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Power Grid Simulation Model for Long Term Operation Planning

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In this paper a comprehensive model of electrical power grid with outage planning and forced outage simulation for prospective studies of transmission system operators is presented. The model is formulated as a mixed-integer linear programming (MILP) optimization problem with overall costs minimization being the objective. The power flow through the transmission system is estimated by DC load flow method. Thermal plants are modelled as multi-block, multi-fuel units with spinning reserves holding capability. Pumped-storage as well as conventional hydroelectric power plants are modelled.
Outage planning problem is formulated as a MILP considering network load profile and marginal prices of power plants. A forced outage algorithm with partial unit commitment fixation is used for the grid behaviour simulation during and after unexpected plant failures.
The computational results of an annual simulation of Czech 400 kV high voltage network (with 61 power plants, 110 blocks and 31 nodes connected by 53 lines) are presented. A state-of-the-art commercial general-purpose solver Gurobi is used to solve MILP models.

1. Introduction

Transmission networks are highly complex and linked systems. Many companies across different fields of interests utilize computer simulations of those networks in attempt to predict their future behaviour. One type of these companies is transmission system operators (TSOs). TSOs are companies entrusted with transporting energy on a national or regional level, using fixed infrastructure. Many TSOs are currently dealing with more complex conditions in their networks mainly due to massive increase in wind and solar sources with intermittent power production. Comprehensive simulation software is often necessary to predict power resources commitment for the network development planning. In this paper such a simulation model is presented. This model was developed and tested in collaboration with Czech TSO.

1.1 Modelling approaches

Long term operation planning of complex transmission networks is a difficult and challenging task. The dimension of this problem significantly grows with the number of connected power sources and the level of detail modelled. This problem generally consists of two subproblems dependent on each other - the unit commitment (UC) problem and the corresponding network power flow. The power flow computation is in general a non-linear task which in combination with NP-hard unit commitment problem makes the task so difficult.
A simple iterative strategy represents one of the first modelling approaches. The UC solution is found first and the corresponding variables are fixed. Then a power flow solution is computed. A disadvantage of this approach is that for a feasible UC solution no power flow solution may exist and correction steps must be performed. This approach was used by Yong Fu et al. (2005) to generate a secure hourly generation schedules of the day-ahead market.

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More recent approaches consider both problems at once. The ways to deal with such a large problem is the use of specialized tools (solvers) for solving optimization problems. The combined task of UC and power flow can be described by a mixed integer nonlinear programming (MINLP) model. Solving MINLP models is hard task even for current state-of-the-art solvers. One way to deal with this complexity is to linearize the model. Nonlinear nonconvex functions can be approximated by piece-wise linear functions and the nonlinear AC power flow equations can be approximated with linear ones. Linearized version of AC load flow is called DC load flow and is widely used among simulation models. Samarakoon et al. (2001) used this simplified power flow in their least cost transmission network expansion planning model. Also Lei Wu et al. (2010) used DC load flow for a long-term maintenance scheduling of generation units. These examples demonstrate a practical use of the simplified power flow for large transmission networks optimization problems.
In order to develop a comprehensive simulation model various functionality must be incorporated. Apart from basic technical constraints (e.g. minimum operating points, ramp rates, piece-wise linear power characteristic) a regular and a forced outages must be considered. The model must also include different kinds of power plants with various economic dispatch (ED) and unit commitment (UC) types.
Delarue et al. (2007) proposed a complex MILP model formulation with forced outage simulation capability. The author concludes that this model can be used for scenario analysis and reliability studies. No solution strategy is however mentioned.

1.2 Proposed model

Proposed model overcomes the Delarue et al. (2007) MILP model formulation by additional functionality. The level of detail is increased by dividing the power plants into independent blocks. Also the strategy to solve annual simulations is incorporated. The dimension reduction is achieved by division the annual simulation to shorter segments which are sequentially solved. Each section result is set as an initial condition to the next one. The length of segments must be long enough to ensure that the error is small enough in comparison with all-at-once approach. Each segment represents a MILP optimization problem which is solved by state-of-the-art general-purpose solver Gurobi. Moreover the chosen modelling framework Yalmip (Löfberg 2004) provides compatibility with any supported solver.
The important features of the proposed model are

- Hour granularity of proposed solutions,
- Simulation horizons from hours (power flow analysis) to years (network evolution analysis),
- User-definable power grid structure,
- Power plants with different unit commitment and economics dispatch types,
- Reasonable computational times (up to 5 min and 2 h for short- and long-term problems),
- Integrated outage planning algorithm and forced outage simulation support,
- Inclusion of ramping limits, minimum up and down times, start-up and emission costs.

2. Transmission network model

Model is formulated as optimization problem which minimizes the power production and transmission cost. The production costs consist of unit's startup and energy cost with fixed and variable component. The transmission cost corresponds to a positive and negative undelivered power penalization. The objective function is minimized with subject to:

- Demand constraints
- DC load flow and maximum transmitted power constraints,
- Minimum and maximum generation limits,
- Power plant characteristic constraints,
- Power plant minimum up and down times,
- Ramp rates,
- Unit commitment and economic dispatch constraints,
- Spinning reserves constraints,
- Outage constraints,
- Forced outage constraints.

Supported unit commitment and economic dispatch types are summarized in Tables 1, 2.

Table 1: Unit commitment types

1	Basic (economic) oriented commitment
2	All blocks must run
3	A minimum number of blocks must run

Table 2: Economics dispatch types

1	Basic (economic) oriented dispatch
2	Maximum production dispatch
3	Minimum forced production
4	Forced production, can be violated only in case of overproduction
5	Forced production, can be violated when all dispatch type 4 plants are shut down

As mentioned in the Section 1.2 proposed model employs time decomposition to solve large problems. The length of decomposed sections is for models with no forced outage simulations set to one week. In case of the annual simulation with hour granularity 52 models are sequentially solved. One week (168 time steps) is a compromise between the problem size and solution time. Simulation length with allowed forced outage simulation is not fixed to one week, instead is derived from the time between forced outages. The number of sequentially solved models in this case depends on forced outage position. This type of time decomposition is further discussed in Section 3.2.

In order to create accurate transmission network model a wide variety of power sources is modelled. General power plant characteristic is modelled as a piece-wise linear function. Different start and run fuel combinations are definable by fuel ratios. This general plant model can be used as a nuclear, combined cycle gas turbine or coal plant. Among other supported types including pumped storage and water dam plants, which are usable for active power balance regulation, the renewable resources (RES) are also modelled. Dispatch types 4 and 5 presented in the Table 2. are reserved to RES production simulation ensuring their proper functionality.

In addition to the predefined plant outages the model also implements iterative algorithm that computes optimal outage plan for all power blocks in the network. This algorithm can be used when the outage position is unknown and is further described in Section 3.1.

The implemented forced outage simulation is based on the approach presented by Delarue et al. (2007). Their approach represented an iteratively ran simulation. In the forced failure occurrence, the simulation is restarted throwing out all the computed results after the failure. In combination with the multiple hour start ramp the simulation results were good. However, the proper modelling of multiple hour start ramp require additional binary variables and new constraints to be introduced that enlarge the problem.

This approach can be simplified by introduction a start block for uncommitted power plants for their start ramp time. This leads to the same behaviour as previously published algorithm but the overall problem size is decreased. A comprehensive description of our algorithm is presented in Section 3.2.

3. Solution methodology

3.1 Outage planning algorithm

An outage is a planned unavailability of a power source. The task of outage planning for large power grids is a difficult optimization problem. Its dimension grows significantly with the increasing number of power sources and the time scale used.

The proposed algorithm iteratively computes the outage schedule with increasing time scale level. In each iteration a MILP outage planning optimization problem with finer time scale is formulated. If a previous solution is available, constraints that allow only small reposition of previously planned outages are added. This cuts possible solution space and reduces overall solution time. After solving, the solution time scale is then upscaled and the solution is used in the next iteration as an initial condition further simplifying the problem. The algorithm ends when the desired time scale is achieved.

The optimization problem uses the marginal cost of substitute energy to minimize the overall production cost of sources committed to cover up the outages.

The optimization is subject to:

- Number of outages per year and their length,
- Minimum time between two outages of the same block,
- Maximum number of concurrent block outages in one power source

The main idea of this algorithm is that the upscaled optimal solution of simplified problem is only a slightly suboptimal in comparison with the optimal solution of the original full size problem.

For example the annual outage plan of 110 blocks with one day granularity will be divided into two iterations, the first one with 52 time steps and the second one with 365 steps. The dimension of the second problem is reduced by allowing reposition of planned outages only by 5 weeks (35 time steps). If the required solution time scale is one hour a third step with 24 hour allowed reposition is used.

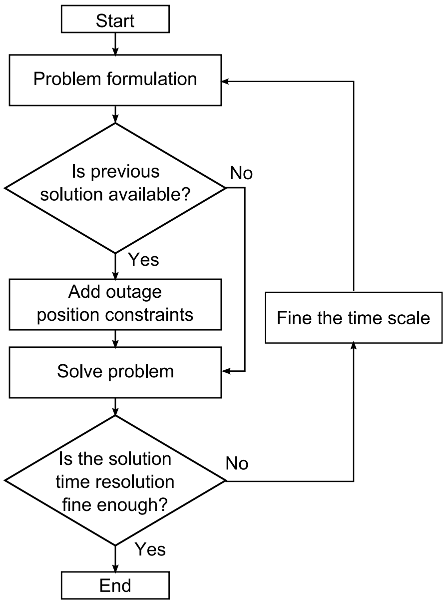

Figure 1: Outage planning algorithm

3.2 Forced outage simulation

The basic idea of the proposed algorithm is a sequential simulation with receding time horizon. In each iteration a time interval between two sequential outages with a short overlap is solved. In the interval only the forced outages which occurred in the first hour of the interval or in a previous interval are considered. The future forced outages are ignored because they are taken into account in the next iteration.
The time overlap between the iterations is introduced in order to obtain more accurate results. In the case of two failures the second starting one hour after the first, the interval would be only one hour which would lead to poor solution quality. The overlap part of the interval can be further used to model multiple-hour startup ramp. This ramp is used to model different reaction times of power sources and is used only for forced outage simulations. Finally the overlap part is also used to determine which plants will start in near future to cover up the current forced outage or the increase in the load demand. Those units are in the next iteration blocked only to the moment of their previous start in the overlap part.

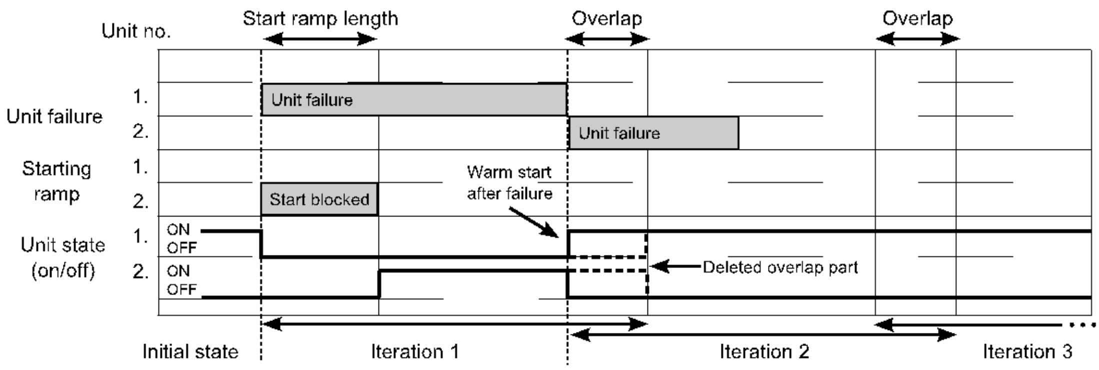

Figure 2: Forced outage simulation example

An example of forced outage simulation for one node power network with two connected generators is shown on the Figure 2. Initially before the forced outage the first unit produces enough energy to cover up the load demand (demand not shown). The second unit is shut down. At the beginning of the first iteration a failure occurs and the start of the second unit is blocked for its start ramp time length. The unit nearest start is allowed in the first hour after the start block end. In this case the second units start on the first possible hour and runs to the end of the extended interval while first unit remains shut down (dashed lines). At the beginning of the second iteration the overlap part is deleted and the second failure is taken into account. Second unit is shut down while the first one starts immediately. This is because the units with forced outage are considered to be in hot-standby state thus no start ramp is applied to them when the failure ends.

4. Example

In this section an example of the proposed model practical utilization on the Czech transmission network is presented. Two network models annual simulations are presented. Both models considered electricity prices and the renewable power source productions based on the values estimated by the Czech TSO for the year 2020. Both simulations were performed with identical outage and forced outage plans with overlap value set to 24 h.

4.1 Setting up the carbon emission cost

It is assumed that in the year 2020 the major part of the energy cost on coal sources will be formed by the emission costs. This situation will lead to a change in energy amounts produced by the sources with high CO_2 emissions. In comparison with today's situation, in which almost a half of the energy is produced by coal plants, the future power production will preferably consist of low-emission sources.
In this example, the results of two scenarios of 2013 and 2020 transmission networks with different emission costs are presented. First scenario contains current electricity prices with today's emission taxes. In the second scenario the emission cost is set to the estimated value about two times today's value. Overall production distribution and power plants capacity factors are on Figures 3, 4.

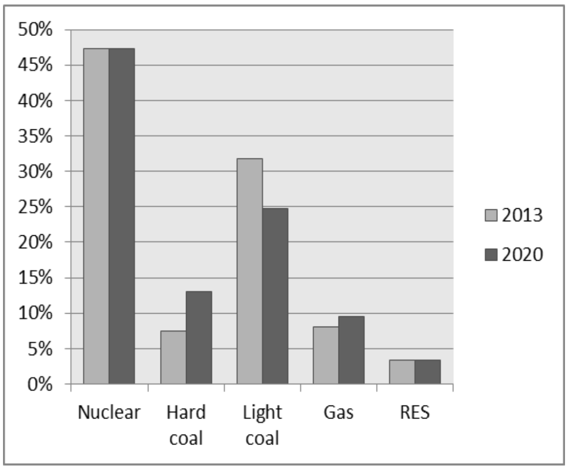

Figure 3: Overall production distributed by power plant types of annual simulations with different emission costs.

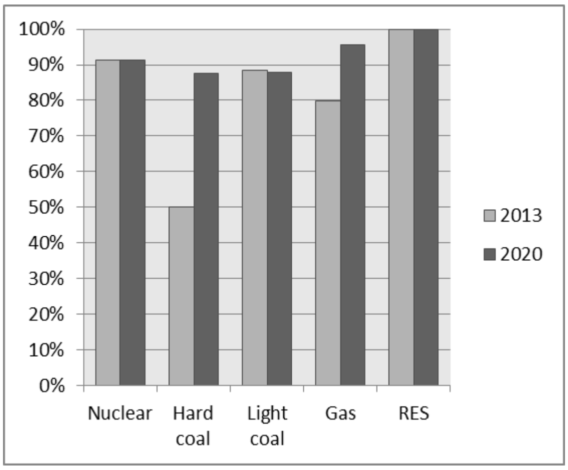

Figure 4: Overall capacity factor by power plant types of annual simulations with different emission costs.

The results demonstrate a decrease in production share of high emission power sources, mainly of the lignite plants. The 2020's emission cost lead to increased utilization of gas and hard coal sources. Relatively small change in the lignite plants capacity factor is due to their large installed capacity, implying that even a small change of this value corresponds to large overall production change.

5. Conclusion

In this paper a comprehensive simulation model of transmission networks for long term operational planning was presented. The important feature of this model is its ability to perform annual simulations with forced outages without additional binary variables for multi hour start ramps. The proposed outage planning algorithm can be used to determine probable outage position of power sources when no external data is available. The presented time decomposition method is applicable even to larger networks than provided. All the simulation results were verified by the Czech TSO.

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