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Impacts of Dynamic Line Rating on Power Dispatch Performance and Grid Integration of Renewable Energy Sources

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Abstract—The potential benefits of employing dynamic line rating (DLR) for the grid integration of variable renewable energy sources (RES), such as wind and photovoltaic (PV) units, are presented and analyzed. Unlike nominal line rating (NLR), DLR takes advantage of the fact that the physical power transmission capacity of overhead lines is a function of ambient conditions (temperature, wind speed, wind angle and solar insolation). DLR is hence often less conservative than NLR, which assumes more challenging ambient conditions.

A simulation study has been performed on a functionally modeled six-node benchmark power system loosely based on the German power system. Simulations with high time resolution were accomplished using a predictive power dispatch scheme that directly incorporates line constraint information. Historic load demand, wind and PV in-feed profiles, as well as scaled-up profiles for high RES scenarios are used. Dispatch impacts of line constraints derived via DLR and NLR are compared and their effect on RES grid integration is assessed.

I. INTRODUCTION

Facing the challenge of having to reduce CO₂ emissions due to climate change concerns as well as security of supply issues with fossil fuels, many countries nowadays are committed to increasing the share of renewable energy sources (RES) in their electric power systems, especially of variable RES (var-RES), i.e. wind and PV units. In Germany, for example, the RES share of electricity generation has increased from 4.7% of net load demand in 1998 to more than 20% in 2012 [1]. Overall RES electricity generation is dominated by wind, PV and hydro generation with an absolute share of net load demand of 8.3%, 5.0% and 3.9%, respectively, in 2012. The remainder was made up of biomass, land-fill and biogas generation (3–4%) [1].

However, existing transmission capacity limitations in many power systems are increasingly impeding the grid integration of ever larger RES energy sources. While building new transmission lines is costly and often requires lengthy legal procedures due to regulations and public concern, a short-term alleviation of the capacity limitation problem is to improve the capabilities, and hence the utilization, of existing transmission grids by adopting measures such as dynamic line rating (DLR) for overhead lines [2].

A recent case study showed that applying DLR to a 132 kV line between Skegness and Boston in the US would enable the grid integration of 20–50% more wind generation than by using the more conservative NLR [3].

In this paper, an in-depth investigation of how much DLR can improve the grid integration of RES in-feed in power systems is performed with the following approach:

- Deriving a DLR model algorithm, including line rating and conductor surface temperature calculation.
- Assessing the effects of ambient conditions on DLR.
- Reconstructing of these ambient conditions.
- Establishing a benchmark power system model with high renewable energy shares and testing the improvement on power transmission performance obtained when applying DLR in power dispatch.
- Performing and analyzing full-year dispatch simulations with high time resolution.

The remainder of the paper is structured as follows: Section II introduces the modeling of DLR, the dispatch model is described in Section III, simulation are shown in Section IV, followed by conclusions in Section V.

II. DYNAMIC LINE RATING MODELING

A. Steady-state Heating Balance

The rating of the transmission line is determined based on the heating balance of the conductor in steady-state, as defined by a CIGRE standard [4]. A simplified version of the heating balance equation is given by

\[ P_J + P_S = P_C + P_R, \]

where \( P_J \) is Joule heating, \( P_S \) is solar heating, \( P_C \) is convective cooling and \( P_R \) is radiative cooling. The resulting DC current rating \( I_{DC} \) of Eq. 1 is thus

\[ I_{DC} = \sqrt{\frac{P_C + P_R - P_S}{R_{DC}[1 + \alpha(T_{AVG} - 20)]}}, \]

where \( R_{DC} \) is the DC resistance, \( \alpha \) is the temperature coefficient of the resistance and \( T_{AVG} \) is the average
temperature of the conductor\textsuperscript{1}. The equivalent AC rating ($I_{AC}$) can be calculated as

$$I_{AC} = \frac{I_{DC}}{\sqrt{1.0123 + 2.319 \times 10^{-6} T_{DC}}}. \quad (3)$$

Procedures for obtaining $P_S$, $P_e$ and $P_t$ are given in [4].

As shown in Fig. 1, wind speed ($V$) has the largest impact on $I_{AC}$, which increases from 700A at $V = 0 \text{ m/s}$ to around 3300A at $25 \text{ m/s}$ $\left(+371\%\right)$. Besides this, the wind attack angle ($\delta$) and the ambient temperature ($T_{Amb}$) also have a significant effect on $I_{AC}$, with an increase of $35\%$ and a decrease of $41\%$, respectively. The global solar radiation ($S$), in comparison, has a small effect on line rating. In our simulations $I_{AC}$ dropped by only $5\%$ of it’s initial value for high solar insolation levels.

### B. Average Conductor Temperature

The temperature of the conductor can be calculated from $V$, $\delta$, $S$, $T_{Amb}$ and $I_{AC}$ using the following algorithm:

#### Algorithm 1

Calculate average conductor temperature

1: **procedure** CALAVGTEMP ($V$, $\delta$, $S$, $T_{Amb}$, $I_{AC}$)
2: $T_{AVG} \leftarrow 50^\circ C$
3: while ($\Delta T_{AVG} > \delta_{Toi}$) do
4: $T_{AVG,new} \leftarrow T_{AVG} - \frac{P_{11} + P_{0u} - P_{0c} - P_{0h}}{\pi C_{AVG} + \pi C_{AVG} + \pi C_{AVG}}$
5: $\Delta T_{AVG} \leftarrow |T_{AVG} - T_{AVG,new}|$
6: $T_{AVG} \leftarrow T_{AVG,new}$
7: end while
8: return $T_{AVG}$
9: **end procedure**

Technically, the initial guess of $T_{AVG}$ can be any value, however, it is sensible to choose a value between the current ambient temperature $T_{Amb}$ and the maximum allowable conductor’s surface temperature $T_{AVG,max}$. From our experience it is recommended to choose $T_{AVG} = 50^\circ C$ as an initial guess, with which the calculations are usually finished within three to four iterations. The tolerance is set to $\delta_{Toi} = 0.1^\circ C$ in this work, which corresponds to an error of 0.014% for the calculated DLR value.

### C. Correlation of DLR with Generation & Load Volatility

While wind power in-feed is proportional to $V^3$ and solar power in-feed is proportional to $S$ [5], there exists a well-known negative proportionality of load demand and $T_{Amb}$, i.e. the outdoor temperature, during the winter season, for example in France [6]. A linearized model, which relates DLR with generation and consumption is presented in Table I, was obtained by fitting a first-order curve to the steady-state rating analysis in the previous section (wind angle is not included here as it is assumed to be fixed at $\delta = 45^\circ$). Wind speed ($V$) has an influence on DLR that is $40 \times$ stronger than that of ambient temperature ($T_{Amb}$) $\left(4.00\%/\%\right) = 40$, and close to $300 \times$ stronger than that of solar insolation ($S$) $\left(4.00\%/\%\right) \approx 286$.

\textsuperscript{1}Temperature is assumed to be distributed coherently across the conductor, thus, conductor surface temperature is equal to $T_{AVG}$.

\textsuperscript{2}Flat part in wind angle curve is due to that wind cooling power in this region is smaller than the conductor’s natural cooling power.

#### TABLE I: Impact of Ambient Parameters on DLR.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Absolute</th>
<th>DLR</th>
<th>Percentage</th>
<th>Influence on DLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>-0.14%</td>
<td>0.13%</td>
<td>$T \in [-20, 40]^\circ C$</td>
<td>7 \times</td>
</tr>
<tr>
<td>Load</td>
<td>-1%</td>
<td>1%</td>
<td>$V \in [0, 25]m/s$</td>
<td>300 \times</td>
</tr>
<tr>
<td>Wind</td>
<td>+11.1%</td>
<td>1%</td>
<td>$S \in [0, 10000]W/m^2$</td>
<td>1 \times</td>
</tr>
</tbody>
</table>

### III. DESCRIPTION OF SIMULATION & ANALYSIS

With the calculation methods for DLR established, it is now possible to add DLR into a power dispatch optimization setup and examine the improvement of the dispatch result. Here, we have used a previously established predictive economic power dispatch model [7]–[9], in which dispatchable and non-dispatchable generators, controllable and non-controllable loads as well as different types of storage units are modeled and processed. The economic predictive dispatch problem is formulated as

$$\min J(k) = \sum_{l=k}^{l=k+N} u_l^T R_{u}^l u_l + R_{lin} u_l + \delta u_l^T \delta R_u \delta u_l$$

s.t. \begin{align*}
(a) & \quad x_{l+1} = A \cdot x_l + B \cdot u_l , \\
(b) & \quad 0 \leq x_{min} \leq x_l \leq x_{max} \leq 1 , \\
(c) & \quad u_{min} \leq u_l \leq u_{max} , \\
(d) & \quad \delta u_{min} \leq \delta u_l \leq \delta u_{max} , \\
(e) & \quad u_{bin}, l - G_{map} u_l = 0 , \\
(f) & \quad v_{bin}, l - G_{line} P_{line,l} = 0 , \\
(g) & \quad P_{line} = B \delta \Theta = 0 , \\
(h) & \quad P_{line,l} = P_{line,l} \leq P_{max}, l , \\
(i) & \quad \Theta_{min} \leq \Theta_l \leq \Theta_{max} , \end{align*}

where $k$ is the current time step. $x_l$ represents state variables, i.e. the state-of-charge of storage units and $u_l$ is the power nodes’ in/out-feed, for prediction time step $l$. $R_{lin}$, $R_{quad}^l$ and $\delta R_u$ represent linear and quadratic marginal as well as ramping cost terms, respectively. Sampling time is 15 minutes, and the prediction horizon $N$ is 64 hours (perfect prediction of load, wind&PV in-feed is assumed).

Eq. 4 (a) represents the (linear) Power Nodes model of the power system, 4 (b–d) denote system constraints, 4 (e–f) define the grid topology, and 4 (g–i) the (linear) DC power flow as well as line and voltage angle constraints. Terms $P_{line,l}$ and $P_{line,l}$ are constant for the NLR case while for the DLR case they represent time-variant profiles.

DLR profiles are calculated from temperature, wind speed, and solar radiation profiles. The temperature profile is reconstructed from the daily minimum and maximum temperature using a sinusoidal approximation [10], [11], while wind speed and solar radiation profiles are reconstructed from wind and PV in-feed time-series [11].

Fig. 2 depicts an reconstruction example, while Fig. 3 is an illustration of the simulation and dispatch scheme.
Fig. 2: Reconstruction of ambient conditions for DLR.

Fig. 3: Economic power dispatch with DLR.

**IV. BENCHMARK SYSTEM & SIMULATION**

In our study, the German power system is chosen as the reference of the benchmark model used for the dispatching simulation. In Germany, wind is stronger in the north while sunshine is stronger in the south. Most wind turbines are installed in the northern part, while the majority of PV units are installed in the south [12]. If Germany is to increase its energy share from RES units, it will be facing the problem to transmit the wind and solar power nationwide. This is especially true for the north-south transmission corridors, which constitute more and more a transmission capacity bottleneck [13]. This makes it a fine benchmark case for testing DLR performance.

A. **Topology Design of the Benchmark Model**

The four transmission system operators (TSO) in Germany roughly split Germany’s transmission network into four zones. While having other TSO zones unmodified, the Tennet TSO zone is split into three smaller zones (north, middle and south). In the end, a 6-node benchmark power system is obtained. Fig. 4a shows the designed benchmark power system model, while Fig. 4b shows its simplified 6-node grid topology.

B. **Simulation Parameters**

The generation and load profiles with high time-resolution (15 min.) for 2011 were obtained from the four TSOs in Germany [15]. Profiles from Amprion, TransnetBW, and 50Hertz are mapped to benchmark zones B, C, and E respectively. The load profile from TENNET TransnetBW, and 50Hertz are mapped to benchmark zones A, D, and F according to population proportions, while wind&PV profiles are split according to installed RES capacity proportions. The pumped-hydro storage (PHS) capacity is also determined.

The transmission capacity between two zones is determined by counting the 220kV and 380kV overhead lines connecting them, using the ENTSO-E network map [14]. In our accounting scheme, lines that go across neighboring countries, which are known to be highly relevant for the German transmission system are counted (i.e., 380kV lines from Berlin to Munich go across the Czech Republic), whereas lines that only come from neighboring countries and are known to be less important are not counted (i.e., 380kV lines from Netherlands to Bremen). Min/max line rating values are obtained from full-year simulations.

**TABLE II: Federal States contained in Benchmark Zones.**

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Corresponding Federal States in Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (BREMEN)</td>
<td>Bremen, Niedersachsen, Schleswig-Holstein</td>
</tr>
<tr>
<td>B (COLOGNE)</td>
<td>Nordrhein-Westfalen, Rheinland-Pfalz, Saarland</td>
</tr>
<tr>
<td>C (STUTTGART)</td>
<td>Baden-Württemberg, Bayern (south-eastern part)</td>
</tr>
<tr>
<td>D (MUNICH)</td>
<td>Bayern (all except south-eastern part)</td>
</tr>
<tr>
<td>E (BERLIN)</td>
<td>Berlin, Brandenburg, Mecklenburg-Vorpommern, Hamburg, Sachsen, Sachsen-Anhalt, Thüringen</td>
</tr>
<tr>
<td>F (FRANKFURT)</td>
<td>Hessen</td>
</tr>
</tbody>
</table>

**TABLE III: Comparison of NLR versus DLR (year 2011).**

<table>
<thead>
<tr>
<th>Zone Connection</th>
<th>NLR (MVA)</th>
<th>DLR (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ↔ B</td>
<td>1778</td>
<td>1686</td>
</tr>
<tr>
<td>A ↔ E</td>
<td>1529</td>
<td>1470</td>
</tr>
<tr>
<td>A ↔ F</td>
<td>592</td>
<td>560</td>
</tr>
<tr>
<td>B ↔ C</td>
<td>2340</td>
<td>2029</td>
</tr>
<tr>
<td>B ↔ F</td>
<td>2371</td>
<td>2189</td>
</tr>
<tr>
<td>C ↔ D</td>
<td>592</td>
<td>454</td>
</tr>
<tr>
<td>C ↔ F</td>
<td>889</td>
<td>819</td>
</tr>
<tr>
<td>D ↔ E</td>
<td>1186</td>
<td>1119</td>
</tr>
<tr>
<td>D ↔ F</td>
<td>1825</td>
<td>1692</td>
</tr>
<tr>
<td>E ↔ F</td>
<td>583</td>
<td>555</td>
</tr>
</tbody>
</table>
using the installed PHS capacity in each federal state of Germany [16]. The overall dispatchable generation capacity is set to 78 GW and split according to the population share [12]. Wind velocity and solar radiation is reconstructed from the generation profile, wind angle is assumed fixed at 45°, and ambient temperature is reconstructed from daily maximum and minimum temperature obtained from the German Meteorological Service (Deutscher Wetterdienst (DWD)) [17]. Reconstruction details are given in [11].

V. RESULTS

Simulations are performed with actual or scaled renewable in-feed and load profiles. The rating of the transmission lines is set to be either the NLR or DLR value. The dispatch performance of the power system is compared. As simulations with original in/out-feed profiles did not exhibit curtailment for both NLR and DLR cases, profiles were scaled-up by increasing wind and PV in-feed, while decreasing dispatchable generation capacities. With scaled profiles, adopting DLR allowed 15’209 GWh more energy per year to be transmitted through the network, an increase of 66.7% when compared to the NLR case. Fig. 5 shows how much, as a daily average, DLR surpasses NLR in transmission capacity. Fig. 6 shows a comparison between NLR and DLR for the transmission line between benchmark zones A (BREMEN) and B (COLOGNE).

The NLR case has a load curtailment of 2’729 GWh (0.5% of yearly load demand, counted by summing curtailments in all six zones), while total wind generation curtailment is 1’072 GWh (1.1% of yearly wind in-feed). In the DLR case, load and wind generation curtailments are 2’325 GWh (0.4%) and 46 GWh (0.05%) – a reduction of 15% and 95.7% compared to NLR. No PV curtailment occurs in either case. Fig. 7 shows the curtailment for zone A (BREMEN) in December 2011, for which wind in-feed occurs in either case. Fig. 8 shows the comparison of line loading of zone A (BREMEN) to B (COLOGNE) during this period is shown in Fig. 8.

VI. CONCLUSION

In this paper, a DLR model is established for a 6-node benchmark power system, loosely based on the German power system. The simulation with actual load and generation data shows that no load or generation curtailment happened, which means that with NLR the simplified German power system is currently still capable of integrating all RES in-feed, and there is thus no need for DLR at present. However, the simulation with scaled-up RES generation capacity is not merely a hypothetical scenario but describes a probable future situation in 10–20 years time, especially in light of the unexpectedly rapid deployment of wind and PV units in the past. RES generation development is still growing in Germany. In the future, instead of building new transmission lines, using DLR might solve or at least alleviate upcoming grid issues.

By applying DLR to the grid, more generation can be integrated into the power system, especially wind power in-feed. With proper frameworks and upgrades on the system, it is possible to introduce DLR into power dispatch scheduling or congestion. Accurate and fine-grained measurements of ambient conditions are a critical requirement for the good performance of DLR assessments, as pointed out in [18]. This requires necessary investments in fine meshed sensor networks, communication and robust system models in order to accurately measure (and estimate) local ambient conditions of overhead lines.

Such control-based grid adaptation measures are potentially cheaper than costly hardware-based grid adaptation, i.e. building physical transmission lines.

REFERENCES


Fig. 5: Ratio of average power rating of DLR versus NLR.
Fig. 6: Transmission corridor of zone A (BREMEN) to zone B (COLOGNE): NLR versus DLR (full-year 2011).

Fig. 7: Predictive dispatch and curtailment of in/out-feed curtailments for zone A (BREMEN) in December 2011 using NLR (upper and middle plot) or DLR (lower plot) (red: load curtailment, blue: wind curtailment, orange: PV curtailment).

Fig. 8: Line loading from zone A (BREMEN) to zone B (COLOGNE) in December 2011 (red: DLR, blue: NLR).