Dynamic thermal rating application to facilitate wind energy integration

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Abstract— **The depletion of fossil fuel resources as well as commitments to lower the global emission of green house gases are driving many countries to make substantial investments in renewable energy resources, especially wind energy. In this regard, the United Kingdom has launched many off-shore and on-shore wind power projects which are planned to supply around 15% of energy demand by 2020. The network expansion required to accommodate this level of wind power is prohibitively expensive and time-consuming. Instead, some "Smart Grid" ideas can be used to enhance the utilization of network assets so that the transmission network expansion can be deferred or even avoided. Among these ideas, dynamic thermal rating is being investigated by National Grid for possible implementation in the Humber Estuary region where a high penetration of wind power is scheduled. In this paper, a probabilistic approach is introduced to answer two questions: i) which transmission lines in Humber Estuary need to be considered in dynamic thermal rating scheme and ii) how much benefit can be achieved by online monitoring of network thermal ratings? To answer these questions, probabilistic models for seasonal off-shore wind power as well as seasonal dynamic thermal ratings of overhead lines are developed, taking into account past meteorological data.**

Index Terms— **Wind power generation, smart grid, Dynamic thermal rating, transmission network, probabilistic model.**

I. INTRODUCTION

In order to meet the Kyoto protocol commitments, the contribution of renewable energy to the future generation mix will need to rise considerably above current levels. The European Commission has proposed an ambitious target that 20% of total energy consumption should be supplied by renewable energy sources by 2020. The United Kingdom (UK) has set a target of 15%, which is lower than the average commitment made by other European countries. Nonetheless, even with 15% integration of renewable energies, the UK has the largest growth in deploying renewable energies, as currently just around 2% of the UK's total energy consumption is supplied by renewable resources. Among all green energy resources, wind energy seems the most promising, as it can potentially fulfil the UK's commitments by 2020. In the "Gone Green" scenario, which is the roadmap for the UK's future generation scheme, 30% of total installed generation capacity is from wind power plants [1].

One of the challenges to meet the Gone Green scenario targets is to expand or enforce the transmission network in order to accommodate the large penetration of wind energy. The lead time of transmission network projects, however, is usually longer than the time required to construct a wind power plant. Therefore, wind farms may be ready to generate power, whereas there is not sufficient transmission capacity to transfer that power. Consequently, wind power plants usually need to curtail the generation and work below their potential capacity factor. Nonetheless, the now ubiquitous "smart grid" solutions suggest that there is some potential to use the existing network more efficiently, so that wind power plants are less likely to be constrained off due to network congestion [2].

In the UK, National Grid (NG), which is responsible for planning and operation of the 275 & 400 KV transmission network in England and Wales, is investigating methods and strategies of facilitating the integration of wind energy. The main approaches that NG is currently studying as smart grid solutions are: i) using dynamic thermal ratings of transmission lines, ii) application of wide area monitoring, iii) deploying generator intertrip schemes and iv) quadratic boosters optimisation. In order to experiment with these ideas NG has set up a pilot zone, Humber Estuary, which is to face congestion problems due to connections of upcoming off-shore wind farms.

This paper studies the impact of dynamic thermal rating of transmission lines on the amount of wind power that can be integrated in the Humber Estuary. The volatility of wind power is modelled in the form of seasonal probability distribution function (PDF), using six years data of off-shore wind speeds. Also, based on weather conditions and characteristics of transmission lines, seasonal PDFs for thermal rating of each transmission line are estimated. A probabilistic approach is used to determine the best location of temperature monitoring facilities, as well as the expected benefit from monitoring the real temperature of the transmission lines. In addition, "N-1" and "N-D" security criteria are considered in this study as all operation and planning schemes conducted by NG should comply with these criteria. The rest of the paper is organised as

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follows: In section II the thermal rating calculation is elaborated. Section III describes the methodology. Humber Estuary is introduced in section IV along with the probabilistic models for wind power and dynamic thermal ratings. Section V presents the results. Finally, some concluding remarks are given in section VI.

II. DYNAMIC THERMAL RATING

National Grid, and many other transmission utilities, usually considers a constant seasonal thermal rating for the overhead lines. This rating is a conservative value, which in turn is very likely to be lower than the actual thermal rating which varies based on the weather conditions [3]. The thermal rating is calculated based on the thermodynamic balance between the heat generated inside the conductor and the heat lost by the conductor through radiation and convection [4, 5], as mathematically expressed by (1):

$$P_J + P_s = P_R + P_C \tag{1}$$

P_J, P_s, P_R, and P_C are Joule heating, solar heating, radiative cooling and convective cooling, respectively.

The Joule heating is mainly generated due to current flowing in the conductor. The resistance of conductor changes accordingly while the conductor's temperature varies. The Joule heating complies with equation (2) [6].

$$P_J = k.R_{dc}.I^2.(1 + \alpha.(T_c - 20)) \tag{2}$$

Where,

k Skin effect factor

R_{dc} DC resistance at 20°C (Ω/m)

I Current flowing in the conductor (A)

T The conductor temperature (°C)

In a transmission line the sag depends on the core temperature. Therefore the surface temperature mentioned in equation (2) should be translated to core temperature. Morgan et al. [7] elaborate the relationship between core temperature and the surface temperature of a conductor.

The solar heating is another factor that increases the conductor's temperature. Solar heating is expressed by (3).

$$P_s = a.S.D \tag{3}$$

Where

a Solar absorption coefficient

S Solar radiation (W/m²)

D External diameter of conductor (m)

The heat loss through convection depends on the wind velocity, the angle of wind direction and the ambient temperature. IEEE standard 378 [4], suggests two equations used for high and low wind speed, as formulated by (4) and (5), respectively.

$$P_c = \left(0.0119\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.6}\right)K_f.K_{angle}.(T_c - T_a) \tag{4}$$

$$P_c = \left(1.01 + 0.0372\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.52}\right)K_f.K_{angle}.(T_c - T_a) \tag{5}$$

Where

k_f Thermal conductivity of air

K_{angle} Wind direction factor

V_m Wind speed

ρ_f Density of air

μ_f Dynamic viscosity of air

T_c The conductor temperature

T_a The ambient temperature

Radiation also helps the cooling process of the conductor. The conductor losses heat through the radiation as formulated by (6)

$$P_R = 0.0178.D.\varepsilon\left[\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right] \tag{6}$$

ε is the emissivity of conductor.

The most influential parameters on thermal rating are wind speed, wind direction, conductor characteristics, ambient temperature and the profile of overhead line. Transmission companies usually calculate a seasonal thermal rating for the overhead lines, assuming conservative amounts for the influential parameters. National Grid calculates three different thermal ratings representing spring/fall, winter and summer. For example, for a two bundles transmission line with Redwood conductor, National Grid conservatively considers 3070 MW, 2880 MW and 2660 MW as the constant thermal rating in winter, spring/fall and summer, respectively. Considering the actual wind speed and ambient temperature, however, the actual thermal rating can be higher than the constant seasonal ratings. The hourly thermal rating of the aforementioned transmission line is calculated using heat

balance equation (1) along with hourly ambient temperatures and wind speeds recorded in past years. The solar heating is neglected in this calculations as the solar radiation in the UK is very low [8]. In Fig. 1, the results of calculations the actual thermal rating are compared with the constant seasonal thermal ratings for four consecutive years. As can be seen in Fig. 1, the actual thermal rating is higher than the constant seasonal rating, there are also some rare cases that the dynamic thermal rating falls under seasonal rating.
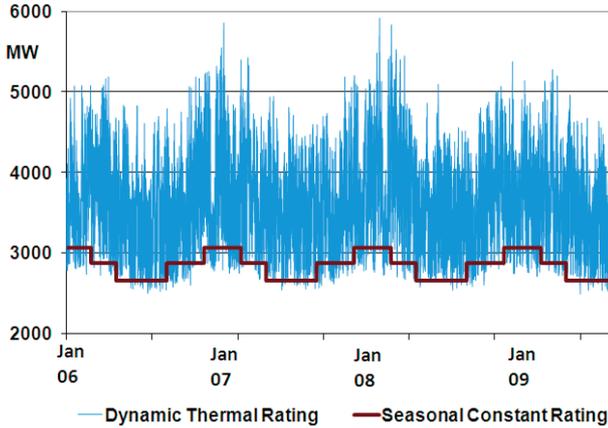

Fig. 1 Dynamic thermal rating and seasonal constant thermal rating for a double bundle overhead line with a Redwood conductor (AAAC)

III. METHODOLOGY

In this study, while focusing on Humber Estuary region, the aims are to firstly find those transmission lines which by monitoring their dynamic thermal ratings facilitate the integration of wind power, secondly, to quantify the possible benefit from monitoring the thermal rating of transmission lines. This study is in essence a long-term planning study which requires the modeling of system behavior in a horizon years.

As demonstrated in the previous section, the variation of weather parameters imposes a varying thermal rating of transmission line. For long-term studies, it is almost impossible to accurately predict these variations. Instead, by using the past weather data, the thermal rating of each individual line can be estimated with a probability density functions (PDF). This will be elaborated in section IV.

Wind speed is another source of uncertainty which makes the output of wind power plants a difficult parameter to predict. In this study, the seasonal outputs of off-shore wind farms are estimated with PDFs taking into account six years recorded data of off-shore wind speed and the aggregated power curve of the wind power plant. Considering PDFs of thermal ratings and wind power plants, 500 possible scenarios representing different values for thermal ratings and wind power are generated. Latin hypercube sampling (LHS) [8] is used to generate wind power-thermal rating scenarios. These scenarios should comply with the correlations between wind farms, as well as correlations between the thermal ratings of transmission lines. Moreover, in this work the correlation between off-shore wind farms and dynamic thermal ratings of transmission lines is taken into account. These correlations are given in section IV.

The Security and Quality of Supply Standard (SQSS) [9] used by NG in planning and operation studies stresses the robustness of the network against single and double circuit outages, "N-1" and "N-D" security criteria. Therefore, in this study, for all those 500 scenarios the power flowing through transmission lines is calculated, taking into account the intact network as well as "N-1" and "N-D" contingent networks. The results of power flow calculation are compared with the case where a constant seasonal thermal rating is considered for transmission lines, according to NG traditional practice. These calculations can be conceived as a sensitivity analysis which shows the expected level of overload alleviation in the congested transmission lines when dynamic thermal rating is assumed. Therefore, those transmission lines which need online temperature monitoring are singled out.

Furthermore, the economic benefit of monitoring the temperature of transmission lines is calculated. In a daily operation planning, in order to comply with SQSS, some generators should be constrained off. This increases the total operating cost of the system as out-of merit generators take advantage of the network congestion to participate in the supply-demand chain. Using dynamic thermal rating of transmission network decreases the likelihood of network congestion so that a rather non-discriminatory environment can be offered to generators. The benefit is the average reduction in operating cost when thermal rating monitoring is assumed to be in place. The operating cost is the generation cost determined by a Security Constrained Optimal Power Flow (SCOPF) whose objective function is given by (7).

$$Minimise \sum_{i=1}^{N_g} D_i.C_i.G_i \qquad (7)$$

Where,

C_i Generation cost of generator i (£/MWh)

G_i The output of generator i (MW)

D_i The duration in which generator i generates G_i (hour)

The objective function (7) should respect the Kirchhoff's current law and Kirchhoff's voltage law (KCL and KVL) and power system components limits. In this study, for sake of simplicity, a dc reduced model of NG network is assumed for Humber Estuary region. Dash Xpress, which is decision making software, is used to solve the optimization problem (7).

National Grid explores smart grid ideas on a part of the transmission network, which is shown in Fig. 2. This region has been selected because high penetration of wind energy is scheduled to connect the network. Although network expansion is planned as part of the Humber project, wind power projects are very likely to be ready to generate power before transmission expansion projects are concluded. Therefore, power plants including Gas, Coal and Wind in this region will be constrained off due to deficit in the transmission capacity. The existing generation in the Humber region consists of 2850 MW CCGT and 1200 MW CHP. In addition, two off-shore wind power plants, Dogger Bank and Hornsea, are scheduled to reach the total installed capacity of 4 GW and 2 GW by 2020, respectively.

A. Wind power modeling

Dogger Bank and Hornsea wind power plants are under construction in the Humber Estuary region. Six years measurements of hourly off-shore wind speed in the area close to these two wind power plants are available. NG cooperated with a consultancy company to calculate the hourly capacity factor of upcoming wind power plants in that region. In this paper, we used this data to estimate the probabilistic model of capacity factor in different seasons. Three seasons spring/fall, summer and winter are considered. The best PDF matching with past data is Beta distribution function expressed in (8).

$$f(x) = \frac{1}{B(a,b)}.x^{a-1}.(1-x)^{b-1} \qquad (8)$$

The Beta function is defined on the interval $x \in (0,1)$. a and b are shape parameters.

The Beta functions estimating the seasonal capacity factors of off-shore wind power plants in Humber region are illustrated in Fig. 3. The relevant shape parameters are given in Table I.

TABLE I
SHAPE PARAMETERS OF BETA FUNCTIONS MODELING THE CAPACITY FACTOR OF OFF-SHORE WIND POWER IN HUMBER REGION

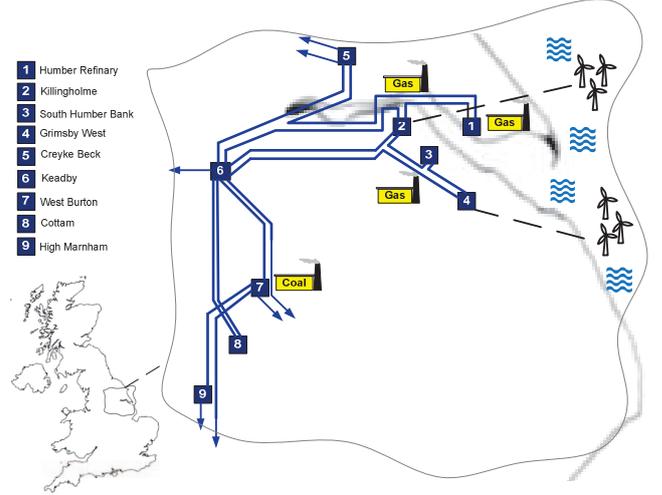| Season	a	b
Winter	0.56	0.43
Spring/Fall	0.56	0.65
Summer	0.61	1.53

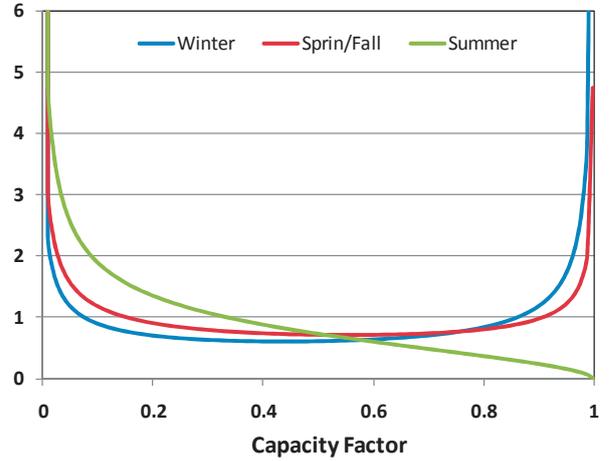Fig. 2 The transmission network in the Humber Estuary region.

Fig. 3 Probability distribution functions of capacity factor of offshore wind power in Humber region

B. Dynamic thermal rating modeling

The meteorological data including the historical hourly ambient temperatures and wind speeds of four years were gathered by one of the synoptic stations in the Humber region. This data as well as the characteristic transmission lines are used to calculate the hourly thermal limit of each transmission line shown in Fig. 1. As the weather conditions change in the course of the year, a varying thermal rating is calculated. These variations can be modeled with a PDF. The best PDF matching with the calculated thermal ratings is concluded to be Generalized Extreme Value distribution function expressed by (9).

$$f(x) = \left(\frac{1}{\sigma}\right).\left(1+k.\frac{(x-\mu)^{-\frac{1}{k}}}{\sigma}\right).e^{\left(-\left(1+k.\frac{(x-\mu)^{-\frac{1}{k}}}{\sigma}\right)\right)} \qquad (9)$$

In (9) μ is location parameter, σ is called scale parameter, and k is the shape parameter.

For each transmission line seasonal PDFs of thermal rating are estimated. The corresponding parameters for seasonal PDFs of thermal ratings are tabulated in Table II. As an example, the seasonal PDFs for Grimsby West-South Humber Bank are illustrated in Fig. 4.

C. Correlation

In order to have scenarios which closely represent the reality, the correlations between uncertainties should also be taken into account. The four years data of hourly thermal ratings of Grimsby West-South Humber Bank are compared with the hourly capacity factor of off-shore wind farms in the similar interval to calculate the correlation between offshore wind powers and thermal ratings of transmission lines. Table III shows the resultant correlations in the Humber region.
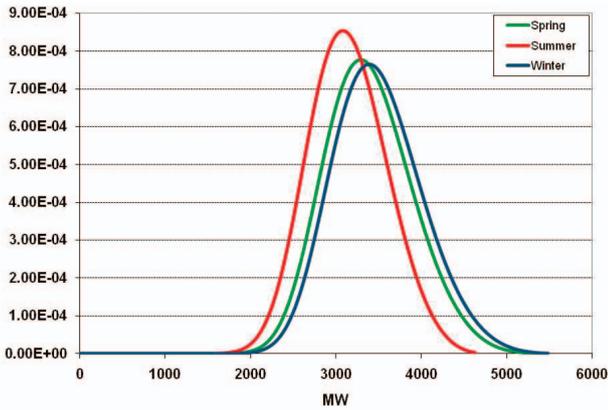

Fig. 4 Probability distribution functions of thermal ratings of Grimsby West-South Humber Bank for different seasons.

TABLE II
PARAMETERS OF PDFS REPRESENTING SEASONAL THERMAL RATINGS OF OVERHEAD LINES IN HUMBER REGION

OH Lines		Spring			Summer			Winter		
From	To	k	σ	μ	k	σ	μ	k	σ	μ
3	2	-0.19	499.91	3395.10	-0.22	458.20	3185.15	-0.18	507.31	3481.10
2	6	-0.19	499.91	3395.10	-0.22	458.20	3185.15	-0.18	507.31	3481.10
4	6	-0.19	506.91	3492.09	-0.22	464.42	3285.01	-0.17	514.22	3572.25
4	3	-0.20	483.32	3187.84	-0.23	443.13	2971.20	-0.19	490.48	3287.14
2	1	-0.19	506.72	3491.41	-0.22	464.58	3285.71	-0.17	514.45	3572.45
1	5	-0.19	506.72	3491.41	-0.22	464.58	3285.71	-0.17	514.45	3572.45
2	6	-0.19	506.72	3491.41	-0.22	464.58	3285.71	-0.17	514.45	3572.45
6	7	-0.19	533.47	3134.00	-0.24	487.35	2831.70	-0.21	547.42	3308.77
6	7	-0.19	533.47	3134.00	-0.24	487.35	2831.70	-0.21	547.42	3308.77
8	6	-0.19	372.86	2468.92	-0.21	334.57	2319.49	-0.23	410.67	2525.25
8	6	-0.19	372.86	2468.92	-0.21	334.57	2319.49	-0.23	410.67	2525.25
7	9	-0.19	372.86	2468.92	-0.21	334.57	2319.49	-0.23	410.67	2525.25

TABLE III
THE CORRELATION BETWEEN THERMAL RATING OF OVERHEAD LINES AND OFF-SHORE WIND POWER IN HUMBER REGION

	Thermal Rating		
	Spring/Fall	Summer	Winter
Capacity Factor of Wind farms	0.549	0.47	0.659

Also, the correlation between thermal ratings of transmission lines is assumed to be 0.8 as all transmission lines experience similar weather condition. The two wind power plants in the Humber region, Dogger Bank and Hornsea, are geographically close to each other so they are very likely to be exposed to the same wind regime. Therefore, a high cross correlation of 0.8 is also assumed for these two wind power plants.

V. RESULTS

Latin Hypercube Sampling (LHS) is used to generate 500 scenarios each of which consists of realizations of thermal ratings for transmission lines, along with outputs of wind power plants. Additionally, all scenarios comply with the correlation between wind power plants, correlations between the thermal ratings of overhead lines, and correlation between thermal ratings and outputs of wind power plants. The horizon year is assumed to be 2015 when the installed capacities of Dogger Bank and Hornsea are 3 GW and 2 GW, respectively. Fig. 5 illustrates the five hundred scenarios of wind powers associated with Dogger Bank and Hornsea in winter. Each spot in Fig. 5 represents one wind power scenario. The distribution of spots demonstrates a high correlation between wind power generated by Dogger Bank and Hornsea, as the correlation is originally set to be 0.8 between wind power plants. Dogger Bank is assumed to be connected to Killinghome substation and Hornsea is connected to Grimsby west.

A. Sensitivity analysis

A dc power flow is run for the intact network as well as "N-1" and "N-D" contingent networks, taking into account all 500 scenarios. Fifteen single outages for "N-1" networks and 11 double outages for "N-D" networks are considered.

The overloads of transmission lines in Humber region are calculated for two different cases where in the one case the thermal ratings comply with 500 scenarios and in another case, the traditional approach, the constant seasonal thermal ratings are considered. The comparison between these two cases shows those transmission lines which are likely to experience overload and also how much overload may be reduced if dynamic thermal ratings are considered. Table IV shows the probability of the line experiencing overload in the intact network as well as contingent networks. For example, 500 load flow scenarios are calculated for the intact network where in

38.3% of scenarios the intact network observes overload in transmission line 6-7 (Keadby-West Burton) if constant thermal rating is assumed. This line experiences overload for 28.1% of 500×15 cases (500 wind generation scenarios multiplies 15 single outages). Nonetheless, if dynamic thermal ratings are taken into account the likelihood of overload in Keadby-West Burton dramatically drops to 2.7% and 2.9% for intact network and "N-1" networks, respectively. It should be stressed that in Table VI only overloaded transmission lines are reported. It can be concluded from the sensitivity analysis results given in Table IV that transmission lines 6-7 and 7-9 (Keadby-West Burton and West Burton- High Marnham) are the best candidates to be included in dynamic thermal rating scheme as a considerable drop in the likelihood of overload is observed when dynamic thermal rating is assumed.

B. Constraint cost

There are three different types of generation in the Humber region namely gas, coal and wind. Some power plants should be constrained off in order to prevent overloading the network after a single or double circuit outage. The SCOPF formulated by (7) is run for all 500 scenarios to determine the average amount by which each generator needs to be constrained off. The cost of wind generation is neglected as wind power is assumed to have priority over fossil fuel-based generators. Also it is assumed that NG incurs 70 £/MWh for constraining off the fossil fuel-based generation. The calculation is carried out only for the winter when the congestion is more likely to occur. The winter load duration curve consists of eight load levels, as given in Table V.

The constraint cost is compared between the system with constant thermal rating and the system with dynamic thermal rating. In Fig. 6 the constraint costs for both cases at each load level are illustrated. As results show, in total 53% reduction in constraint cost (equal to £1.2 million annual saving) can be expected to be achieved if the real time temperatures of conductors are monitored.

VI. CONCLUSION

This paper has explored the application of dynamic thermal rating of transmission lines to enhance the amount of wind power that can connected to a transmission system close to its operating limit. Uncertainties in wind output were modeled in the form of probabilistic density functions using historical hourly measurements of on-shore and off-shore wind speeds. A probabilistic approach was applied to generate possible scenarios of wind power output and thermal ratings of overhead lines. The proposed approach suggests the best location where temperature monitoring facilities should be installed to enable dynamic thermal rating. Finally, the potential benefit of dynamic line rating by way of reduced

constraint costs was quantified for the Humber region within the National Grid system.
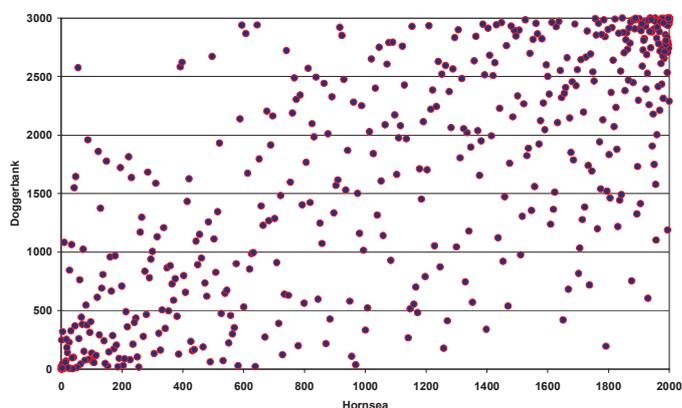
Fig. 5 Scenarios of wind power generated by Dogger Bank and Hornsea

TABLE IV
THE POSSIBILITY OF OVERLOAD IN TRANSMISSION LINES IN HUMBER REGION

OHL		Intact Network (500 cases)	"N-1" Networks (500×15 cases)	"N-D" Networks (500×11 cases)
From	To			
Constant thermal rating				
6	7	38.3%	28.1%	24.9%
7	9	1.3%	15.6%	16.8%
8	6	0.0%	5.0%	4.9%
2	6	0.0%	1.1%	7.1%
Dynamic seasonal rating				
6	7	2.7%	2.9%	9.3%
7	9	0.7%	1.6%	2.9%
8	6	0.0%	0.6%	0.4%
2	6	0.0%	0.1%	4.4%

TABLE V
LOAD DURATION CURVE IN WINTER

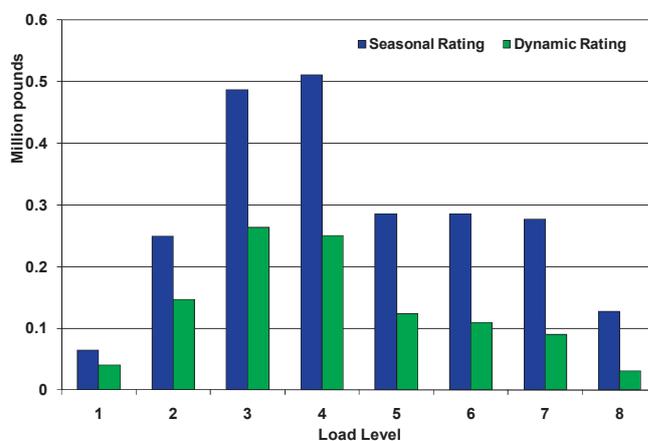| Load level (% of peak)	100%	91%	85%	79%	73%	67%	61%	52%
Duration (hour)	56	247	555	678	448	542	656	442

Fig 6. Comparison between constraint costs at different load levels in winter considering Dynamic thermal ratings and constant thermal ratings

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