UPGRADING THE GRID FOR WIND ENERGY: OPTIMIZATION BEFORE REINFORCEMENT BEFORE BUILDING NEW LINES

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Summary

Instead of building new lines in many cases momentary reductions of possible wind energy input during the frequent but very short wind peaks allow almost all of the wind energy supply except a few short extreme peaks to be fed into the grid. If an increase in transmission capacity is still necessary, the replacement of conventional conductors of existing lines by high temperature conductors combined with real time monitoring of conductor temperature is often the preferable solution. It meets no resistance from citizens and costs by far less than the planning and building of new lines.

1. Wind energy and transmission lines

1.1. Geographical and statistical distribution of wind energy potential

Wind is a stochastic source of energy showing rather irregular fluctuations with short unpredictable peaks on all time scales from seconds to years. Only the short fluctuations up to the 10 minute time scale are averaged out in a typical wind park of some km spatial extension. Reasonably reliable 3 to 6 hours predictions for 1-hour-averages are usually available from meteorological services. This allows control and reserve planning of the entire power station and transmission system even when – as in some regions – the share of wind energy goes to 25% and beyond.

1.2. Transmission to centers of demand

Geographically regions of high wind energy potential like the North Sea coasts in Europe or the big plains in Wisconsin or Texas in the USA are often far away from the centers of electric energy demand. Hence the growth of wind energy production requires increased long distance transmission capacity. With the climatic stabilization goal in mind many countries aim at a 20% share and more of wind energy in their total electric energy production within the next 10 to 15 years. Even if some fossil fired and nuclear power plants are shut down in this process making some transmission capacity available for renewables, a wind related upgrading of the grid will be unavoidable in many cases.

1.3. Design capacity for different types of wind related lines

There is another important distinction to be made: local lines for wind energy collection versus long distance lines for the transmission to regions of high demand.

(a) On the input side regional wind parks with a typical installed total generator power of some tens to some hundreds of megawatt feed into the grid. Line reinforcement where possible, or new lines, usually in the voltage range of 60 to 120 kV with typical lengths of 10 km to 50 km are required for the connection with the very high voltage transmission grid. Due to the high correlation of wind speeds within the limited area of such windparks these ´wind-devoted´ local lines must be able to carry a typical peak power of 90% to 95% of the installed generator power of the windpark feeding into them.

(b) On the transmission side, operating at voltages of 300 kV and above – in the future also with dc-technology at or above 500 kV – the situation is usually different: the temporal and spatial correlation of all windparks in a large and diverse region feeding into this overlay grid is not very high, c.f. table 1: In Germany 2006 the total wind power production added up to 83% of the total installed wind power for only 15 minutes, and to 70% for only 100 hours.

Table 1 : Wind energy produced

	East Germany		Germany
	2006	2007	2006
	wind power installed [GW]		
	7,6 (100%)	8,6 (100%)	19,3 (100%)
[h]	wind power produced [GW]		
0,25	6,8 (90%)	7,7 (90%)	16,1 (83%)
10	6,6 (87%)	7,4 (87%)	15,4 (80%)
100	5,4 (72%)	6,8 (79%)	13,5 (70%)
200	5,0 (67%)	6,4 (75%)	12,4 (64%)
300	4,7 (63%)	6,0 (70%)	11,6 (60%)

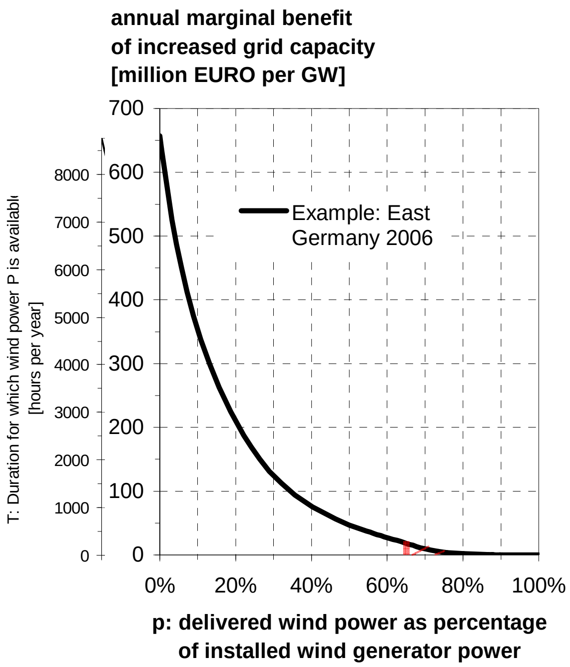
2. Economic optimum

The economic optimum criterion for wind related investments in the high voltage grid is the usual one: the marginal benefit must be just above the marginal cost. For investments to increase the power capacity of the electric grid for increased wind power input this means: The additional annual economic benefit of wind energy per additional transmission capacity (measured e.g. in EURO per kW) must be equal to or slightly larger than the additional annual cost in EURO per kW of additional transmission capacity.

2.1. Benefit of wind energy supply and marginal benefit as a function of grid capacity

To determine the optimum one may use a wellknown statistical tool: the annual duration-power-curve of wind energy input, a curve that is determined by the utilities from the wind power input into their grid during all 10 to 15 minute intervals of the current year, c.f. fig. 1. This curve shows for each percentage p of the total installed wind generator power $P_{installed}$ in the utility´s domain, for how many hours T of the year this power was available.

Fig. 1 : Duration-power-curve



Installed wind power in 2006 was 7.6 GW

(a) As a result of the fundamental formula ´energy = power times duration´ the area under the curve (i.e. the integral of the corresponding function) from p_0 = 0% to a fixed value, e.g. p_1 = 65%, multiplied with the value $P_{installed}$, equals the annual energy yield fed into the grid, when the input is limited to such a fixed value P_1, e.g. because the limiting power P_1 is the maximum power that the transmitting grid can support.

(b) If the annual energy yield [kWh] is multiplied by an appropriate monetarization factor [EURO or US$ per kWh] the area under the curve (right hand scale on the vertical axis) equals the monetary benefit of the wind energy input. This monetarization factor ought to represent at least a proxy for the value that a kWh renewable energy represents for society at large. In Germany (and similarly in many other countries) this proxy has been fixed by legislation in the ´Renewable Energy Act (EEG)´ by defining a minimum feed-in tariff for wind energy of around 0.075 EURO per kWh. Example: 8.000 hours per year (first axis of fig. 1) times 0.075 EURO per kWh equals 600 million EURO per GW (second axis of fig. 1).

(c) But when the area under the curve equals the total benefit, the curve itself at a given value of P (i.e. the derivative of the integral) represents the marginal benefit: additional benefit per additional grid capacity [EURO per kWh]. Thus up to a scale factor the duration-power-curve determines the marginal benefit curve, a result that – to our knowledge – has not been known before.

2.2. Cost and marginal cost of grid capacity reinforcements

The cost of an upgrading of the grid **with a given technical solution** is approximately proportional to the required increase in allowed maximum power – and, of course, to the length of the line(s) to be reinforced. Thus the marginal cost – additional line cost per additional transmission capacity – is roughly constant at a given length and for a given technology. Compared to a new conventional 380 kV overhead line the investment cost of a three phase underground cable – where applicable – is supposed to be at least three times higher, that of a very high voltage dc line in gasfilled tubes at least five times higher. But the investment cost for upgrading existing lines with monitored high temperature conductors is only 50% or less of the cost for a new line of the same transmission capacity.

For East Germany with the wind energy statistics given in fig. 1 a recent study [1] comes to the result that a planned new overhead line with 2 three-phase 380 kV systems and a length of 160 km would amount to an annual cost of roughly 17 million Euro per GW. This relatively high figure is explained by the fact that the line cuts through a regional nature park, hence high external cost, making up half the annual cost, and with difficult topography, hence high technical cost of around 1 million Euro investment cost per km.

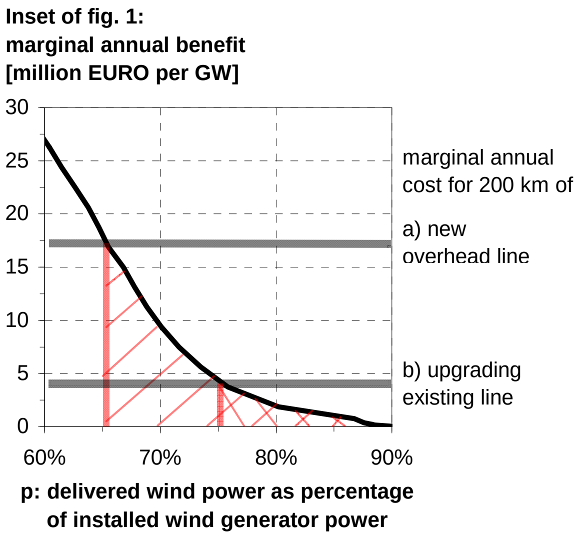
The alternative in this case, the reinforcement of an existing neighbouring line in the grid with high temperature conductors and real time monitoring leads to a projected cost of only about 4 million Euro annually.

2.3. The economic optimum of grid capacity reinforcement

As stated before an economic optimum with respect to the deployment of a variable factor (in our case the transmission power up to which the grid is reinforced) prevails, when the marginal benefit obtained is at least equal to the required marginal cost.

With the graph of the marginal benefit function given in fig. 1 (for the specific regional wind energy production in eastern Germany), and the marginal cost figures of sec. 2.2, one finds the intersection of benefit and cost curves shown in fig. 2.

Fig. 2 : The optimum – intersection of marginal benefit and marginal cost curves



Result for the optimum in this case: a new 200 km overhead line should be designed for a maximum power of about 65% of the installed wind power. Line reinforcement by replacing the conductors of existing lines by monitored high temperature conductors is optimal at around 75% of the installed wind power.

If the ´rejected´ wind energy, given by the shaded area under the curve to the right of the 65% or 75% limit, is compared with the total potential annual wind energy input, one finds that less than 1% or 0.3% respectively must at most be excluded from the grid.

At closer inspection at least for Germany the economic optimum for the power capacity of this grid lies at 60% to 70% of the total installed generator power of all windparks delivering their momentary power. Even this averaged-out power of let´s say only 65% of the installed wind power is exceeded so rarely in a typical large and geographically diverse region (coastal plains, hilly areas, mountain ranges far from the sea etc.) that building up an additional transmission capacity of more than 65% of the total installed wind generator power would represent an overinvestment.

Including other examples one comes to the general conclusion that the optimum design for the long distance grid transporting wind energy must allow something between 60% and 80% of the total installed wind generator power to be admitted, ´discarding´ no more than 1% and less of the potential production.

3. Technical alternatives for upgrading the grid

When the need for an upgrading of the existing very high voltage grid (above 300 kV) has been shown, the consecutive steps to be taken have been described by E.ON, Germany´s leading utility, as follows: Optimization of the grid before reinforcement before building new lines.

As it turns out methods and materials for the optimization and the reinforcement of the existing lines have been developed and set to work on a large scale world wide in the last decade.

3.1. High temperature conductors and real time temperature monitoring

Conventional aluminum-steel conductors are designed for full load temperatures of about 80°C with short excursions of up to 100°C. Today leading producers offer conductors that can operate at 120°C up to 180°C continuously with allowed short peak temperatures of well above 200°C. These conductors use one or several of the following features:

- Annealed and prestressed aluminum,
- also aluminum-alloys with zirconium,
- improved heat transition to the surface of the cable by the use of Al-strands of trapezoidal instead of circular cross section,
- a gap-design by which the mechanical tension is carried predominantly by the steel core with its low thermal expansion;
- finally a high temperature resistant steel or invar core.

For a recent overview c.f. CIGRE papers [2] and [3], where also a list of current types is given. In recent years such conductors have been installed worldwide on all voltage levels, also above 345 kV. In Japan alone obout 40.000 km are in operation.

Operating such conductors at constant power rating, i.e. without real time temperature monitoring, the thermal limit load may be increased to 160% to 200% of the allowed maximum power transmission of comparable conventional lines.

If the increased transmission capacity is needed largely for the intermittent wind energy transport with typically only 1,500 to 2,500 annual hours of full power input, then it is likely that many of the peak wind energy input hours coincide with high wind speed or low air temperatures also along the entire transmission line. This is where temperature monitoring comes in.

One proven system of real time measurement of the actual conductor temperature is based on the functional dependence of the mechanical tension in the cable on its length between two fixed points on adjacent suspension pylons which in turn, due to thermal expansion, is determined by the average cable temperature. Thus with a tension gauge on the zero voltage side of the insulator at some critical sections of a line and online radio transmission to the next control station, any overheating of the line can be avoided. In addition to the general advantages of this temperature monitoring – saved cost for dispensable more expensive reinforcements, less intervention of reserve power etc. – it is particularly useful along lines that are designed for large scale wind energy transmission, as another look at the typical power-duration-curve in fig. 1 shows: Even if the design capacity of the line were limited to, let us say, 50% of the installed wind generator power, this limit would be surpassed only during around 500 hours per year and, as the real time statistics of the intermittent wind energy production shows, mostly only for very short periods of some hours or less. Most of these peaks can safely be accommodated by the monitored grid. The amount of ´discarded´ wind energy is in the one percentage range of the potential yield.

On the European standard voltage level of 380kV one 3-phase-circuit with ACSS/EHS high temperature conductors combined with temperature monitoring will allow a thermal limit of power of well above 3 GVA, for short peaks most of the time above 4 GVA.

3.2. Wind energy and monitored high temperature conductors – a perfect match

There are several specific features of wind energy systems that make the proposed cost efficient technical solution – reinforcement of existing lines with high temperature conductors and real time temperature monitoring – particularly attractive:

(a) The power output of modern wind turbines is completely controllable within seconds by changing the pitch, i.e. the attack angle of the rotor blades. Any reported overload of the relevant transmission lines can thus be avoided within their typical reaction time of several minutes.

(b) A detailed analysis of wind speed statistics for Germany shows that momentary reductions of possible wind energy input during the intermittent short wind peaks result in very small losses in total wind energy yield. Similar results are expected for other countries or regions with strongly intermittent wind. The windmill owners may even be compensated for these losses from the considerable savings in investment cost for the avoided new additional lines.

(c) Because of its fluctuating character wind energy has to be backed up with fast sources of control and reserve energy anyhow. Thus when temperature monitoring shows that a reduction of wind energy input is required to avoid overload, this reduction is **not** carried through to the electric energy consumers any more than a slackening of wind speed. This distinguishes a largely wind energy devoted supply line from a consumer devoted distribution line which has to carry the momentary demand at any time.

3.3. Cost comparison

It is generally accepted that the cost for the conductors amounts to roughly one third of the total cost of the typical 2-system overhead high voltage line. For high temperature conductors with a temperature resistant steel core the cost is about twice that of a conventional Al/St-conductor. Including the cost for the real time monitoring system – at most an additional 10% of the total investment cost of a new conventional line – one may estimate that the optimum upgrading of an existing line with these new technical features costs less than one half of the investment cost of building a new line.

With respect to the running cost it is true that the electric energy loss per kWh to be transmitted is approximately two times higher when only one line with high temperature conductors is available than when the existing line is supplemented with an equivalent new line. But one must also take into account that when the additional load is largely due to wind power, the number of full power hours is limited (1,500 to 2,500 hours per year) and the electric loss is compensated with renewable wind energy thus without additional CO_2 emission.

Keeping in mind that the cost of any type of reinforcement of the grid is eventually paid by the consumer it is evident that wherever technically possible the upgrading of existing lines with the new, but internationally proven technology of monitored high temperature conductors should be the preferred solution, in particular when the reinforcement is needed largely for wind energy transmission.

References:

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[2] Conductors for the uprating of overhead lines. Methods for increasing the thermal rating of existing overhead transmission lines: weather data and load profiles fed into computer programs, real-time monitoring, re-assessment of electrical clearances under an existing line, replacement of existing conductors. REF. 244, SC B2 WG B2.12, Conseil International des Grands Réseaux Electriques, http://www.cigre.org, Paris, 2004.

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