Summary PhD Thesis Gabriela Molinar

Machine Learning Tool for Transmission Capacity Forecasting of Overhead Lines based on Distributed Weather Data

Abstract

The increment of intermittent renewable energy sources in the electrical power system is a challenge for grid operators. One example is the increase in congested overhead lines in Germany, because of the increment of wind energy transport from north to south. This problem reflects directly into the electricity costs of the end-users. Besides the construction of new overhead lines, a weather-dependent system operation is a short-term solution to improve the current utilization of the system. The analysis of a sample line in Germany presents a median increment of about 28% of the transmission capacity, which can mean a reduction of congestion measures costs in around 55%. The system presented in this dissertation forecasts the transmission capacity of overhead lines for 48 hours using machine-learning algorithms, giving transmission system operators the possibility to create ahead a more reliable power generation plan. This system improves the transmission capacity prediction with respect to the state-of-the-art reference model in 6.13% in average. The approach adjusts the meteorological forecasts to the local weather situation along the line. These adjustments are necessary due to changes in topography along the line route and wind-shadows from the surrounding trees, which cannot be described by the meteorological models. Moreover, the models developed in this dissertation are able to compensate the prediction accuracy deviations from day to night hours, which corresponds to an improvement in the current capacity forecast. Thus, an increment of 10% in the efficiency of the power transmission plan compared to the state-of-the-art has been achieved. Additionally, the positioning of the weather stations has been optimized to cover those spots that are more susceptible to experiencing the highest conductor temperatures of the line. The installation costs of a distributed sensor network covering Germany were compared to the reduction in redispatching costs, giving a return-of-investment of three years. A tool has been developed for the visualization of the weather measurements and the capacity predictions once the system is installed and running. This dissertation presents a solution to support a flexible electrical grid, which is necessary for a successful energy transition plan.

Germany has the goal to achieve 60% of the final gross consumption of energy and 80% of the gross electricity consumption made up by renewable sources by 2050. A nuclear phase-out is also planned by 2022 because of the potential risks of nuclear power plants and the uncertain long-term handling of their residues. Besides the benefits that this has against global climate change, it also represents a challenge for electrical network operators.

The increasing number of wind parks in the north of Germany and the nuclear power phase-out have unbalanced the spatial distribution of the generation centers. The transmission network is prepared for a traditional structure, where the power plants are near to the consumption areas. Therefore, the amount of congestion (episode at which an electrical equipment cannot transport the power required to fulfill the load) has been increasing in the past years, as reported by the German Federal Network Agency.

The Transmission System Operators (TSOs) have a sequence of steps to follow, when congestion occurs. First, they are allowed to do redispatching, i.e., change the generation schedule of the conventional power plants. Thus, reducing the power flow in some lines and increasing it in others. If the congestion could not be solved using this method, then they can apply feed-in management measures, i.e., curtailment of Intermittent Renewable Energy Sources (IRES's). The application of these measures has been increasing from the beginning of the energy transition plan, called *Energiewende* in German. In 2018 5.4 TWh of IRES's were curtailed (9.7 times more compared to 2013), which meant a cost of 635 Million Euros.

Therefore, a power grid expansion is necessary to achieve the climate and energy targets. Plans to build new overhead lines or underground cables have been discussed at least from a decade ago, and only some of them have been approved. One of the main reasons for this slow process is the lack of the population's acceptance of this infrastructure. The German Federal Network Agency states the NOVA-Pinciple to cope with the slow growth of the electrical network. It prioritizes short-term alternatives, as optimization measures, over the construction and reinforcement of transmission lines. Network optimization consists of using the maximum transmission capacities of the overhead lines, instead of the conservative limits considered nowadays. Overhead Line Monitoring Systems (OLMS's) are a grid optimization method, which retrieve the conductor's maximum power transmission capacity, also called Dynamic Line Rating (DLR).

The DLR is determined by the maximum permissible conductor temperature and the minimum distance allowed from conductor to ground. Consequently, the current-carrying capacity depends on the weather conditions, since high wind speeds, low ambient temperatures, and no solar radiation can reduce the conductor temperature, and vice versa. When monitoring systems are not available, the maximum transmission capacities are not known. Instead, they are approximated as a conservative limit (the so-called static line rating), which is determined for the worst-case weather conditions: high ambient temperature, full solar radiation, and low wind speed. This maximum limit is fixed independently of the actual weather scenario, which means that the electrical network is most of the time operating under sub-optimum levels.

Most of the DLR systems available in the market provide real-time current-carrying capacities. However, many decisions in system operations are taken one to two days ahead. The calculations of the operational limits, as the capacity allocations (Net Transfer Capacity) for cross-border energy markets, are carried out two days in advance. Network security calculations are executed one day ahead after the electricity market trade is closed. Therefore, real-time DLR is difficult to exploit by the TSO, while DLR predictions are necessary. That is the main reason why OLMS's have not been completely adopted, although the technology exists since the 1950s.

The straightforward solution to calculate the forecast for the current-carrying capacity corresponds to the direct utilization of the existing weather prediction models. Weather predictions for two days ahead are found with a spatial resolution of down to 1 km. Nevertheless, irregular topographies, as mountainous places, can show dramatic changes in the weather conditions even at scales below that grid size. Moreover, forest routes, as those followed by overhead lines, produce wind turbulence, which is challenging to be described by atmospheric models. The improvement in the spatial resolution of the numerical solution of the weather prediction models is a trade-off for its forecast scope. The limitation is the total calculation time required to solve the set of differential equations numerically. Downscaling is a meteorological method, which interpolates the weather models solution horizontally using topographical features of the area. The method uses distributed measurements of the weather conditions as calibration points, to improve the spatial resolution of the weather predictions. However, a vertical interpolation to the overhead line-height, as expected for OLMS's, is still a challenge nowadays.

This dissertation presents a solution for the problems of the state-of-the-art, as a tool for TSOs with four main characteristics. First, weather observations are collected along the overhead line routes at conductor height. Thus, aiming to a description of the weather conditions along the line as accurate as possible. Second, the DLR is calculated for real-time monitoring, but also it is predicted for 48 hours. The DLR forecast is based on an adjustment of the meteorological predictions to the weather conditions along the line, using machine-learning methods because of the possibility to optimize directly the DLR prediction accuracy. Third, a pre-installation procedure for the location of the weather stations along the overhead lines has been developed, which reduces the investment costs while still covering the conductor hotspots. Fourth, a thermal transient analysis, which tell TSOs the time, if any, they have to transmit more than the current-carrying capacity without overheating the conductor (normally around several minutes), thus coping with short-term congestion scenarios.

Prior to beginning developing the tool, the economic impact of dynamic line rating has been analyzed on a sample overhead line in Germany. The study is based on abstractions of the German electrical network and a generalization of the additional current-carrying capacities of the overhead lines. When these optimization mechanisms are used, the transmission capacity has the potential to be 50% of the time 28% bigger than the static line rating approach. This extra-capacity is translated into the amount of power that could have been transmitted, instead of redispatched or curtailed. Therefore, the use of dynamic line rating can reduce the redispatching measures in 42%, which means a reduction in the congestion management costs of around 55%. Considering a cost of 1438 Million Euros in 2018, the use of these optimization mechanisms have clear benefits.

In the framework of this dissertation a solution for 48 hours current-carrying capacity forecast was developed, which adjusts the meteorological predictions to the weather conditions along the line, based on weather observations collected in the surroundings of the conductor. The partitioning of the problem into models based on weather observations and those based on numerical weather predictions showed that the former had a better prediction accuracy in the first hours, while the latter was more appropriate for the last prediction period. An ensemble model resulted in a combination of the strengths of each approach. The result had an average accuracy increment with respect to the baseline (direct calculation of the current-carrying capacity from numerical weather predictions) of 6.13%.

The TSOs consider the safety of the electrical network as the highest priority when taking decisions. This means that overloading the grid has to be avoided. The machine learning models were trained to predict with a confidence rate of 50%, i.e., centering the mean error on zero. That leads to having statistically as many overestimations as underestimations of the transmission capacity. In the development phase, especially when comparing different algorithms, this behavior is useful and wanted. For the application of this system in operations, a bias was added to the model output to reduce the overestimation probability to 2%. Comparing the machine learning result presented in this dissertation to the state-of-the-art, this safety factor could be improved in about 300 A for the third forecast hour.

The impact of dispatch based on the result of this dissertation was calculated by running a redispatching analysis using this system and compared to the static-line-rating case. The redispatch power was reduced in 3 TWh in a year, when adding the DLR predictions under their safety factor. In the studied simplified scenario, that corresponds to a total of 26 million Euros saved costs.

By defining the efficiency of the power transmission plan as the percentage of the actual current-carrying capacity that is utilized if the plan is carried out, the 48 hours generation plan had an efficiency of 64.7% by planning based on the final model of this dissertation, 53.3% for the corrected baseline and 47.9% for the static line rating. Meaning more than 10% gained efficiency with the forecast model presented in this dissertation.

Moreover, the number of necessary weather stations and their positioning along the overhead line routes are two important key-points for the success of the application of this system. A procedure to locate the weather stations at the hotspots (places along the line route, where the conductor temperature tends to be higher than the rest of the line) was developed and tested on a sample overhead line in Germany (see Figure 1). The number of sensor nodes is also adjusted to the available budget of the TSO. For the sample line of 45 km length, an amount of 20 weather stations covering the most important hotspots of the line implied an average sensor node density of 2.2 km. Considering a cost per weather station of about 4000 Euros, plus the installation costs of 1000 Euros per station, the total cost for this line adds up to 100 thousand Euros. For the German transmission grid with around 35000 km overhead lines, a coarse scaling up results in a total installation cost of around 70 Million Euros. Considering the redispatching costs saving in case DLR with a prediction safety factor is used of around 26 million Euros for 2018, the return-of-investment for the installation of a distributed weather measurement system is almost three years. This is a rough calculation, not considering that in the north of Germany less weather stations per kilometer may be needed because of the flat topography. Maintenance costs are also not considered in this result. However, it gives the order of magnitude of the investment return for the system.

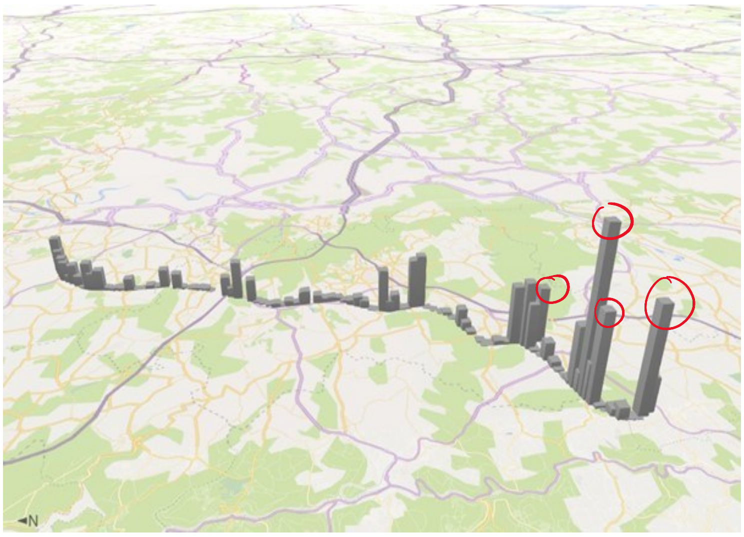

Figure 1 – A procedure to locate the hotspots on a line route, i.e. the places where the conductor temperature tends to be higher than the rest of the line, was created and tested on a sample overhead line in Germany. After locating the hotspots, the installation places for the weather stations can be determined based on a given budget.

The next steps in the development of the final current-carrying capacity forecasting model of this dissertation corresponds to the reduction of the time to put the system into operations. The results of this dissertation require a year of weather measurements after installation of the hardware. Using transfer-learning methods, pre-trained models can have just small adjustments in a short period. Moreover, continuous learning can be implemented to have a constant update of the models based on the current measurements from the system.

In general, research is required on forecasting low wind speeds, which is the most influencing factor in the current-carrying capacity estimation. Meteorologists are working on the use of downscaling techniques and the integration of more sophisticated wind turbulence descriptions into mesoscale meteorological models. These models could take advantage of the distributed weather measurements, for example.

Finally, other applications, in the area of smart grids or smart cities, could find valuable a network of weather observations distributed over vast areas coupled with predicting models. For example, the prediction of air quality curves is today important to organize the traffic flow in the cities and reduce the localized levels of urban air pollution. That could be managed by a network of sensors collecting weather information (primarily wind measurements) and a machine-learning model, which correlates the traffic peak hours, the location of the cars, and the weather conditions.

This dissertation is part of the first steps towards a flexible electrical grid. Optimization mechanisms, as dynamic line rating forecasting systems, offer a short-term solution to extend the need of the construction of new overhead lines. Machine learning algorithms showed the possibility to adjust the current-carrying capacity prediction to the surrounding conditions of the conductor. The dataset, carefully created for training and evaluation, was published open-source to motivate a standardized analysis of the models, allowing other researchers to compare their results[1]. The hope is to see a constant growth of systems supporting the energy transition plan in the years to come.

[1] The open-source dataset is found in github.com/prognonetz/benchmark_idaho