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Predictive Power Dispatch for the Integration of High Renewable Shares Incorporating Dynamic Line Rating

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Abstract

In this thesis, the impact of dynamic line rating (DLR) on the power dispatch of power system with high penetration of renewable energy sources generation is assessed. Methods to calculate the DLR and conductor’s surface temperature are presented, the effect of different ambient parameters on the DLR both in steady-state and as well as the transient behaviour is discussed.

A power dispatch simulation with a time step of 15 minutes, using model predictive control and the Power Node modeling framework, of a six-node benchmark system loosely based on the German power system is performed with both nominal line rating (NLR) and DLR, using both actual wind and PV in-feed data and scaled generation data. Besides, methods used to acquire or reconstruct load, generation and ambient condition data used in the simulation are also introduced. The simulation results are compared and analyzed with the objective to assess how much DLR can improve the integration of RES generation, and the necessity to apply DLR to the current power system.
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<td>DLR</td>
<td>Dynamic Line Rating</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>HV</td>
<td>High-voltage</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra High-voltage</td>
</tr>
<tr>
<td>NLR</td>
<td>Nominal Line Rating</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>NTC</td>
<td>Net Transmission Capacity</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>PSH</td>
<td>Pumped-storage Hydroelectricity</td>
</tr>
</tbody>
</table>
List of Symbols

\[\alpha\] temperature coefficient of resistance
\[\alpha_s\] absorptivity of conductor surface
\[\Gamma(t)\] sinusoidal approximation function
\[\delta\] wind attack angle
\[\varepsilon\] emissivity
\[\eta_{\text{gen}}\] efficiency power node generator unit
\[\eta_{\text{load}}\] efficiency power node load unit
\[\theta\] voltage angle
\[\lambda_f\] thermal conductivity of air
\[\mu\] dynamic viscosity of air
\[\xi\] provided/demanded primary/use energy flow
\[\rho\] air density
\[\rho_0\] air density at sea level
\[\rho_r\] relative air density
\[\sigma_B\] Stefan-Boltzmann constant

\[A\] rotor area of wind turbine
\[c\] specific heat capacity of air at constant pressure
\[C\] storage capacity
\[C_p\] coefficient of performance of wind machine
\[D\] external diameter of conductor
\[Gr\] Grashof number
\[h_c\] coefficient of convective heat transfer
\[I_{dc}\] direct current
\[I_{ac}\] alternating current
\[m\] mass per unit length
\[N\] number of steps
\[N_u\] Nusselt number
\[P_c\] convective cooling power
\[P_i\] corona heating power
\[P_J\] Joule heating power
\[P_M\] magnetic heating power
\[P_r\] radiative cooling power
\[P_S\] solar heating power
List of Symbols

$P_w$ evaporative cooling power
$Pr$ Prandtl number
$R_{dc}$ direct current resistance
$R_{ac}$ alternating current resistance
$Re$ Reynolds number
$S$ global solar radiation
$S_{ij}$ transmission capacity between i and j
$T_a$ ambient temperature
$T_{av}$ average conductor temperature
$T_{max}$ daily maximum temperature
$T_{min}$ daily minimum temperature
$T_s$ conductor surface temperature
$u_{gen}$ real generator power grid injection
$u_{load}$ real load power grid injection
$v_f$ kinematic viscosity
$V$ wind velocity
$w$ waste term
$x_{km}$ reactance of transmission line between node k and m
$y$ height above sea level

$B$ nodal admittance matrix
$P$ vector of net injections
Chapter 1

Introduction

1.1 Matching Transmission to RES Generations

Due to the scarcity of fossil fuels, people nowadays are committed to improving the share of renewable energy sources (RES) in the electric power industry, especially the new renewable energy sources, like wind and solar. For example, in Germany, the RES share of electricity generation has increased from 4.7% in the year 1998 to 17% in the year 2010, and for the RES electricity generation in the year 2010, 36.5% of it is wind energy, and for photovoltaic (PV) the percentage is 11.3% [1]. However, there are difficulties for further increasing RES generations, due to the limitation of the existing power system transmission capacity, especially in the countries where RES are located far from loads. For example, apart from Germany, in China electricity consumption is higher in the east where population is denser, while most of its RES potential is in the west. In which case ultra high-voltage (UHV) lines are being built connecting west and east [2][3].

One significant characteristic of electricity, which distinguishes it from other forms of energy such as coal or oil, is that the electric power cannot be easily stored and has to be transmitted simultaneously with the generation [4], therefore transmission lines with matchable capacity need to be installed together with a power plant. In other words, if the transmission capacity installed is not sufficient compared to its full production capacity, the generator has to operate at a lower rating to match the transmission, which means part of the power plant’s production potential is wasted. So, if new generation units are to be installed, a supporting integration network and probably new high-voltage transmission lines may have to be build as well. However, building new transmission lines may be difficult and economically costly, especially when crossing densely populated areas, where people are against building new lines, which had become a factor affecting the integration of RES generations, especially in countries where wind and solar resources are unevenly distributed and an expansion of the power system is
CHAPTER 1. INTRODUCTION

Another problem appears when deciding how much transmission capacity should be installed for wind and PV generation, due to the reason that this generation will vary with weather condition, i.e., wind speed and solar radiation, and will not operate at a fixed rate. Although for most wind turbines and PV cells there exists a maximum production rating [6, p.354-362, 460-468], studies show that during most time of the year wind speed and solar radiation are more likely to stay at a medium level value [7][8]. For example, a typical wind turbine may have a rated speed of 15m/s [9], but for most of the time in a year, the speed of wind will probably vary between between 3m/s to 12m/s. Therefore, a trade-off will be facing when deciding the transmission capacity installed to wind turbines and PV cells, which is whether to install the grid capacity matching the full production capacity, corresponding to higher building cost and higher production ability, or to choose a lower capacity, corresponding to lower building cost and lower production. In addition, due to the stochastic behavior of wind, wind generation has to be forecasted. Although forecast error nowadays usually can be kept below 5% to the actual value, still, maximum error can reach up to over 40% in a few selected cases [10]. So if wind farms are sharing HV transmission lines with other power plants, it may become a problem to balance the total generation such that it stays below the rating of the HV lines.

1.2 Alleviating Transmission Congestions using DLR

A solution to the transmission problem described in the previous section is to improve the utilization of the existing power grids by adopting the dynamic line rating (DLR) to the overhead lines in the power system. The rating of a transmission line is its maximum power transmission capacity, therefore DLR refers to that the rating of the transmission line is not a fixed value and will inevitably vary with weather condition [11]. Nominal line rating (NLR) is defined in a standard operating condition, in which the potential carrying capacity due to the dynamic thermal behavior of the conductor is neglected. For example, higher wind speed will result in increase of both the line rating and wind power generation, in which case fewer transmission lines may be needed to transmit the excess generation compared with NLR. A case study showed that applying DLR to the 132kV line between Skegness and Boston enabled 20% to 50% more wind generation to be connected and integrated to the grid, which is a cost effective solution with regards to the inherent constraint of NLR [12].

To make a further research on how much can DLR reinforce the existing power system, the idea of this project is to study what improvement can DLR bring to power dispatching once it is applied to HV transmission lines.
This project will focus on the following:

\( a \) Derive algorithm for DLR model based on current research results on DLR, including steady-state line rating and conductor surface temperature calculation in both steady-state and transient state.

\( b \) Research how different ambient parameters affect DLR.

\( c \) Reconstruction of ambient conditions.

\( d \) Establish a benchmark power system model with high renewable shares and test its improvement on power transmission performance once DLR is applied.

1.3 Structure of this Report

The first section of Chapter 2 will introduce the basic model for DLR modeling. Then method of calculating DLR and surface temperature will be presented. The last section of Chapter 2 will discuss the sensitivity of ambient parameters on the DLR model and calculation method.

Chapter 3 will present how the benchmark model is chosen and established, and also how wind speed, solar radiation and ambient temperature data is reconstructed, followed by a simulation and analysis of DLR for one exemplary day.

Chapter 4 will introduce the power flow calculation method used in the benchmark model. Chapter 5 is the performance analysis of DLR when applied to the benchmark model. Chapter 6 covers the discussion and conclusion of this project.
Chapter 2

Dynamic Line Rating Modeling

A transmission line is capable of carrying current and transmits power in a power system. Therefore, there exists a maximum allowable conductor temperature under standardised worst-case conditions that can keep the transmission line from suffering excessive line sag or loss of conductor strength, and the current carried by the transmission line that results in this temperature is the NLR of the conductor [11].

DLR refers to the current rating of the transmission line under a certain ambient condition. A mathematical model exists to determine the specific DLR by taking the ambient condition parameters (wind velocity, wind attacking angle, global solar radiation and ambient temperature), as well as the physical parameters of the conductor (diameter, conductor type, material...) into account. This chapter is to establish the relationship between the DLR and factors mentioned above. As a result, the steady-state and transient state mathematical model will be derived.

2.1 Steady-state Heating Balance [13]

This section is to deliver the steady-state model of the DLR according to environmental factors and coefficients from conductor’s structure and thermal behavior. In the steady-state, the heat supplied to the conductor is balanced by the heat dissipated, which means no heat energy is stored in the conductor. A heat balance equation can thus be written as

\[
\text{Heat gain} = \text{heat loss}
\]

\[
P_J + P_M + P_S + P_i = P_c + P_r + P_w, \tag{2.1.1}
\]
where

\[ P_J = \text{Joule Heating} \]
\[ P_M = \text{magnetic heating} \]
\[ P_S = \text{solar heating} \]
\[ P_i = \text{corona heating} \]
\[ P_c = \text{convective cooling} \]
\[ P_r = \text{radiative cooling} \]
\[ P_w = \text{evaporative cooling}. \]

Note that \( P_M, P_i \) and \( P_w \) can be neglected according to [13]. So the equation can be simplified to

\[ P_J + P_S = P_c + P_r. \] (2.1.2)

### 2.1.1 Joule Heating

Joule Heating refers to the heating of the conductor due to the resistance of the conductor. The calculation of Joule Heating varies with the type of conductor. In this model, the calculation for steel cored conductors is considered (a common approach which is widely used).

The Joule heat gain is calculated by

\[ P_J = I_{dc}^2 R_{dc}[1 + \alpha(T_{av} - 20)], \] (2.1.3)

where \( R_{dc} \) is the DC resistance, and \( \alpha \) is the temperature coefficient of the resistance. The power input must be the same for both AC and DC for the same average temperature of the conductor. Thus

\[ I_{dc}^2 R_{dc} = I_{ac}^2 R_{ac}. \] (2.1.4)

For aluminium-steel conductors with three layers of aluminium wires, \( R_{ac}/R_{dc} = 1.0123 + 2.36 \cdot 10^{-5}I_{ac} \), therefore

\[ I_{ac} = \frac{I_{dc}}{\sqrt{1.0123 + 2.36 \cdot 10^{-5}I_{dc}}} \] (2.1.5)

\[ I_{dc} = I_{ac}\sqrt{1.0123 + 2.36 \cdot 10^{-5}I_{ac}}. \] (2.1.6)

### 2.1.2 Solar Heating

Solar Heating is the heating due to solar radiation over the conductor. The solar heat gain \( P_S \) depends on the diameter of the conductor, the absorptivity \( \alpha_s \) of the surface of the conductor and the global solar radiation. The solar heating equation can be written as
$P_S = \alpha_s S D,$  \hspace{1cm} (2.1.7)

where

\begin{align*}
\alpha_s & = \text{absorptivity of conductor surface} \\
S & = \text{global solar radiation} \\
D & = \text{external diameter of conductor}.
\end{align*}

The value of $\alpha_s$ varies from 0.23 for a bright stranded aluminium conductor to 0.95 for a weathered conductor in an industrial environment. For most purposes a value of 0.5 may be used for $\alpha_s$.

### 2.1.3 Convective Cooling

The heated surface of the conductor heats up air adjacent to it, therefore the conductor surface can be cooled down due to natural convection ($V = 0$), or forced convection ($V \neq 0$).

The following parameters are used in the calculation of convective cooling:

\begin{enumerate}
\item[a)] The Nusselt number, $N_u = h c D / \lambda_f$, where $h c$ is the coefficient of convective heat transfer (W/m$^2$K) and $\lambda_f$ is the thermal conductivity of air (W/mK).
\item[b)] The Reynolds number, $Re = \rho_r V D / v_f$, where $V$ is the wind velocity (m/s), $v_f$ is the kinematic viscosity (m$^2$/s) and $\rho_r$ is the relative air density ($\rho_r = \rho / \rho_0$, where $\rho$ is the air density at the altitude in question and $\rho_0$ is the air density at sea level).
\item[c)] The Grashof number, $Gr = D^3 (T_s - T_a) g / (T_f + 273) v_f^2$, where $T_s$ is the conductor surface temperature and $T_a$ is the ambient temperature.
\item[d)] The Prandtl number, $Pr = c \mu / \lambda_f$, where $c$ is the specific heat capacity of air at constant pressure (J/kgK) and $\mu$ is the dynamic viscosity of air (kg/ms).
\end{enumerate}

The empirical equations for calculating the above variables are:

\begin{align*}
   v_f &= 1.32 \cdot 10^{-5} + 9.5 \cdot 10^{-8} T_f \\
   \lambda_f &= 2.42 \cdot 10^{-2} + 7.2 \cdot 10^{-5} T_f \\
   P_r &= 0.715 - 2.5 \cdot 10^{-4} T_f \\
   g &= 9.807 (m/s^2) \\
   T_f &= 0.5 (T_s + T_a) \\
   \rho_r &= \exp (-1.16 \cdot 10^{-4} y), \text{ where } y \text{ is the height above sea level (m)}.
\end{align*}
The convective heat loss is given as

$$P_c = \pi \lambda f (T_s - T_a) N_u.$$ (2.1.8)

As shown in Eq. (2.1.8), the convective cooling power $P_c$ is proportional to the Nusselt number $N_u$. Therefore, the method used to determine the convective cooling power is to compare $N_u$ from natural convection ($V = 0$) and the forced convection ($V \neq 0$), and chose the $N_u$ with higher value for calculating $P_c$.

In the normal operating range of film temperature $T_f = 0.5(T_s + T_a)$, the Nusselt number for forced convective cooling with perpendicular wind direction can be represented by

$$N_{u90} = B_1 (Re)^n,$$ (2.1.9)

where $B_1$ and $n$ are constants depending on the Reynolds number and conductor surface roughness $R_f = d/[2(D - d)]$ ($d$ is the outer layer wire diameter), see Table B.1.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$Re$ from</th>
<th>$Re$ to</th>
<th>$B_1$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stranded all surfaces</td>
<td>$10^2$</td>
<td>$2.65 \cdot 10^4$</td>
<td>0.641</td>
<td>0.471</td>
</tr>
<tr>
<td>Stranded $R_f \leq 0.05$</td>
<td>$&gt; 2.65 \cdot 10^4$</td>
<td>$5 \cdot 10^4$</td>
<td>0.178</td>
<td>0.633</td>
</tr>
<tr>
<td>Stranded $R_f &gt; 0.05$</td>
<td>$&gt; 2.65 \cdot 10^4$</td>
<td>$5 \cdot 10^4$</td>
<td>0.048</td>
<td>0.800</td>
</tr>
</tbody>
</table>

Table 2.1: Constants for calculation of forced convective heat transfer from conductors with steady crossflow of air (this table is a reproduction of Table I from [13], page 6).

The Nusselt number of forced convective cooling also varies with the wind direction (angle of attack $\delta$), as shown in 2.1.10:

$$N_{u\delta} = N_{u90} [A_1 + B_2 (\sin \delta)^m],$$ (2.1.10)

where

- $A_1 = 0.42$, $B_2 = 0.68$ and $m_f = 1.08$ for $0^\circ < \delta < 24^\circ$
- $A_1 = 0.42$, $B_2 = 0.58$ and $m_f = 0.90$ for $24^\circ < \delta < 90^\circ$

$N_{u90}$ is the Nusselt number at $\delta = 90^\circ$, as calculated in (2.1.9).

When the wind blows parallel to the conductor the Nusselt number with $\delta = 0^\circ$ drops to around $0.42 \cdot N_{u90}$. This is due to swirling of the flow due to the stranding of the conductor.
CHAPTER 2. DYNAMIC LINE RATING MODELING

With low wind velocity \((V < 0.5 m/s)\) the effect of wind direction is small and therefore the Nusselt number can be represented by \(0.55 \cdot N_{u90}\).

Therefore, the Nusselt number for the forced convective cooling can be represented as

\[
N_{u,forced} = \begin{cases} 
    \text{maximum}(N_{u,\Delta \theta}, 0.42N_{u90}) & \text{for } \delta \geq 0.5 m/s \\
    0.55N_{u90} & \text{for } \delta < 0.5 m/s 
\end{cases}.
\]  

(2.1.11)

The Nusselt number for natural convective cooling is as following

\[
N_{u,nat} = A_2(Gr \cdot Pr)^{m_2}.
\]  

(2.1.12)

Value for constants \(A_2\) and \(m_2\) depends on \(Ge \cdot Pr\), see Table 2.1.3:

<table>
<thead>
<tr>
<th>Ge \cdot Pr from \text{ to}</th>
<th>A_2</th>
<th>m_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^2) (10^4)</td>
<td>0.850</td>
<td>0.188</td>
</tr>
<tr>
<td>(10^4) (10^6)</td>
<td>0.480</td>
<td>0.250</td>
</tr>
</tbody>
</table>

Table 2.2: Constants for calculation of natural convective heat transfer from conductors in air (this table is a reproduction of Table II from [13], page 7).

Summing the discussion above, the Nusselt number can be represented as:

\[
N_u = \text{maximum}(N_{u,forced}, N_{u,nat})
\]  

(2.1.13)

And the convective cooling power is calculated in (2.1.8).

2.1.4 Radiative Cooling

The calculation for radiative cooling power is as following

\[
P_r = \pi D \varepsilon \sigma_B [(T_s + 273)^4 - (T_a + 273)^4],
\]  

(2.1.14)

where

\(\varepsilon\) is emissivity (suggest value 0.5)
\(\sigma_B\) is the Stefan-Boltzmann constant
\(T_s\) is the ambient temperature
\(T_a\) is the conductor surface temperature.
2.2 Calculation of Current Rating in Steady-State Conditions

The goal of this section is to develop a function that calculates the steady-state rating. The top level of the function of the steady-state model is as shown in Eq. (2.2.1).

\[ \text{SteadyState DLR} = f_{\text{SSDLR}}(V, \delta, S, T_a, T_s, \text{conductor's coefficients}) \]  

(2.2.1)

where \( V \) is wind velocity, \( \delta \) is shooting angle of the wind, \( S \) is global solar radiation, \( T_a \) is ambient temperature, \( T_s \) is conductor’s surface temperature, and conductor’s data is coefficients of the conductor.

As discussed in Section 2.1, the heat balance equation is shown as Eq. (2.1.2). To calculate the current rating, which is the maximum allowable current, corresponds to the maximum allowable conductors surface temperature. Eq. (2.1.2) can be written as

\[ P_J = P_c + P_r - P_S, \]  

(2.2.2)

substitute Eq. (2.1.3) in to Eq. (2.2.2) leads to

\[ I_{dc}^2 R_{dc}[1 + \alpha(T_{av} - 20)] = P_c + P_r = P_S, \]  

(2.2.3)

and finally

\[ I_{dc} = \sqrt{\frac{P_c + P_r - P_S}{R_{dc}[1 + \alpha(T_{av} - 20)]}}, \]  

(2.2.4)

As for the conversion between AC and DC current, see Section 2.1.1. For the calculation of \( P_c, P_r \) and \( P_S \), see Section 2.1.

2.3 Calculation of Conductor Temperature in Steady-State Conditions

In this section, a numerical method for calculating the conductor’s steady state surface temperature at a constant current \( I \) is presented. The top level can be described as

\[ \text{SteadyState T} = f_{\text{SSTs}}(V, \delta, S, T_a, I, \text{conductor's data}), \]  

(2.3.1)

where \( V \) is wind velocity, \( \delta \) is shooting angle of the wind, \( S \) is global solar radiation, \( T_a \) is ambient temperature, and conductor’s data is coefficients of the conductor.
To apply numerical method to calculate the steady-state surface temperature, rewrite eq. (2.1.2) as
\[ P_J + P_S - P_c - P_r = 0, \]  
(2.3.2)

This should be satisfied for the correct conductor’s surface temperature. Therefore, the numerical method algorithm for calculating the surface temperature is as described in Fig. 2.1.

Figure 2.1: Numerical method for calculating steady-state surface temperature (resulting error \( \leq 0.1^\circ C \)).

Note that in this algorithm, \( P_S \) is ignored when calculating the derivative \( dP_S/dT_S \) since \( P_S \) is independent of \( T_S \) (see Section 2.1.2) and therefore \( dP_S/dT_S = 0 \).

Technically, the initial guess of \( T_S \) can be any value, however, it makes more sense to choose a value between the ambient temperature \( T_a \) and the maximum allowable conductor’s surface temperature \( T_{S,max} \). Simulations show that with \( |D| < 0.1 \) as the exit condition, and choosing \( T_S = 50 \), the
algorithm can be finished within four loops for current ranging from 0 A to 1000 A.

2.4 Transient Conductor Temperature

The current flows through the transmission line will not be a constant value and will vary with power in-feed and consumption. However, when the magnitude of current changes, the temperature of the conductor will not immediately change into the steady-state value, but will enter a transient due to imbalanced thermal power. The surface temperature of the conductor will gradually approach the steady-state temperature. The transient model is to describe the temperature variation of the conductor versus time when the current in the conductor encountered a step change, either to a larger value (a heating process) or a lower value (a cooling process). This can be used to determine, or forecast, the surface temperature of the conductor, to be used in conjunction with the DLR model, to ensure that the actual conductor surface temperature will not exceed the limitation.

For example, the maximum surface temperature for the conductor used in a transmission line is $85^\circ C$, at 20:00 - 21:00h of that day, the DLR of this transmission line shows that during this period it is capable of carrying 600 A of current at maximum (which means the static surface temperature for this conductor at the ambient condition is $85^\circ C$), however, this transmission line was carrying 700 A of current before 20:00h, so due to the transient temperature variation, the actual temperature of this transmission line will probably be higher than $85^\circ C$, if it is used to carry 600 A of current, and thus the transmission line may be damaged. On the contrary, if this line was carrying a much smaller value of current, say 200 A, then it might be able to transmit more than 600 A during 20:00 to 21:00. So the transient temperature calculation will both protect the transmission line, and to improve the efficiency in usage. Fig. 2.2 shows a comparison between the steady-state calculation and transient-state calculation for conductor surface temperature in one hour, when the current carried by the conductor is measured in a time step of 15 minutes.
The differential equation for transient is as following [13]

\[ mc \frac{dT_{av}}{dt} = P_J + P_S - P_r - P_c, \]  

(2.4.1)

where

\begin{align*}
P_J & = \text{Joule Heating} \\
P_S & = \text{solar heating} \\
P_c & = \text{convective cooling} \\
P_r & = \text{radiative cooling}
\end{align*}

Note that \( P_M, P_t \) and \( P_w \) is neglected as described in Section 2.1.

In the case of a steel-cored conductor one has

\[ mc = m_ac_a + m_sc_s, \]

(2.4.2)

where the subscript \( a \) and \( s \) refer to the non-ferrous and ferrous sections, respectively.
The differential equation Eq. (2.4.1) can be understood as that once the heating balance in the steady-state of the conductor is broken, the excessive power will be absorbed by the conductor and thus the temperature of the conductor will change. In order to calculate how the surface temperature behaves in the transient, Eq. (2.4.1) is integrated

\[
\int \frac{mc}{P_J + P_S - P_r - P_c} dT = \int dt. \tag{2.4.3}
\]

Figure 2.3: Discrete integration method for calculating unsteady-state conductor surface temperature.

However, as described in Section 2.1, except \( P_S \), the rest of thermal powers are all dependent on the surface temperature, especially in the case of convective cooling \( P_c \) that the function is quite complicated due to different cases and can be very difficult to solve in a differential equation. Thus, the method used in this project is using discrete integration

\[
dT = \frac{P_J + P_S - P_r - P_c}{mc} dt. \tag{2.4.4}
\]
In this method, the change of the surface temperature over a time-step is calculated by the time step multiplying \( \frac{P_J + P_S - P_r - P_c}{mc} \), with the assumption of the ambient condition being constant during the calculation. In this case, all thermal power values are assumed to be constant during one time step, and will be updated before entering the next step. The algorithm is as showed in Fig. 2.3.

So one can clearly see that the smaller the time step is set, the smaller the resulting error will get. But the cost is the amount of calculation will increase, since the number of iteration used in the algorithm is equal to \( \frac{\text{duration of simulation}}{\text{simulation time-step}} \). In this project, the full-year simulation of a 6-node power system will result in a huge amount of calculation, therefore, as a trade-off between accuracy and efficiency, the time step used is chosen to be 60 seconds, in the simulation testing the error caused by this step is fairly small when the surface temperature is calculated in a time step of 15 minutes.

### 2.5 Sensitivity Analysis of Model Parameters

In this section, the previously established model for steady-state current rating and unsteady-state conductor’s surface temperature variation will be simulated to exam how a single parameter can effect the result. The simulation in this section is performed in Matlab.

#### 2.5.1 Steady-state Current Rating

Four ambient parameters are used in calculating the steady-state current rating: wind velocity \((V)\), attack angle of the wind \((\delta)\), global solar radiation \((S)\) and ambient temperature \((T_a)\). In the simulation, one of these four parameters will be varied while the rest will be held as constant. Also, in the simulation, the conductor’s surface temperature is set to the maximum allowable temperature \((85^\circ C)\), which means the conductor is always operating at maximum carrying capacity. The conductor type used in the simulation is 428-A1/S1A-54/7 'Zebra'.

As shown in Fig. 2.4, compared to other parameters, wind speed \((V)\) has a much larger effect on the current rating. In the wind velocity simulation, the current rating increased from 700A at 0m/s wind speed to around 3300A at 25m/s, an increase of 371%. Besides, the wind attack angle \((\delta)\) and the ambient temperature \((T_a)\) also have quite obvious effect on the rating, with an increase of 35% and an decrease of 41%, respectively. The global solar radiation \((S)\) has a quite small effect on the rating, and in the simulation the current rating only dropped 5% of it’s initial value.

In Section 2.1.2 the calculation of \(P_S\) shows that the solar radiative heating only depends on the global solar radiation \(S\). Therefore, according to Eq. (2.2.4), \(P_S\) brings a fixed contribution to \(I_{dc}^2\), so when the effect of \(P_J\) and \(P_c\) (correspond to \(V\), \(\delta\) and \(T_a\)) become stronger (increase of \(V\) or
CHAPTER 2. DYNAMIC LINE RATING MODELING

Figure 2.4: Current rating versus ambient temperature (default ambient condition if not specified: \(V = 2\, \text{m/s}, \delta = 45^\circ, S = 1000\, \text{W/m}^2, T_a = 20^\circ\text{C}\)).

\(\delta\), or decrease of \(T_a\)), the effect of solar radiation will become even weaker. A further simulation showed that, at high wind velocity (\(V = 25\, \text{m/s}\)), variation of \(S\) from 0 to 1000 W/m\(^2\) will only cause the current rating drop to less than 0.9% of its initial value. However, since the calculation of \(P_J\) involves \(V\), \(\delta\) and \(T_a\), the mixed effect of these variables are shown in Fig. 2.5.

As showed in Fig. 2.5, for wind speed (\(V\)), wind attack angle (\(\delta\)) and ambient temperature (\(T_a\)), the absolute effect (rise of current rating value) of a single parameter will be amplified if the effect of one of the other two parameters becomes larger (increase of \(V\) or \(\delta\), or decrease of \(T_a\)). i.e., in Fig. 2.5, the rise of \(V\) from 0 to 25 m/s brings a rise of current rating of about 2kA at \(T_a = 40^\circ\text{C}\), at \(T_a = -20^\circ\text{C}\) the rise is about 3kA.

However, what need to be noted here is that the rating of the transmission line is also limited by the rating of the electrical equipment (i.e., transformer) [12]. And therefore, there will exist a fixed maximum current
Figure 2.5: Current rating versus wind attack angle and ambient temperature ($V = 5 \text{m/s}, \delta = 0 \text{ to } 90^\circ, S = 1000 \text{W/m}^2, T_a = -20 \text{ to } 40^\circ C$).

rating due to these other "bottlenecks" along the transmission path, and
the performance of the DLR may be greatly limited.

2.5.2 Transient-state Surface Temperature

This section is to exam how fast the temperature increases, or decrease,
during the transient of the conductor. The first task is to see how the
conductor surface temperature will change, if there is a step change in the current. The initial temperature of the conductor is set to a fixed value (or a fixed initial current before the step change, if the transmission line is operating under steady-state conditions) and vary the current carried by the conductor after the step change.

Figure 2.6: Transient conductor surface temperature variation with initial surface temperature = 55°C (ambient condition: \( V = 2 \text{ m/s}, \delta = 45^\circ, S = 980 \text{ W/m}^2, T_a = 40^\circ\text{C} \)).

Using the steady-state model, the current corresponding to a surface temperature of 55°C is about 550 A (with ambient condition defined in Fig. 2.6). So from the figure we can see that the smaller the step change of the current, the smaller the resulting change in the conductor surface temperature. Furthermore, the temperature will reach the steady-state value faster.
Figure 2.7: Upper plot: conductor cooling from 70°C to ambient temperature 40°C with varies wind speed; Middle plot: conductor cooling from 70°C to varies ambient temperature; Lower plot: conductor cooling from 70°C to ambient temperature 70°C with varying solar radiation (ambient condition except the varying parameter: $V = 2m/s$, $\delta = 45^\circ$, $S = 980W/m^2$, $T_a = 40^\circ C$).
The next is to see how wind velocity, ambient temperature and solar radiation affect the transient temperature behavior of the conductor (the case of varying wind attack angle is not shown since it is similar as changing the wind velocity). Fig. 2.7 shows the cooling process of the conductor from $70^\circ C$ to ambient temperature, which means no current flows through the conductor. In the case of varying wind speed, the asymptotic temperature of the conductor is the same for different wind speed because of zero conductor current, and we can clearly see that cooling from the same initial temperature to the same asymptotic temperature, the wind velocity can actually affect the rate of change of the surface temperature (for $V = 5m/s$, it takes about 15 minutes for the conductor to cool down, but for $V = 0m/s$, the same process takes more than 60 minutes), a higher wind speed will result in faster cooling, which is the same as in our normal physical sense.

However, ambient temperature and solar radiation work in a different way. The asymptotic temperature varies with the ambient temperature, or solar radiation, but the rate of changing of the conductor surface temperature in all cases are the same. Again from the Fig. 2.7, it is shown that in all cases, both the varying ambient temperature and the varying solar radiation, the conductor reached its asymptotic surface temperature at about 30 minutes, which is actually the same as in the first plot for wind speed equals to $2m/s$. This wind speed is also used in the ambient temperature and solar radiation simulation.
Figure 2.8: Conductor heating from 0A to 800A with varying wind speed (Ambient condition: $\delta = 45^\circ$, $S = 0W/m^2$, $T_a = 40^\circ C$).

One more case to be discussed is the heating of the conductor with varying wind speed. In Fig. 2.8, a heating process is shown for a current step change from 0 A to 800 A with varying wind speed. In this case, the asymptotic temperature of the conductor is no longer the same, and the higher the wind velocity, the smaller the change of the conductor surface temperature. So, at lower wind speed the conductor does heat much faster, but the final temperature is also much higher, as a result, in the case of highest wind speed, the conductor will first reach its steady-state value, while for zero wind speed, the heating process takes the longest time.

So as a conclusion, all of these parameters (current, wind speed and attack angle, ambient temperature and solar radiation) can have an effect on the steady-state, or the asymptotic temperature. But only the current and the wind speed will affect the rate of changing the DLR. With smaller step change of the current, or stronger wind speed, the conductor can reach its asymptotic temperature faster. This would be slower for a larger current step change or a lower wind speed.
2.6 Correlation of DLR with Generation and Load Volatility

The analysis on steady-state DLR done in the previous section shows that DLR is in positive correlation with wind speed, and in negative correlation with solar radiation and ambient temperature rise. However, volatility in these ambient parameters will also have effects on the electricity generation and consumption. So this indirectly creates a relationship between DLR and electricity transport volatility, which is to be discussed in this section.

A linearized model which relates DLR with generation and consumption is presented in Table 2.3, which is by fitting a first-order curve to the steady-state rating analysis in the previous section (wind angle is assumed to be $45^\circ$ and is not included in this table). From the percentage result we can see that wind has 40 times stronger influence than ambient temperature on DLR ($\frac{4.0\%}{0.1\%} = 40$), and about 286 times compared to solar insolation ($\frac{4.0\%}{0.014\%} \approx 286$).

<table>
<thead>
<tr>
<th>Situation</th>
<th>DLR (Current Rating)</th>
<th>DLR (Ratio to nominal rating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Increase (heating due to temperature decrease)</td>
<td>Slightly Increase</td>
<td>0.14% per 1°C drop</td>
</tr>
<tr>
<td></td>
<td>1.1A per 1°C drop</td>
<td>$\approx \frac{0.1% \Delta DLR}{1% \Delta T}$</td>
</tr>
<tr>
<td></td>
<td>(0.24MW at 220kV)</td>
<td></td>
</tr>
<tr>
<td>Wind In-feed Increase</td>
<td>Strongly Increase</td>
<td>11.1% per 1m/s drop</td>
</tr>
<tr>
<td></td>
<td>87.7A per 1m/s increase</td>
<td>$\approx \frac{4% \Delta DLR}{1% \Delta V_{wind}}$</td>
</tr>
<tr>
<td></td>
<td>(19MW at 220kV)</td>
<td></td>
</tr>
<tr>
<td>PV In-feed Increase</td>
<td>Very Slightly Decrease</td>
<td>0.14% per 100W/m² increase</td>
</tr>
<tr>
<td></td>
<td>-6.6A per 100W/m² increase</td>
<td>$\approx \frac{0.014% \Delta DLR}{1% \Delta S}$</td>
</tr>
<tr>
<td></td>
<td>(-1.4MW at 220kV)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Linearized DLR analysis ($\Delta DLR$ in % as a function of % change in reference parameter. temperature bound: $-20^\circ$C to $+40^\circ$C, wind speed bound: 0m/s to 30m/s, solar insolation bound: 0W/m² to 1000W/m²).

In Europe, electricity is used for heating during winter and therefore temperature drop will result in increase in load, while DLR also increases with temperature drop, and there may be possibility to combine these two factors to optimize power dispatch in the power system. And also for the case of wind generation, which also increases with wind speed. Two case
examples are given in the following to offer a more practical illustration.

### 2.6.1 Case Example: Anholt Offshore Wind Farm

Anholt Offshore Wind Farm is a wind farm under construction in Denmark [14]. This wind farm has generation capacity of 400MW, and the turbine installed is SWP-3.6-120 from Siemens, which has a cut-in wind speed of 3-5 m/s and rated speed of 12-13m/s[15]. Using these data, a plot that shows the generation curve of the wind farm as well as both the NLR (170MW) and DLR for a 220kV steel-cored transmission line:

![Anholt offshore wind farm](image)
From the plot it is clearly shown that using NLR, one 220kV line will not be able to transmit all the power generated by the Anholt farm. In fact, with some simple calculation (400 MW/170 MW $\approx$ 3) it can be shown that three 220kV lines are required. However, if we model the 220kV line again using DLR, the result is much different, in which case since the DLR increases with wind speed, only one 220kV is enough to carry the full production of the wind farm.

### 2.6.2 Case Example: Winter Heating in France

An analysis of the French transmission system operator RTE has shown that the electricity load in France increases by 2300 MW per degree drop in temperature during the winter due to heating [16]. Therefore, a scenario can be assumed in which France has an unexpected temperature drop in a winter night and needs to import electricity from Germany and Switzerland. The sum of the Net Transfer Capacities (NTC) values from Germany to France and from Switzerland to France in Winter 2010 - 2011 is 4100 MW [17]. Which can be set as the nominal rating of the import lines. With
this nominal rating, the DLR can also be constructed. Assuming that these cross-border grids are all unloaded before the event (import power due to temperature drop), and assuming that the temperature starts to drop from 0°C, the following plot is obtained.

![Increase in Load vs DLR](image)

*Figure 2.11: DLR and net load increase of heating in France (own illustration).*

In Fig. 2.11 it is shown that in the condition of no wind, the DLR is only slightly larger than the nominal rating, in which case France is only able to satisfy its load increase for about a 2°C drop. The difference is mainly due to the absence of solar radiation since this DLR is calculated at night. And the drop in temperature did not create a large increase in the DLR. However, if this cold winter night comes with a strong wind, which is at least not unlikely, the result will be very different. Simulation shown that with a wind speed of 5m/s, the DLR roughly doubles to more than 1GW, with which France will be able to import twice as much power, and can satisfy a temperature drop of 4°C.
Chapter 3

Application on Benchmark Power System

To test how much the DLR can do in the power dispatch of a typical power system, a benchmark model is presented. The idea of the benchmark model is to design a power system covering a certain area, under an ambient condition varying with time and location, and to embed the DLR into the rating of the transmission lines of the system. By comparing the power dispatching of the fix-rated benchmark model and the DLR benchmark model, the effect of the DLR on the power system can be assessed.

However, since a real power system is very complicated, to reduce the complicity, the idea is to simplify a big power system into certain zones, calculate the transmission capacity between zones, which in the case of this project is how many high-voltage overhead lines are installed between two zones, and set this value to the inter-zone transmission capacity in the benchmark model. If neglecting the power system network within a zone, the benchmark model can then be represented as a connection of nodes, each with individual power generation, load and ambient condition.

Germany is chosen as the prototype of the benchmark model, since we want to see especially how DLR can improve the integration and transmission of wind and PV generation. Due to the reason that in Germany wind is stronger in the north while sun light is stronger in the south, most wind turbines are installed in the northern part, and the majority of the PV units are installed in the south [5]. So if Germany is to improve its share of RES, it will be facing the problem to transmit the wind and solar power nationwide, which makes it a fine model to test the performance of DLR.

3.1 Presentation of the Benchmark system

Germany has four transmission system operators (TSO), which roughly split Germany’s transmission network into four zones (Fig. 3.1). On the border
of the TSO zones there are usually only high-voltage overhead lines and no distribution network. Therefore the TSO zone is very suitable to be used as a base of designing zones for the benchmark system. However, since using the Tennet TSO zone is quite large in the north-south direction, use a single node to represent this zone may not be suitable in this project, especially to research how the wind generation in the north is transmitted to the load in the south. As a solution, the Tennet TSO zone is split into three zones, in the order of north, middle and south. And the border for these three zones are made where high-voltage overhead lines cross and no distribution network exists.

Based on the assumption that the power in-feed and consumption over one zone can be simplified into a single node (city), the weather condition over one zone is the same and can be represented by the weather data of this city. In the benchmark system, Germany’s transmission network is split into six zones (Fig. 3.2) and therefore simplified into six nodes, represented by six cities: Bremen (A), Cologne (B), Stuttgart (C), Munich (D), Berlin (E) and Frankfurt (F). The city code for these cities in the Federal Ministry of Transport, Building and Urban Development [23] (from which the temperature data is obtained) is 691 (Bremen), 2667 (Cologne), 4931 (Stuttgart), 1262 (Munich), 430 (Berlin) and 1420 (Frankfurt).
The next step for establishing the benchmark model is to quantify the transmission rating between the nodes. In the case of this project, one needs to count how many overhead lines are used to connect different zones and the type of conductor used in these overhead lines. For counting of overhead line capacity we used the ENTSO-E network map, on which 220kV lines are represented by green lines and 380kV lines are represented by red lines. (Note that a single transmission line is displayed in different format on this map, which represents a differing number of overhead lines.) In the mode, lines that go across neighboring countries are counted (i.e., 380kV lines from Berlin to Munich go across Czech Republic), but lines that come from neighboring counties are not counted (i.e., 380kV lines from Netherlands to Bremen).

Figure 3.3 shows the established benchmark model for the German network. By assuming that the conductor type used for the 220kV line and
380kV line is the same, the transmission capacity (power rating) between two nodes i and j is:

\[ S_{ij} = DLR_{ij} \cdot (220kV \cdot N_{220kV,ij} + 380kV \cdot N_{380kV,ij}) \] (3.1.1)

where \( N \) presents the number of lines at either 220kV or 380kV voltage level, respectively.

### 3.1.1 Nominal Line Rating in the Benchmark Model

To establish a comparison with the DLR model, NLR in Germany is also needed. However, HV transmission rating in Germany is not obtainable and therefore this value is determined by referring to Germany’s net transmission capacity (NTC) to its neighboring countries, which is available in
However, since these NTC values are not only due to line transmission capacities but are also taking into account other factors such as dispatch capacities, the median of Germany’s cross-boarder NTC values are chosen, which is 800A per line. Again with the assumption that 380kV and 220kV lines have the same current rating, the power transmission capacity of 380kV line is 304MW, and for 220kV line the value is 176MW.

### 3.2 RES Generation Distribution in the Benchmark Model

In this section the wind and PV generation distribution in the benchmark model established in Section 3.1 will be determined. The yearly electricity consumption data of wind, PV and some other RES of each federal state of Germany are available in [5]. By mapping the sixteen federal states of Germany to the six zones designed in the benchmark model, the yearly data of RES generations and electricity consumption in each zone can be obtained. And thus we are able to calculate the percentage of each RES generation type in a certain grid zone, which will be later on used in the power dispatch simulation model.

#### 3.2.1 PV and Wind In-feed in Benchmark Zones

To determine the percentage of RES generation in each benchmark zone. The first step will be mapping the sixteen federal states to the six zones in the benchmark model, based on the map of Germany [30]:

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Corresponding Federal States in Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>BERLIN</td>
<td>Berlin, Brandenburg, Mechlenburg-Vorpommern, Sachen, Sachen-Anhalt, Thüringen</td>
</tr>
<tr>
<td>BREMEN</td>
<td>Bremen, Hamburg, Niedersachsen, Schleswig-Holstein</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>Nordrhein-Westfalen, Rheinland-Pfalz, Saarland</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>Hessen</td>
</tr>
<tr>
<td>MUNICH</td>
<td>Bayern</td>
</tr>
<tr>
<td>STUTTGART</td>
<td>Baden-Württemburg</td>
</tr>
</tbody>
</table>

Table 3.1: Federal states contained in each benchmark zone

In [5], yearly generation and consumption data (in MWh/year) of the sixteen federal states in Germany are available (see Appendix B), sum up these data according to Table 3.1, the following results are obtained:
CHAPTER 3. APPLICATION ON BENCHMARK POWER SYSTEM

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>PV (Percentage)</th>
<th>Wind (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BERLIN</td>
<td>14.47</td>
<td>37.81</td>
</tr>
<tr>
<td>BREMEN</td>
<td>14.39</td>
<td>39.97</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>17.63</td>
<td>16.69</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>4.77</td>
<td>1.97</td>
</tr>
<tr>
<td>MUNICH</td>
<td>14.87</td>
<td>1.67</td>
</tr>
<tr>
<td>STUTTGART</td>
<td>33.87</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Table 3.2: Percentage of each zone’s PV and wind generation in the total PV and wind generation (As of 22.02.2012, Source: energymap.info).

The generation and consumption data in 15 minute step obtained in this project is the wind and PV in-feed data from the four TSOs in Germany. According to how the benchmark model is established, we can simply map the in-feed and consumption data of Amprion, EnBW and 50Hertz to Cologne, Stuttgart and Berlin. However, for the remaining three benchmark zones it is a little more complicated since they all belong to TENNET TSO. So the method used here to determine the in-feed and consumption data of these three benchmark zones is to calculate the percentage of wind and PV generation of each zone from the aggregated installed capacity in the TENNET region. Again using data from Appendix A, the following result is obtained:

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Consumption (Percentage)</th>
<th>PV (Percentage)</th>
<th>Wind (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BREMEN</td>
<td>44.07</td>
<td>42.28</td>
<td>91.66</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>20.25</td>
<td>14.02</td>
<td>4.52</td>
</tr>
<tr>
<td>MUNICH</td>
<td>35.68</td>
<td>43.70</td>
<td>3.82</td>
</tr>
<tr>
<td>TENNET TSO</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.3: Percentage of consumption, PV, wind in-feed of benchmark zone BREMEN, FRANKFURT and MUNICH in TENNET TSO.

Then by multiplying the TENNET data to the percentage of each benchmark zone, the in-feed and consumption data of each zone can be obtained.

3.2.2 Pumped-Storage Hydroelectricity in Benchmark Zones

Pumped-Storage Hydroelectricity (PSH) is used to store electric energy, therefore it’s capacities in the benchmark zones also need to be determined. Using the data from [22], the following result is obtained:
CHAPTER 3. APPLICATION ON BENCHMARK POWER SYSTEM

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Pump Power (MW)</th>
<th>Pump Capacity (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BERLIN</td>
<td>2772.8</td>
<td>17247</td>
</tr>
<tr>
<td>BREMEN</td>
<td>340</td>
<td>1540</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>293</td>
<td>1280</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>620</td>
<td>3906</td>
</tr>
<tr>
<td>MUNICH</td>
<td>1954</td>
<td>10386</td>
</tr>
<tr>
<td>STUTTGART</td>
<td>548</td>
<td>3354</td>
</tr>
</tbody>
</table>

Table 3.4: Pumped-storage hydroelectricity capacity installed in the benchmark zones.

3.3 Data Reconstruction

Because of limited data availability, it’s difficult to directly obtain the ambient condition data needed for DLR calculation, in a time step of 15 minutes. Therefore in this project, ambient conditions are reconstructed from data which are obtainable. For the wind velocity ($V$) and global solar radiation ($S$), the data is reconstructed from wind and PV in-feed power; for the ambient temperature, the data is reconstructed from measured daily maximum and minimum temperature.

3.3.1 Wind Velocity Data Reconstruction

The wind velocity data in a zone of the benchmark model is obtained from the wind power generation in-feed into the power system at this zone. The wind power in-feed data used to reconstruct the wind velocity in this project is recorded in a time step of 15 minutes, since the wind power only depends on the current wind speed. The reconstructed wind velocity data is also using a time step of 15 minutes.

The electricity power produced by a wind machine is

$$P_M = \frac{1}{2} C_p A \rho \nu^3,$$

where $A$ is the rotor area of a wind turbine, $\rho$ is the air density and $C_p$ is the coefficient of performance of the wind machine [6, p.325].

In the power production curve from a wind turbine (Fig. 3.4), there exists a cut-in wind speed and rated wind speed, in between the power delivered by a wind turbine increases with the speed. Once wind speed goes above the rated speed, the power production remains constant, or is even shut down to zero once the wind goes above the cut-out speed [6, p.355-357].

By assuming that the wind velocity in the ambient condition is always between the rated wind speed and the cut-in wind speed, and assuming $C_p$...
to be a constant value for all wind speed, we have:

$$P_W \propto V^3 \quad \text{if} \quad V_{cut} \leq V \leq V_{rated} \quad (3.3.2)$$

Then by further assuming $A$ is the same for all wind turbines used in Germany and $\rho$ the same over all Germany, Eq. (3.3.1) can be written as $P_W = C_W(V - V_{cut})^3$, where $C_W = \frac{1}{2}C_p A \rho$. Then by making another assumption, which is all the wind turbines installed in Germany are always operating, and the number of wind turbines is fixed during the year 2011, we can map the highest in-feed power $P_{W,max}$ to the rated wind speed and the minimum wind power $P_{W,min} = 0$ to the cut-in wind speed. Therefore $C_W$ can be calculated as

$$C_W = \frac{1}{2}C_p A \rho = \frac{P_{W,max}}{(V_{rated} - V_{cut})^3}. \quad (3.3.3)$$

The next step is to choose the rated wind speed and cut-in wind speed for the wind turbine. In this project, 15m/s is set as the rated wind speed and 1m/s for the cut-in wind speed, these values are chosen from the wind turbine design from ENERCON [9], a wind turbine manufacturer that has a market share of nearly 60% in German [26]. So the reconstructed wind speed will vary between 1m/s and 15m/s, which is acceptable since a wind speed density study showed that wind speed in a year will 95% likely to stay within this range[7].

The reconstruction equation from wind power in-feed to wind speed is
CHAPTER 3. APPLICATION ON BENCHMARK POWER SYSTEM

\[ V = \sqrt[3]{\frac{P_W}{C_W}} + V_{cut}, \quad (3.3.4) \]

where \( C_W = \frac{P_{W,\text{max}}}{(V_{\text{rated}} - V_{cut})^3}. \)

Based on the four TSO zones in Germany, the wind speed data are matched to the six zones (labeled by the main cities in these regions) designed in the benchmark model. Wind speed data reconstructed from the wind in-feed from Amprion, EnBW and 50Hertz is assigned to COLOGNE, STUTTGART and BERLIN respectively, which is mostly covered by these TSOs. For the remaining three benchmark zones, an assumption is made that all the wind generation of the TENNET TSO is installed in the northern part of Germany, according to the analysis done in Section 3.2, therefore the wind speed reconstructed from TENNET TSO is assigned to BREMEN. For FRANKFURT and MUNICH, the data from a neighboring zone at similar latitude level are used, which is BERLIN and STUTTGART respectively.

3.3.2 Reconstruction of Global Solar Radiation Data

The global solar radiation data in a zone in the benchmark model is obtained from the PV power generation in-feed into the power system at this zone. The PV power in-feed data used to reconstruct the global solar radiation is recorded in a time step of 15 minutes, since the PV generation only depends on the current solar radiation, the reconstructed global solar radiation is also in a time step of 15 minutes.

\[ I = I_{SC} - I_d \quad (3.3.5) \]

\[ V = V_d - IR_S, \quad (3.3.6) \]
where $I_{SC}$ is the short circuit current and is proportional to the solar radiation [6, p.462]; $R_S$ is the series resistance, $I_d$ and $V_d$ is the diode’s voltage and current. By assuming that $I_d$, $V_d$ and $R_S$ are constant, the power delivered by a photovoltaic cell ($P = VI$) is then proportional to the magnitude of solar radiation ($S$):

$$P_{PV} \propto S \quad (3.3.7)$$

Therefore, the equation can be simplified as $P_{PV} = A_{PV} S + B_{PV}$, where $A_{PV}$ and $B_{PV}$ are coefficients. The method used to determine these two coefficients is by mapping zero PV power in-feed to zero solar radiation, and mapping the average PV power in-feed to the average solar radiation at the in-feed location, with the assumption that the number of PV units installed in Germany is fixed during the year 2011 and all of these PV cells are always operating. The solar radiation sum can be found in [27], and by dividing the sum to the total number of hours in the year 2011, the annual solar radiation can be obtained. Since zero power is mapped to zero solar radiation, the coefficient $B_{PV}$ becomes zero, and the expression for solar radiation becomes

$$S = \frac{P_{PV}}{A_{PV}} \quad (3.3.8)$$

where $A_{PV} = \frac{P_{PV,ave}}{S_{ave}}$.

For assigning reconstructed solar radiation data from the four TSO zones to the six benchmark zones a similar process is done as for the wind speed data. However, from Section 3.2 we can see that distribution of PV generation of TENNET TSO is fairly evenly, so the method used here for reconstructing solar radiation data in BREMEN, FRANKFURT and MUNICH is using the same PV in-feed data, which is from TENNET TSO, but use different annual average solar radiation.

### 3.3.3 Reconstruction of Ambient Temperature Data

The temperature variation within a day can be represented with a sinusoidal curve, and can be represented as [29]

$$T_a(t) = T_{min} + (T_{max} - T_{min}) \Gamma(t), \quad (3.3.9)$$

where $T_a$ is the air temperature, $T_{min}$ and $T_{max}$ is the minimum and maximum temperature in a day, respectively, and $\Gamma(t)$ is the sinusoidal approximation function, ranging from 0 to 1. Besides, the time when $T_{min}$ and $T_{max}$ occurred is also needed, see Table 3.5.

After knowing the time that $T_{min}$ and $T_{max}$ occurred, it is possible to calculate how many time steps are between one day’s minimum and max-
CHAPTER 3. APPLICATION ON BENCHMARK POWER SYSTEM

<table>
<thead>
<tr>
<th>Season</th>
<th>$t_{\text{min}}$(H)</th>
<th>$t_{\text{max}}$(H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (21-Mar)</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>Summer (21-Jun)</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Autumn (21-Sep)</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>Winter (21-Dec)</td>
<td>8</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3.5: Time for daily maximum and minimum temperature to occur at 45° north latitude[24].

minimum temperature, or between one day’s maximum temperature to next day’s minimum temperature, in a step of 15 minutes.

Number of step points from minimum to maximum temperature:

$$N_{\text{min-to-max}} = \frac{60 \cdot (t_{\text{max}} - t_{\text{min}})}{15}.$$  \hspace{1cm} (3.3.10)

Number of step points from maximum to next day’s minimum temperature:

$$N_{\text{max-to-min}} = \frac{60 \cdot (t_{\text{min, next}} + 24 - t_{\text{max}})}{15}.$$  \hspace{1cm} (3.3.11)

Note that $t_{\text{min}}$ and $t_{\text{max}}$ refer to the hour that the minimum or maximum temperature occurs.

With the number of step points, the sinusoidal approximation function from minimum to maximum temperature is

$$\Gamma_{\text{min-to-max}}(n_{\text{step}}) = \sin\left(\frac{\pi}{2N_{\text{min-to-max}}}n_{\text{step}}\right),$$  \hspace{1cm} (3.3.12)

where $n_{\text{step}}$ is the sequence number for the step points and $0 \leq n_{\text{step}} < N_{\text{min-to-max}}$. And for the maximum to minimum temperature

$$\Gamma_{\text{max-to-min}}(n_{\text{step}}) = \sin\left(\frac{\pi}{2N_{\text{min-to-max}}}n_{\text{step}} + \frac{\pi}{2}\right).$$  \hspace{1cm} (3.3.13)

By taking Eq. (3.3.12) and (3.3.13) back into Eq. (3.3.9), a fraction of the temperature variation can be obtained. By connecting the fractions in the order of occurred time, a complete model for time variation is established.

The German Federal Ministry of Transport, Building and Urban Development [23] offers daily climate data values for Germany, which includes the daily maximum and minimum temperature. By using Matlab, together with the corresponding date, can be easily extracted from the downloaded file. To reconstruct the temperature variation for the year 2011, from (2011-01-01 00:00:00) to (2011-12-31 23:45:00), in a time step of 15 minutes, the
daily climate data for the entire year 2011 is used, together with the data for the day 2010-12-31 and 2012-01-01. After the temperature data are reconstructed, step points occurred before (2011-01-01 00:00:00) or after (2011-12-31 23:45:00) are removed from the data array, and then the temperature variation data for the entire year is obtained.

### 3.4 Example of Actual DLR

In Section 2.5.1, the sensitivity of ambient parameters is discussed. However, in order to show how these parameters affect the steady-state DLR in a real case, the DLR in one day is researched in this section based on the data reconstructed using methods described in Section 3.3.
Figure 3.7: DLR of one day in January from 2:00 to 23:45, in a time step of 15 minutes, with wind velocity, solar radiation and ambient temperature.

In the simulation scenario, the solar radiation remains zero during the night and reaches maximum value in the early afternoon, due to the movement of the sun. The ambient temperature varies as an integral function of the solar radiation, which means during the day the sunlight heats up the
air and during the night the air cools down. The wind speed in this scenario is large during the night and relatively small during the day. This may not be a typical case since wind speed is related to weather condition.

Fig. 3.7 shows simulated steady-state DLR in one day in January in Germany. In the simulation, the conductor temperature is assumed to be 85°C for all time, which means that the conductor is assumed to be operating at the maximum allowable temperature, and thus this rating corresponds to the maximum allowable current. Note that the limitation due to other electric devices used in the power system is not counted.

In Fig. 3.7, the shape of the DLR curve is fairly identical to the shape of the wind velocity curve, which is the same as discussed in Section 2.5.1 that the wind is the primary factor affecting the DLR. However, in this simulation scenario the wind speed is low during day-time, due to the reason that the DLR increases with wind velocity and decreases with solar radiation and ambient temperature. The effect of solar radiation and ambient temperature in this case is concealed by the effect of wind and is difficult to see from the DLR plot.

To see how exactly a single ambient parameter can affect the DLR, another simulation is made in which the DLR is only calculated with one ambient parameters vary with time while the remaining two are set to its mean value over the day, and repeat for the rest two respectively. Also, another plot is made by setting the actual DLR as reference and to see the absolute difference of the single-parameter-dependent DLR with the actual DLR (Fig. 3.8).

\[1\] This plot shows the absolute difference between DLR and the labeled curve.
Figure 3.8: Parameter sensitivity simulation, in the upper plot is the DLR with all variables or with a single variable while the rest are set to the mean value over the day; in the lower plot is the difference with the actual DLR. The data used are the same as in Fig. 3.7.

In Fig. 3.8, still, it is obvious that wind is the largest factor effecting the DLR, and the wind-dependent DLR has the smallest difference with actual DLR. Another conclusion from the simulation is that during the day when solar radiation is strong, the actual DLR has the largest difference with the wind-dependent DLR, while during the night these two curves are most similar. So if simplification are to be made on the DLR model, it is feasible to assume that the DLR only varies with wind speed, if the wind speed is higher than a certain value, while for solar radiation and ambient temperature it is only necessary to know their intra-day average value, but a certain margin needs to be considered during the day time, as the effect of solar radiation.
Chapter 4

Power Flow Calculation and Modeling

4.1 DC Power Flow Calculation [31]

DC power flow calculation is an fast-solving approximation for solving power flow problems in power systems. The derivation of the DC power flow equation presented in [31].

By making the following approximations:

- a) Neglect active power losses in the transmission line
- b) Voltage value at both ends of a transmission line is nominal: \( U_k \approx U_m \approx 1 \text{ p.u.} \)
- c) Angle difference between two ends are very small: \( \sin \theta_{km} \approx \theta_{km} \)

The active power flow can be represented as:

\[
P_{km} = \frac{\theta_{km}}{x_{km}} = \frac{\theta_k - \theta_m}{x_{km}},
\]

where \( x_{km} \) is the reactance of the transmission line.

This equation is analogous to a resistor carrying a DC current, in which \( P_{km} \) is the DC current, \( \theta_k \) and \( \theta_m \) are the DC voltages at the resistor terminals, and \( x_{km} \) is the resistance.

The matrix formulation of the DC power flow equations is:

\[
P = B' \theta,
\]

where

- \( P \) is the vector of the net injections \( P_k \),
- \( B' \) is the nodal admittance matrix and \( \theta \) is the vector of voltage angles \( \theta_k \).
4.2 Economic dispatch optimization [33]

Economic dispatch optimization is to schedule power system units to minimize the cost while maintaining the power balance in the system considering all operational and technical constraints. This is an optimization problem for the Power Node portfolio [32]. The continuous dynamics of the Power Node portfolio are described by this set of algebraic and first-order differential equations:

\[
\begin{align*}
\xi_1 - \omega_1 &= -\eta_{\text{load},1} u_{\text{load},1} \\
\xi_2 - \omega_2 &= \eta^{-1}_{\text{gen},2} u_{\text{gen},2} \\
\xi_3 - \omega_3 &= \eta^{-1}_{\text{gen},3} u_{\text{gen},3} \\
C_4 \dot{x_4} &= \eta_{\text{load},4} u_{\text{load},4} - \eta^{-1}_{\text{gen},4} u_{\text{gen},4} \\
C_5 \dot{x_5} &= \eta_{\text{load},5} u_{\text{load},5} - \eta^{-1}_{\text{gen},5} u_{\text{gen},5} \\
\xi_6 &= \eta^{-1}_{\text{gen},6} u_{\text{gen},6} \\
C_5 \dot{x_5} &= \eta_{\text{load},7} u_{\text{load},7} + \xi_7 - a_7 (x_7 - x_{o,7}).
\end{align*}
\]

For numerical computing, the above continuous differential equations are discretized with sampling time T, resulting in a system of discrete differential equation

\[
x(k + 1) = A \cdot x(k) + B \cdot u(k).
\]

Hence, the economic dispatch optimization problem in time step \( k \) with objective function \( J(k) \) can be formulated as follows:
\[ \min J(k) = \sum_{l=k}^{l=k+N-1} (x(l) - x_{ref})^T \cdot Q_x \cdot (x(l) - x_{ref}) \quad (4.2.9) \]

\[ + u(l)^T \cdot Q_u \cdot u(l) + R_u \cdot u(l) \]

\[ + \delta u(l)^T \cdot \delta Q_u \cdot u(l) \]

\[ \text{s.t.} \quad (a) \quad x(l+1) = A \cdot x(l) + B \cdot u(l) \]

\[ \quad (b) \quad 0 \leq x^\text{min} \leq x(l) \leq x^\text{max} \leq 1 \]

\[ \quad (c) \quad u^\text{min} \leq u(l) \leq u^\text{max} \]

\[ \quad (d) \quad \delta u^\text{min} \leq \delta u(l) \leq \delta u^\text{max} \]

\[ \quad (e) \quad \xi_1(l) = \xi_{\text{drv},1}(l \cdot T) \]

\[ \quad (f) \quad \xi_2(l) = \xi_{\text{drv},2}(l \cdot T) \]

\[ \quad (g) \quad \xi_3(l) = \xi_{\text{drv},3}(l \cdot T) \]

\[ \quad (h) \quad \xi_7(l) = \xi_{\text{drv},7}(l \cdot T) \]

\[ \quad (i) \quad u_{\text{gen},4}(l) \cdot u_{\text{load},4}(l) = 0 \]

\[ \quad (j) \quad u_{\text{gen},5}(l) \cdot u_{\text{load},5}(l) = 0 \]

\[ \quad (k) \quad \sum_{i=\{2,3,4,5,6\}} u_{\text{gen},i}(l) - \sum_{i=\{1,4,5,7\}} u_{\text{load},i}(l) = 0 \]

\[ \forall l = \{k, ..., k + N - 1\} . \]

The above constraint equations are to express (a) the linear Power Node equations, (b) the normalized and bounded state of change, (c) the non-negative and bounded input variables, (d) the rate-constrained input variables, (e-h) the externally driven demand/supply processes of the Power Nodes \( i \in \mathcal{N} = \{1, 2, 3, 7\} \), (i,j) the two storage do not possess two separate conversion systems and thus cannot feed-in and draw energy from the grid at the same time, and (k) the power balance of the single bus system has to be fulfilled.
Chapter 5

Performance Analysis of DLR

In this section, the benchmark model together with the data obtained or reconstructed in Section 3 will be simulated, with both NLR model and also the DLR model, and the results from the simulations will be compared and to analysis the impact that DLR had on the benchmark power system. Matlab is used to perform the simulation, the power dispatch simulator is developed in [33], part of the code is modified in this project in order to adapt the 6-node benchmark model and the DLR line model.

One criterion that we’ll mainly look into is the curtailment in load or generation. Curtailment in generation means that part of this generation is not integrated into the grid, in other words, wasted, and curtailment in load means not enough power is supplied to this zone and there was power outages. The curtailment shows how well the power was dispatched, and whether the generation is sufficient. Another criterion that is of our interest is the transmission line load, which is the power transmitted in the transmission line. By considering these two criteria, we can analyze whether the grid is limiting the power dispatch or not, and if the DLR can improved the power dispatch.

5.1 Simulation and Result

A sum up of all the assumptions and simplifications made in the benchmark model (assumptions made in the data reconstruction are not included):

a) The electric power generation and consumption within one benchmark zone can be represented by one node.

b) The ambient conditions (wind velocity and angle, ambient temperature, solar radiation and sea levels) within one benchmark zone is the same.
c) The model is treated as being isolated from the European Network (no power flow to or from aboard).

And the assumption or simplification made in calculating the DLR (assumptions made by [13] are not included):

a) Magnetic heating Power ($P_M$), corona heating power ($P_i$) and evaporative cooling power ($P_W$) are neglected.

b) steady-state conductor surface temperature calculation is done using numerical method with exit condition of error smaller than 0.1°C.

c) Transient-state conductor surface temperature calculation is done using discrete integration with a time-step of 1 minute.

d) Wind attack angle is held constant at 45° in all benchmark zones at all time.

e) All HV (220kV and 380kV) line conductor type is 428-A1/S1A-54/7 ‘Zebra’.

f) The conductor’s maximum surface temperature is 75°C.

g) The conductor surface temperature and average temperature is the same.

h) Rating constrains from power system equipements are not considered, i.e., transformers and power electronic converters.

The simulation can be held for one year from 2011.1.1 00:00:00 to 2011.12.31 23:45:00, and is also capable for a certain duration in between (i.e., 2011.12.1 00:00:00 to 2011.12.31 23:45:00). The simulation step is 15 minutes. The input to the simulator includes:

a) Load step data (in each zone).

b) Wind, PV generation step data (in each zone).

c) Pump-hydro storage pump power and storage capacity (in each zone).

d) Dispatchable power generation capacity (in each zone).

e) Grid-node topology.

f) Inter-zone transmission capacity (can be nominal or dynamic).

g) Scaling factor (percentage share in total generated/consumed energy), can be enabled or disabled.
The scaling factor is used to scale the load or in-feed data. When enabled, the simulator will scale the data to the desired share in total energy. For example, by setting the wind in-feed share in BREMEN to 40, which is the actual share, while double the total generated wind energy, BREMEN’s wind in-feed data input to the simulator will be doubled. The scaling function can be disabled, in which case the actual data will be fed into the simulator.

The result of the simulation includes:

a) Load step data and corresponding curtailment step data (in each zone).

b) Pump-hydro load step data.

c) Wind, PV, pump-hydro and dispatchable (biomass, conventional, etc.) in-feed step data and corresponding curtailment step data (in each zone).

d) Pump-hydro storage level (in p.u.) step data (in each zone).

e) Inter-zone power transmission step data.

And by integrating the step data we can obtain the corresponding total energy during the simulation period.

5.1.1 Simulation with Actual Load and In-feed Data

The result of simulation with actual load and in-feed data using NLR is shown in Appendix C. The dispatchable generation capacity is in total 78GW and is splited according to population distribution. It is shown that in the simulation no load or generation is curtailed, which means all wind and PV generation are successfully integrated and transmitted to the loads. Adopting DLR is not necessary since few can be improved in this scenario, and the simulation with DLR is not performed.

5.1.2 Simulation with Scaled In-feed Data

In order to see what can be improved using DLR, it is necessary to modify the in-feed profile to create some in-feed or load curtailment in the nominal rating simulation, which can be compared with the result of DLR rating. So the method used in this project is to double the wind and PV generation value, while reduce the dispatchable generation capacity to 80% of its original value (63GW), the rest of the system is left unchanged. The simulation result with NLR and DLR rating is showed in Appendix C. In addition, to offer a more detailed view of the data, the 15-minute step result of grid load as well as the load and in-feed in BREMEN and STUTTGART (BREMEN has very serious wind generation curtailment, while STUTTGART has very
serious load curtailment) in December, during which there was very high wind generation and at the same time very low PV generation. Their results are shown in the form of plots in Appendix C.

In the NLR simulation result, the total load curtailment is 2729 GWh, and the wind generation curtailment is 1072 GWh, while no PV generation is curtailed. In BREMEN, the wind generation curtailment is 872 GWh, which is about 2.2% of the total wind generation in BREMEN, while in STUTTGART and FRANKFURT there was 1422 GWh load curtailment, corresponding to 1.1% of the total load in these two zones.

In the DLR simulation result, the total load curtailment is 2325 GWh, and the wind generation curtailment is 46 GWh, and again, no PV generation is curtailed. In BREMEN, the wind generation curtailment dropped to 0.1%, while the load curtailment in STUTTGART and FRANKFURT dropped to 0.6%.

5.2 Result Analysis

From the comparison between the NLR and DLR simulation using scaled generation data, it is shown that DLR has a quite obvious effect on the integration of wind generation.

The result from the simulation showed that by applying DLR, 95.7% of the curtailed wind generation in the NLR case is integrated, while load curtailment is reduced by 15%. However the reduced wind generation curtailment is much larger than the reduced load curtailment, which is due to the volatility of wind power and insufficient storage capacity. With the DLR model, more wind power can be integrated during high wind situations and the dispatchable generations can produce less. However, without the aid of sufficient storage units, these reduction in dispatchable generation cannot be used to compensate the load during other periods. So load curtailment occurred during the time of low wind can hardly be supplied, and thus lead to the phenomenon described above.

If we take a closer look into the data from December, during which there was large wind power production and low PV power, in other words, larger generation in the north and less in the south. Therefore it was necessary to transmit the power from north to the south. In the figure for NLR grid load in Appendix C, for most of the time the power is transmitted from North to South. Lines from BREMEN to FRANKFURT, and FRANKFURT to STUTTGART are quite heavily loaded, the percentage of the time during which the power transmitted in the line is higher than 95% of the rating limit is 63% and 48%, respectively. From the load and generation profile for BREMEN and STUTTGART, we can see how the wind and load curtailments are distributed in time in these two areas.

In the simulation with DLR, the situation looks different. First, the
transmission lines from BREMEN to FRANKFURT and FRANKFURT to STUTTGART are able to transmit much more power, and the line occupancy percentage is only 3% and 0.2%, which is mainly due to the fact that by applying DLR the line has higher rating. And again, the load and generation profile plots also showed that there was fewer load and generation curtailment.

On the other hand, in the scaled simulation there’s still no solar energy curtailment. One reason for this is that the PV generation is lower compared to wind, and is also due to the fact that solar energy only occurs in the day time when load demand is also high. And from the PV energy distribution table in Appendix B, we can see that PV generations are distributed relatively evenly compared to wind, so PV generation can utilized within the zone and no need for inter-zone transmission.

Summing the discussion above, by applying DLR in the benchmark system, for most of the time the transmission lines are capable of transmitting more power than their nominal rating, and more wind generation can be integrated into the system with the same power grid, and less dispatchable (conventional) generation is needed.
Chapter 6
Discussion and Conclusion

In this project, the idea of applying DLR into the power system to optimize the RES integration and power dispatch is presented. Unlike NLR, DLR depends on ambient conditions and needs to be calculated, methods used to calculate the DLR and conductor’s surface temperature is introduced, and the effect of different factors is analyzed. A six-node benchmark model based on Germany is presented, together with methods to obtain or reconstruct the data for the benchmark model. At the end of the project the benchmark model is simulated with both DLR and NLR and the result is compared and analyzed.

In the following, the benchmark model and scenario limitations shall be discussed. Besides, an outlook of adopting DLR into the power system and its necessity will be presented. Finally, this thesis closes with concluding remarks.

6.1 Limitation from the Data and Model

Due to limited effort and data availability, various approximation methods were used in this project to reconstruct the ambient condition data and to perform the simulation, but still there are limitations and the actual situations may differ from the simulation, and for some factors this error may be very large.

First is the effect of wind attack angle. In this project this angle is assumed to be 45°, however results from the parameter analysis showed that the wind angle has a quite large impact on the DLR. If assuming the wind blows from north-east to south-west, then transmission lines in the north-west to south-east direction would have larger ratings, while those in the north-east to south-west direction would have a smaller rating. This would certainly make a difference in the power dispatch.

Another issue is the spatial distribution of the ambient conditions. In the benchmark model the ambient conditions are assumed to be homogenous
along the whole of the transmission line. However this is certainly not possible. For example, the temperature varies with altitude, and wind speed tends to be higher in the mountains and in the valleys. As a result the DLR may change significantly. Even the same transmission line may have different ratings in different sections.

6.2 Introducing DLR into Current Power System

There are certain limitations in the current power system structure that DLR cannot be directly introduced into power dispatching without upgrades of the power system.

A framework of calculating DLR and estimating its actual capacity need to be established. This will include real-time ambient data collection along the power line and monitoring the transmission line’s surface temperature. In the transient-state, the power transmitted by the transmission line will affect its surface temperature, while the surface temperature will again affect its rating. If to achieve the maximum utilization of the grid, the transmission line’s surface temperature needs to be forecasted, and have to be considered in the power dispatching.

The equipments used in the power system also need to be upgraded. The capacity of the power system is not only limited by the rating of the transmission line, but also the rating of other equipments used in the power system, i.e., transformers and power electronic devices. If DLR is to be applied, the rating of the transmission line can be expected to be four times larger at maximum. If these potential capacity is to be used, all the electric equipment used in the grid needs to be upgraded to higher power ratings.

6.3 Adopting DLR in Germany

The simulation with actual load and generation data shows that no load or generation curtailment happened. From this result we can see that, with NLR the grids in Germany are doing OK, and there is no need to apply DLR at present. However, the simulation with scaled generation capacity is not a scenario which only exist in the assumption, but will probably become realistic in 10 to 20 years, RES generation development is still growing rapidly in Germany, while all the nuclear power plants are being shut down. By that time, instead of building new transmission lines, introducing DLR might be able to solve the problem. But as discussed in the previous section, the DLR cannot be directly applied, and the establishment of the framework and the upgrade of the equipment needs time.
6.4 General Conclusion

In this thesis, the DLR model is established and simulation is performed with data directly obtained or reconstructed. It is shown that by applying DLR to the grid, more generation can be integrated into the power system, especially for wind power since the DLR can be treated as a monotonically increasing function of wind speed.

With proper framework and upgrade on the system, it is possible to introduce DLR into power dispatch scheduling or congestion, or wind farm construction planning. DLR can provide support for solving the grid constraints due to growing RES generation.
Appendix A

Data Plots
Figure A.1: Reconstructed temperature variation of year 2011 in six cities in Germany.
Figure A.2: Reconstructed temperature variation of year 2011 in six cities in Germany.
APPENDIX A. DATA PLOTS

Figure A.3: Reconstructed temperature variation of year 2011 in six cities in Germany.
Figure A.4: Reconstructed temperature variation of year 2011 in six cities in Germany.
Appendix B

Wind and PV Generation in Germany
APPENDIX B. WIND AND PV GENERATION IN GERMANY

<table>
<thead>
<tr>
<th>Region</th>
<th>Consumption (MWh/year)</th>
<th>Solar power (MWh/year)</th>
<th>Wind power (MWh/year)</th>
<th>Population (citizen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baden-Württemberg</td>
<td>79,468,699</td>
<td>3,121,670</td>
<td>758,790</td>
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<td>45,087,393</td>
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<td>896,322</td>
<td>6,092,891</td>
</tr>
<tr>
<td>Mecklenburg-Vorpommern</td>
<td>12,631,800</td>
<td>347,023</td>
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<tr>
<td>Niedersachsen</td>
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<td>1,871,610</td>
<td>11,599,514</td>
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<tr>
<td>Nordrhein-Westfalen</td>
<td>133,174,995</td>
<td>2,479,827</td>
<td>4,891,565</td>
<td>17,996,621</td>
</tr>
<tr>
<td>Rheinland-Phalz</td>
<td>30,041,069</td>
<td>1,010,493</td>
<td>2,447,478</td>
<td>4,059,604</td>
</tr>
<tr>
<td>Saarland</td>
<td>7,770,000</td>
<td>210,911</td>
<td>259,164</td>
<td>1,050,000</td>
</tr>
<tr>
<td>Sachsen</td>
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<td>572,540</td>
<td>1,354,091</td>
<td>4,250,000</td>
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<tr>
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<td>18,278,000</td>
<td>562,487</td>
<td>4,883,351</td>
<td>2,470,000</td>
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<tr>
<td>Schleswig-Holstein</td>
<td>20,934,496</td>
<td>1,109,705</td>
<td>6,225,650</td>
<td>2,828,986</td>
</tr>
<tr>
<td>Thüringen</td>
<td>17,279,000</td>
<td>392,888</td>
<td>1,283,564</td>
<td>2,335,000</td>
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<tr>
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<td>608,050,600</td>
<td>21,604,202</td>
<td>49,299,610</td>
<td>82,169,000</td>
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</tbody>
</table>

Table B.1: Wind and PV generation annual value and population in Germany, As of 22.02.2012, Source: energymap.info.
## APPENDIX B. WIND AND PV GENERATION IN GERMANY

### Table B.2: Wind and PV generation annual value and population in the benchmark zones, As of 22.02.2012, Source: energymap.info.

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Consumption (MWh/year)</th>
<th>Solar power (MWh/year)</th>
<th>Wind power (MWh/year)</th>
<th>Population (citizen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BREMEN</td>
<td>98,145,496</td>
<td>3,019,922</td>
<td>18,197,825</td>
<td>13,262,986</td>
</tr>
<tr>
<td>BERLIN</td>
<td>123,889,216</td>
<td>3,036,324</td>
<td>17,214,677</td>
<td>16,741,746</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>170,986,064</td>
<td>3,701,231</td>
<td>7,598,207</td>
<td>23,106,225</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>45,087,393</td>
<td>1,001,263</td>
<td>896,322</td>
<td>6,092,891</td>
</tr>
<tr>
<td>MUNICH</td>
<td>79,468,699</td>
<td>3,121,670</td>
<td>758,790</td>
<td>10,739,000</td>
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<tr>
<td>STUTTGART</td>
<td>92,311,200</td>
<td>7,108,866</td>
<td>860,393</td>
<td>12,488,000</td>
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</tbody>
</table>

### Table B.3: Percentage of each zone’s PV and wind generation in the total PV and wind generation. As of 22.02.2012, Source: energymap.info.

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>PV (Percentage)</th>
<th>Wind (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BERLIN</td>
<td>14.47</td>
<td>37.81</td>
</tr>
<tr>
<td>BREMEN</td>
<td>14.39</td>
<td>39.97</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>17.63</td>
<td>16.69</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>4.77</td>
<td>1.97</td>
</tr>
<tr>
<td>MUNICH</td>
<td>14.87</td>
<td>1.67</td>
</tr>
<tr>
<td>STUTTGART</td>
<td>33.87</td>
<td>1.89</td>
</tr>
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</table>

### Table B.4: Population (Load) percentage of the benchmark zones.

<table>
<thead>
<tr>
<th>Benchmark Zone</th>
<th>Population (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BREMEN</td>
<td>16.14</td>
</tr>
<tr>
<td>BERLIN</td>
<td>29.37</td>
</tr>
<tr>
<td>COLOGNE</td>
<td>28.12</td>
</tr>
<tr>
<td>FRANKFURT</td>
<td>7.41</td>
</tr>
<tr>
<td>MUNICH</td>
<td>13.07</td>
</tr>
<tr>
<td>STUTTGART</td>
<td>15.20</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100.00</td>
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</table>
Appendix C

Simulation Results
## APPENDIX C. SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Total energy of</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load BREMEN</td>
<td>88963.14</td>
</tr>
<tr>
<td>Load curtailment BREMEN</td>
<td>0.00</td>
</tr>
<tr>
<td>Load COLOGNE</td>
<td>154996.50</td>
</tr>
<tr>
<td>Load curtailment COLOGNE</td>
<td>0.00</td>
</tr>
<tr>
<td>Load STUTTGART</td>
<td>83781.90</td>
</tr>
<tr>
<td>Load curtailment STUTTGART</td>
<td>0.00</td>
</tr>
<tr>
<td>Load MUNICH</td>
<td>72041.40</td>
</tr>
<tr>
<td>Load curtailment MUNICH</td>
<td>0.00</td>
</tr>
<tr>
<td>Load BERLIN</td>
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<tr>
<td>Load curtailment BERLIN</td>
<td>0.00</td>
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<tr>
<td>Load FRANKFURT</td>
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<tr>
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<tr>
<td>Wind_gen curtailment STUTTGART</td>
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<tr>
<td>Wind_gen MUNICH</td>
<td>746.68</td>
</tr>
<tr>
<td>Wind_gen curtailment MUNICH</td>
<td>0.00</td>
</tr>
<tr>
<td>Wind_gen BERLIN</td>
<td>17356.18</td>
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<td>Wind_gen FRANKFURT</td>
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<tr>
<td>Wind_gen curtailment FRANKFURT</td>
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<tr>
<td>PV_gen BREMEN</td>
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<tr>
<td>PV_gen COLOGNE</td>
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<tr>
<td>PV_gen curtailment COLOGNE</td>
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<tr>
<td>PV_gen STUTTGART</td>
<td>2891.89</td>
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<tr>
<td>PV_gen curtailment STUTTGART</td>
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<td>PV_gen MUNICH</td>
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<tr>
<td>PV_gen BERLIN</td>
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<tr>
<td>PV_gen curtailment BERLIN</td>
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<tr>
<td>PV_gen FRANKFURT</td>
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</tr>
<tr>
<td>PV_gen curtailment FRANKFURT</td>
<td>0.00</td>
</tr>
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</table>

| Total load curtailment | 0.00 |
| Total wind_gen curtailment | 0.00 |
| Total PV_gen curtailment | 0.00 |

Table C.1: Power Dispatch Simulation with Actual Load and In-feed Value and Nominal Line Rating from 01.01.2011 to 31.12.2011.
## APPENDIX C. SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Load</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load BREMEN</td>
<td>88637.25</td>
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<td>325.89</td>
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<td>Load COLOGNE</td>
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</tr>
<tr>
<td>Load curtailment COLOGNE</td>
<td>363.09</td>
</tr>
<tr>
<td>Load STUTTGART</td>
<td>83107.31</td>
</tr>
<tr>
<td>Load curtailment STUTTGART</td>
<td>674.58</td>
</tr>
<tr>
<td>Load MUNICH</td>
<td>71732.64</td>
</tr>
<tr>
<td>Load curtailment MUNICH</td>
<td>308.76</td>
</tr>
<tr>
<td>Load BERLIN</td>
<td>111969.79</td>
</tr>
<tr>
<td>Load curtailment BERLIN</td>
<td>308.97</td>
</tr>
<tr>
<td>Load FRANKFURT</td>
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</tr>
<tr>
<td>Load curtailment FRANKFURT</td>
<td>747.41</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Wind_gen STUTTGART</td>
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<tr>
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<tr>
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<tr>
<td>Wind_gen BERLIN</td>
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<td>Wind_gen curtailment BERLIN</td>
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<td>Wind_gen curtailment FRANKFURT</td>
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<tr>
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<tr>
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<td>PV_gen curtailment MUNICH</td>
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<td>PV_gen BERLIN</td>
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<td>PV_gen curtailment BERLIN</td>
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<td>PV_gen FRANKFURT</td>
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<tr>
<td>Total load curtailment</td>
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</table>

Table C.2: Power Dispatch Simulation with Scaled Load and In-feed Value and Nominal Line Rating from 01.01.2011 to 31.12.2011.
Figure C.1: Grid loads in Scaled NLR Simulation from 01.12.2011 to 31.12.2011.
Figure C.2: Load and in-feed in BREMEN in Scaled NLR Simulation from 01.12.2011 to 31.12.2011.
Figure C.3: Load and in-feed in STUTTGART in Scaled NLR Simulation from 01.12.2011 to 31.12.2011.
### APPENDIX C. SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Total energy of</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load BREMEN</td>
<td>88581.20</td>
</tr>
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</tr>
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<td>383.65</td>
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<tr>
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<tr>
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<tr>
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<tr>
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</table>

Table C.3: Power Dispatch Simulation with Scaled Load and In-feed Value and DLR from 01.01.2011 to 31.12.2011.
Figure C.4: Grid loads in Scaled DLR Simulation from 01.12.2011 to 31.12.2011.
Figure C.5: Load and in-feed in BREMEN in Scaled DLR Simulation from 01.12.2011 to 31.12.2011.
Figure C.6: Load and in-feed in STUTTGART in Scaled DLR Simulation from 01.12.2011 to 31.12.2011.
Bibliography


