thus this method fairly reproduced the operation of the power transmission system operator that is responsible for the most effective and reliable distribution of power.

2 Parameterizing the model

Our electricity network database [4] contains the information about:

- the network topology – the set of edges $\{\langle ij\rangle\}$ and nodes $\{i\}$ (with country information)

- the length (l_{ij}) and the voltage level (U_{ij}) of transmission lines

- the fuel type (nuclear, coal, natural gas, fuel oil, lignite, wind, biomass, hydro, etc.) and the nominal capacity of power plants (C_i^g)

- the population belongs to the nearest substation

Hourly consumption data of European countries available from the page of the European Network of Transmission System Operators [2]. Combined with the population information we assigned the consumption values (P_i) to the consumer nodes in the ratio of the corresponding populations.

The determination of the generation and transmission costs (K^g and K^t) is based only on expert estimation which doesn't take into account political and geographical and such specific factors that can affect the real costs. In our model the generation cost depends only on the fuel type of the power plant.

3 Line loadability

For the purpose of determining the line loadability, we apply the method originally proposed by St. Clair [6], and which later on analytically derived by Dunlop et al. [5]. Although the method has some limitations, and is based on several assumptions (like the neglect of resistance, the terminal system impedance and the effect of series or shunt compensation etc.), it is a good approximation for quickly estimating the line loading limit. The papers cited above showed that the loadability characteristics for uncompensated high voltage transmission lines is universal, the maximal power in units of surge impedance loading (SIL) is independent of voltage levels, and depends only the line length. Three factors influence the maximal power that can be transmitted, these are:

1. the thermal limitation;
2. the line-voltage-drop limitation;
3. the steady-state-stability limitation.

The thermal limitation is relevant only for lines shorter than 80 km, and within this range the maximal power is approximately $3 \cdot \mathrm{SIL}$. The maximum allowable voltage drop along the line is 5%, and relevant in the 80–320 km region. The steady-state-stability limitation is important for lines longer than 320 km. The steady-state-stability margin is defined as $100\% \cdot (P_{\max} - P_{\text{limit}})/P_{\max}$ and it is assumed to be 35% (corresponds to $\delta = 40.5^\circ$ power angle). Fig. 1 shows the loadability curve, which we used to determine the power transmission capability of the transmission lines in our load flow simulation. This is the so called St. Clair curve which gives the load carrying capability in the units of SIL. We applied the following typical SIL values (Tab. 6.1 in [3]):

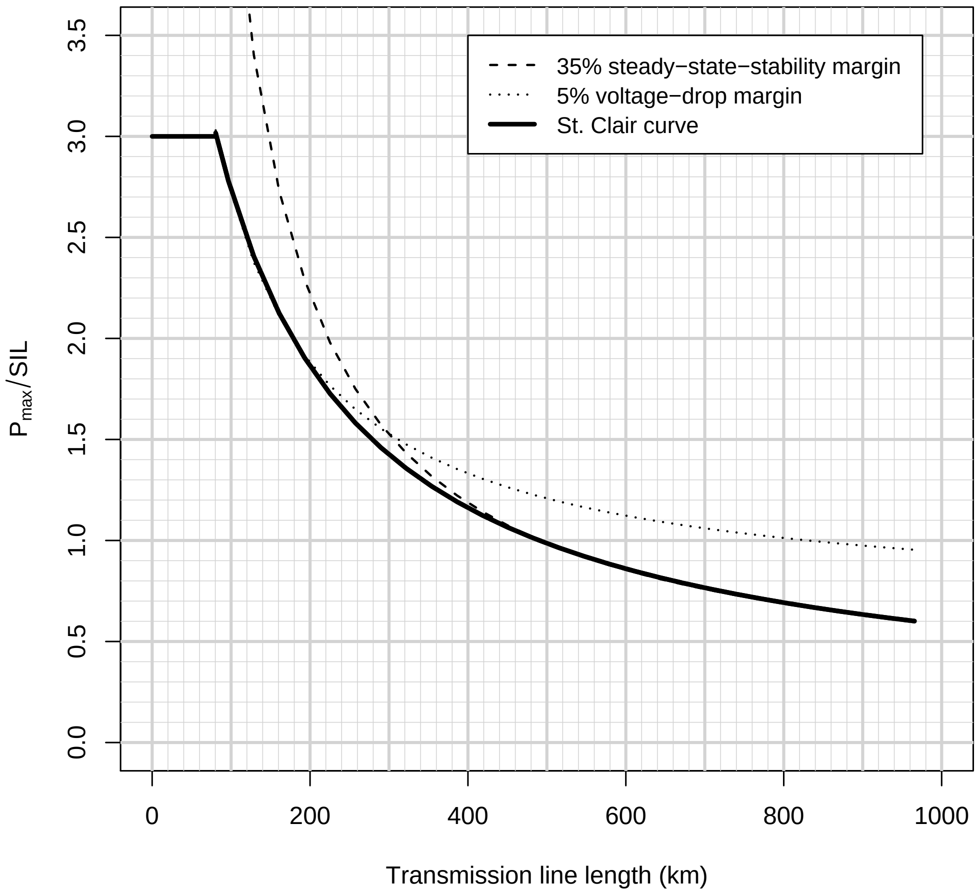

Figure 1: Loadability curve for uncompensated overhead transmission lines

Voltage levels	230 kV	345 kV	500 kV	765 kV	1100 kV
SIL	140 MW	420 MW	1000 MW	2280 MW	5260 MW

For other voltages we interpolated the SIL values correspond to the nearest voltage levels.

4 Breakdown process

A failure in the power network can cause successive failures which can propagate to the whole system. For example, when a transmission line (power plant) fails, the other lines (power plants) have to supply the missing carrying (generating) capacity that may lead to overload of some network components. This cascading failure mechanism causes the large blackouts, like the disturbance of the European power system on 4 November 2006, when the European interconnected power system was split into three independent parts [7].

In our linear programming approach (with linear equality and inequality constraints) there is no information about which line become overloaded, because if a constraint can't be satisfied the linear programming problem became infeasible. To find the weak lines in the system and to perform the cascading breakdown process we followed the next steps:

1. Decreasing the total consumption P to the limit P_{lim}, where the solution of the problem still doesn't exist, but for appropriately small further decrease of P_{lim} the problem becomes feasible

2. Finding the lines which the problem should become feasible with at P_{lim} if they have infinitely large capacity

3. Removing the lines found in the previous step. Updating the total consumption P if some node(s) dropped out.

4. Repeating these steps unless the electricity network becomes operable again

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