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Potential of Improved Wind Integration by Dynamic Thermal Rating of Overhead Lines

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***Abstract*-- Local concentration of future thermal power plants and wind farms in northern Germany cause network congestions that are in most cases resolved by interventions into generation schedules of thermal power plants or curtailment of wind power production. Right now, improving wind integration by dynamic thermal ratings is discussed. This investigation shows that there is a potential for avoiding the redispatch of thermal power plants due to the feed-in priority of wind power by utilizing dynamic thermal ratings.**

***Index Terms*-- Dispatching, Power System Monitoring, Power System Simulation, Transmission Lines, Wind Energy**

I. Introduction

In Germany there are ongoing changes in the composition of power generation. Newly built thermal power plants will be locally concentrated in coastal areas due to area dependent low primary energy prices. Moreover, there is a growing electricity generation from wind farms promoted by political incentives which is also concentrated in coastal areas and offshore. Subsequent network congestions are so far remedied by redispatch of generation in the short-term and network expansion in the long-term. As there is a feed-in priority for electricity from renewable sources [1], thermal power plants are subject to redispatch in the first place. This causes significant expenses that are expected to increase in the future [2]. Recently, field tests have been carried out in Germany on utilizing reserves of existing distribution networks by dynamic thermal rating (DTR) of overhead lines in order to improve the integration of wind power [3]. The constantly determined thermal ratings of overhead lines used so far are replaced by dynamic ratings. These can be obtained by measuring weather conditions as well as further data such as line tension or line temperature [4]-[6].

DTR of overhead lines seems especially reasonable not only in distribution networks but also in transmission systems with a high share of wind power, as high loadings of the system coincide with high transmission capacities due to increased cooling of the overhead lines by convection. Previous investigations have proven this coincidence for overhead lines in central Germany [7]. However, in order to assess the potential of DTR to improve the integration of wind power generation into the transmission system, the beneficial effects of DTR on the congestion management including the avoidance of redispatch have to be considered in addition to the mere gain in transmission capacity. In this context, it is of particular interest whether the redispatch of thermal power plants due to the feed-in priority of wind power can be avoided.

Therefore, in section II, a model of the weather dependent congestion management of transmission networks is presented. In section III this model is applied in a case study for north-western Germany for an expected situation in 2015. Wind power feed-in and thermal ratings are analyzed and congestion management is simulated with and without DTR. Finally, in section IV the findings are summarized and the need for further research is discussed.

II. Weather Dependent Congestion Management

A. Thermal Model of Overhead Lines

The temperature of an overhead line conductor T_c is determined by heat gains from solar radiation (q_s) and ohmic losses on the one hand and by heat losses due to convection (q_c) and radiation (q_r) on the other hand. Ohmic losses can be calculated from the square of the current I_C and the temperature dependent conductor resistance R. Summing up these influences yields the static heat balance equation of an overhead line conductor

$$q_c + q_r = q_s + I_C^{\,2} R(T_C). \tag{1}$$

Based on this equation, in [8] calculation methods well proven in practice are defined for calculating the thermal rating of overhead line conductors. These methods are used in this investigation. Special attention is paid to the dependence of convective heat losses on the angle of attack of the wind. Forced convective heat losses are proportional to the wind direction factor K_{angle}, given by

$$K_{angle} = 1.194 - \cos(\Phi) + 0.194\cos(2\Phi) + 0.368\sin(2\Phi), \tag{2}$$

where Φ is the angle between the wind direction and the conductor axis. K_{angle} varies between 1 for perpendicular wind and 0.388 for parallel attack. This is why the wind directions and the directions of overhead line routes have to be considered.

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B. Processing of Weather Data

For the calculation of ampacities, historical weather data are used. As these data are measured by synoptic weather stations that are remote from the overhead lines, weather data have to be imaged to the locations of the lines. This imaging is achieved by the established method of inverse distance weighting. Weather data for a point of interest are calculated as a weighted average of the values of the surrounding synoptic stations, with the reciprocal value of the geographic distance between the point of interest and the synoptic station as a weighting factor, according to (3). Here x_0 denotes the imaged value, x_i the measured values at the synoptic stations, d_i the distances between the point of interest and the synoptic stations and n the number of stations considered in the interpolation.

$$x_0 = \frac{\sum_{i=1}^{n} d_i^{-1} x_i}{\sum_{i=1}^{n} d_i^{-1}} \qquad (3)$$

The optimal number of surrounding stations to be considered is found by minimizing the mean interpolation error by cross-validation, i. e. interpolating at a point where measured values are available and comparing interpolation results to measured values. The weather-dependent thermal rating is then calculated for piecewise linear sections of the power lines using the thermal model [8] based on the meteorological variables wind speed, wind direction and ambient temperature. The separation of lines into piecewise linear sections is necessary to calculate the angle of attack and is based on the assessment of air photographs.

C. Network Model Comprising Load and Generation

In order to simulate congestion management, a model of the transmission network is necessary. In this investigation, a model of the European UCTE system based on publicly available sources is used [9]. It contains stations and lines according to published network data. Standardized types of equipment are used for 380 kV and 220 kV overhead lines and transformers. For overhead lines described in detail by public data, e. g. tie lines between different countries, the exact electric parameters are used.

The load allocation considers population density and large industrial consumers. Generation schedules of power plants are derived from a macroeconomic optimization, considering technical characteristics of generation technologies such as minimum operating hours, minimum rest periods, non-availability and heat consumption curves as well as network restrictions [10]. The assumption of a macroeconomic optimal dispatch of generation is the most realistic assumption, presuming a successfully liberalized electricity market. Each power plant connected to the German transmission network is modeled as a separate unit according to power efficiency. The allocations of power plant connection points to network substations are estimated from geographic positions. Neighboring countries are represented by their primary energy shares. These countries have to be included in the optimization of generation in order to calculate power transits across the German borders.

D. Model of Congestion Management

In electric power systems, network operators are obliged to ensure (n-1)-security of the system [11]. Therefore, preventive measures already have to be performed in case (n-1)-security is lost and not only when an overloading of network equipment occurs. As overloadings of network equipment are significantly more seldom than the loss of redundancy, it is sufficient to consider the latter for the evaluation of weather dependent thermal ratings in network operation. Therefore, congestion management is simulated based on a deterministic (n-1)-contingency analysis.

As illustrated by Fig. 1, weather dependent thermal ratings are calculated for all hours of interest based on the above mentioned thermal model. In order to estimate the potential of DTR, it is assumed that the network operator is aware of the actual thermal ratings.

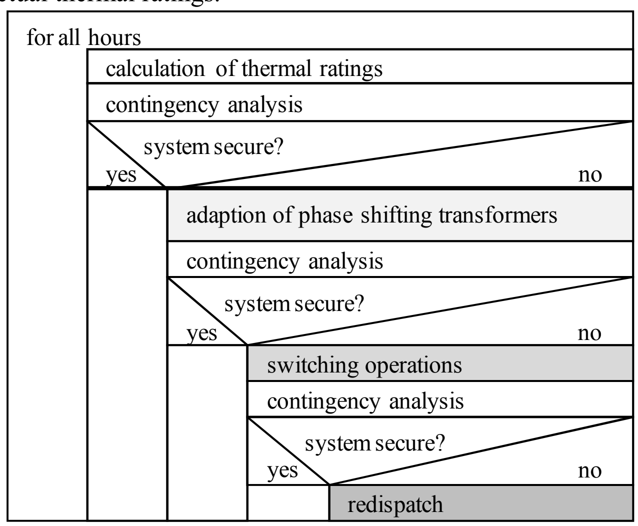

Fig. 1: Algorithm of congestion management

Afterwards, the security of the system is surveyed by a contingency analysis. If the system is not secure, first of all the settings of phase shifting transformers are adapted. If system security is still violated, the network topology is adjusted. As a third and last measure, the costly redispatch of power plants is performed. All these actions aim at avoiding a violation of current limits and are thus strongly dependent on the ampacities of overhead lines. For adapting the phase shifting transformers and redispatching generation, a linear optimization is used in order to minimize interventions [12]. For switching operations, a heuristic approach is chosen.

III. Case Study for North Western Germany

A. Assumptions on Future Network and Generation System

The case study is supposed to be conducted for a future scenario with increased installed capacity of wind power. Therefore, the year 2015 is chosen for the investigation. Network expansions are modeled according to [13], which gives an outlook of a network that is supposed to be generally well fitted for the integration of wind energy. According to [14], onshore wind farms are scaled up to 26 GW. For offshore wind power it is assumed that all offshore wind farms according to [15] that have already been authorized will be realized in their first stage of expansion until 2015. This results in an installed capacity of 7.1 GW, with 1.2 GW in the Baltic Sea and 5.9 GW in the North Sea. Concerning thermal power plants, a total capacity of 17 GW is added to the model compared to today. In return, a total of 22.2 GW of thermal power plants is assumed to be decommissioned until 2015. While newly built power plants in coastal areas add up to a capacity of 7.3 GW, decommissioned power plants in this area add up to a capacity of only 1.6 GW. Thus, there is a significant shift of thermal generation to coastal areas in addition to the growing capacity of wind farms.

B. *Scope of the Case Study*

Due to the concentration of thermal power plants and wind farms at the coast, the north-west of Germany is surveyed. The area of interest, i. e. the area where contingency analyses are performed, is marked by a dashed border in Fig. 2. Weather dependent thermal ratings of 15 circuits of the EHV network are calculated and used for the simulation of congestion management. The routes where these circuits are installed are drawn in bold black lines in Fig. 2. These lines have been chosen for DTR because they tend to be heavily loaded and are situated in an area with high average wind speeds giving rise to the expectation of high thermal ratings. As mentioned in II. B., the circuits with DTR need to be separated into piecewise linear sections. For the 15 circuits in this case study there is a mean of about 15 linear sections per circuit, longer circuits having more sections.

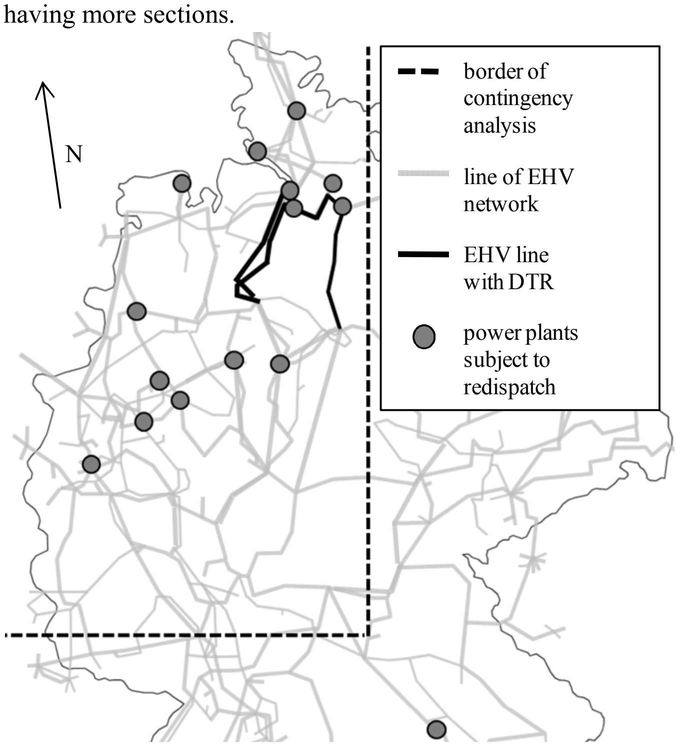

Fig. 2: Area of investigation

Grey circles in Fig. 2 mark the network connection points of power plants taking part in redispatch. Load flow and contingency analyses are conducted with the complete model of the German transmission network. Calculations are performed with historical weather data of the year 2006 and respective time series of wind power feed-in adapted to the situation in 2015. As there are no time series of the feed-in of offshore wind farms available so far, such time series are calculated from offshore windspeed measurements [16] using the characteristics of typical offshore wind power plants. The feed-in of onshore wind farms is derived from historical time series of 2006 that are scaled up to the situation in 2015. It is crucial to use time series of weather data and wind power from the same time period in order to obtain reliable results.

C. *Data Analysis*

Prior to the simulation of network operation, weather dependent data are analyzed in order to facilitate the interpretation of subsequent simulation results. In [17] the thermal rating distribution, i. e. a frequency distribution of weather dependent transmission capacities, is introduced as a measure for transmission reserves in existing networks. The thermal rating distribution for the longest of the circuits within this case study (approx. 130 km) reveals an enormous potential of increased transmission capacities with the relative rating being above 125 % for more than 50 % of the time. On the other hand, there are also times when actual ratings are below today's constant values. In this example, this is the case for about 5 % of the time. While such situations remain unnoticed so far, they can be detected by DTR and consequently be remedied by congestion management if necessary.

Besides the thermal rating distribution, the correlation of thermal ratings and wind power feed-in is crucial for the improvement of wind integration by DTR. In Fig. 3 a scatterplot of the above mentioned line's relative thermal rating versus the total feed-in of wind power is given. The visual impression of a high correlation is approved by the calculation of Spearman's rank correlation coefficient which is 0.72. There is a spread of thermal ratings because wind power feed-in is independent of the wind direction due to the azimuth control of wind turbines if hourly values are considered. In contrast, convective heat losses are strongly dependent on the angle of attack. Therefore, changes in the direction of the routes as well as inhomogeneous wind fields result in the existence of multiple thermal ratings for the same value of wind power feed-in.

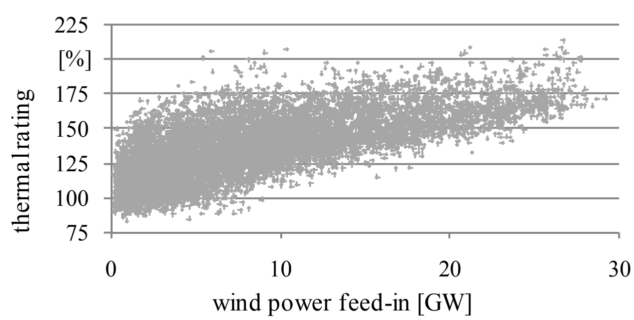

Fig 3: Scatterplot of thermal rating vs. total electricity generation of onshore and offshore wind farms.

D. Simulation Results for Congestion Management

First of all, network operation and congestion management are simulated without DTR on any line. For all hours of the year, congestions are identified by contingency analysis and remedied by congestion management according to the procedure described by Fig. 1. If there are still congestions after switching operations they result in a certain amount of generation being shifted from the power plants where generation was originally scheduled to other power plants. The choice of these power plants is an optimization result. For the purpose of this study it is of subordinate importance which power plants face redispatch. Instead, the total power shift per hour is assessed. Integration of redispatched power with respect to time yields the amount of redispatched energy for a certain period of time. In Fig. 4 redispatched energy for each month of the year under investigation is indicated by black columns.

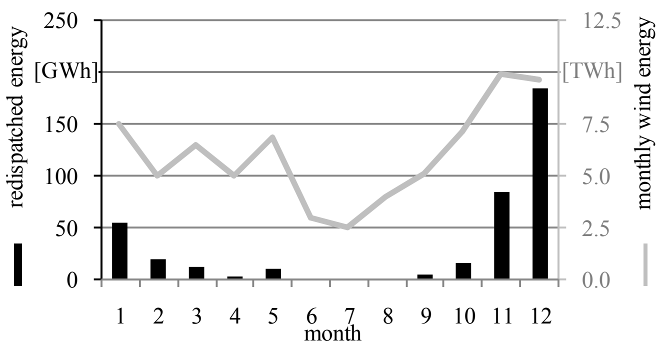

Fig. 4: Comparison of monthly redispatched energy without DTR and monthly wind energy

While there is no need for interventions into scheduled generation during the summer months, significant changes to the schedules take place in autumn and winter. Comparison with the monthly energy fed in by wind farms (grey curve in Fig. 4) shows a high congruence for the months from January to November. This justifies the conclusion that congestions are mainly caused by wind power feed-in. However, in December the amount of redispatched energy is twice as large as in November although electricity production from wind farms is slightly lower. This seeming contradiction is resolved by refining time resolution. Fig. 5 shows the redispatched power and the total wind feed-in on an hourly basis for the months November and December. Comparison of the time series reveals that there is still a high congruence of the two quantities. Moreover, it can be stated that redispatch mainly occurs in situations with high wind power feed-in, i. e. wind power feed-in above 18 GW. Such situations are much more frequent in December than in November, which results in a higher amount of redispatched energy. On the other hand there is a long period of low wind power feed-in during the second half of December. Therefore, the monthly wind energy is slightly lower in December than in November.

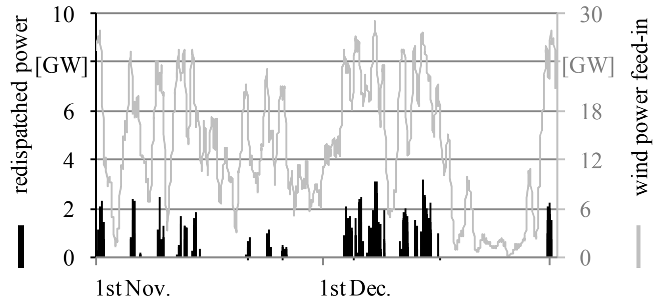

Fig. 5: Comparison of redispatched power without DTR and wind power feed-in during November and December

After the identification of wind driven redispatch the effects of DTR on congestion management are investigated. Simulations follow the same approach as before, the only difference being the transmission capacities of the lines equipped with DTR within this case study. Fig. 6 illustrates the redispatched energy for each month of the year with and without DTR. Considerable amounts of energy need to be redispatched only in November and December if DTR is utilized. Moreover, during the whole year redispatched energy is reduced by about 85 %. Thus, there is a significant potential of avoiding interventions to generation schedules by DTR even if only a comparably small number of lines is equipped with DTR.

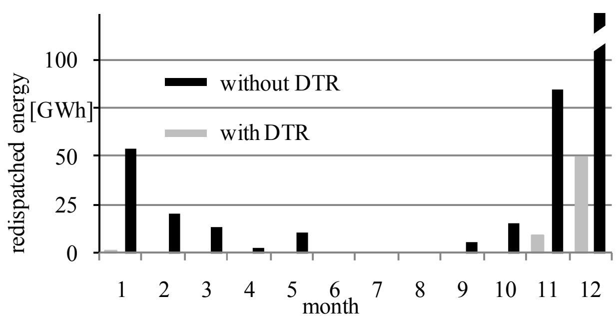

Fig. 6: Monthly redispatched energy without and with DTR

IV. Conclusion and further need for research

The results of this investigation illustrate the potential of DTR to reduce interventions in generation schedules which are due to the priority of wind feed-in. In a future scenario for 2015 with newly built hard coal power plants in coastal areas and a strong expansion of wind power, redispatch of generation is most often due to wind power feed-in. As there is a high correlation between the weather dependent thermal ratings of overhead lines and wind power feed-in, the wind associated redispatch of generation can be significantly reduced by DTR, even if only a comparably small number of lines is equipped with this technology.

Beyond this investigation, further need for research is left considering the exact modeling of wind shelters. Moreover, network operators need to be aware of the transmission capacities of their lines in advance in order to use DTR in day-ahead congestion management. Therefore, further research will be carried out on forecasts of the rating of overhead lines.

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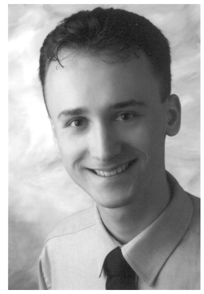
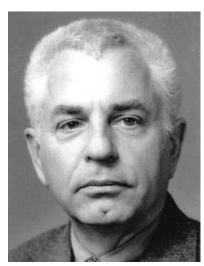
VI. Biographies



Tilman Ringelband was born in Bochum, Germany, on May 27th, 1982. In 2006, he received his diploma in Electrical Engineering from the University of Bochum and is currently pursuing the Ph.D. degree at the Institute of Power Systems and Power Economics at RWTH Aachen University.

Matthias Lange, leading associate of Energy & Meteo Systems GmbH, studied physics in Oldenburg, Warwick (UK) and Marburg. A scholarship recipient of the “German Foundation for the Environment” (Deutsche Bundesstiftung Umwelt - DBU) he was awarded a doctorate in the year 2003 by the Carl von Ossietzky Universität Oldenburg on the subject of the uncertainties of wind power prediction. Before co-founding Energy & Meteo Systems in the year 2004, he was project leader for the grid integration and prediction of wind energy at the ForWind center for wind energy research. Prior to that, he conducted on-location surveys for wind power facilities. Furthermore, Matthias Lange belongs to the co-developers of the wind power prediction system Previento and as such works for its transfer into operational service.

Martin Dietrich was born in Rostock, Germany, on July 3rd, 1983. In 2008, he graduated from RWTH Aachen University in Business Administration and Engineering. His diploma thesis dealt with the weather dependent operation of transmission networks. Currently he is participating in a trading qualification program at E.ON Energy Trading, headquartered in Düsseldorf, Germany.



Hans-Jürgen Haubrich was born in Montabaur, Germany, on March 1st, 1941. He received his diploma and Ph.D. in Electrical Engineering from the Technical University of Darmstadt, Germany, in 1965 and 1971 respectively. In 1973 he joined a power supply company where he was head of the main department network planning. At the same time, he was teaching at the University of Bochum and the University of Dortmund as an Honorary Professor. From 1990 to February 2009 he was head of the Institute of Power Systems and Power Economics and the Forschungsgemeinschaft Energie (FGE) at RWTH Aachen University. His research is focused on technical and economic aspects of electrical power engineering. In 1999 he became the president of the ETG in the VDE (Association of Electrical Engineering, Electrics, and Information). He is member of the Engineering Convention of the Academy of Science North Rhine-Westphalia and member of the German Academy of Science and Engineering. Since 2001 he has been chairman of the board of Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e. V., FGH (research society for electrical power systems and power economics). He is also a senior member of IEEE.