Weather-based dynamic line rating of overhead transmission lines over Europe interconnected network

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Abstract. For the impact of the Dynamic line rating application on ancillary service, it is necessary to offer a better understanding of real lines capacity to the operator, in order to choose this technology as an alternative. An extended case study with the influence of applying the DLR in the Europe interconnected network is presented. This data have then been simulated through the 118-bus transmission expansion benchmark case with renewable generation capacities systems which calculated optimal investments in generation considering static rating or DLR, and provided historical time series of power flows through the interconnections in the two scenarios. Thereby, the simulation results are analysed with the objective to determine the impacts of applying the DLR on the power system's hosting capacity for fluctuating wind power infeed and the requirement for dispatchable generation units. The economic aspect is also discussed based on the simulation result of the electricity price.

1. Introduction
With the increasing penetration of renewable energy sources and the fundamental changes inside many power systems, the power flow changing more frequently and the peak electricity demand need higher capacity. Today, the maximal transit capacity considered by European TSOs for imports and exports are called the Net Transfer Capacities (NTC). However, these values can be conservative compared to the physical capacity of the lines, which highly depends on weather conditions. Allowing climatic dependent capacities is another approach referred as Dynamic Line Rating (DLR) and can have a positive impact on the integration of renewables in the interconnected grid. For example, an increase in wind speed contributes at the same time to an increase in wind power, and to the cooling of the lines which increases the maximum allowable transit.

The methods of power line ampacity, which applied in a fixed period, are defined in the standards, such as IEEE [1], IEC [2] and CIGRE [3]. The main related weather parameters are wind speed, wind direction, ambient temperature and solar radiation, and the wind influence most [4] so many studies focus on the wind power connection [5]. The wide range of application of the Dynamic line rating brings potential benefits for both capacity and flexibility dispatch of the whole grid [4], [6]. Researchers paid much attention on the methodology of optimization and secure of the DLR.

However there are still several barriers limit its practical application, both in techniques and economic ways. The economic benefits determination of DLR is a multilateral case which is difficult to evaluate, and there are not many papers discussing about the evaluation of the economic benefits of the
DLR. This study aims at determining the increase in transmission capacity with the application of DLR on the European network and its impact on the reserve in order to find a techno-economic optimum. The main objective of this study is to define a methodology to establish the impact of the application of DLR on the quantity of the reserve and electricity price. The purpose of this study is to define a methodology to evaluate the impact of using DLR instead of NTC values: On the operation of a fixed generation portfolio, and the need for peaking generation (CCGT, OCGT) in a Capacity Expansion Planning framework (CEP).

2. DLR modeling and methodology

2.1. Steady-state heating balance
In order to establish the models and start to analysis, we need to calculate the Real Time Thermal Rating (RTTR) and the Dynamic Line Rating (DLR). In this paper, the methodology and model is defined by the standard CIGRE [5] based on the heating balance of the conductor in steady-state, and the necessary factors are discussed in the below.

The DLR is compared with static seasonal line rating which calculated through determine weather data in each season. The static seasonal ratings that applied to overhead lines for determining the requested clearance are also defined according to the standard CIGRE.

With typical ambient parameters and the related conductor data, the temperature of the conductor could be calculated through the following algorithm in figure 1. Consider with the shadowing scenario, the wind speed is calculated at the height of 10 meters with a high soil roughness factor and the wind direction is considered parallel to the conductor. These are conservative but reasonable to think that over the length of the circuit.

\[
\begin{align*}
\text{The ambient temperature (Ta)} \\
\text{The radiation (S)} \\
\text{The wind speed (Ws)} \\
\text{The wind direction (Wd)} \\
\text{The load current (S)}
\end{align*}
\]

\[
\begin{align*}
\text{Conductor Ampacity (I)} \\
\text{Conductor Temperature (Tc)} \\
\text{Standard CIGRE Conductor current model} \\
\text{Iterative method} \\
\text{Consider Shadowing scenario}
\end{align*}
\]

Fig.1 The RTTR calculation framework

With the ambient weather data and related constant conductor parameters, the ampacity at which the conductor reaches its maximum permissible temperature (in this case 80°C) which also corresponds to the maximum permissible conductor sag. In this paper we solved the temperature of the conductor (Tc) through an iterative approach, and the error is small than 0.1°C. After this, the RTTR of the circuit is calculated as the minimum value of the RTTR of all the points belonging to the circuit.

2.2. The Dynamic Line Rating and climatology
In order to calculate the DLR, the following approach will be applied to calculate the DLR for a single circuit. For each hour of the year, an array of representative RTTR is selected. Regarding the selection of the representative circuit’s RTTR for a specific hour and day combination, the following criteria is used: the ratings of the circuit relative to the same hour and to the five days before and after the day are considered. This will let to increase the number of observation and obtain a more precise description of the probability distribution. There is one notice requirement that we cannot consider several hours ago or later, or the large time scale in order to neglect incurring in problems related to the change of season or the evolution of sunrise and sunsets times.

A probability distribution is fitted to this new dataset rearranged from the small to the top. With this distribution we could roughly consider a quantile forecast of the DLR. We only fitted with the lowest
around 30% of the value by the extreme value distribution. The probability density function (2) for the extreme value distribution with location parameter $\mu$ and scale parameter $\sigma$ is:

$$y = f(x|\mu, \sigma) = \sigma^{-1} \exp\left(\frac{x-\mu}{\sigma}\right) \exp\left(-\exp\left(\frac{x-\mu}{\sigma}\right)\right)$$

(2)

This form of the probability density function is suitable for modeling the minimum value. Extreme value distributions are often used to model the smallest or largest value among a large set of independent, identically distributed random values representing measurements or observations. Due to the fact that we only have two year weather data, so here we arbitrarily choose the 30%. If there could gather 10 years or even more, then the percentage could choose much lower than that.

Finally, a value corresponding to a selected probability of exceedance is selected as DLR for the specific time/day combination. Regarding the selection of the DLR applied to the circuit, a risk based criteria will be used.

2.3. Optimization model

In order to find the relevant demand and the reserve sizing, we choose the IEEE 118 test model with renewable generation capacities and hourly availability for a model year as a benchmark for transmission expansion algorithms[7]. The simulation choose the Germany-based economic dispatch methodology. The economic model could simplified as a system of linear equations, which can be formulated as continuous-time state space model[8].

In this paper the reserves is referring to the real power capacity which could be taken for the load balance. It considered with the increased total reserve requirements both upward and downward when applying the DLR, including the primary, secondary and manual reserves. The activated reserve is determined when the load is greater than 1% DLR. In order to meet the demand of the balancing of the system, this part is mainly the fast start units which could cover the demand in short period.

The methodology is a rough assumption of the reserve required with the application of the DLR, which offer an economic aspect of the influence of the ancillary services.

3. System simulation & case study

In this case we mainly discuss about the onshore interconnections transmission lines in the Europe, corresponding to the countries of continental Europe with the exception of Russia and Albania. The geographical coordinates of each circuits and the related substations are identified through the ENTSO-E European transmission grid map [9] and the SciGRID European geo-referenced power system model [10].

Then due to the rough location, the two sources of historical meteorological weather records are used for the historical values of wind speed (and direction), ambient temperature and the solar radiation from the year 2009 and 2010 of NASA’s MERRA[11]. The first service provides global reanalysis for several weather parameters with a temporal resolution of one hour and a spatial resolution of 40km, and it provides data from the ’90s. The second service provides historical estimations of global solar irradiance from satellite images with a temporal resolution of 15 minutes and a spatial resolution of 3km.

To calculate the RTTR and DLR in each point along the circuit, the weather condition is one aspect, the details of the conductor is another factor which need to consider. For the difficulty of identifying all the type of the conductor, there is a rough estimation considering the standard[12] with each voltage level. The conductor code is LYNX, PANTHER, ZEBRA and MOOSE which related to the 110,220, 330 and 400 voltage level.

4. Results and discussion

4.1. DLR forecasts

Here it is an example for the result gained for one year is shown in Figure 2. In this figure it compared with the static line rating, the RTTR based on the data of French and Germany in 2009, and the 1%, 3% and 5% quantile of the DLR based on the method previously mentioned. The difference between the DLR and RTTR is rather obviously through the figure 2. Through the figure 2 we could see that the
rating is affected by the daily weather and seasonal factor. For a normal day, the ambient situation is basically that the higher solar radiation in the noon, and the wind speed in the night.

Fig.2 Consecutive day-ahead DLR forecasts whole year compared with RTTR

4.2. Electricity generation and Transmission Capacity

In table 1 there is the percentage of each type of the yearly generation electricity changed by the using of DLR. The load loss of the four countries have significantly decreased when using DLR. Due to the fact that the wind power generation increased in the Portugal with the application of the DLR, more clean electricity could be transmitted to other countries with larger transmitted capacity. But this also result higher capacity of the reserve, especially Spain which is next to the Portugal. The total consumption of the CCGT and oil all decreased slightly and especially the usage of oil in Portugal decreased 11.59%. The biomass also could increase a small amount especially in Spain and Portugal (8.76% and 7.26% respectively).

|        | Wind onshore | Coal cluster | CCGT cluster | Biomass cluster | OCGT cluster | Oil cluster | Nuclear fleet | Hydro turbine cluster | Transmision | Pumped storage cluster | Load Loss |
|--------|--------------|---------------|--------------|-----------------|--------------|-------------|---------------|-----------------------|-------------|------------------------|-----------|
| DE     | 0.00%        | -0.07%        | -0.28%       | -0.64%          | -7.57%       | -0.01%      | 0.00%         | 0.00%                 | 2.58%       | -0.80%                 | -57.33%   |
| ES     | -0.67%       | 0.41%         | -1.09%       | 8.76%           | 15.08%       | -1.89%      | 0.17%         | -0.65%                | -3.13%      | 1.11%                  | -70.52%   |
| FR     | 0.00%        | 0.43%         | 0.07%        | 0.27%           | -2.43%       | -2.26%      | 0.13%         | 0.50%                 | 3.35%       | -0.90%                 | -72.46%   |
| PT     | 23.66%       | 0.00%         | -4.26%       | 7.26%           | 2.27%        | -11.59%     | 0.00%         | -0.67%                | -16.15%     | 0.00%                  | -32.12%   |

For the transmission capacity we mainly discuss the transmission line between the France and Spain, and France and Germany. For the transmission line between the Spain with the France, the maximum transmission capacity increased both direction in the winter, and decreased in the summer. With scaled profiles, adopting DLR allowed 700.77 GWh more energy per year could transmit through the network, an increase of 5% when compared to the NLR case. On the other hand, the capacity transmitted from the France to Spain has decreased 334.163 GWh.

The situation of the interconnection between France to Germany is a different case compared with the one between Spain to France. The total transmission capacity have increased in both directions, from Germany it increased 160.37 GWh (39.6% by the original capacity) and from France is 291.79 GWh (30.7%). The electricity from France is more than twice as the one transmitted from Germany. The two direction increased the transmission capacity in winter and spring with applying DLR but decreased in summer and autumn.

4.3. Electricity Price
With the result of the simulation we have obtained the electricity price of the Germany, Spain, France and Portugal in each hour. Here we consider the average electricity price first to have a general comparison with the application of the DLR.

Table 2. Annual average electricity price (€/MWh)

|       | DE   | ES   | FR   | PT   |
|-------|------|------|------|------|
| NO DLR| 77.770 | 55.395 | 66.851 | 56.882 |
| With DLR | 77.781 | 55.817 | 66.936 | 56.806 |
| Difference | -0.011 | -0.421 | -0.085 | 0.076 |

Based on the table 2 we could see that the price of most countries have slightly increased except Portugal. The Portugal could benefit most with this technology. For Germany, the electricity is not influenced much by the DLR, especially compared with the other countries. The decreased case is mainly happened in the winter. The maximum decreased and increased price difference is 17.32€/MWh and 25.32€/MWh, is rather small compared with the other countries. For France is worse in winter and spring, better in summer, which is related with the average seasonal price previously. In summer the DLR mainly push the price up, but in the winter to the contrary the price decreased much.

Then the situation of the Spain and Portugal is quite same, and the price in Portugal is more being effected by the application of this technology considering it increased the installed capacity of the wind power. The electricity price in Spain is more unstable, but the price in Portugal saw an opposite trend which is more stable. The maximum increased and decreased price difference is both 89 €/MWh.

4.4. Installed capacity and reserve

We could find that generally there is a large decrease on the total installed capacity of the OCGT and CCGT, except France which increased 570 megawatt OCGT and 89 megawatt CCGT. The total installed capacity of the OCGT and CCGT is decreased 627.6 megawatt. For the wind installed capacity, only two countries is influenced which are the Spain and the Portugal. Although the wind installed capacity in Spain decreased 534 megawatt but the Portugal could increase 1141 megawatt. Due to this fact that the total wind installed capacity still could rise to 607 megawatt.

The result proved the methodology is reasonable to make a rough estimation of the reserve needed to be equipped with. And if the capacity directly choose the maximum value of the reserve sizing, it means the total reserve sizing is doubled or even more.

5. Conclusions and future work

In this paper, a methodology of determining the DLR based on historical real time thermal rating has been proposed considering the security and stability of the power grid. It also intended to study the influence and performance of applying DLR through different aspect, include operation and economy. An accurate estimation of a line's DLR this been made based on the historical weather data in 2009-2010 over all areas passing through by the line of the Europe interconnection network. A simulation of the power system dispatch optimization in Germany, France, Spain and Portugal has been made in order to study the impact of the application of the DLR.

The DLR could bring more transmission flexibility especially winter for the abundant wind source, which decreased the wind curtailment and load loss in general. The DLR calculated with this methodology overall seems to reduce the overall transmission capacity of the lines; this is actually a finding of the study and shows that security can be improved.

For the overall aspect, the application of DLR could decrease the necessary capacity of the OCGT and CCGT, and the electricity price as well. Considering the economic aspect in each country, some countries may not likely use this technology, such as France. And the Portugal could benefit most with the application of the DLR, due to the increased wind installed capacity and lower annual electricity price.
The impact of the DLR need further study for larger electricity network model. Mostly the electricity price will not change, but the price would be a bit of unsteadiness except Portugal. Also the application of the DLR require additional reserve sizing which may increase the investment. With higher demand of decreasing the carbon dioxide emission, the non-dispatchable renewable energy is growing rapidly worldwide, this technology could be a choice with less investment. Considering the limitation of the model scale and the methodology, the determination of DLR could be more applicable with larger historical dataset. Also the percentage of the quantile could also be flexible considering the situation.

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