Risk Analysis of Smart Solutions to Increase Wind Power Hosting Capacity in Subtransmission Network

Elforsk rapport 13:51

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Förord

Denna rapport är framtagen av programmet "Riskanalys II", som är en fortsättning av det tidigare genomföra programmet "Riskanalys I" som drivs av Elforsk. Projektet är genomförd av STRI AB, kontaktperson Nicholas Etherden, nicholas.etherden@stri.se.

Jag vill tacka programstyrelsen för Riskanalysprogrammet och programmets kunder för bra samarbete och att de möjliggjort pojektet *Riskanalys av nya lösningar för att öka acceptansgränsen i regionnät*.

Programmets programstyrelse består av följande ledamöter:

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Fortum Distribution AB;   C4 Elnät AB;
Svenska Kraftnät;   Öresundskraft AB;
Göteborg Energi AB;   Gävle Energi AB;
Jämtkraft AB;   Sundsvall Energi Elnät AB;
Borås Elnät AB;   AB Borlänge Energi.
Föreningen Industriell Elteknik, FIE;

Rapporten redovisar att genom att tillämpa lösningar som fjärrutlösning, produktionsbegränsning och dynamisk belastningsförmåga kan acceptansgränsen för vindkraft i regionnät öka väsentligt, vilket medför att risken flyttas från elnätsföretag till andra intressenter som i sin tur får ekonomiska fördelar. For att kunna bedöma fördelarna sett från de olika intressenterna beskriver denna rapport en bedömning av riskerna.


Susanne Olausson, Elforsk AB

Sammanfattning

Genom att tillämpa smarta elnät lösningar som fjärutlösning, produktions-nedstyrning och dynamisk belastningsförmåga kan acceptansgränsen för vindkraft i regionnät ökas betydligt. Riskerna förknippade med införandet av dessa lösningar studeras i denna rapport.

Sådana lösningar möjliggör att risken flyttas från elnätsföretag till andra intressenter som i sin tur får ekonomiska fördelar genom att man kan undvika investeringar i nätet som annars hade medfört höga anslutningsavgifter. För att bedöma fördelarna för de olika intressenterna analyseras de olika ekonomiska och tekniska risker som lösningarna medför. Analysen baseras på en utförlig analys av ett subtransmissionsnät.

Rapporten beskriver metodiken för att kvantifiera ökningen i acceptansgränsen för de olika lösningarna. Ökningar av acceptansgräns för vindkraft i regionnätet med de undersökta smarta lösningarna i kombination med produktions nedstyrning var visas för en nod i det studerade nätet i figuren nedan.
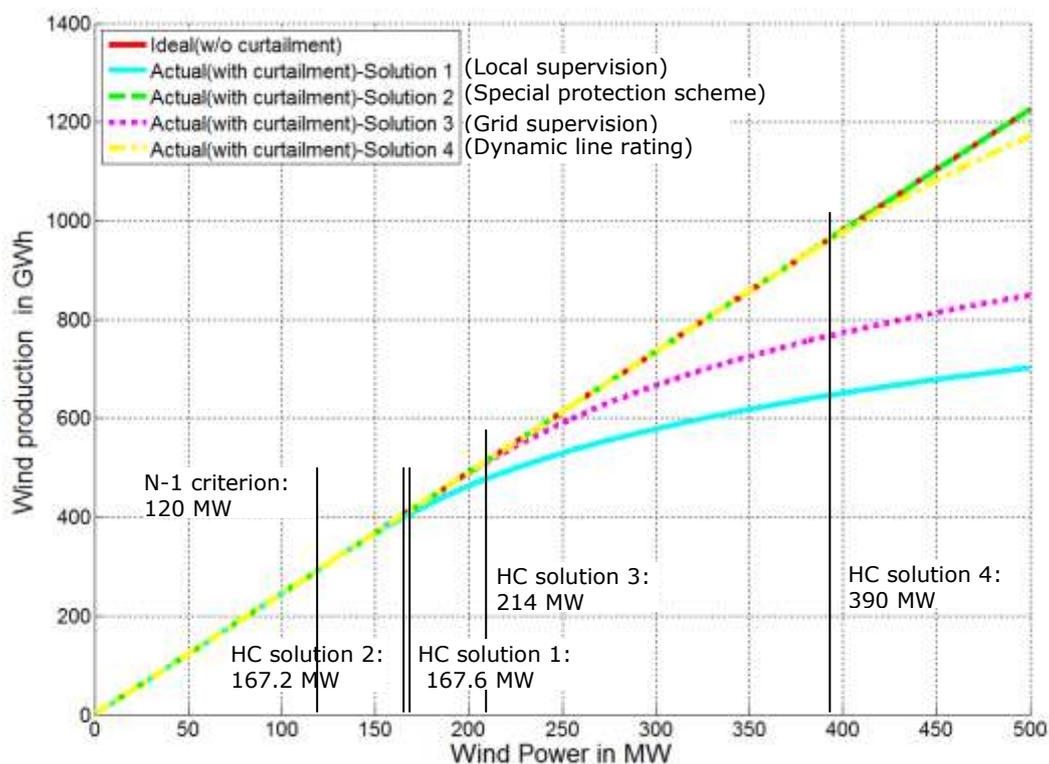
Jämförelse av acceptansgräns och produktions nedstyrning för fyra olika smarta lösningar. (Reproducerad från avsnitt 4.4.1 av rapporten).

Summary

This report analyses the risk associated with applying smart grid technologies to allow more wind power production than is permitted with classical network planning. The smart technologies studied include local supervision of network loading, special protection schemes (inter-tripping), grid wide supervision and dynamic line rating of overhead lines. By applying such solutions in combination with production curtailment the hosting capacity of wind power in the subtransmission network can be greatly increased.

These solutions make it possible to transfer risks associated with overloading of the network from the network operator to other stakeholders. The other stakeholders in response receive economic benefits by avoiding grid strengthening that would otherwise increase their connection fee. In order to assess the different stakeholders benefits technical and economical risks associated with the solutions are analysed. The analysis is based on results from detailed simulation of the solutions applied to a subtransmission grid in central Sweden.

The report describes in detail the hosting capacity concept and the used method to determine the limit for the different applied solutions. Using curtailment schemes or special protection systems allows for a large increase in hosting capacity without an increase in risk of overloading. This is shown for one node in the studied grid in the figure below.
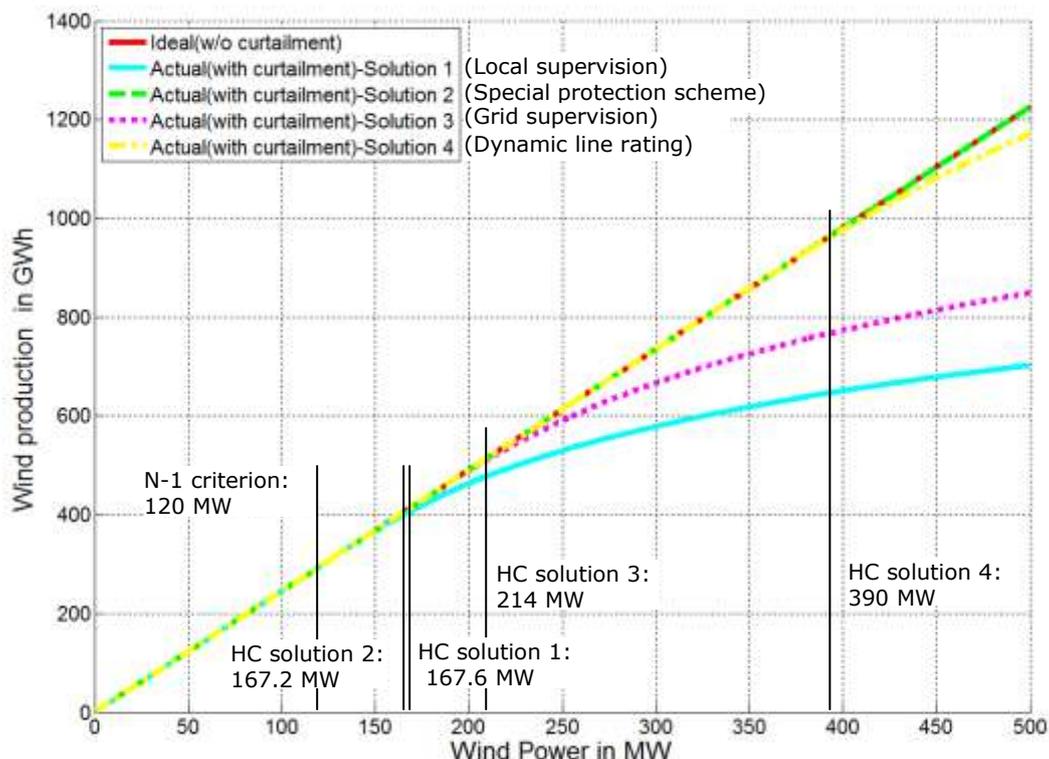

Figure 11 Power curtailment comparison, reproduced from Section 4.4.1. Superimposed as vertical lines is the hosting capacity for the different solutions as shown in Table 2 of the same section.

Contents

List of abbreviation, acronyms

HC	Hosting Capacity
DLR	Dynamic Line Rating
POC	Point of Connection
NHC	Network Hosting Capacity
PHC	Park Hosting Capacity
OHL	Overhead Line

1 Introduction

1.1 Project Background

The desire and need to connect more renewables such as wind power to the electrical network is one of the major challenges that network operators face today. When increasing the amount of connected renewable generation capacity to a distribution or subtransmission network the reliability and power quality for other customers must be kept acceptable. The term hosting capacity (in Swedish "acceptansgräns") was introduced by STRI as part of the European project EU-DEEP and is the subject for continued academic studies at STRI [1]. Hosting capacity is a measure that indicates the amount of renewable generation that can be connected to the network without compromising reliability and power quality for other users of the network [2]. The concept has been recommended by the European energy regulators [3] and the European grid operators [4] as a way to quantify the performance of future electricity grids (the "smart grid"). The Swedish Energy Markets Inspectorate has started a project with the goal of developing new performance index and hosting capacity is likely to be one of the important indices in a future regulation [3] [5]. The realization of the single European electricity market work is ongoing at EU level to develop common "grid codes". A number of grid codes are being developed by ENTSO-E in cooperation with ACER. A consultation process has started for the requirements to be met by all production units [6]. Work with other grid codes is ongoing.

Hosting capacity: There are a number of new technologies to increase the Hosting capacity without having to build new lines or cable connections. The benefits of such "smart grid" solutions are increased flexibility, shorter lead time as well as lower total cost. With some solutions it is also possible to transfer the risk of power outages to a limited number of network users which enables the wind producer to take over the risk as well as the responsibility of the reserves and balance this transfer of risk against the cost of conventional network reinforcements otherwise required. The report studies solution such as local and network supervision, inter-tripping and dynamic line rating coupled to curtailment in the form of gradual reduction of power output from the wind parks. The IT communication infrastructure and control system plays an important role in realising these solutions. See also [7] [8] [9] [10] [11] for more information on these methods.

Risk analysis of smart grid solutions: With smart grid solutions, such as those presented in this report, it is possible to connect more wind power but with the risk to the electrical network associated with the production will change. The overall risk may increase but this increase can be transferred to a limited number of network users. The risk can be transferred to a wind park owner that can feed more energy but at the same time taking a conscious risk of having to reduce production during at network congestion. The benefit for the wind park owner is lower connection fee. In the same way there may also be industrial or domestic customers who are willing to accept lower reliability for a lower connection fee and/or network tariff. The important point is that the solutions do not increase the risk for other network users or the network

operator. Possible risks for other network users are an increase in the number of interruptions due to errors in communication and control systems associated with the smart solutions. This implies a financial risk for the electricity companies as the number of interruptions affect revenue framework. The risk spectrum is changing in other words, in terms of both network stability and reliability, but also current economic risks. It is also important that the definition of reliability index, such as SAIFI and SAIDI, adapted to "demand response" and "curtailment" cannot be regarded in the same way as unplanned outages.

1.2   Increasing the Hosting Capacity

Hosting Capacity (HC) is defined as the amount of distributed generation for which the performance becomes unacceptable. One possible way of HC calculation is presented as follows:

- Choose a phenomenon and one or more performance indices;
- Determine a suitable limit or limits;
- Calculate the performance index or indices as a function of the amount of generation;
- Obtain the HC.

More details can be found in [2] and in Appendix C of this report.

In this study, the maximum one-hour average line (including both OverHead Line (OHL) and cable) current is chosen as the performance index, and the line rating (ampacity) is considered as the limit. Previous STRI studies have shown this to be the limiting performance index for subtransmission grids [12] [13]. There could be two ways to set the ampacity limits: one is to select the static maximum ampacity; the other is to consider the Dynamic Line Rating technique (DLR) which is only for OHLs. With DLR, the ampacity limit varies according to the real-time weather condition, which more accurately reflects the realistic loading capability of OHLs.

With both performance index and index limit determined, the values of such index should be calculated as a function of the amount of wind power at a specific Point of Connection (POC). Thus, the HC of the wind power can be decided when the index reaches the limit.

For clarity purpose, two Hosting Capacity concepts are further defined as follows, as well illustrated in Figure 1:

- Network Hosting Capacity (NHC), indicating the maximum amount of wind power that can be absorbed by the network itself without considering actual consumption at the POC.
- Park Hosting Capacity (PHC), indicating the maximum amount of wind power that can be injected into a specific POC, considering the actual consumption at the same POC.
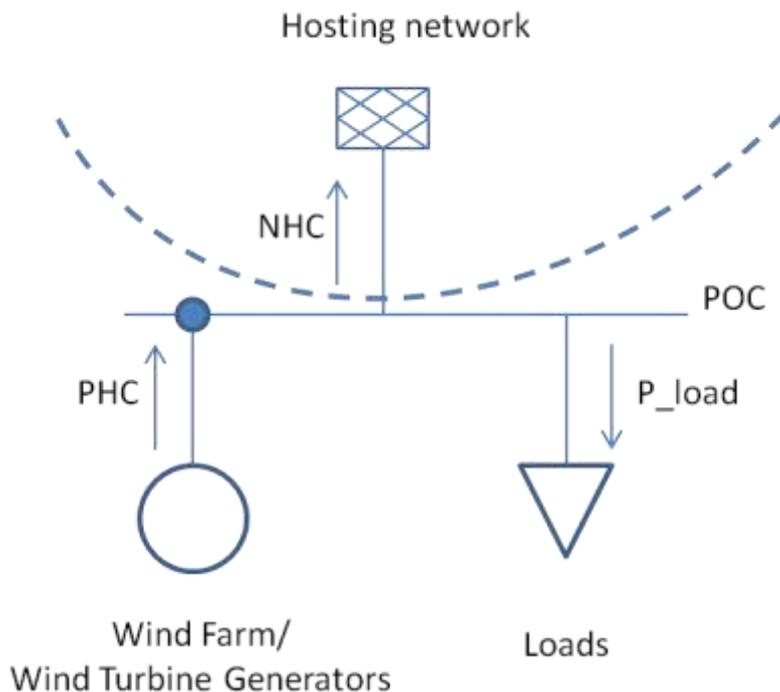
Figure 1 Illustration of NHC and PHC definition

The main difference between these two hosting capacity definitions is that the PHC only concentrates on the wind park itself, while NHC only focuses on the network itself, excluding the POC. Thus, whether or not there are other consumers or neighbouring connection at POC can make difference, and usually PHC is larger than NHC. In the case with negative load (injected power to the network, such as storages) connected, PHC is lower than NHC, which is out of the scope of this report. More information about storage related system study can be found in [10].

1.3   Report Structure

There are six main chapters in this report.

Chapter 0 introduces the project background and goals, as well as the Hosting Capacity (HC) concept in Section 1.2. Chapter 2 presents the studied regional network and briefly introduces the applied method. (More information on the method is to be found in Appendix A.) Chapter 0 provides a theoretical assessment of the possibilities to increase the hosting capacity of wind power in subtransmission networks and defines in Section 3.4 to 3.7 the four solution to do this that are handled in this report. In Chapter 5 the economic and operational risks associated with the studied solutions are discussed. A Special subsection describes the possibilities for the various solution present in grid code (Section 5.6) and required changes on continuity of supply indicators (Section 5.7).

2 Network and DC load flow method

2.1 Network Description

In order to serve the study purpose as defined in this project, a Swedish subtransmission network located in the centre of Sweden is selected. More details can be found in [8].

The selected network has been simplified with the following assumptions:

- All consumption and generation has been aggregated to 130 kV level;

- Reserve transformers not normally in use are excluded.

- Connections between substations at lower voltage levels are excluded.

- A reserve connection to the national grid over a neighbouring utilities network was represented by a single bus (bus 15) and assumed to be connected to the same slack bus, operated at 410 kV level.

This network is shown in Figure 2. It has 15 buses, 2 130/400 kV transformers, 7 loads and one wind power connection point at bus 7 with 34 MW wind turbine installation capacity. Actual substations have loads connected to them while line segments connected to each other are modelled as busbar without consumption.

This network is in practice usually operated as radial; with the dashed lines in Figure 2 as normally open reserve lines. By assuming these lines to be closed, the meshed network used as a base case in this study has been obtained.

The load flow data (hourly average of P and Q) of the network during the two years (2009-2010) was obtained by the measurement installed at the 50 kV side of the transformers. The network was selected due to requirements on time correlated wind production data from a 34 MW wind farm installation at bus 7.
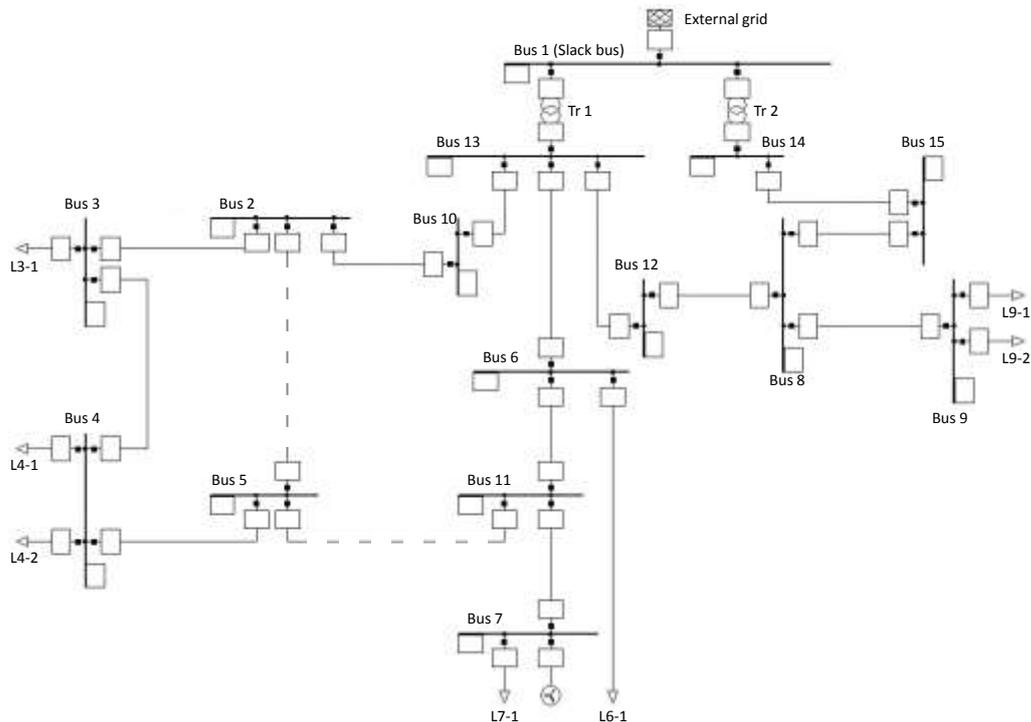
Figure 2 Simplified 130 kV subtransmission network. (Radial operation is without the dashed line.)

2.2 Network adaption

In reality the network is mainly limited by the wind power injection corridor: the line between Bus 7 and 11. This specific phenomenon may exclude the impact that is from the rest of the meshed network. Thus, in this study this weak link is deliberately enhanced by doubling its line rating, and the focus is on how the network would affect both hosting capacity and the power curtailment.

Some calculations on original weak network presented in Section 4.5 including a comparison of the hosting capacity in radial and meshed operated networks.

2.3 DC Load Flow

Calculating the hosting capacity according to the methodology applied in this report requires millions of load flow calculations. This is because a load flow is performed for each hour of the studied years where the installed wind capacity is increased stepwise for each case well beyond the hosting capacity limit in order to evaluate the effects of curtailment. Furthermore all points in the reference network are studied for all possible line failures.

The use of full ac load flow in a conventional power system analysis tool such as SimPow would require a clear prioritization of performed calculation. For each value in Table 1, 1.75 million load flows have been performed and for each curve in Figure 11 about 4.4 million load flows.

DC power flow or DC load flow is of the variations of the Newton method, and is a simplification of a full AC power flow and looks only at active power flows, neglecting voltage support, reactive power management and transmission losses [14]. This method was also applied in a previous Elforsk project [7].

The justification for applying DC load flow is due to its fast computation speed. However, it is worth noticing the difference between its results and the AC load flow results, as presented in Appendix A.

This difference could be variable, depending on how the reactive power flow affects the bus voltages and then the loading. As the line current I is related to both active power P, reactive power Q and voltage U, the line current could be unreliable with DC load flow, which assumes a constant voltage value for all busses and zero reactive power.

Nevertheless, provided that the reactive power flow data was not available for this study, DC load flow can still maintain sufficient accuracy for the study.

A detailed description of the methodology used in the report is described in appendix C.

3 The alternatives studied

3.1 More about the hosting capacity

In the conventional approach for connecting wind power (here to be referred to as "classical solutions") the amount of new production that can be connected to a grid is determined by the requirement that even in the worst case (e.g. maximum production and minimum consumption) there should not be any overload in the grid. Overload might be thermal overload, but also overvoltages, instability or insufficient reserves. In this report we will only consider thermal overload as that typically sets the limit to wind-power connection at subtransmission level. Similar approaches as discussed here can be applied when other phenomena set the limit.

In this report the thermal loading and capacity of transformers and overhead lines is studied. The presence of reserve capacity in stand-by transformers and power lines are often associated with the N-1 criterion. This criterion means that the grid should withstand any given single component failure. This implies that transformers, lines and cables must be able to transport all production and consumption even if a single component fails. This calls for an alternative transformer in stand-by or spare capacity, allowing the operator to redirect the power flow through the faulty component to other parts of the grid.

Consider a wind farm on 50-kV side of a 40 MVA, 130/50-kV transformer. Assume that the maximum loading of the transformer is equal to 40 MW. In that case it is possible to connect a wind farm with an installed capacity of 40 MW without running the risk of overloading the transformer.

Consumption by other network users on 50-kV side of the transformer will reduce the loading of the transformer when the wind park is at high production. When the minimum consumption is 5 MW, it is possible to connect 45 MW wind power without overloading the transformer at any time.

Considering the correlation between consumption and production, it is possible to connect even more wind power. The combination of maximum production and minimum consumption may be sufficiently unlikely to be neglected. But its probability is not known before an evaluation has been made. To make this evaluation, time series of both consumption and production are needed. Obtaining these is not trivial as production is typically not yet available when the hosting capacity should be calculated. Also is the future consumption not the same as the past consumption, although trends in consumption growth or reduction are typically slow. An approach that could be used is to combine historical consumption data with scaled-up historical production data from a smaller installation nearby or with production data calculated from historical weather data for a nearby location as done in Section 4.4. To obtain accurate results it is important that consumption data and weather data hold for the same period of time, e.g. 2010 and 2011.

From this we see that the hosting capacity is not a unique number but that it can be estimated in different ways, depending among others on the amount of data available and on the kind of models used. The hosting capacity

approach is to compare a performance index with a limit. The performance index in the first two cases (using zero and minimum consumption respectively) the power flow through the transformer and the limit is 40 MW. In the third case (using time series with actual consumption) the performance index is the highest hourly value of the power flow through the line (assuming that hourly values are used). The models can be extended further by including reactive power, by using the rms current as a performance index as in this report, by using shorter time scales, etc. Any change in model or change in index will give a different value for the hosting capacity.

The hosting capacity approach does not solve the question which of these values should be used, but it allows for a systematic and transparent approach towards setting limits. It should be noted that the final decision on how much wind power can be connected is up to the network operator, who is responsible for the reliability and quality of the supply.

3.2 Operating reserves

Consider again the case of calculating the hosting capacity from the rating of the transformer plus minimum consumption.

Operating two transformers in parallel, each with 40-MW capacity, would almost double the hosting capacity from 45 to 85 MW, assuming again a minimum consumption of 5 MW and assuming that the grid can host 80 MW of injected power at 130 kV. If the only aim of the second transformer would be to increase the hosting capacity, this would be a possible approach. However, when one transformer fails, the wind power could overload the other transformer causing an interruption for all grid users connected at 50 kV.

The use of two transformers in parallel is however often a method for increasing the reliability of supply for all network users. The loss of one transformer should in that case not result in an interruption. The remaining transformer, after the loss of one of them, can cope with 40 MW, so that the total power through both transformers should never exceed 40 MW to be able to cope with the outage of one of them. This is called the "N-1 criterion" and it is an important corner stone that has contributed a lot to the high reliability that we have come to expect from transmission and subtransmission grids.

Under the N-1 criterion, the hosting capacity on 50-kV side of two 130/55-kV transformers in parallel would be only 45 MW. The increased reliability comes at the expense of reduced utilization of the transformers, higher costs (two instead of one transformer) and at a reduced hosting capacity (45 instead of 85 MW).

In practice, the N-1 criterion is typically not applied to such transformers in Sweden during operation. Reserve capacity is in most cases available, but as "cold standby". This will not avoid interruptions but it will reduce the duration of interruptions a lot. Also for the subtransmission lines (e.g. 70 or 130 kV) the operation is not always according to the N-1 operational criterion. In the transmission grid this criterion is however used during operation in almost all cases.

3.3   Dynamic versus static hosting capacity

The above discussion assumes that a wind park, once connected, is allowed to inject its produced power into the grid in all cases. In calculating the hosting capacity it is assumed that the network operator will normally not order the owner of the park to reduce production. Such reduction of production is only supposed to take place during exceptional circumstances. The hosting capacity calculated under this assumption is a "static hosting capacity".

Consider again the above example with two transformers in parallel: the maximum installed capacity of the park is set by the situation when one transformer is in operation. A compromise is possible by allowing 85 MW installed capacity when two transformers are in operation, but only 45 MW when one transformer is in operation. This is called "dynamic hosting capacity".

In other words, instead of a static hosting capacity of 45 MW, a dynamic hosting capacity of 85 MW can be used when both transformers are in operation and 45 MW when only one transformer is in operation. In the latter case the production will be limited to 45 MW. It is important to understand that while the static hosting capacity sets an absolute limit to the installed wind farm capacity, a dynamic limit does not but will evaluate production and consumption at a given time.

Four alternative methods for design and operation of the subtransmission grid, are studied in this report that make use of dynamic hosting capacity in order to increase the amount of wind power integration that can be integrated in a subtransmission grid. These solutions are discussed in detail in the forthcoming sections. A qualitative risk analysis associated with these solutions is the subject of Chapter 5.

3.4   Solution 1: Local supervisory system

Consider that a wind farm is connected at 50-kV side of a 130/50-kV transformer (see Figure 3). A varying amount of consumption is also supplied from the same 130-kV bus. The earlier approaches calculated the hosting capacity for location 2 in the figure. This solution instead considers the hosting capacity at location 1.
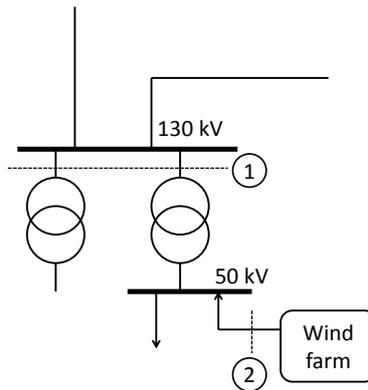
Figure 3 Local supervisory system with network hosting capacity (1) and park hosting capacity (2)

The maximum secure injection into the 130-kV grid is determined first. This is the network hosting capacity as introduced in Figure 1. The local supervisory system measures the power flow between the 50-kV and the 130-kV system (through all the transformers). When the power flow into the grid exceeds the network hosting capacity, the wind-power production is curtailed. The principle is shown in Figure 4 for a configuration with two parallel lines between the 130-kV and the main grid. When each of these lines has a transport capacity of 69 MW and the (N-1) criterion is applied, the network hosting capacity is equal to 69 MW. This would be the same as the static PHC (see Figure 1) in case the worst case of zero consumption is assumed. The gain is however in the fact that with this solution the dynamic PHC, during every hour of the year, is equal to the NHC plus the local consumption. The maximum size of the wind farm is no longer determined by the minimum consumption all of the time, but only when the consumption is actually low.

Low consumption typically corresponds to low electricity prices (assuming that local consumption is correlated with national consumption) so that the curtailment during low consumption is of less concern from an economic viewpoint.

Once curtailment is in place there is no actual need any more to limit the installed capacity, but it would not make economic sense to build a park larger than the NHC plus the maximum consumption as such a park would never be able to inject its maximum production. Therefore all PHCs calculated in this report for solution 1 (and also 3 and 4) including curtailments are equal to the NHC plus maximum consumption.

When the installed capacity of the wind farm is less than the NHC plus minimum consumption, the curtailment will never be activated. When the installed capacity increases this amount, curtailment will result in the annual production being less than in the case of no curtailment. The loss in annual production will increase with increasing installed capacity. As a result the utilization of the park (in hours of full capacity per year) will decrease with increasing installed capacity. The maximum size of the park is no longer a matter of limiting the impact on the grid by the network operator, but an economic trade-off for the owner of the wind farm.

Annual production as a function of installed capacity will be affected by the curtailment as seen in Figure 11 of Section 4.4.1.
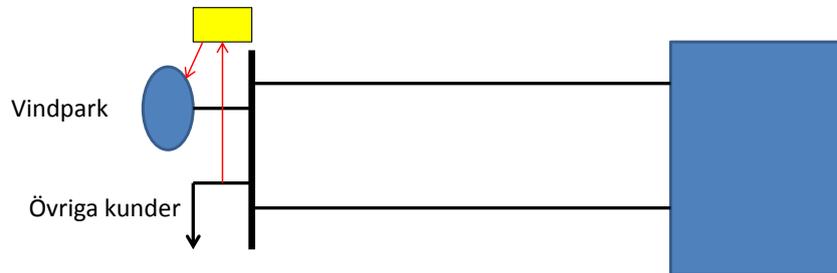
Figure 4 Method 1: wind power curtailment according to consumption

3.5   Solution 2: special protection systems

Consider again the network configuration with two parallel lines between the 130-kV bus under study and the main grid. Each of the lines has a transport capacity of 69 MW and the minimum consumption is assumed to be 9 MW. When the N-1 criterion applies, the static hosting capacity is 69 + 9 = 78 MW. As explained before, in the two-transformer example, a dynamic hosting capacity can be introduced, which would be 2x69 + 9 = 147 MW whenever both lines are in operation. With one line out, the dynamic hosting capacity drops to 78 MW.

A straightforward implementation of this solution is to allow up to 147 MW installed capacity. Whenever one of the four breakers in Figure 5 opens and intertrip signal is generated that removes all or some of the wind power so that the remaining installed capacity is at most 78 MW. Such intertrip schemes are not uncommon in the transmission and subtransmission grids of many countries including Sweden and have been present since long before wind-power became an issue at these voltage levels.

In a modern variant of the scheme, a curtailment signal may be generated instead of a trip signal. In an earlier study a distinction was made between "soft curtailment" (where only the minimum-necessary amount of production is curtailed) and "hard curtailment" (where the whole or part of the wind farm is disconnected). It was shown that the annual production with hard curtailment can be much lower than with soft curtailment [1] [9].

With two parallel lines, intertrip ("fjärrutlösning") or curtailment triggered by line tripping is easy to implement because it is immediately clear which line tripping requires curtailment of the wind-power production. In a meshed grid this is not always obvious and studies are needed to find these relations.
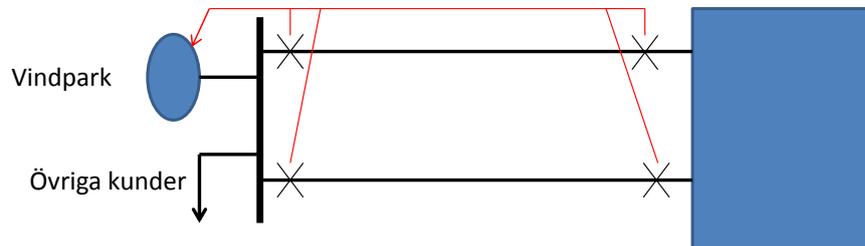
Figure 5 Method 2: wind power curtailment according to 'special protection systems

3.6   Solution 3: grid supervision system

In this solution, the previous two solutions are combined, as shown in Figure 6. The signal generated by the tripping of one of the indicated breakers is no longer directly send to the wind farm but to the local supervisory system. For the case with the two parallel lines, the NHC would normally be set to 2x69=138 MW and to 69 MW when one of the breakers opens. The change in NHC will also result in a reduction of the PHC.
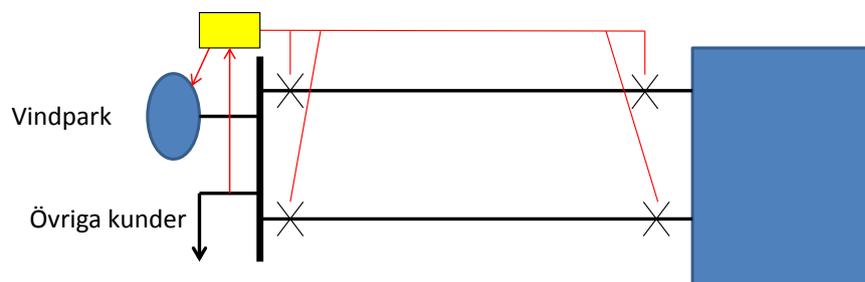
Figure 6 Method 3: wind power curtailment according to both consumption and 'special protection systems'

An alternative implementation of the same solution would be to monitor the currents flowing through the lines and to curtail wind-power production whenever the current through a line comes too close to the ampacity of the line.

In a meshed grid, the practical application of this becomes more complicated, for either of the two implementations, especially when wind power is present in large amounts at different busses. Upon the opening of a circuit breaker a new NHC should be calculated for each local supervisory system. In the alternative implementation, curtailment signals should be sent to one or more local supervisory controllers or to one or more wind farms whenever a line current exceeds its limit.

3.7   Solution 4: Dynamic line rating

In the previous solutions the different hosting capacities have been changed from static to dynamic. With solution 1 the PHC is dynamic but the NHC is static; with solution 2 the NHC is dynamic but the link between the PHC and the NHC remains static (i.e. equal to the minimum consumption); with solution 3, also the link between NHC and PHC becomes dynamic.

But in all cases, the line rating of the lines was considered as a static parameter. The next step is to introduce the ampacity as a dynamic line rating parameter that is no longer based on a worst-case but on the actual conditions at any moment in time, e.g. every hour. This solution is referred to as "dynamic line rating".

With dynamic line rating the ampacity of the line is calculated for example every hour. There are different methods available for this, all of which are still under development. A direct method would be based on measuring the conductor temperature and/or tension at several locations along the line and comparing this with design values. Indirectly, the (dynamic) ampacity might be calculated based on measurements and/or predictions of temperature, wind speed, etc along the line.
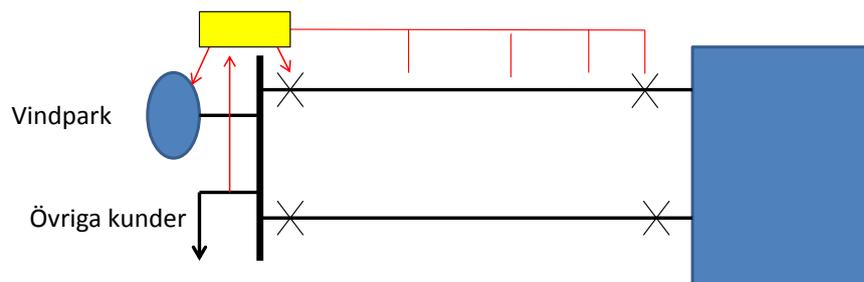
Figure 7 Method 4: wind power curtailment according to both consumption and 'special protection systems' with DLR

4 Impacts of smart solutions

As both network operators (either subtransmission or distribution network) and wind farm developers are concerned about how much wind power could be realistically injected into one specific network, it is necessary for the network operator to investigate the maximum degree of acceptance for wind power in its network. Meanwhile, the wind farm developer would appreciate as much wind power to be injected as possible, which leads to another necessity: to study the smart solutions potential to increase the maximum installed capacity of wind power.

Based on the Hosting Capacity (HC) concept as presented in Section 3.1, this project proposes four solutions to increase the hosting capacity of wind power in one network, as presented in the remainder of Chapter 0.

With different solutions, there will be different wind power hosting capacity, and each solution may lead to certain wind power curtailment for possible hosting capacity increase. Thus, it is necessary to obtain the solid knowledge about how those solutions will affect the hosting capacity, as well as how much power curtailment is needed for each solution. The understanding of the difference among different solutions can therefore benefit both network operators and wind farm developers for wind farm planning and smart solution selection.

To serve such purpose, the network as presented in Chapter 4 has been considered as a specific example for the investigation. Some adaptions are assumed as presented in Section 4.2. This chapter will first introduce the general calculation methodology, and then present the results for the network.

Section 4.1 presents the calculation methodology for hosting capacity acquisition and the power curtailment calculation. Section 4.2 focuses on the meshed operation for the network with maximum wind production consideration for the hosting capacity calculation, which is the conservative case. As an example, Bus 7 is selected as the POC. In Section 4.3, the study is extended to other POCs. Instead of the maximum wind production, Section 4.4 presents the study with the real wind power production. For comparison, Section 4.5 conducts a similar study on the network without adaption, for both meshed and radial operation with maximum wind production.

4.1 Calculation method

In order to calculate both Hosting Capacity and power curtailment, there must be some inputs available as Figure 8 illustrates.

For Hosting Capacity, the following inputs are necessary for calculation:

- Network data: busbars/terminals, lines, transformers, loads, generators, etc.;
- Definition of the Point of Connection (POC);
- Line rating for each line, indicated by current in kA;
- Load and generation measurement data;

- Step increase for integrated wind power;
- For Dynamic Line Rating (DLR), weather condition including wind speed, wind direction, ambient air temperature, solar altitude, etc. are used to calculate a real-time value of the overhead lines current rating, referred to as the ampacity;

For power curtailment in a network, the following inputs are necessary:

- NHC and PHC;
- Load and generation measurement data;
- Probability for lines to be off.
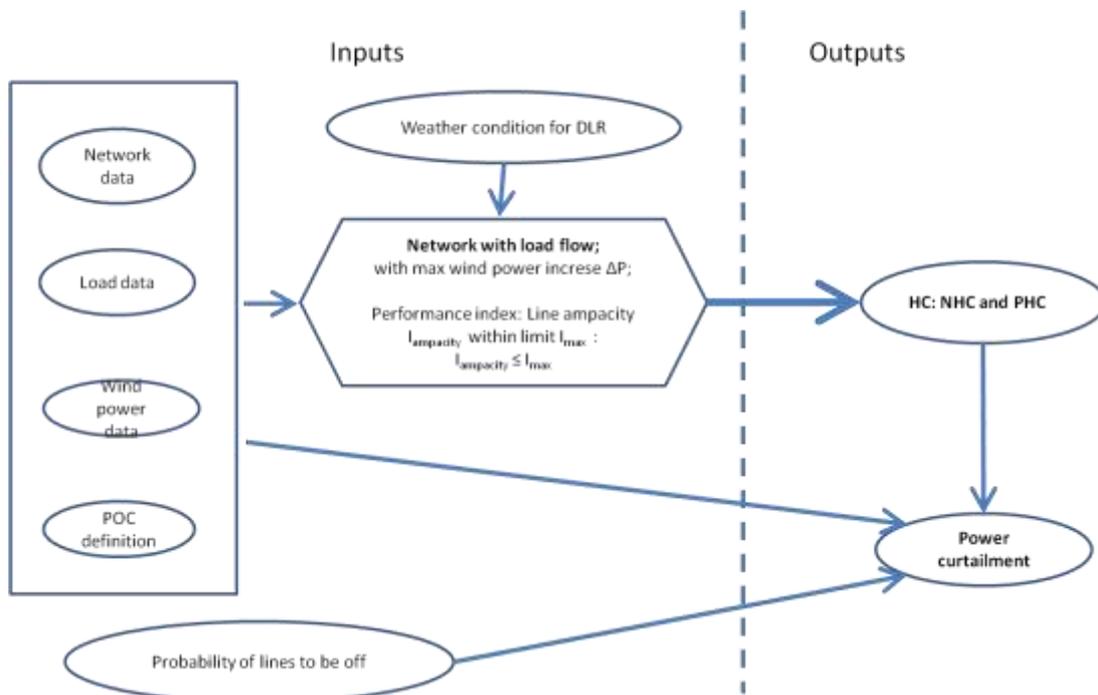
Figure 8 Illustration of inputs and outputs for HC and power curtailment acquisition

Detailed description of the calculation method is to be found in Appendix C.

4.1.1 Impact of system operation status and local consumption

As discussed in Chapter 0, the total wind power hosting capacity PHC includes two parts: the maximum power that the network can hold (NHC) and the power that is related to the local consumption at the same POC. The former would be affected by different system operation status. In this study, the normal operation status as defined as System operation A and the one-line-off operation status as defined as System operation B are considered. For different proposed solutions, both parts would vary. For secure system operation, the sudden transition for the system status from the normal operation (System operation A) to one-line-off operation (System operation B) should always be taken care of, either by (N-1) criterion or by wind power curtailment if wind power production is more than the amount that is allowed

to be injected at the moment. Thanks to the introduction of power curtailment, the Hosting Capacity can be increased. In general, such benefit has been discussed in Chapter 0. In fact, those proposed solutions indeed involve the power curtailment function.

For the case without any curtailment, the N-1 criterion is considered: the wind power production should always be less than the minimum NHC and the minimum local consumption. The minimum NHC is obtained with the one-line-off status.

For solution 1 with the local supervisory system, the maximum power that can be injected into the network should be decided by the N-1 criterion. Thus, the maximum acceptable power is determined with the one-line-off operation status. In addition, the maximum local consumption can be taken into account, as the wind farm/turbines can be adjusted in accordance with the consumption by the local supervisory system.

For solution 2 with the special protection system, the maximum power with the normal operation status should be considered. Instead of the maximum local consumption, the minimum consumption should be applied for wind power hosting capacity calculation, as the wind farm/turbines no longer can curtail the output according to the consumption. Once there is a contingency occurring in the network (in this study, only the one-line-off contingency is considered; this can be extended to other contingencies as well), the protection system would trip the wind power output, considered as the power curtailment.

For solution 3 with the grid supervisory system, the wind farm/turbines can curtail the output according to both the one-line-off contingency and the local consumption. Thus, the maximum power held by the network should be the one with normal operation status. The total wind power hosting capacity is the sum of that power and the maximum consumption. This solution combines solution 1 and 2 together.

For solution 4, it applies the Dynamic Line Rating (DLR) based on solution 3. With DLR, NHC should be updated with the dynamic line ampacities. Thus, the total hosting capacity is the sum of the updated NHC and the maximum consumption.

4.1.2 Hosting capacity calculation

The hosting capacity is calculated by performing a large number of load flow calculations for different hours during the year and with increasing amount on installed wind-power capacity.

First of all, the 'line current' is selected as the performance index. After the load flow with different installed wind power capacities, different actual line currents for all lines can be obtained which would be compared with their corresponding static ampacity limits (with DLR, the dynamic ampacity limits are applied instead). Thus, the maximum wind power that is allowed to be injected into the network (NHC) can be found when the actual line current of any lines in the network reaches its limit. With the corresponding local consumption, the total hosting capacity would be obtained. More details can be referred to Appendix C.

This is the most conservative case or the worst case, as in this calculation method, the maximum wind power output is always considered. However, the wind power output, during the most of the time, is below the maximum output. Therefore, the moment when the line current reaches its limit may rarely occur in reality, and it is possible to obtain a higher NHC. Since the wind power is intermittent, higher NHC obtained based on the real wind power output would introduce the risk that this low probability event does happen. As DLR would be introduced, the risk for such event is further reduced, and the network operator may become more confident to accept higher NHC.

4.1.3 Power curtailment calculation

Once the hosting capacity has been obtained, the corresponding power that needs to be curtailed in order to ensure the system security can be calculated based on the real wind power production. How much power that should be curtailed depends on which specific solution is applied. The curtailment calculation would also be different between the normal operation status and the one-line-off status. During the normal operation status, as the local consumption varies, and most of the time it is lower than the maximum consumption, the power curtailment is needed, when the wind power production is larger than the summation of the NHC and the consumption. For the one-line-off status, the total power curtailment is determined by both the reduction of NHC due to the one-line-off case, and the lower local consumption. The calculation uses the variable probability for each line-off case, as listed in Table 9 of appendix C, together with the corresponding NHC for each line-off case. Once DLR is applied, the NHC with each one-line-off case would vary as well.

However, due to the low probability for the one-line-off status, the most curtailed power would take place during the normal operation for solution 1, 3 and 4. There is no need for power curtailment for solution 2 during the normal operation, as Solution 2 only curtails the power when there is an inter-trip signal due to the one-line-off emergency.

The details for calculation are presented in Appendix C.

4.2 Study with meshed operation and maximum wind production consideration

Based on the adapted meshed network, as described in Section 2.2 (With the stronger line 7-11), the rest network would have higher weight for the impact on both the hosting capacity and the corresponding power curtailment. For this study, Bus 7 is selected as POC. Besides, the maximum wind production is considered when calculating the Hosting Capacity, which is the conservative case as defined previously.

The results have been summarized in the Table 1.

In Table 1 the case with 'N-1 criterion' is included for reference purposes only and does not correspond to any of the solutions applied in Sections 3.4to 3.7.

Solution 4 is not applicable in this case, as Solution 4 considers DLR, which requires the actual wind power production when calculating Hosting Capacity.

'Theoretical production' indicates the possible wind power production in GWh with the specific installed capacity that is determined by 'Hosting capacity PHC in MW'. This installed capacity is also the basis of the power curtailment calculation.

For certain operation period, there are two parts for power curtailment as Section 4.1.3 describes: curtailment during normal operation and curtailment during one-line-off operation. In reality, there are 34 MW installed wind capacity injected at Bus 7. For different hosting capacity except 34 MW, the wind power production is scaled up or down on the basis of the wind power production for the 34 MW wind capacity.

All the calculations are based on the Appendix C.

Table 1 Summary of HC and power curtailment for different smart solutions for meshed network

Case	Hosting capacity PHC in MW	Theoretical production for one year in GWh	Corresponding power curtailment	
			During normal operation in GWh	During one-line-off operation in GWh
N-1 criterion	61,17	149	N/A	N/A
Solution 1	108,60	265	10,5	N/A
Solution 2	158,23	387	0	0,0020
Solution 3	205,63	502	4,3	0,0048
Solution 4	N/A	N/A	N/A	N/A

If there is no power curtailment at all (N-1 criterion case), the meshed network can only allow 61 MW wind power injection at Bus 7. This limit is calculated by summing the minimum NHC with one-line-off operation status 55 MW and the minimum local consumption 6 MW together.

For Solution 1, the PHC is about 108,6 MW. This is because Solution 1 applies the local supervision, which can follow the local consumption variation. Thus, the maximum consumption 53 MW is applied instead of minimum consumption, compared to the N-1 criterion case. Together with the minimum NHC of 55 MW, the total hosting capacity 108,6 MW is obtained.

For Solution 2, it applies the special protection systems. This enables the power curtailment in accordance with the variation of NHC due to different line-off cases. Thus, the NHC without any line failure (normal operation, 152 MW) and the minimum load consumption (6 MW) should be considered, which leads to 158 MW as the hosting capacity.

For Solution 3, the grid supervision system, both the local consumption and the network are supervised. This implies that the power curtailment is possible no matter whether it is due to the variation of the local consumption or the variation of the NHC. Therefore, the PHC should be the summation of the NHC during the normal operation (152 MW) and the maximum load consumption (53 MW), namely 205 MW.

Based on the individual hosting capacity, its corresponding production and power curtailment can be calculated, as listed in Table 1.

There are several observations that should be noticed:

- With solution 1, 2, and 3, the hosting capacity is increased by 77,5%, 158,7%, and 236,1%, respectively. Accordingly, the yearly theoretical production is also increased. The wind energy efficiency is around 28% for one year.

- During the normal operation, there is no power curtailment for Solution 2 with the special protection systems; once the system enters the one-line-off operation, only a small amount of power should be curtailed due to the low probability of the one-line-off operation.

- For either Solution 1 or 3, the power curtailment during the normal operation is larger than the one-line-off operation.

- For the Solution 2, it is not realistic to inject the wind power that is higher than the PHC 158 MW. If more than 158 MW wind power is injected, the system may still be operated under the overloading situation without initiating the inter-trip to curtail the total wind farm/turbines. However, this will increase the probability for the one-line-off case, and the corresponding power curtailment will increase dramatically.

4.3 Investigation of hosting capacity at different POCs

Previous Section 4.2 has considered the POC at Bus 7. In this section, different POCs are considered. For each POC, both NHC and PHC for radial network, meshed network, and different cases during the one-line-off operation situation are studied.

Figure 9 and Figure 10 present the different NHCs and PHCs for different cases. During the one-line-off operation, there are already lines that are thermally overloaded, for example, line 2-10 and line 5-11, due to the consumption. With this regard, a decent amount of wind power at certain busses could help to release the already existing stress in the network. Once the wind power exceeds certain amount, the system will experience the overload situation again, but with a reversed direction of power flow.

For both Figure 9 and Figure 10, such benefit can only be observed when the POC is with Bus 2, 3, 4, 5, 7, 11. When POC is at Bus 6, 10, or 12, the wind injection will not help to release the stress when the line 6-11 or line 6-13 is off, no matter how much wind is injected because the wind power will not help to ease the consumption overloading in these cases. (See Figure 2 of Section 2.1.)

If the one-line-off operation with line 6-11 or line 6-13 is excluded, there are mainly four groups with similar pattern in terms of different operating status: Group 1 when POC is at Bus 6, 7, 11; Group 2 with Bus 2, 5; Group 3 with Bus 3, 4; Group 4 with Bus 10, 12. This observation can be verified by investigating the location or peripheral environment of those busses.

NHC comparison

	Radial	Meshed	Line 2-3 off	Line 2-5 off	Line 2-10 off	Line 3-4 off	Line 4-5 off	Line 5-11 off	Line 6-11 off	Line 6-13 off	Line 8-12 off	Line 8-15 off	Line 10-13 off	Line 12-13 off	Line 14-15 off
POC at Bus 2	75	120	112	107	61	114	114	75	82	82	120	120	61	120	120
POC at Bus 3	69,04	111,6	75,49	107,19	55,18	69,04	69,04	69,04	76,5	76,5	111,6	111,6	55,18	111,6	111,6
POC at Bus 4	70,58	109,16	76,9	103,46	56,74	75,49	70,58	70,58	77,08	77,08	109,16	109,16	56,74	109,16	109,16
POC at Bus 5	75	117	108	109	61	106	106	75	82	82	117	117	61	117	117
POC at Bus 6	122	146	145	145	128	144	144	122	0	62	146	146	128	146	146
POC at Bus 7	114,69	152,2	148,93	148,99	119,99	147,66	147,66	114,69	55,17	55,17	152,2	152,2	119,99	152,2	152,2
POC at Bus 10	103	112	110	111	98	111	111	103	0	0	112	112	61	112	112
POC at Bus 11	122	160	157	157	128	156	156	122	62	62	160	160	128	160	160
POC at Bus 12	99	103	103	103	103	103	103	103	0	0	98	99	103	74	99

Off-line cases

Figure 9 NHC comparison for different POCs

PHC comparison

	Radial	Meshed	Line 2-3 off	Line 2-5 off	Line 2-10 off	Line 3-4 off	Line 4-5 off	Line 5-11 off	Line 6-11 off	Line 6-13 off	Line 8-12 off	Line 8-15 off	Line 10-13 off	Line 12-13 off	Line 14-15 off
POC at Bus 2	75	120	112	107	61	114	114	75	82	82	120	120	61	120	120
POC at Bus 3	75	123	81	118	61	71	75	75	82	82	123	123	61	123	123
POC at Bus 4	75	113	81	111	61	76	75	75	82	82	113	113	61	113	113
POC at Bus 5	75	117	108	109	61	106	106	75	82	82	117	117	61	117	117
POC at Bus 6	122	146	145	145	128	144	144	122	0	62	146	146	128	146	146
POC at Bus 7	122	160	157	157	128	156	156	122	62	62	160	160	128	160	160
POC at Bus 10	103	112	110	111	98	111	111	103	0	0	112	112	61	112	112
POC at Bus 11	122	160	157	157	128	156	156	122	62	62	160	160	128	160	160
POC at Bus 12	99	103	103	103	103	103	103	103	0	0	98	99	103	74	99

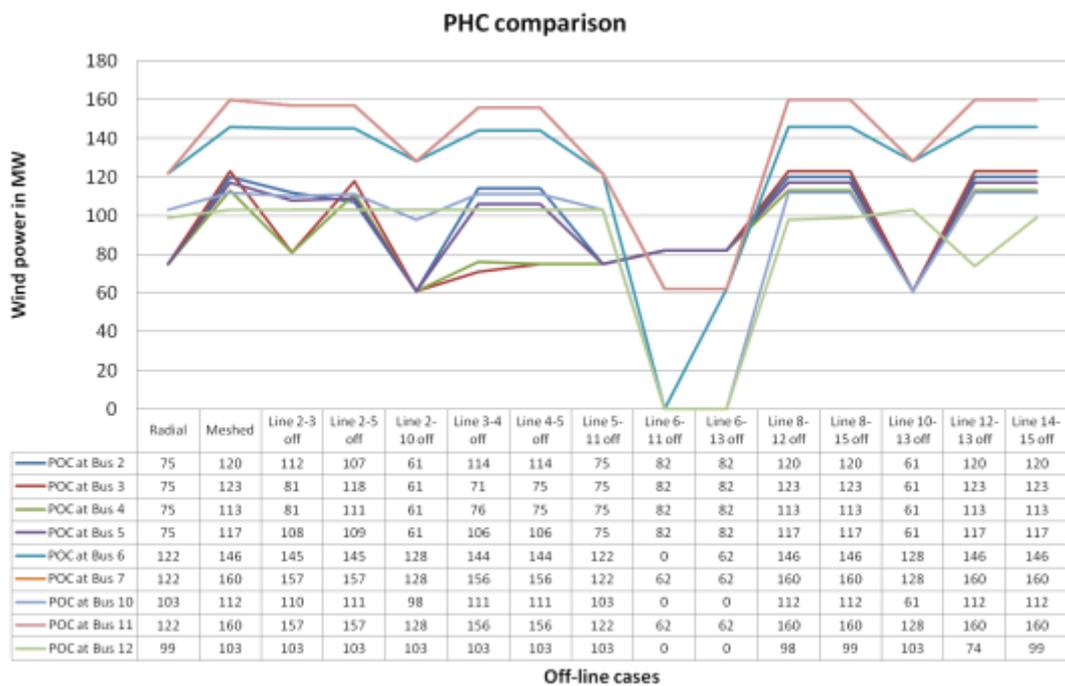Off-line cases

Figure 10 PHC comparison for different POCs

4.4   Study with real wind power production

4.4.1 Summary of hosting capacity and power curtailment

In this section, the POC is assumed at Bus 7. In Section 4.2, the conservative case that assumes the constant maximum wind power is applied for Hosting Capacity calculation. In this section, the real wind power production is assumed instead.

Therefore, the Solution 4 with dynamic line rating can be applied to investigate the benefit for hosting capacity increase in reality.

The following table summarizes the hosting capacity and the power curtailment.

In the table, the case with 'N-1 criterion' applies no solution and power curtailment.

'Theoretical production' indicates the possible wind power production in GWh with the specific installed capacity that is determined by 'Hosting capacity PHC in MW'. This installed capacity is also the basis of the power curtailment calculation.

There is curtailment during normal operation and curtailment during one-line-off operation.

In reality, there are 34 MW installed wind capacity injected at Bus 7. For different hosting capacity except 34 MW, the wind power production is scaled up or down on the basis of the wind power production for the 34 MW wind capacity.

All the calculations are based on the Appendix C.

Table 2 Summary of HC and power curtailment for different smart solutions for meshed network with real wind power production

Cases	Hosting capacity PHC in MW	Theoretical production for one year in GWh	Corresponding power curtailment	
			During normal operation in GWh	During one-line-off operation in GWh
N-1 criterion	120,2	294	0	N/A
Solution 1	167,6	409	5,90	N/A
Solution 2	167,2	409	0	0,0013
Solution 3	214,6	525	4,04	0,0032
Solution 4	390,0	956	1,45	0,0058

If there is no solution namely no power curtailment at all (N-1 criterion case), the meshed network can only allow maximum 120 MW wind power injection at Bus 7. This limit is calculated by summing the minimum NHC with one-line-off operation status 114 MW and the minimum local consumption 6 MW together.

For Solution 1, the PHC is about 167 MW. This is because Solution 1 applies the local supervision, which can only follow the local consumption variation.

Thus, the maximum consumption 53 MW is applied instead of minimum consumption, compared to the N-1 criterion case. Together with the minimum NHC 114 MW with one-line-off operation status, the total hosting capacity 167 MW is obtained.

For Solution 2, it applies the Special protection systems. This enables the power curtailment in accordance with the variation of NHC due to different line-off cases. Thus, the NHC during the normal operation (161 MW) and the minimum load consumption (6 MW) should be considered, which leads to 167 MW as the hosting capacity.

For Solution 3, the grid supervision system, both the local consumption and the network are supervised. This implies that the power curtailment is possible no matter it is due to the variation of the local consumption or the variation of the NHC. Therefore, the PHC should be the summation of the NHC during the normal operation (161 MW) and the maximum load consumption (53 MW), namely 214 MW.

For Solution 4, the NHC with the normal operation should be updated due to the application of DLR, which is increased to 337 MW. Together with the maximum local consumption 53 MW, the total PHC can reach 390 MW.

Based on the individual hosting capacity, its corresponding production and power curtailment can be calculated, as listed in the table above.

There are several observations that should be noticed:

- With solution 1, 2, and 3, the hosting capacity is increased by 39%, 39%, 78%, and 225%, respectively. Accordingly, the yearly theoretical production is also increased. The wind energy efficiency is around 28% for one year.

- During the normal operation, there is no power curtailment for Solution 2 with the special protection systems; once the system enters the one-line-off operation, only a small amount of power should be curtailed due to the low probability of the one-line-off operation.

- For either Solution 1, 3 or 4, the power curtailment during the normal operation is larger than the one-line-off operation.

- Notice that the hosting capacity for Solution 1 and 2 is quite close to each other, which is a coincidence for this specific case.

- Clearly, Solution 4 can considerably increase the hosting capacity, while keeping the power curtailment at a low level. Compared with Solution 3, the DLR almost doubles the hosting capacity.

- For comparison purpose, Figure 11 illustrates the difference among different solutions with different wind power hosting capacity, in terms of the power curtailment.

- For the Solution 2, it is not realistic to inject the wind power that is higher than the PHC 167 MW. If more than 167 MW wind power is injected, the system may still be operated under the overloading situation without initiating the inter-trip to curtail the total wind farm/turbines. However, this will increase the probability for the one-

> line-off case, and the corresponding power curtailment will increase dramatically.

It is clear from the Figure 11 that power curtailment occurs when the wind power capacity is higher than PHC. The power that needs to be curtailed could be considerably increased for Solution 1, 3 and 4. It is also true for Solution 2 as discussed above, even though it is not reflected in the figure, as the probability for the one-line-off operation is assumed to be the same as other solutions.

Solution 4 requires the least amount of power curtailment, and for Solution 1, the wind production may hardly increase any more even though the wind power hosting capacity is still increasing after 500 MW.
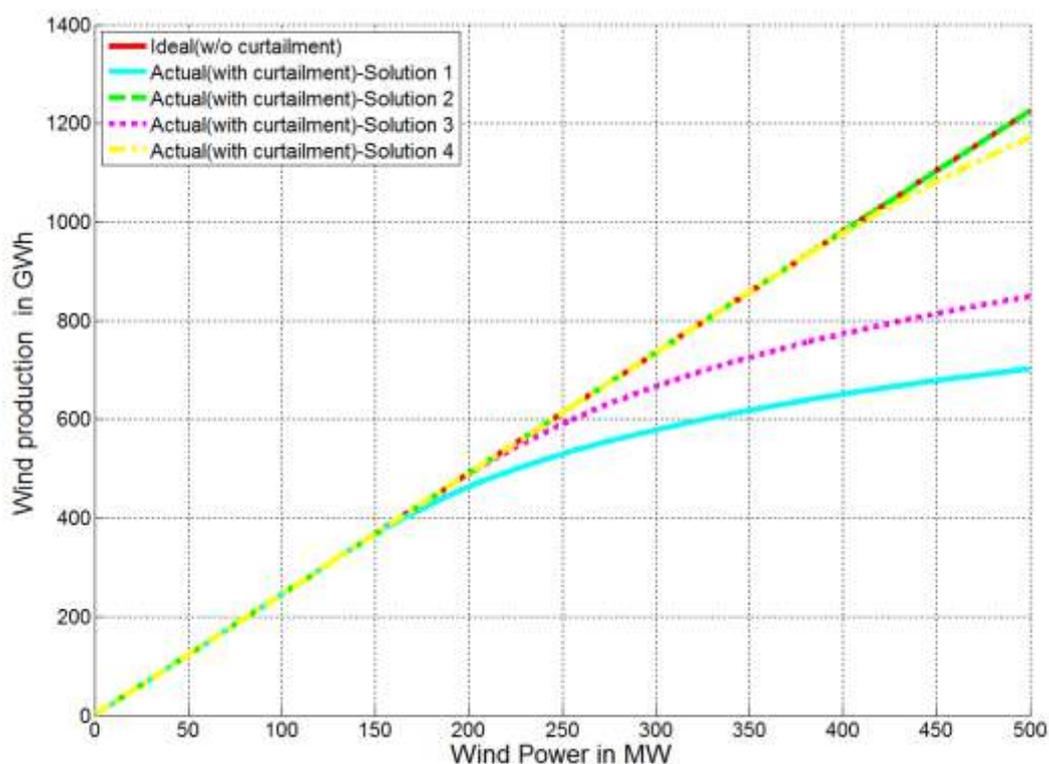
Figure 11 Power curtailment comparison

4.4.2 Benefit with real wind power production

To acquire the benefit from the Solution 4, both the real wind power production and DLR should be considered, instead of the conservative case with maximum wind power production for Hosting Capacity calculation.

The conservative case assumes that the wind turbines or wind farm would always produce the maximum power output, which is unrealistic in reality, as wind power is intermittent and varying all the time. Thus, this conservative case takes no risk at all by sacrificing the potential increase of the wind power hosting capacity. This would be pretty much appreciated by the distribution network operators.

On the contrary, the possible increase of wind power hosting capacity, which has been verified by the results as presented in this report, would be appreciated by wind farm developers or operators.

Such increase is because it is a low probability event to have constant maximum wind power all the time, and it is also rare to have the moment when the maximum wind power output meets the minimum load consumption at the same POC. Such moment limits the wind power transferred into the network (namely NHC as defined in this report).

Figure 12 illustrates the margin between the case with Maximum wind production which is considered as the conservative case and the case with the real wind power production.
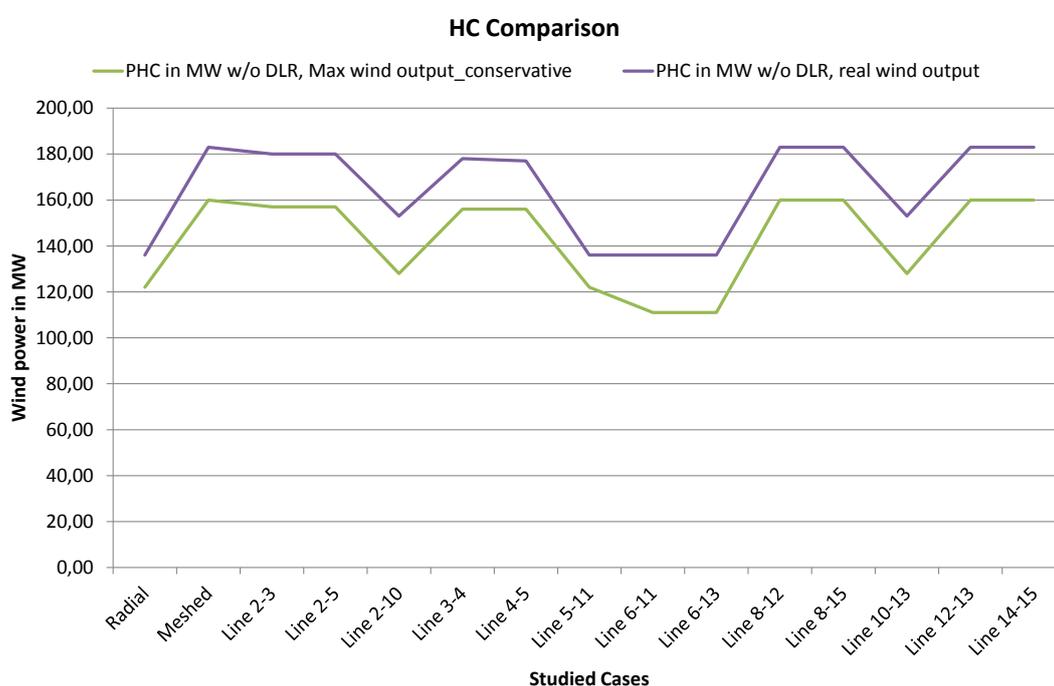
HC Comparison

Figure 12 Wind HC comparison: conservative case vs. real wind power output

4.4.3 PHC comparison for different years

Figure 13 presents the hosting capacity (with and without DLR) for year A and B, respectively.

There are mainly four observations as described below:

- When comparing the two cases without DLR in Figure 13, the data from different years do not influence the hosting capacity significantly;

- When comparing the two cases with DLR, the hosting capacities deviate from each other with a larger degree, except the operation status with line 6-11 or 6-13 off; this could be due to the different load flow for each year;

- When comparing the hosting capacity without DLR to with DLR, either for year A or B, the hosting capacity is doubled for both two years when introducing DLR, except the operation status with line 6-11 or 6-13 off;

- For one-line-off operation with line 6-11 or line 6-13 off, DLR does not improve the hosting capacity a lot. This is due to the cable 4-5 that sets the limit, as DLR does not apply to cables.
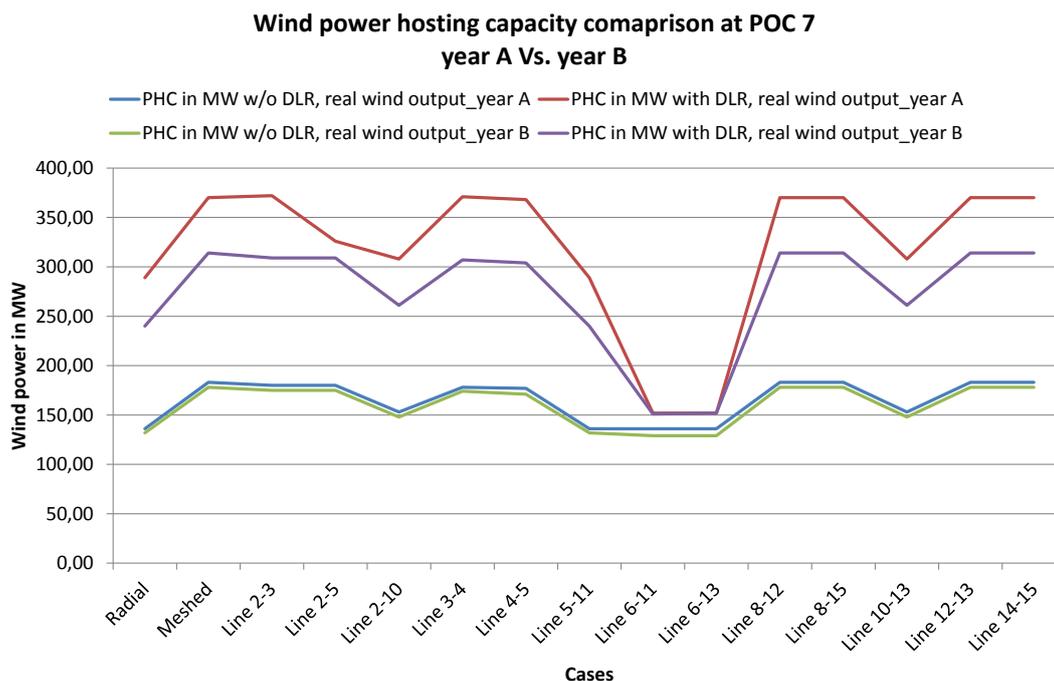
Figure 13 Wind HC comparison with POC at Bus 7: year A vs. year B

4.5   Study on the original network

The main purpose of this study is to investigate the impacts of different proposed smart solutions on the wind power hosting capacity.

When selecting an appropriate real network for study, there are always some special unique characteristics that prevent a generic study, and it is unavoidable to make reasonable assumptions or adaptions to the original network. With this regard, Section 4.2 to 4.4 have applied minor alterations to the line rating of the overhead line connecting bus 7, as described in Section 2.2.

In this section, the original network will be considered, and the related results are presented.

4.5.1 Study on meshed operation with maximum wind production

As explained before, line 7-11 has been strengthened in order to investigate the impact of the network itself on the wind power injection. In the original

network, the weak line 7-11 limits the wind power injection for Solution 2-3. The results have been summarized in the following table with the conservative case, namely with the maximum wind power production.

In the table, the case with 'N-1 criterion' applies no solution and power curtailment.

Solution 4 is not applicable in this case, as Solution 4 considers DLR, which requires the actual wind power production when calculating Hosting Capacity.

'Theoretical production' indicates the possible wind power production in GWh with the specific installed capacity that is determined by 'Hosting capacity PHC in MW'. This installed capacity is also the basis of the power curtailment calculation.

In reality, there are 34 MW installed wind capacity injected at Bus 7. For different hosting capacity except 34 MW, the wind power production is scaled up or down on the basis of the wind power production for the 34 MW wind capacity.

All the calculations are based on the Appendix C.

Table 3 Summary of HC and power curtailment for different smart solutions for meshed network

Smart solution	Hosting capacity PHC in MW	Theoretical production in GWh	Corresponding power curtailment	
			During normal operation in GWh	During one-line-off operation in GWh
N-1 criterion	61,17	149	N/A	N/A
Solution 1	108,6	265	10,5	0,0042
Solution 2	120,7	297	0	0,00073
Solution 3	168,1	412	6	0,00353
Solution 4	N/A	N/A	N/A	N/A

If there is no solution namely no power curtailment at all (N-1 criterion case), the meshed network can only allow maximum 61 MW wind power injection at Bus 7. This limit is calculated by summing the minimum NHC with one-line-off operation status 55 MW and the minimum local consumption 6 MW together.

For Solution 1, the PHC is about 108 MW. This is because Solution 1 applies the local supervision, which can only follow the local consumption variation. Thus, the maximum consumption 53 MW is applied instead of minimum consumption, compared to the N-1 criterion case. Together with the minimum NHC 55 MW, the total hosting capacity 108 MW is obtained.

For Solution 2, it applies the Special protection systems. This enables the power curtailment in accordance with the variation of NHC due to different line-off cases. Thus, the NHC during the normal operation (115 MW) and the minimum load consumption (6 MW) should be considered, which leads to 121 MW as the hosting capacity.

For Solution 3, the grid supervision system, both the local consumption and the network are supervised. This implies that the power curtailment is possible no matter if it is due to the variation of the local consumption or the variation of the NHC. Therefore, the PHC should be the summation of the NHC during the normal operation (115 MW) and the maximum load consumption (53 MW), namely 168 MW.

Based on the individual hosting capacity, its corresponding production and power curtailment can be calculated, as listed in the table above.

There are several observations that should be noticed:

- With solution 1, 2, and 3, the hosting capacity is increased by 77,5%, 97,3%, and 175%, respectively. Accordingly, the yearly theoretical production is also increased. The wind energy efficiency is around 28% for one year.

- During the normal operation, there is no power curtailment for Solution 2 with the special protection systems; once the system enters the one-line-off operation, only a small amount of power should be curtailed due to the low probability of the one-line-off operation.

- For either Solution 1 or 3, the power curtailment during the normal operation is larger than the one-line-off operation.

- For the Solution 2, it is not realistic to inject the wind power that is higher than the PHC 121 MW. If more than 158 MW wind power is injected, the system may still be operated under the overloading situation without initiating the inter-trip to curtail the total wind farm/turbines. However, this will increase the probability for the one-line-off case, and the corresponding power curtailment will increase dramatically.

4.5.2 Study on radial operation with maximum wind production

The original network is normally in radial operation. In fact, there are already wind farms with a total of 34 MW wind power installed capacity that are connected at Bus 7.

Often a wind farm will be automatically disconnected once there is a fault occurring along the wind power injection corridor. Thus, the wind power hosting capacity is limited by the power injection corridor, and the whole wind farm is curtailed during the one-line-off operation.

In order to increase the hosting capacity, the local supervision system can be introduced. With that, the total PHC can reach the summation of the NHC that is set by the power injection corridor and the maximum local consumption.

According to the load flows, the limit of the power injection corridor is 115 MW. Together with the minimum local consumption 6 MW, this indicates that the PHC for the normal operation with wind farm disconnection capability is 121 MW. This leads to the theoretical production equal to 297 GWh for one year. When considering the 0,04% line-off probability, the corresponding power curtailment would be 0,12 GWh.

Further, once the local supervision system is introduced, the PHC is equal to the summation of 115 MW and the maximum local consumption 53 MW, which is 168 MW. Such PHC corresponds to 412 GWh theoretical production and 6 GWh power curtailment.

All the results are summarized in the Table 4.

Table 4 Summary of HC and power curtailment for different smart solutions for radial network

Cases	Hosting capacity PHC in MW	Theoretical production for one year in GWh	Corresponding power curtailment in GWh
Radial without solution	121	297	0,12
with local supervision system	168	412	6

Compare to the present 34 MW wind power installed capacity, there is a potential of 87 MW more wind power integration, even without local supervision system.

When introducing the local supervision system, in total 168 MW wind power can be integrated.

However, attention should be paid to the fact that all these are theoretical values. In reality, how much wind that can be integrated depends on other issues; in part on economics, environment, public acceptance, etc. and in part on the reliability of the used measurement, supervision, communication and curtailment schemes. A thorough feasibility study is needed. Nevertheless, the hosting capacity method applied in this project is suitable to explore the potential of the system hosting capacity for wind power using smart solutions, which formulates the basis for further discussion.

4.6 Discussion on solution impacts

The power curtailment occurs when the wind power capacity is higher than PHC. The power that needs to be curtailed could be aggressively increased for Solution 1, 3 and 4. It is also true for Solution 2 if curtailment signal would be sent instead of inter-trip signal.

The conservative case assumes that the wind turbines or wind farm would always produce the maximum power output, which is unrealistic in reality, as wind power is intermittent and varying all the time. Thus, this conservative case takes no risk at all by sacrificing the potential increase of the wind power hosting capacity. This would be pretty much appreciated by the network operators.

On the contrary, the possible increase of wind power hosting capacity, which has been verified by the results as presented in this report, would be appreciated by wind farm developers or operators.

Such increase is because we no longer dimension the network based on the low probability event to have maximum wind power output coincide with the minimum load consumption.

As has been shown, Solution 4 can considerably increase the hosting capacity, while keeping the power curtailment at a low level. Compared with Solution 3, the DLR almost doubles the hosting capacity.

To determine the benefit from the Solution 4, both the real wind power output and DLR should be considered.

The wind power HC almost remains the same for different years, when no DLR is considered. Once DLR is present, the hosting capacities deviate from each other with a large degree. This is because the hosting capacity with DLR is sensitive not only to variation in consumption and production but also in the weather conditions affecting the ampacity of the overhead lines.

Attention should be paid, however, to the fact that DLR does not improve the hosting capacity a lot, if the cable sets the limit, as DLR does not apply to cables any more. During a N-1 contingency also cables in remote parts of the electrical network will affect the hosting capacity, resulting a worst case that makes the application of DLR questionable for the entire network.

5 Discussion of the risk

This chapter will discuss the consequences of the different solutions and calculation methods for the different stakeholders. We will mainly discuss the economic risks for the different stakeholders and the risk on supply interruptions for the network users. This chapter will also include a section on the relation between this work and the proposed European grid codes for production units and a section on required changes in the reporting of interruptions when the smart solutions discussed in this report are getting commonly used.

5.1 Base case

5.1.1 Operation according to (N-1) criterion

The (N-1) criterion ensures that no single component outage will result in an interruption for any of the network users. The criterion is only applicable for meshed networks. In transmission systems, the (N-1) criterion is restored within typically 15 minutes when it no longer holds after the outage of a component. At subtransmission level restoration of the N-1 criterion is not always possible without disconnecting consumption. The outage of a second component during the repair of another component could result in a supply interruption in that case. We will see later that a line is unavailable during less than 1% of the time. The probability of a supply interruption in a meshed operated grid is thus reduced by a factor of more than 100 compared to radial operation.

The drawback of the high reliability obtained by the (N-1) criterion is that it reduces the amount of wind power that can be connected to the grid. For a park that exceeds the hosting capacity, investments in the grid are needed in the form of new lines. Not only are there high costs associated with this, also it may take many years before such new infrastructure can be in place.

5.1.2 Calculation of Hosting Capacity

As was discussed in Section 3.1, there is no unique way of calculating the hosting capacity. The assumption made and the calculation models used can have a big impact on the resulting hosting capacity limit, i.e. on the largest wind park that can be connected without investment in the grid.

Let us, to start with, consider the difference between the network hosting capacity (NHC) and the park hosting capacity (PHC). The difference between the two, the PHC being the higher one, is due to the local consumption. Three cases are considered:

1. The lowest PHC is obtained when maximum production is assumed together with zero consumption. In that case NHC and PHC are the same. The probability of overload in the grid is very small in that case.

2. A higher PHC is obtained when maximum production is assumed together with known minimum consumption. The PHC is in that case equal to the NHC plus the minimum consumption. Grid overload might occur in this case when the consumption is lower than the expected minimum at the same time that the production is high. This probability depends mainly on the method used to estimate the minimum consumption. When hourly data from one or more years is used, this probability is perceived low, unless there are clear changes in type of consumption.

3. An even higher value of the PHC is obtained when hourly values of production and consumption are used. The increased in hosting capacity obtained by true time-series data depends on the correlation between production and consumption. The limitation of this method is that data will only be available for a limited number of years and in many cases production data has to be estimated (e.g. from past weather data) as no production was present at or near the location of the new installation. As shown in Figure 12 of Section 4.4.2, use of actual wind production data instead of installed capacity (or maximum wind production) raises the PHC by 20 to 30 MW (15 to 25%). It is further shown in Figure 13 of Section 4.4.3 that the difference between the two years used in this study is small. It is this possible to obtain a suitable value for the PHC from the hourly data over a small number of years. The risk here is that large changes in consumption pattern occur where a reduction of consumption (e.g. due to energy efficiency measures) will result in less wind power being able to be connected. When no curtailment is possible (which is the assumption for the base case), such a reduction in consumption would require additional investments in the grid to be carried by the network operator.

Also for the NHC different calculation methods are possible. One can in principle distinguish the same three cases as above but now for the consumption at other busses in the network: zero consumption; minimum consumption; hourly consumption. The possibility should be considered however that zero consumption might not be the worst case. Some other nodes might also contain production that possibly exceeds the local consumption. Also could, in meshed networks, the situation occur that consumption elsewhere reduces the amount of power that can be injected without overloading the network. System studies of different consumption and production patterns are needed to decide if this is the case. Using hourly values of the net consumption or production for all nodes appears the most appropriate approach.

Also here the risk, for the network operator, is the possibility that consumption and/or production patterns at other nodes change in the future. It is not possible to estimate the probability of such happening but performing different scenarios could give an impression of this.

A general observation that can be made is that a higher hosting capacity will in general result in higher risks for the network operator (risk of line overloading; risk of future investments) and for other network users (risk of supply interruptions due to line overloading, risk of increased use of system tariffs to cover future investments). A higher hosting capacity has advantages

for the wind park owner (more installed capacity for same connection), for society as a whole (more energy from renewable sources) and for the network owner (if their income is determined by transfer fees and not purely by capital and operation cost).

5.1.3 Reactive power and ac load flow

The calculations presented in this report are all based on dc load flow. As shown in Appendix A, the difference in results in small unless the reactive power plays an important role. For the study presented here, it has not been possible to obtain data on the reactive power because this has not been recorded for the network under study.

For actual hosting-capacity studies, to decide about the need for new investments in the grid, an ac load flow is more likely to be acceptable by all parties. In that case it is however important that the reactive-power data is available or that an accurate estimation is made. When hourly values are used, the variation of reactive power with time should also be considered.

5.1.4 The hosting capacity threshold

Adding a wind park of such a size that the hosting capacity is exceeded requires investments in the grid, typically in the form of new lines and/or transformers. This is the case even when the installed capacity exceeds the hosting capacity by a small amount. The building of a new line or lines will however typically increase the hosting capacity by much more than needed for that specific park.

The discussion about who should carry the costs of that investment is known under the name "threshold effect" ("tröskel effect" in Swedish). This could be a serious barrier against connection of wind power to the subtransmission network.

5.2 Local supervision (solution 1)

The use of local supervision resolves any discussion about the variations in local consumption. The PHC becomes dynamic: its momentary value is equal to the NHC plus the momentary local consumption. There is no longer any limit to the installed capacity that can be connected to the grid. Instead the production is curtailed whenever the NHC is exceeded by the net production at this bus.

5.2.1 The hosting capacity threshold

As there is no longer a hard limit to the installed capacity, the threshold effect (Section The hosting capacity threshold) is no longer present either.

5.2.2 Rearrangement of risks

A higher installed capacity will no longer result in an increased probability of overload, but in an increased amount of curtailed energy. The risk is thus

moved from the network operator and other network users to the wind-park owner. The amount of curtailed energy is shown in Figure 11 of Section 4.4.1 for a POC at bus 7. The conservative PHC for this bus is about 109 MW (according to Figure 12, lowest value, conservative case). But curtailment has negligible impact on the delivered energy up to about 160 MW.

When the installed capacity exceeds the NHC plus the maximum consumption, the maximum production will always be curtailed. Any installed electrical capacity (like transformer sizes) above this value would never be used. A higher "mechanical capacity" (like the length of the blades) would still give higher energy production during periods with low wind speed. The economic limit, above which it is no longer worth investment in additional capacity, is expected to be somewhere between the NHC plus minimum consumption and the NHC plus maximum consumption. The actual economic limit will depend on the investment costs, the local wind conditions, the price paid for energy injected into the grid and the variations in local load.

Any uncertainties and risks associated with the calculation of the NHC are not impacted by this solution.

5.2.3 Economic risks for the wind-park owner

Curtailment of wind-power production will result in a loss of income for the wind-park owner. To quantify the economic impact of this, a distinction should be made between income from sales of electricity on the wholesale market and income from compensation for producing renewable electricity (like green certificates and feed-in tariffs). For the latter a 10% curtailment of annual production will result in a 10% reduction in income. For the former the reduction in income will likely be less if the proportion of production from wind power in the market is sufficient to affect the overall energy price.

High production from a specific wind park has typically a positive correlation with high production in the whole country or price area. This has in turn a positive correlation with low electricity prices. In the same way is there typically a positive correlation between low consumption locally, low consumption in the whole country or price area, and low electricity prices. Curtailment takes place when high production coincides with low consumption, which is likely during periods of low electricity prices.

5.2.4 Different wind parks

The curtailment risks might not be the same for all wind parks. For example the rule could be that only new wind turbines will be curtailed. This will depends on operational rules used by the network operators, on local laws and regulations, and on the contractual agreements between the network operator and individual wind-park owners.

It is also possible to set up market-based schemes to share the curtailment over the different wind parks. A further discussion on this is beyond the scope of this report.

5.2.5 Model uncertainties

Uncertainties in future production or consumption will no longer result in a risk for the network operator and other network users. Instead such uncertainties will result in an uncertainty of the amount of curtailed production which is an economic risk for the wind-park owner. If, for example, the local consumption is less than expected, the curtailment will be more than expected and the income of the wind-park owner less than expected.

In this case the economic risk lies with a stakeholder that does not have direct access to the data needed to estimate the risk. However, it may not be possible for the wind-park owner to estimate future production equally well as the network operator and only the network operator has access to past consumption data.

5.2.6 Failure of the curtailment

There is a finite probability that the curtailment does not work as planned. This might be due to failure of the current measurement, failures in the supervisory unit, failure of the communication between that unit and the wind park, or a failure in the wind park. It is not possible to estimate the probability of such a curtailment failure without detailed knowledge of all these components. The network owner will need to review any proposal for curtailment schemes by a wind-park owner in order to assess if the scheme provides acceptable reliability and sufficient operation time.

It is important to consider this in the development of curtailment schemes and equipment. It is also important to include "fail-safe" mechanisms that prevent large-scale blackouts due to curtailment failures as much as possible. In the simplest form this will be as traditional overload protection to isolate the overloaded components, in case the curtailment does not operate.

5.3   Special protection systems (solution 2)

With this solution through e.g. intertrip ("fjärutlösning"), reduction of the production is only needed when a line is out of operation. The maximum installed capacity (the hosting capacity) is the amount that can be injected into the meshed grid when there is no need for reserves.

5.3.1 Rearrangement of risks

The special protection system is a way of shifting the operational reserves from the network to the wind-park owner. Instead of building on extra line as a reserve, the risk of a line outage is shifted to the wind-park owner.

In Sweden, the costs for such an extra line would be carried by the wind-park owner, so that this one can make a trade-off between these costs and the economic consequences of occasional reduction of production.

5.3.2 Gain in hosting capacity

With reference to Figure 10 of Section 4.3, the hosting capacity is the value for "meshed" grid operation. The hosting capacity for the base case (N-1

criterion) is the lowest value for any of the line outages. The PHC for the base case ("without SPS") and for solution two ("with SPS") is presented in Table 5. The use of the special protection system allows for much more wind power to be connected.

Table 5 Increase in hosting capacity using a special-protection system

POC	Hosting capacity (PHC)	
	Without SPS	With SPS
2	61 MW	120 MW
3	61 MW	123 MW
4	61 MW	113 MW
5	61 MW	117 MW
6	*	146 MW
7	62 MW	160 MW
10	*	112 MW
11	62 MW	160 MW
12	*	103 MW

* The loss of certain lines will cause the network to be overloaded due to consumption. Although wind power installation may not necessarily deteriorate the situation, a wind park Point Hosting Capacity (PHC) cannot be defined in these cases.

5.3.3 Curtailment risk

When any of the lines is out of operation, the production should be limited such that no overload occurs in the network even for maximum production and minimum consumption. The value to which the production should be limited when a certain line is out of operation is the value with that line in Figure 10. For most line outages, the maximum production is only slightly less that the hosting capacity will all lines in operation. But in some cases a large reduction is needed; effectively a halving of the maximum allowed production (for outage of line 2-10 or line 10-13). In some other cases the line loss (for outage of line 6-11 or 6-13) resulted in overloading from consumption. In this case curtailment of production most be specially considered as the removal of production may even make the overloading worse.

Line outages do occur only during a very limited part of time. Here it is important to distinguish between "permanent outages" and "temporary outages". Temporary outages are restored by automatic reclosing and last up to a few minutes. Permanent outages are restored manually and last anything from less than an hour up to several days. The unavailability of a line (the percentage of time during which the line is not in operation) is by far dominated by permanent outages. The values for the lines in this study are given in Table 9 (Appendix C). The sum of the unavailability's for all lines is 0.04% or less than four hours per year.

For the temporary outages previous branch praxis in Sweden[1] allowed the lines to exceed thermal limits by 20 degrees for a few hours per year. This would allow the wind production to be maintained without the curtailment for a temporary fault.

For permanent faults reduction of the production is needed only during 0.04% of the time. When the production is reduced to zero (the worst case) the loss of production will be only 0.04%. Even if this amount is low a permanent outage of the "wrong" line over several months may be catastrophic for the economy of a small wind farm owner. Rather than investing in grid redundancy for such a low probability event it may be more economical to purchase insurance against this risk.

When it takes a certain time to restore the production, the behaviour during temporary outages becomes of importance. With intertrip schemes, the opening of a breaker will result in automatic tripping of the park. Reconnection of the park will typically be manual and thus require a certain amount of time. The unavailability of the park due to temporary outages might easily be more than the unavailability due to permanent outages.

To get an impression of the order of magnitude, consider that there are 10 outages per year that result in tripping of all wind-power production. Assume further that it takes 2 hours to restart production. Together with the before-mentioned 4 hours due to permanent outages, the park of disconnected during 24 hours per year or 0.3% of time. Even in this extreme case the loss of production will be only 0.3%.

Even though this 0.3% is a small percentage (the uncertainty in the prediction of the number of production hours per year is bigger), an economic assessment can be done. Consider for this a 120 MW wind park with a production equivalent to 3000 hours/year. Assume that the price paid for the energy from the park (green certificates plus day-ahead spot price) is 700 SEK/MWh. The annual income of the park would be 252 million SEK/year, and 0.3% loss of production would correspond to a loss of income equal to 756 000 SEK/year.

The building of a 130 kV transmission line costs around 1 million SEK/km plus the costs in the substation[2]. Even when considering a 30 year pay-back-time, the gain in production would not cover more than one or two kilometres of line. Note that we have used an upper limit for the loss of production; a value of 0.1% or less appears more realistic.

5.3.4 Failure of the special protection system

Also here there is a finite risk that the reduction in production will not take place when needed. The discussion in Section 5.2.6 also applies here.

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[1] Per Norberg, personal communication.
[2] According to Swedenergy (Svensk Energi) AB/EBR KLG 2:08 "*Kostnadskatalog Regionnät 36-145 kV*", page 11, 2008

5.3.5 Hosting capacity threshold

The use of a special protection system still results in an actual limit of the amount of production capacity that can be connected to the network. The threshold effect thus also applies here. The threshold is shifted to a higher value but it remains a hard limit.

5.4 System supervision (solution 3)

This solution is a combination of solution 1 (local supervision) and solution 2 (special protection system).With both solution 1 and solution 3, curtailment is activated when the production exceeds the NHC plus the local consumption. With solution 3, the NHC is a lot higher, when no line is out. The NHC for solution 3 does not include the need for reserves. The difference between solution 1 and 3 can be explained by means of the values in Table 5. With no line out of operation, curtailment starts for the values in the second column with solution 1 and for the values in the third column with solution 3. When a line is out of operation (which is a very small percentage of time) the second column applies to both solutions.

Most of the discussion in the previous two sessions also applies here.

For solution 2, there was still a hard hosting capacity: the NHC for the meshed network without the need for reserves plus the minimum local consumption. For solution 3, it is possible to connect more installed capacity; when the net production at the POC exceeds the indicated NHC, the production of the park is curtailed.

When the installed capacity exceeds the NHC for the meshed network without the need for reserves plus the maximum local consumption, any additional installed capacity will not be used anymore. This is however not a hard limit and no threshold effect applies here.

The amount of curtailment as a function of the installed capacity is shown in Figure 11. The curtailment can be translated into annual loss of income (as in Section 0) as a function of the installed capacity. For a certain installed capacity will be loss of income be sufficient to justify investment in an additional transmission line.

5.5 Dynamic line rating (solution 4)

Dynamic line rating (DLR) combines the earlier three solutions with a momentary rating of the lines based on the available weather conditions.

5.5.1 Conservative approach

Under the conservative approach for calculating the hosting capacity, it is assumed that maximum wind-power production can occur any time, independent of consumption or weather conditions. This assumption makes that DLR does not give any increase in hosting capacity; maximum production may occur when the line rating is at its lowest.

An important first step in the application of DLR is to use a higher wind speed for the calculation of the line rating during periods with high wind-power

production. Studies done by Vattenfall have shown that when the wind production is high there is a wind speed between 1 and 3 m/s (in the direction giving most cooling) for lines within a 100 km radius from the park. Because of this, Vattenfall have started to use 2 m/s wind speed (compared to 0.6 m/s traditionally used) to calculate line rating during periods with high wind-power production[3].

5.5.2 DLR without curtailment

It is possible to use DLR without curtailment, by keeping the probability of overload (momentary loading higher than momentary rating) sufficiently low. The calculations presented in [5] resulted in these probabilities for a constant production. The calculations in this report (Figure 13, difference between the two upper lines) show that a multi-year period with data from production, consumption and weather is needed to be able to estimate this risk.

If we consider the lowest value from the two years in Figure 13, the following hosting capacity values are obtained (DLR without curtailment):

➢ Fixed line rating; reserves in the grid: 130 MW;

➢ Dynamic line rating; reserves in the grid: 150 MW;

➢ Fixed line rating; special protection system: 180 MW;

➢ Dynamic line rating; special protection system: 320 MW.

The small increase in hosting capacity for the second case is due to the presence of cables in the network (see Section 5.5.5). In this case, it is the combination DLR and SPS that gives the biggest increase in hosting capacity.

5.5.3 DLR with curtailment

The combination DLR, SPS and curtailment is shown to be very advantageous. Even for very high installed capacity (see Figure 11) the amount of curtailed production is small. A few comments are however at its place here:

➢ Line outages have not been considered for DLR. But as was discussed before (Section 0) the impact of this on the delivered energy is well below 1% and does not impact any of the conclusions here.

➢ It has been assumed that all lines experience the same weather. Production data was obtained from an existing 34-MW wind park connected to bus 7. Weather data was obtained at 10 meters altitude from a weather station about 40 km away from this park; this data was used for all lines. In reality not all lines will experience the same weather and even along one line the weather will not be the same everywhere. Some lines or line sections will experience a lower momentary rating than the one used in the calculations. It is the lowest rating (among the heavily loaded lines) that determines the momentary hosting capacity. The amount of curtailment needed will thus be more than what has been obtained from our calculations. How

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[3] Per Norberg, Vattenfall, personal communication.

big this impact is cannot be estimated without detailed models for the weather conditions along the lines.

This uncertainty does not impact the applicability of DLR, only the estimation of the economic risks for the wind-park owner.

➢ It has been assumed that the momentary rating of the lines can be perfectly estimated. In reality this is obviously not the case and a safety margin will be used, for example, between the estimated momentary rating and the line current at which curtailment starts (where the latter is the lower one). The more accurate the highest conductor temperature along a line can be estimated, the smaller the margin needed. A direct measurement of conductor temperature at different locations along the line allows for a smaller margin. The threshold at which curtailment would be activated could be defined in terms of temperature in such a case. Tension measurement with a load cell mounted on the line gives the thermal expansion in the conductor corresponding to the average temperature over greater distances than is achievable with a single temperature measurement and may therefore allow for even smaller margins.

This uncertainty is actually a barrier against the wide-scale introduction of DLR. The good news is that several demonstrations projects are in place and that studies are ongoing to calculate weather conditions along a line with high geographical resolution.

5.5.4 DLR and risks

With the full use of DLR, including accurate knowledge of conductor temperatures, the economic risks are with the wind-park owner. When the momentary rating is exceeded, the production is curtailed. This includes the risk due to uncertainty in prediction of conductor temperatures (see Section 5.5.3, second item) making that the amount of curtailment could be (much) more than considered in the investment decision.

The risks that the DLR or SPS does not result in the required amount of curtailment is carried by all stakeholders. See the discussion on this in Section 5.3.4.

When there is no accurate knowledge of the conductor temperature, as will be the case for a while, additional risks are introduced. There is the risk that the current exceeds the actual rating but not the estimated rating. This is an overload situation that is not detected by the overload protection as this one uses the estimated rating.

To prevent such a situation from occurring, a safety margin is introduced. This will result in more curtailment which has economic consequences for the wind-park owner. The network operator might even decide to increase the safety margin in the future because it is perceived as too small. This is again an economic risk for the wind-park owner.

The remaining risk is that the current exceeds the actual rating but not the threshold at which curtailment is activated. This poses a risk for the network operator and the network users.

5.5.5 DLR and cables

The presence of cables can reduce the effect of DLR a lot as was shown in this study. Weather conditions that increase the rating of lines a lot have none or very limited impact on the rating of cables. The bottleneck in the network will, with such weather conditions, be quickly shifted to an underground cable. Even a short cable section (like a few hundred meters) can strongly limit the advantages gained by DLR.

With only a small number of cables in the network (as in this network example and which is typical for most subtransmission networks outside of the urban areas) the combination SPS and DLR will still allow for the full gain of DLR.

In future subtransmission networks, it is likely to become more common to have multiple short cable sections. This could limit the gain of DLR, even in combination with SPS. As long as it concerns short cable sections, their rating can be increased relatively easy by adding one or more additional cables in parallel to the existing cable or cables.

5.6   European network codes

5.6.1 Aim and overview of network codes

At this moment a number of network codes are under development by ENTSO-E (the European Network of Transmission System Operators for Electricity[4]) in cooperation with ACER (the Agency for the Cooperation of European Regulators[5]). The aim of these network codes is to remove barriers against cross-border trade of electricity within the European Union. These codes are minimum requirements for all transmission system operators and for all so-called "significant network users" in the European Union. The definition of significant network users varies between different codes and remains an issue of discussion. But it will almost certainly cover much more than only those network users directly connected to the transmission system. Even many low-voltage customers will be impacted by the network codes.

The following codes are at different stage of development at the moment of which the first two are described on more detail in Section 5.6.2 and 5.6.3:

- ➢ Requirements for generators;
- ➢ Operational security;
- ➢ Capacity allocation and congestion management;
- ➢ Forward capacity allocation;
- ➢ Balancing;
- ➢ Demand connection;
- ➢ HVDC connection;

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[4] http://www.entsoe.eu
[5] http://www.european-regulator.eu

> ➢ Operational planning and scheduling;

> ➢ Load-frequency control and reserves.

5.6.2 Requirements for generators

The ENTSO-E network code for "Requirements for grid connection applicable to all generators" sets requirements that have to be fulfilled by all generators (the term "power generating module" is used in the code) that are bigger than 800 W. Different requirements are in place depending on the size of the generator, where the following four classes are distinguished (for the Nordic region; different threshold exist for other geographical regions)

> ➢ Class A: connection point below 110 kV and capacity 800 W or more but less than 1.5 MW,

> ➢ Class B: connection point below 110 kV and capacity 1.5 MW or more but less than 10 MW;

> ➢ Class C: connection point below 110 kV and capacity 10 MW or more but less than 30 MW,

> ➢ Class D: connection point at 110 kV or higher and/or capacity 30 MW or more.

A wind park consisting of multiple turbines is considered as one generator (power generating module). The installed capacities that were discussed in this report range from about 50 MW up to a few hundred MW. This could be spread over multiple parks. Of interest for this study are thus the requirements for Class C and Class D.

This document contains among others requirements on frequency control and on fault-ride through, which are not relevant to the kind of applications within the scope of this report.

However for Class C and Class D generators, "*Single-phase or three-phase auto-reclosures on meshed network lines, (..) shall be withstood by (generators) without tripping.*" The reason for this requirement is that the tripping of wind power would cause a local and global unbalance between production and consumption that has to be coped with by the transmission-system operator. This could limit the use of a special protection scheme to prevent (local) overloading. Coordination between the network operator of the subtransmission network and the transmission system operator is needed here before such a scheme is implemented and the curtailment scheme may need to be blocked during certain (global) unbalances adding additional complication to the scheme.

Another requirement (for Class B, C and D) that could impact the applicability of a special protection scheme is the following one: "*With regard to capability of reconnection after an incidental disconnection due to a network disturbance, the relevant TSO shall adopt a decision (..) defining the conditions under which a (generator) shall be capable of reconnecting to the network after an incidental disconnection has taken place due to a network disturbance. Installation of automatic reconnection systems shall be subject to prior authorization by the relevant network operator subject to reconnection conditions specified by the relevant TSO.*" This could limit the possibilities of

reconnecting the wind park after a trip by the special protection scheme. It again calls for coordination between the network operator of the subtransmission network and the transmission system operator.

The network code also sets several requirements that require communication between the network operator and the wind park. This will make it easier to implement the different solutions discussed in this report.

The network code also requires, even for Class A generators, the ability to reduce production as part of the frequency control. The ability to reduce production on demand will thus in future be present in all wind parks.

5.6.3 Operational security

The ENTSO-E network code for operational security[6] sets minimum requirements on the operation of transmission systems that have to be fulfilled by the transmission system operators within the European Union.

This document defines among others the use of the (N-1) operational criterion. This criterion is defined as follows:

"(N-1)-Criterion means the rule according to which elements remaining in operation after a fault of one element within TSO's control area must be capable of accommodating the new operational situation without exceeding operational security limits."

The following congestion management is prescribed to maintain this criterion: "*If after a contingency when the steady-state operation is re-established, the transmission system is not compliant with the (N-1)-criterion, the TSO shall initiate remedial actions to recover compliance with the (N-1)-Criterion as soon as reasonably practicable. If there is a risk of a post contingency disturbance propagation involving neighbouring TSOs or enhanced probability of further faults, the TSO shall initiate remedial actions as soon as possible.*"

This does not appear in contradiction with the use of special protection schemes or curtailment as discussed in this report.

The document further states that:*" Non-compliance with the (N-1)-Criterion is acceptable:*

a) during switching sequences;

b) if it only has local consequences within the TSO responsibility area; and

c) during the time period required to activate the remedial actions".

The operation of the SPS can be seen as a switching action or as a remedial action. Also, as long as the amount of wind power tripped or curtailed is limited it will only have local consequences.

There are however limits on the use of SPS and curtailments schemes. In the Nordic grid the dimensioning contingency is the loss of 1200 MW production. Curtailment or tripping of 1200 MW would thus be the absolute limit. The actual limit will require coordination with the TSO and during some operational conditions of the transmission system, pre-emptive disconnection

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[6] The latest available draft, dated 17 August 2012, has been used.

of wind power may be necessary to prevent any potential unacceptable impact beyond local consequences.

5.7 Continuity of supply indicators

In most European countries, the energy regulator collects data on the number of supply interruptions experienced by electricity customers. An overview of this is presented every two or three years by the European Energy Regulators in their benchmarking reports[7]. In the fifth benchmarking report, published in 2012, a distinction is made between the following types of interruptions:

> ➢ Unplanned long interruptions, excluding exceptional events;

> ➢ Unplanned long interruptions, all events;

> ➢ Short interruptions;

> ➢ Planned interruptions;

> ➢ Interruptions on the transmission networks.

In Sweden data on supply interruptions is collected, at the level of individual customers, by the Energy Markets Inspectorate, the national regulatory authority for Sweden. The details of the reporting requirements are defined in regulation EIFS2010:5[8]. In the reporting, a distinction is made between the following types of interruptions (presented here somewhat simplified):

> ➢ Planned interruptions due to events in the local network;

> ➢ Planned interruptions due to events beyond the local network;

> ➢ Long non-planned interruptions due to events in the local network;

> ➢ Long non-planned interruptions due to events beyond the local network;

> ➢ Short non-planned interruptions due to events in the local network;

> ➢ Short non-planned interruptions due to events beyond the local network;

Interruptions for generators are not reported under the existing regulation. For a complete overview of the performance of the network, such interruptions should be included in the statistics as well. It appears as most appropriate to the authors to have separate indicators for generators and for consumers. How to treat network users that do both ("prosumers") remains a point of discussion.

The introduction of SPS and curtailment introduces a type of interruptions that is not well covered by the subdivisions above. Using the definitions of the different types, these new types of interruptions would fall under "non-planned interruptions" as the customer does not get sufficient pre-notice of them. Treating them statistically the same as non-planned interruptions would

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[7] See http://www.energy-regulators.eu

[8] Energimarknadsinspektionens föreskrifter och allmänna råd om skyldighet att rapportera elavbrott för bedömning av leveranskvaliteten i elnäten, 22 juli 2010. http://www.ei.se

imply that they are considered the same as interruptions due to faults in the network. This might be seen as an acceptable argument for interruptions due to SPS, but certainly not in all cases for interruptions associated with curtailment. Curtailment is only a partial reduction not a complete disconnection. There is also voluntary element involved in this: a wind-park owner can opt for SPS or curtailment instead of paying for investments in the grid.

Another reason for using separate statistics on these new types of interruptions is that they give information about the status of the transitions to a smart grid. It is therefore suggested to keep track of the following indicators when SPS and/or curtailment are in place:

- ➢ The number of times per year that wind-power production is reduced or tripped by SPS;

- ➢ The annual loss of wind-power production due to the intervention of SPS; as an absolute value (MWh/year), as a percentage (% of min/year); and per participating wind park.

- ➢ The number of times per year that curtailment of wind power is activated.

- ➢ The annual loss of wind-power production due to curtailment, as an absolute value (MWh/year), as a percentage (% of min/year); and per participating wind park.

Such statistical indicators should be kept by each wind park but also by the network operator. They may change over time due to general changes in consumption and production patterns in the network outside the control of the wind park operator requiring re-assessment of economic evaluation of curtailment and SPS schemes.

6 Conclusions

This report analysis the risk associated with applying smart grid technologies to allow more wind power production than is permitted with classical network planning. The smart technologies studied include local supervision of network loading, special protection schemes (inter-tripping), grid wide supervision and dynamic line rating of overhead lines. By applying such solutions in combination with production curtailment the hosting capacity of wind power in the subtransmission network can be greatly increased.

These solutions make it possible to transfer risks associated with overloading of the network from the network operator to other stakeholders. The other stakeholders in response receive economic benefits by avoiding grid strengthening that would otherwise increase their connection fee. In order to assess the benefits for different stakeholders the technical and economical risks associated with the solutions are analysed. The analysis is based on results from detailed simulation of the solutions applied to a subtransmission grid in central Sweden.

The report describes in detail the hosting capacity concept and the used method to determine the limit for the different applied solutions. The report shows that the method and input data used when calculating the hosting capacity, impact the value of the hosting capacity and therewith the amount of wind power that would be allowed to be connected to the electricity network.

For classical solutions to reinforce the electrical network to be able to host more wind power, a higher resulting value of the hosting capacity is generally associated with a higher risk of overloading in the network. These risks are carried by the network operator and the network users. Using more accurate models of production and consumption allows for a higher value of the hosting capacity without increasing the risk of overloading. It is therefore recommended to gather, at least hourly, data on variations in active and reactive power at all relevant locations in the grid.

The distinction between network hosting capacity and park hosting capacity allows for a separate treatment of the limitations set by the network and the limitations due to the local variations in production and consumption.

Using curtailment schemes or special protection systems allows for a large increase in hosting capacity without an increase in risk of overloading, as has been shown in this report. Instead the risk is carried by the wind-park owner through loss-of-production during periods with (otherwise) increased risk of overload.

In the base case, with a meshed operated grid without applying the studied solutions the hosting capacity is a static limit that cannot be exceeded. The resulting threshold effect is known as a possible barrier against wind power. With curtailment schemes, the hosting capacity is no longer a hard limit and the threshold effect disappears.

The (N-1) operational criterion ensures a high reliability of transmission and subtransmission networks. It does however set a severe limit to the amount of wind power that can be connected. The use of special protection schemes allows for the full capacity of the network to be used without an increased risk of overloading of the network. For the network under study, the hosting capacity is increased by 50 to 100 MW, depending on the location. The resulting economic risk for the wind-park owner is small and much less than the costs of building a new transmission line.

The use of curtailment, through a local or global supervisory unit, increases the hosting capacity by the difference between minimum and maximum consumption. Using local supervision only variations in local consumption are compensated; using global supervision also variations at other busses are compensated. Using such schemes, the intermittency of production and consumption no longer limits the hosting capacity. Instead a trade-off can be made between the economic losses due to curtailment and the costs of investing in additional subtransmission lines.

Dynamic line rating has the ability to increase the hosting capacity a lot, even without curtailment or special protection scheme. However the combination of the three allows for even larger amounts of wind power to be connected without large economic risks associated with curtailment. The largest increase in delivered energy is obtained when the conductor temperature along the line can be accurately estimated. If this is not the case, safety margins are needed that will increase the amount of curtailed energy.

The presence of cables or cable sections in a subtransmission network limits the gain that can be obtained from dynamic line rating.

Failure of the curtailment scheme or special protection scheme could result in a large-scale interruption of the supply. Mechanisms are needed to avoid this, e.g. through the introduction of a "fail- safe" mechanisms that prevent blackouts due to failures of the smart grid solutions.

Further studies are needed on the implementation of the various solutions discussed here, including detailed protection, control and communication rules to guarantee a maintained high reliability of the supply for all network users. Pilot installations will also be required to evaluate the real-time and practical aspects of the schemes before wide-scale adoption.

The new European network codes, which are currently under development, do not appear to set serious limits to any of the solutions discussed in this report. It is however required for the subtransmission network operator to coordinate with the transmission system operator to avoid unacceptable impact on the security of the transmission system. The new European network codes do put requirements on communication between wind parks and the network operator, which will make it easier to implement the kind of solutions discussed in this report.

With the introduction of curtailment schemes and special protection systems it is recommended to keep separate statistics on the number of events and the total reduction in energy production. Such events should not be included in the regular interruption statistics.

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8   Appendix A DC load flow results

From the comparison as shown below, the DC load flow is acceptable, although it has some difference from the results with AC load flow.

This difference percentage could be variable, depending on how the reactive power flow affects the bus voltages and then the loading.

As the line ampacity I is related to both active power P, reactive power Q and voltage U, the line current could be unreliable with DC load flow, which assumes a constant voltage value for all busses and no Q.

Provided that the reactive power data is not reliable in this case and DC load flow is faster, we apply DC load flow anyway.
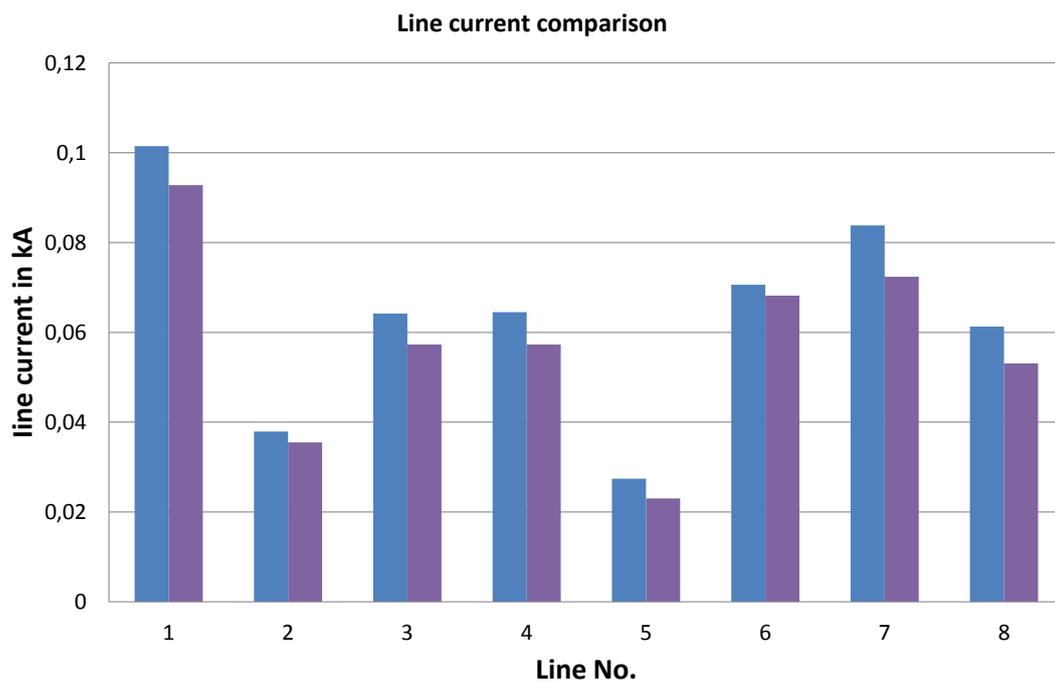
Comparison for radial network

Figure 14 Line current comparison for radial network

Comparison for meshed network

There are four cases as shown in the following table:

Table 6 four study cases

Case No.	Load in MW														Wind in MW
	LT4		LT7_1		LT7_2		GT1		LK1		LT6_1		LT6_2		
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	
1	8.49	2,79	6.72	4.17	7.02	4.35	12.65	7.84	4.61	2.86	0.20	0.12	5.29	3.28	0
2	8.49	2,79	6.72	4.17	7.02	4.35	12.65	7.84	4.61	2.86	0.20	0.12	5.29	3.28	300
3	8.49	0	6.72	0	7.02	0	12.65	0	4.61	0	0.20	0	5.29	0	0
4	11,62	3,83	0	0	13,12	8,13	27,04	16,76	0	0,001	0,19	0,12	3,27	2,03	19,64

Figure 15 Line current comparison for meshed network: case 1

Line current comparison

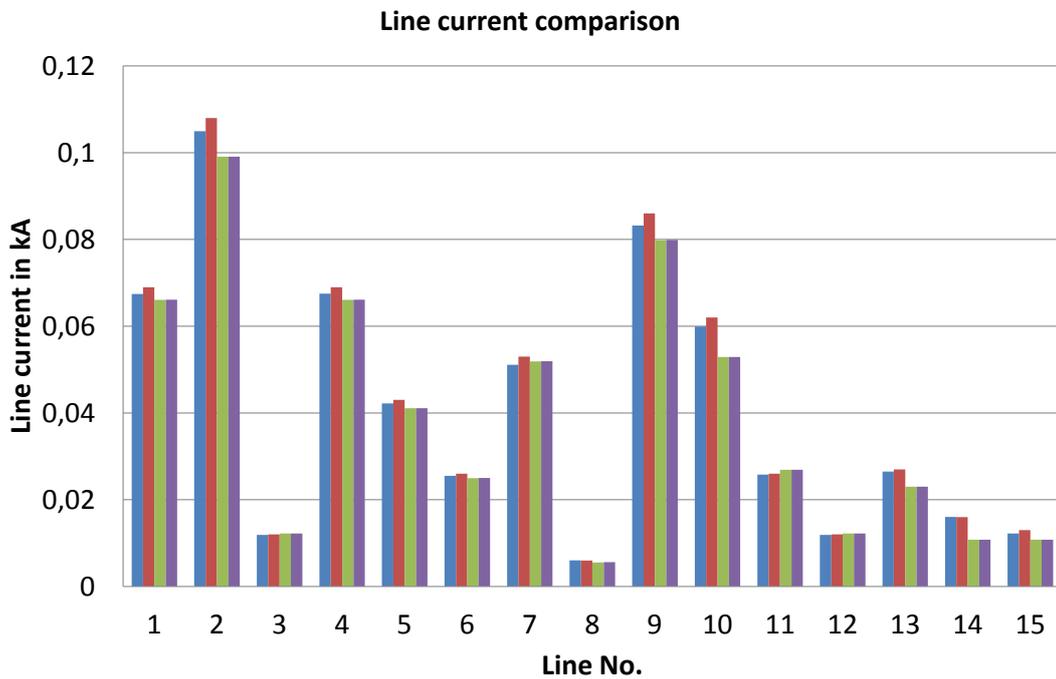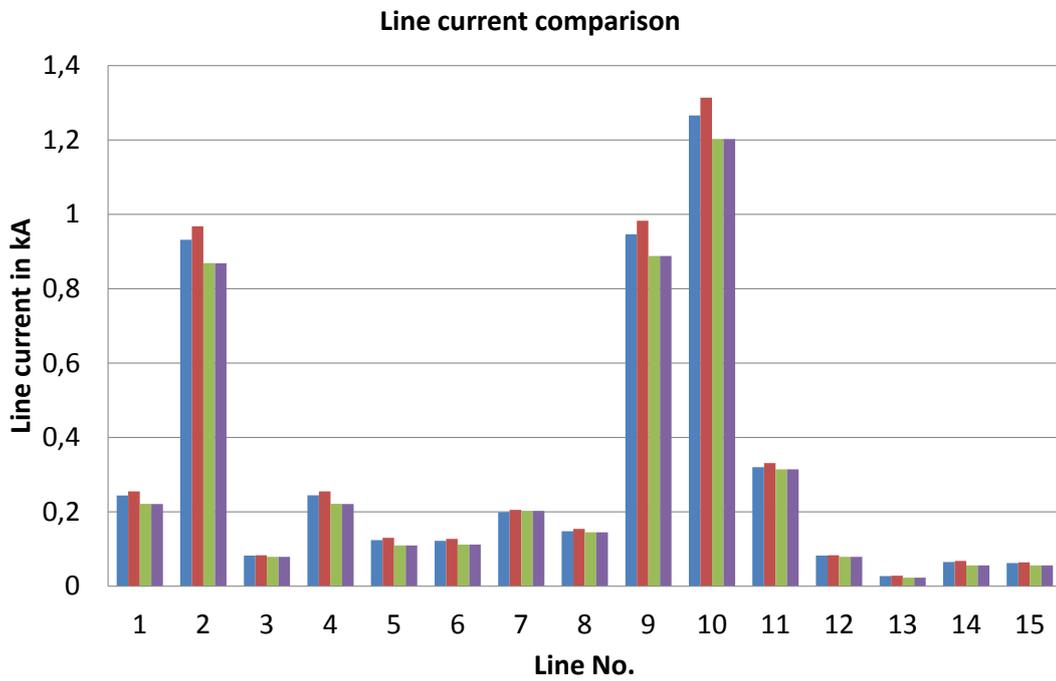**Figure 16 Line current comparison for meshed network: case 2**

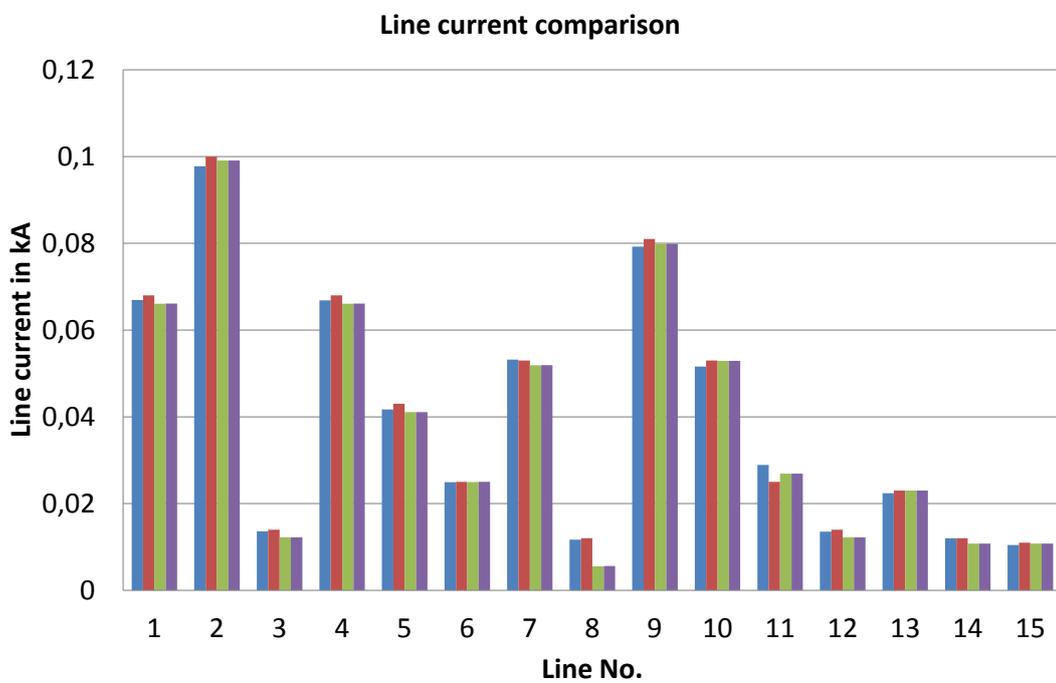**Line current comparison**

Figure 17 Line current comparison for meshed network: case 3
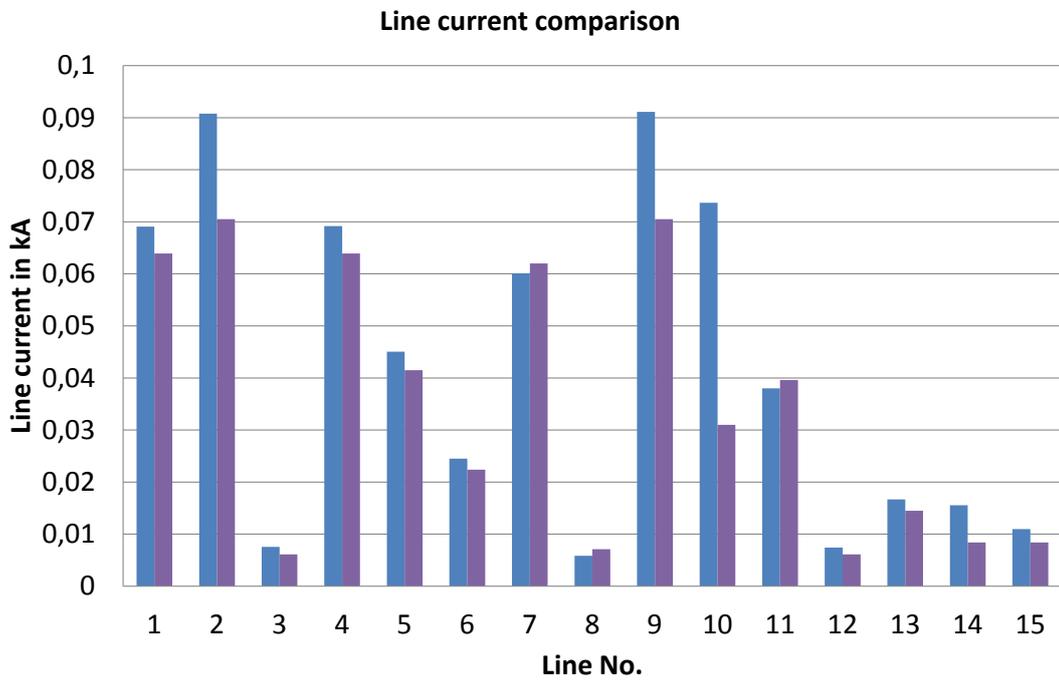
Figure 18 Line current comparison for meshed network: case 4

9 Appendix B Alternative implementation of curtailment

9.1 Introduction

According to Section 4.1.3 the probability for each line-off case, as listed in Table 9 of appendix C is used together with the corresponding NHC for each line-off case. This implies that information of which line is out must be used when calculating the wind parks curtailment requiring a list of different hosting capacity limits to be maintained for each possible line fault. This is referred to as method 2 in the detailed methodology description in appendix C.

The special protection and intertrip schemes could be simplified by introducing an alternative method where the wind park is curtailed to a conservative value of the hosting capacity (here corresponding to the minimum hosting capacity found for any line fault). This method corresponds to reducing wind park production to a predetermined and fixed hosting capacity limit for any contingency situation in the network. This is referred to as method 1 in the detailed methodology description in appendix C.

Method 1 assumes a fixed probability for line outage of 0.04%, i.e. that no line fault exist on any line 99,96 % of the time. When a fault occurs anywhere in the network the minimum NHC is used in calculating the curtailment. Method two applies the probability for each line-off case and a variable NHC that corresponds to the specific NHC for a given line fault.

Once DLR is applied, the NHC with each one-line-off case would vary as well.

9.2 Curtailment with maximum wind production

Using method 1 the results for maximum wind production given in Table 1 of Section 4.2 will now include an additional column as given below in Table 7.

Table 7 Summary of HC and power curtailment for different smart solutions for meshed network. This corresponds to Table 1 with the addition of the alternative method 1 to calculate the curtailment.

Case	Hosting capacity PHC in MW	Theoretical production for one year in GWh	Corresponding power curtailment		
			During normal operation in GWh	During one-line-off operation	
				Method 1: with minimum NHC in GWh	Method 2: with variable NHC in GWh
N-1 criterion	61,17	149	N/A	N/A	N/A
Solution 1	108,604	265	10,5	0,0042	N/A
Solution 2	158,229	387	0	0,045	0,002

Solution 3	205,634	502	4,32	0,058	0,00475
Solution 4	N/A	N/A	N/A	N/A	N/A

The curtailed power calculated by Method 2 during the one-line-off operation is less than the power obtained by Method 1. This is because Method 1 only applies the minimum NHC while Method 2 applies different NHCs in accordance with different one-line-off case.

Although the curtailment is up to twenty times higher with this simplified, worse case, special protection system it is still very small compared to the gains in annual energy delivered to the grid.

9.3   Curtailment with real wind power production

Using method 1 the results for maximum wind production given in Table 2 of Section 4.4 will now include an additional column as given below in Table 8.

Table 8 Summary of HC and power curtailment for different smart solutions for meshed network with real wind power production. . This corresponds to Table 2 with the addition of the alternative method 1 to calculate the curtailment.

Cases	Hosting capacity PHC in MW	Theoretical production for one year in GWh	Corresponding power curtailment		
			During normal operation in GWh	During one-line-off operation	
				Method 1: with minimum NHC in GWh	Method 2: with variable NHC in GWh
N-1 criterion	120,2	294	0	N/A	N/A
Solution 1	167,6	409	5,9	0,00236	N/A
Solution 2	167,2	409	0	0,00736	0,00132
Solution 3	214,6	525	4,04	0,016	0,00322
Solution 4	390,0	956	1,45	0,113	0,00578

Again the curtailed power calculated by Method 2 during the one-line-off operation is less than the power obtained by Method 1. This is because Method 1 only applies the minimum NHC while Method 2 applies different NHCs in accordance with different one-line-off case. The difference is much more apparent for Solution 4.

Although the curtailment is up to twenty times higher with this simplified special protection system it is still very small compared to the gains in annual energy delivered to the grid.

10 Appendix C Hosting Capacity and power curtailment calculation

There are two system operations defined in Section 4.1.1:

System operation A: normal operation status, and

System operation B: one-line-off operation status corresponding to a N-1 contingency situation.

Besides, there are four smart solutions that are proposed, aiming at increasing the wind power Hosting Capacity (HC).

In order to obtain the HC and power curtailment in a network, the following input data is necessary:

- Network data: busbars/terminals, lines, transformers, loads, generators, etc.;
- Definition of the Point of Connection (POC);
- Ampacity of each line, indicated by current in kA;
- Load and generation measurement data;
- Step increase for integrated wind power;
- For Dynamic Line Rating (DLR), weather condition including wind speed, wind direction, ambient air temperature, solar altitude, etc. are used to calculate a real-time value of the over head line rating, referred to as the ampacity.

In order to calculate the power curtailment in a network, the following input data is necessary:

- NHC and PHC (as defined in Chapter 0);
- Load and generation measurement data;
- Probability of lines to be off.

In this appendix, general introduction to the necessary input data is firstly discussed. Thereafter, the calculation methods for both HC and power curtailment are presented.

10.1 Data preparation

10.1.1 Network data

The studied subtransmission network data is based on [8], as described in Section 2.1.

10.1.2 Definition of Point Of Connection

Originally, the wind power POC is at Bus 7 as described in Section 2.1. For comparison, several other POCs (at Bus 2, 3, 4, 5, 6, 10, 11, 12) are investigated as well in Section 7.2.

10.1.3 Line rating

The maximum continuous current through a line is calculated with STRI I-Line computation tool [15], which calculates the thermal load capacity for overhead conductors according to [16].

For cables, the line ratings are obtained from [17] and [18].

Figure 19 presents the line rating, which is the limit of the performance index: line current.
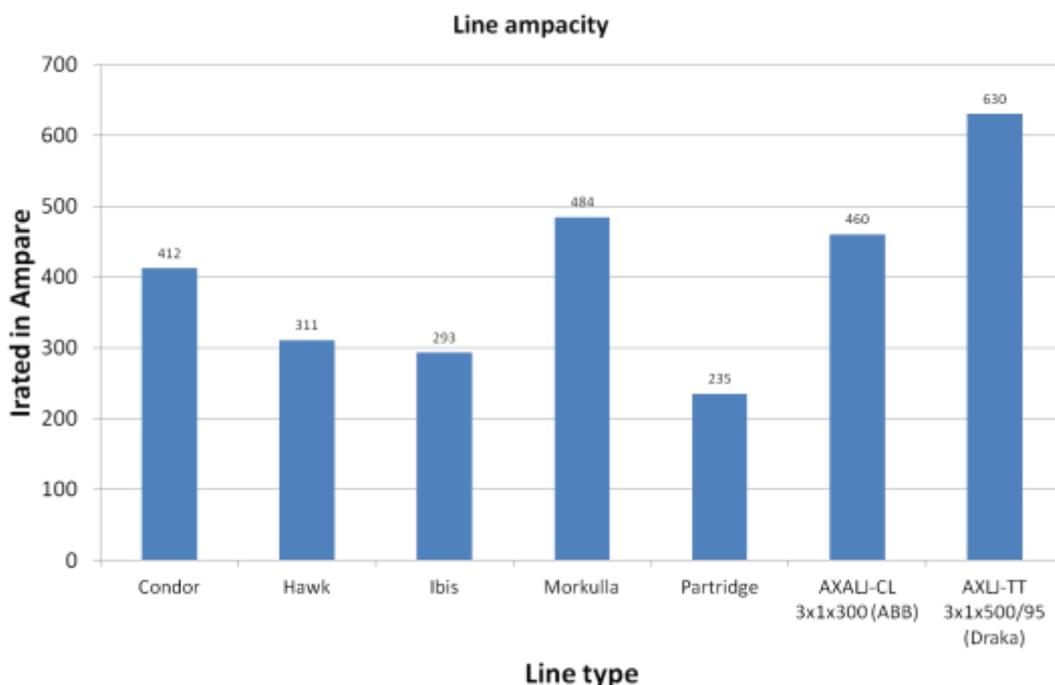

Figure 19 Line ratings used in the report

10.1.4 Load and generation measurement data

Both load and generation measurement data for the studied network is based on [19].

The one hour average wind power data is used for power curtailment calculation. In order to investigate the development trend of the real wind power production against injected wind power capacity, it is also artificially scaled down and up.
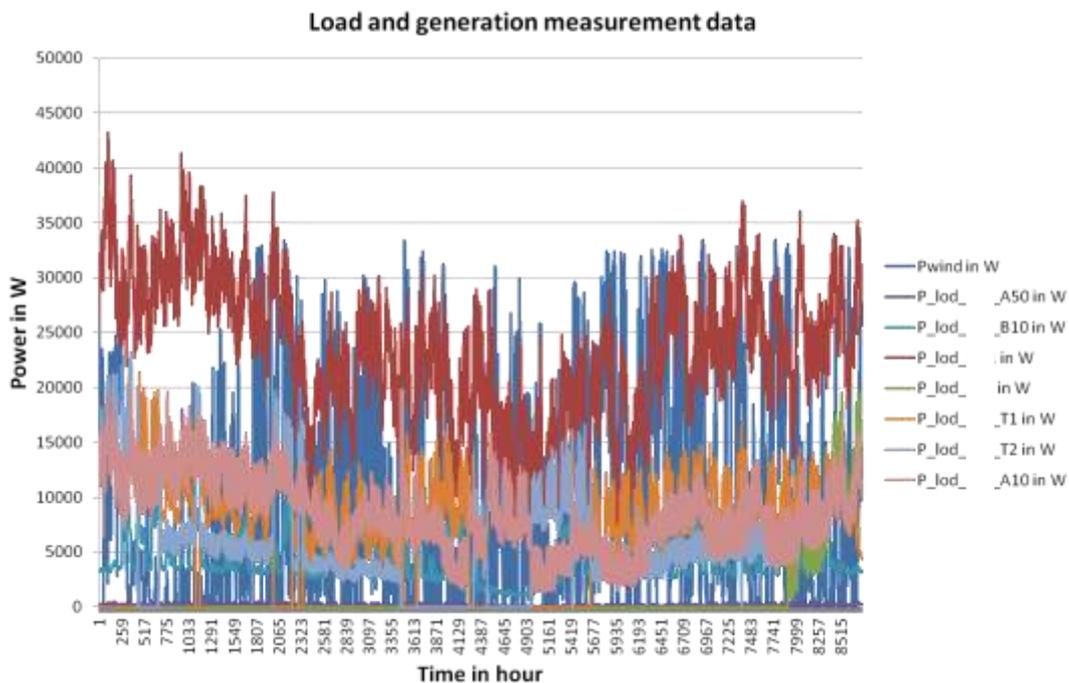
Figure 20 Load and generation measurement data example (one year)

10.1.5   Step increase of wind power

During the HC calculation, there is a loop for increase of wind power. More accurate and smooth results would be obtained with small step increase, while more time would be needed for computation. Therefore, the step should be appropriately selected to balance between the accuracy and the computation burden. In this study, the step increase is selected to be 1 MW if there is no specific notification in the context.

10.1.6   Data for Dynamic Line Rating

The DLR calculation is based on [20]. Thanks to DLR, system operator may defer the network reinforcement for wind power integration [21]. This is because wind conditions greatly affect the thermal cooling of the over head line conductors. Therefore high wind production and high transfer capacity (ampacity) of the conductors are likely to coincide.

The previous Elforsk project [7] has presented its feasibility and benefits in terms of the wind power integration.

The weather data for DLR is from [7] [19], which was based on the real weather conditions in 2009 and 2010 measured by Swedish meteorological bureau at 10 meters altitude some 40 km from the center of the studied grid.

Instead of the static line ampacity, the dynamic rating is varying with the time as observed in Figure 21. Apparently, the DLR is larger than the static rating most of the time, except some short period during the summer time that the

static rating may underestimate the real line thermal capability. However, this underestimation only occurs when there is little wind and hence also little wind production.
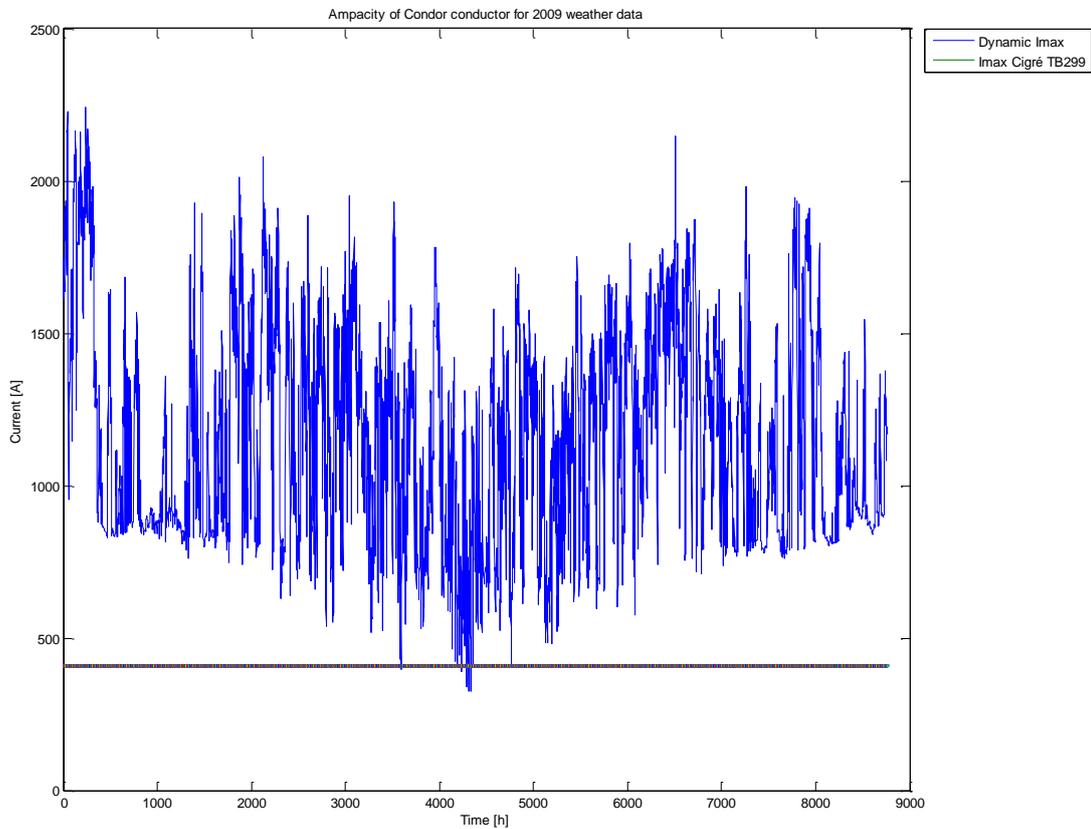

Figure 21 Dynamic Line Rating example

10.1.7   Reliability of lines

For subtransmission network, the reliability of lines is considered as 0,0274% of the time period per 100 km [7]. The detailed out of service rate for each line is summarized in Table 9. The total out of service rate is calculated to be 0,04%, which corresponds to 3,5 hours for one year.

Table 9 Summary of line out of service rate

Line No.	From bus No.	To bus No.	Line type	Length km	out of service in % of time
1	2	3	Ibis	2,6	0,0007124
2	2	5	Ibis	3,9	0,0010686
3	2	10	Ibis	6,4	0,0017536
4	3	4	AXLJ-TT 3x1x500/95 (cable)	4,4	0,0012056
5	4	5	AXALJ 3x1x300 (cable)	1,5	0,000411
6	5	11	Patridge	6,5	0,001781
7	6	11	Morkulla	1,6	0,0004384

8	6	13	Morkulla	3,5	0,000959
9	8	12	Hawk	2,7	0,0007398
10	8	15	Morkulla	40	0,01096
11	10	13	Condor	1,8	0,0004932
12	12	13	Condor	1,55	0,0004247
13	14	15	Morkulla	70	0,01918
Total				146.45	0.04

10.1.8 Availability of communication system

As the proposed smart solutions require power curtailment, the communication between the wind farm/wind turbine and load, as well as the line switches (protection system for inter-trip signal) is necessary.

A reliable and dependable communication system is preferred for the smart solution implementation. The risk of the failure of those communication systems should be studied.

10.2 Calculation of hosting capacity and power curtailment

In order to obtain the hosting capacity and power curtailment for different solutions, both NHC and PHC for normal operation status (System operation A) and one-line-off operation status (System operation B) should be calculated first.

10.2.1 Calculation for System operation A: normal operation status

The radial network or meshed network is within the normal operation status if there is no line off, which is abbreviated as SOA.

Section 3.1defines both NHC and PHC. For the SOA, NHC and PHC, as noted as NHC_{SOA} and PHC_{SOA}, can be calculated as explained below.

Assume the wind power converted into the network at moment t as $P_{grid}(t)$, local consumption at the same POC as $P_{load}(t)$, and the wind power injected as $P_{wind}(t)$, as illustrated in Figure 22.
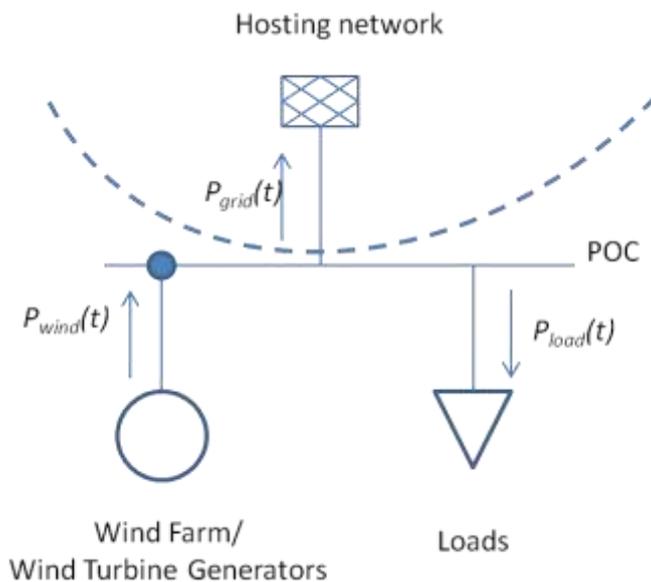
Figure 22 Illustration for NHC and PHC calculation

Thus:

Define *NHC_SOA* to be the maximum power that can be held by the network, thus:

And

This implies that the maximum *P_wind* or *PHC_SOA* can only be the sum of *NHC_SOA* and the minimum load consumption at the same POC:

Both *NHC_SOA* and *PHC_SOA* can be obtained by the following procedures which are illustrated in Figure 23 as well:

- Step 1: to define the wind power connection point POC and to clarify the load that is connected at the same point;

- Step 2: to allocate both load and generation data at time *t*; this is the first loop;

- Step 3: to select the amount of wind power that would be integrated at POC; this is the second loop;

- Step 4: to run the load flow to calculate the value of the performance index: line current;

- Step 5: to assess whether the line current is over the limit; if positive, continue with Step 6; if negative, repeat the second loop with increase of the wind power at Step 3;

- Step 6: to obtain and record the hosting capacity at a specific time moment *t*, as well as the load connected at the same POC; thus, the NHC at the moment could be derived;

- Step 7: to assess if all time period has reached: if positive, quit the loop and continue with Step 8; otherwise repeat the first loop at Step 2 with time increase;

- Step 8: to select the minimum NHC, which is NHC_{SOA} within the certain period for the network; thus, PHC_{SOA} can be determined.
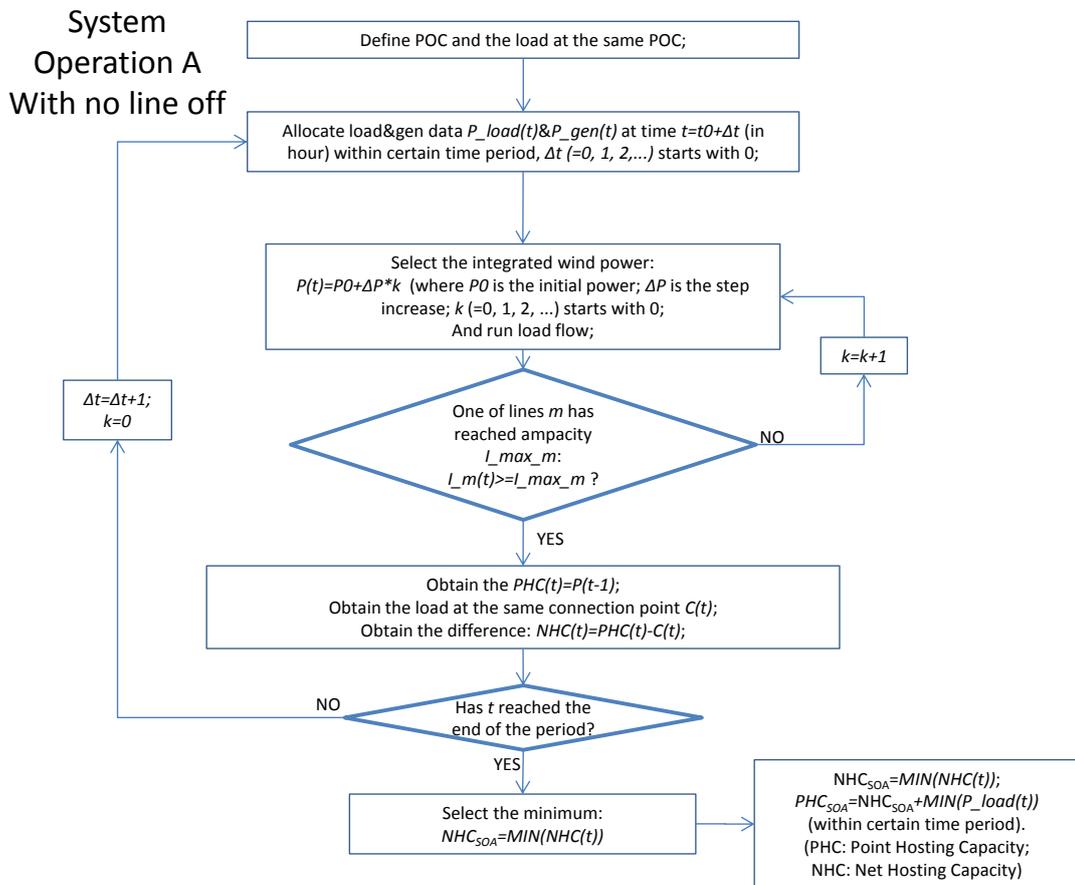

Figure 23 Flow chart for HC calculations with system operation A

There are two loops involved for this system operation A:
- loop for load flow calculation within certain time period, and
- loop for increase of wind power.

The presented calculation procedures can be repeated for different POCs.

10.2.2 Calculation for System operation B: one-line-off operation status

The System operation B is defined as the status that there is only one line off. With such case, N-1 criterion could be applied to ensure the stable operation. In [22], N-1 criterion means the rule according to which elements remaining in operation after a Fault of one element within TSO's Control Area must be capable of accommodating the new operational situation without exceeding Operational Security Limits. The case with one-line-off is considered as part of the N-1 criterion.

Once the maximum HC during System operation B is obtained, it will be compared with the HC during System operation A to select the maximum HC while still meeting the N-1 criterion.

Section 3.1 defines both NHC and PHC. For the System operation B, NHC and PHC, as noted as NHC_{SOB} and PHC_{SOB} can be calculated as explained below.

For one case with line x off, there is a corresponding NHC and PHC, which are defined as $NHC_{SOB\_case(x)}$ and $PHC_{SOB\_case(x)}$.

Assume the wind power converted into the grid at moment t as $P_{grid}(t)$, local consumption at the same POC as $P_{load}(t)$, and the wind power injected as $P_{wind}(t)$, as illustrated in Figure 22.

Thus:

As $NHC_{SOB\_case(x)}$ is the maximum power that can be held by the network, when line x is out of service, thus:

And

This implies that the maximum P_{wind} or $PHC_{SOB\_case(x)}$ for case x can only be the sum of $NHC_{SOB\_case(x)}$ and the minimum load consumption at the same POC:

Once the NHC for each case have been obtained, the NHC_{SOB} can be selected by:

Where

, representing the case number with line x off.

Finally, PHC$_{SOB}$ can be calculated by:

The calculation procedures can be illustrated by the flow chart in Figure 24 and listed below as well:

- Step 1: to define the wind power connection point POC; to clarify the consumption at the same point;

- Step 2: to select one line to be switched off; this is the first loop;

- Step 3: to allocate the load and generation at a specific time *t* for load flow; this is the second loop;

- Step 4: to select the amount of wind power at the same time *t* that would be integrated at POC; this is the third loop;

- Step 5: to run the load flow based on the load flow data during a certain time period; at the same time, to obtain the currents of all lines;

- Step 6: to compare the monitored line current with its limit: if the current exceeds the limit, continue with Step 7; if the current is still below the limit, repeat the third loop at Step 4 with increased wind power;

- Step 7: to obtain and record the hosting capacity at this moment *t* for the case with line *x* off, as well as the load at the same POC; thus, the NHC could be derived at this specific moment;

- Step 8: to assess if all time period has reached: if positive, quit the loop and continue with Step 9; otherwise repeat the second loop at Step 3 with time increase;

- Step 9: to assess if all the lines have been selected: if positive, continue with Step 10; if negative, repeat the first loop at Step 2;

- Step 10: to select the minimum NHC within the time period which is the $NHC_{SOB\_case(x)}$ for case *x* and $PHC_{SOB\_case(x)}$ as well, which can be determined as the summation of $NHC_{SOB\_case(x)}$ and the minimum load at the same POC during the time period;

- Step 11: to select the minimum NHC among $NHC_{SOB\_case(x)}$, noted as NHC_{SOB}; thus PHC_{SOB} is obtained by adding the minimum load P_{load_min}.
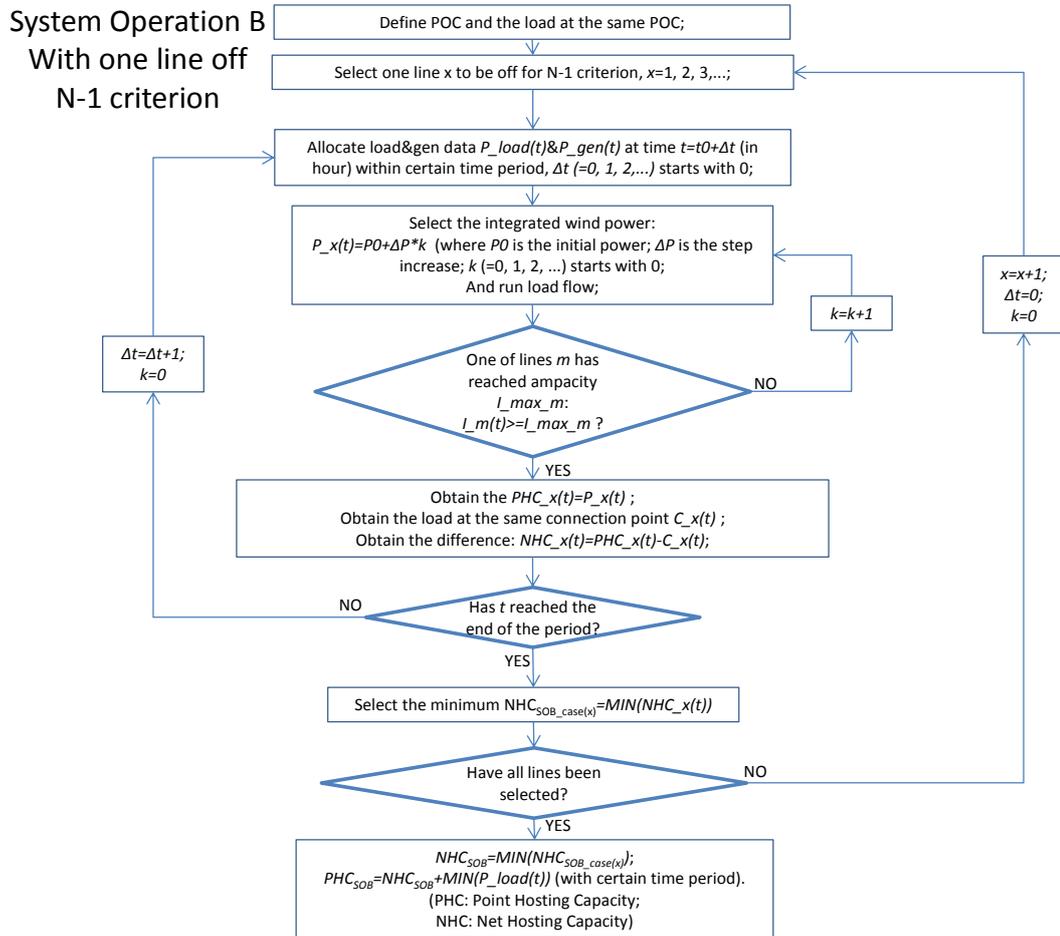
Figure 24 Flow chart for HC calculation with System operation B

There are three loops involved for system operation B:

- loop for selection of a line to be off,
- loop for load flow within certain time period, and
- loop for increase of wind power.

The presented calculation procedures would be repeated with different POCs.

10.2.3   Calculation for Solution 1: local supervisory system

Solution 1 enables the wind farm (WF) power curtailment when the wind power is larger than the sum of consumption and the power that can be accepted by the network, based on the feasibility of communication between the load consumption and wind farm.

Hosting capacity calculation
Based on the System operation B, the NHC for Solution 1 NHC_{SS1} is equal to NHC_{SOB}:

Since the WF can adjust the power production, the total PHC for Solution 1 is the sum of the NHC_{SS1} and the maximum consumption at the same point P_{load_max}, noted as PHC_{SS1}:

Power curtailment calculation
When the total wind power production ($P_{wind}(t)$) is larger than the sum of the power that can be accepted by the network (NHC_{SS1}) and the consumption at the same point ($P_{load}(t)$), the WF curtailment function should be in operation no matter it is under normal operation or under one-line-off operation. The amount of power curtailment is calculated by:

When   .

Such curtailment would take place during both normal and line-off operation.

10.2.4 Calculation for Solution 2: Special Protection Systems

Solution 2 enables WF to reduce its wind power output according to the line tripping signal during the one-line-off contingency, which can be sent by the 'Special Protection Systems'. Thus, the total HC can be increased during normal operation.

Hosting capacity calculation
The limited power that the network can accept (NHC_{SS2}) is calculated based on System operation A with all lines in operation:

.

The total PHC PHC_{SS2} is the sum of NHC_{SS2} and the minimum consumption at the same POC P_{load_min}:

When there is a line off, the power that the network can accept (NHC_{SS2}') is calculated based on System operation B:

.

This NHC_{SS2}' would be used for power curtailment calculation, which is the most conservative case, defined as Method 1 with fixed NHC.

Alternatively, each NHC of each case with line off should be utilized for calculation if more precise power curtailment is required:

, where x represents the case number.

This is defined as Method 2 with dynamic NHC.

However, this raises a higher requirement on the detection of the line off case. The benefit would be the less wind power curtailment.

Power curtailment calculation
If there is a line off, and the wind power production ($P_{wind}(t)$) is larger than the sum of the power that can be accepted by the network (NHC_{SS2}') and the minimum consumption at the same point (P_{load_min}), the trip signal together with the curtailment power should be sent to the wind farm.

The curtailment power is calculated by:

When   .

$Prob_{tot}$ indicates the total line-off probability.

Such curtailment only takes place during the line-off situation.

Alternatively, different NHC for different line off case should be utilized for curtailment calculation:

When   .

$Prob_{case(x)}$ indicates the probability of out of service for line x.

More simply, the whole wind farm/turbines would be shut down by the inter-trip signal, without considering how much power should be curtailed.

In this project, we assume the more precise method since the smart solution is discussed.

10.2.5   Calculation for Solution 3: Grid supervisory system

This Solution combines the Solution 1 and 2 together.

Hosting capacity calculation
The NHC for Solution 3 NHC_{SS3} is equal to NHC_{SOA}:

.

This NHC would be used for power curtailment calculation during the normal operation.

The PHC for such solution PHC_{SS3} is, according to Section 5.4, the sum of the power that can be accepted by network with all lines in operation (NHC_{SOA}) and the maximum consumption (P_{load_max}):

When there is a line off, the power that the network can accept (NHC_{SS3}') is calculated based on System operation B:

.

This $NHC_{SS3}{}'$ would be used for power curtailment calculation during one-line-off operation, which is the most conservative case, defined as Method 1 with fixed NHC.

Alternatively, each NHC of each case with line off should be utilized for calculation if more precise power curtailment is required:

, where x represents the case number.

This is defined as Method 2 with dynamic NHC.

Again, this raises a higher requirement on the detection of the line off case. The benefit would be the less wind power curtailment.

Power curtailment calculation
For power curtailment calculation, there are two situations that need to be discussed: the normal operation and the one-line-off operation.

During the normal operation, the power curtailment is calculated by:

when

$Prob_{tot}$ indicates the total line-off probability.

If there is a line off, the curtailed power should be:

When

Alternatively, different NHC for different line off case should be utilized for curtailment calculation:

When

.

$Prob_{case(x)}$ indicates the probability of out of service for line x.

10.2.6   Calculation for Solution 4: Dynamic Line Rating

Hosting capacity calculation
This solution is based on Solution 3. The only difference is that DLR is introduced with dynamic line ampacity limits, instead of the static limits.

Once the static limits (I_{max}) are replaced by dynamic limits ($I_{max}(t)$), NHC_{SOA} and NHC_{SOB} must be updated, noted as NHC_{SOA_DLR} and $NHC_{SOB\_DLR.}$ Thus, both NHC and PHC with Solution 4 are presented as below.

The NHC for Solution 4 NHC_{SS4} is equal to NHC_{SOA_DLR}:

.

This NHC would be used for power curtailment calculation during the normal operation.

And the PHC for such solution PHC_{SS4} is the sum of the power that can be accepted by network with all lines in operation (NHC_{SOA_DLR}) and the maximum consumption (P_{load_max}):

When there is a line off, the power that the network can accept ($NHC_{SS4}^{'}$) is calculated based on System operation B:

.

This $NHC_{SS4}^{'}$ would be used for power curtailment calculation during one line off operation, which is the most conservative case, defined as Method 1 with fixed NHC.

Alternatively, each NHC of each case with line off should be utilized for calculation if more precise power curtailment is required:

, where x represents the case number.

This is defined as Method 2 with dynamic NHC.

Again, this raises a higher requirement on the detection of the line off case. The benefit would be the less wind power curtailment.

Power curtailment calculation
During the normal operation, the power curtailment is calculated by:

when

$Prob_{tot}$ indicates the total line-off probability.

If there is a line off, the curtailed power should be:

When

Alternatively, different NHC for different line off case should be utilized for curtailment calculation:

When

.

$Prob_{case(x)}$ indicates the probability of out of service for line x.

10.3 Hosting capacity and power curtailment comparison

The following table summarizes the calculation of both hosting capacity and power curtailment for different operations and solutions, based on the discussion above.

$Prob_{tot}$ is defined as the total probability for one-line-off operation. In this report, $Prob_{tot}$ equals 0,04% according to Table 9**.**

$Prob_{case(x)}$ is defined as the probability for one-line-off operation case x.

Table 10 Summary of the calculation of HC and power curtailment

Case	NHC in MW, indicating the maximum wind power that can be accepted by the network	PHC in MW, indicating the maximum wind power that can be accepted at the POC	Power Curtailment		
			Normal operation	One line off operation	
				Method 1: with minimum NHC	Method 2: with variable NHC
System operation A	NHC_{SOA}	$PHC_{SOA}=NHC_{SOA}+P_{load\_min}$	N/A	N/A	N/A
System operation B	NHC_{SOB}	$PHC_{SOB}=NHC_{SOB}+P_{load\_min}$	N/A	N/A	N/A
Smart Solution 1	$NHC_{SS1}=NHC_{SOB}$	$PHC_{SS1}=NHC_{SS1}+P_{load\_max}$ $=NHC_{SOB}+P_{load\_max}$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS1}-P_{load}(t)) \cdot (1-Prob_{tot})$ $=(P_{wind}(t)-NHC_{SOB}-P_{load}(t))\cdot(1-Prob_{tot})$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS1}-P_{load}(t)) \cdot Prob_{tot}$ $=(P_{wind}(t)-NHC_{SOB}-P_{load}(t))\cdot Prob_{tot}$	N/A
Smart Solution 2	$NHC_{SS2}=NHC_{SOA}$ $NHC_{SS2}'=NHC_{SOB}$ $NHC_{SS2\_x}'=NHC_{SOB\_case(x)}$	$PHC_{SS2}=NHC_{SS2}+P_{load\_min}$ $=NHC_{SOA}+P_{load\_min}$	No need for curtailment	$P_{curtailment}=(P_{wind}(t)-NHC_{SS2}'-P_{load\_min}) \cdot Prob_{tot}$ $=(P_{wind}(t)-NHC_{SOB}-P_{load\_min}) \cdot Prob_{tot}$	$P_{curtailment}=\Sigma[(P_{wind}(t)-NHC_{SS2\_x}'-P_{load\_min})\cdot Prob_{case(x)}]$ $=\Sigma[(P_{wind}(t)-NHC_{SOB\_case(x)}-P_{load\_min})\cdot Prob_{case(x)}]$
Smart Solution 3	$NHC_{SS3}=NHC_{SOA}$ $NHC_{SS3}'=NHC_{SOB}$ $NHC_{SS3\_x}'=NHC_{SOB\_case(x)}$	$PHC_{SS3}=NHC_{SS3}+P_{load\_max}$ $=NHC_{SOA}+P_{load\_max}$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS3}-P_{load}(t)) \cdot (1-Prob_{tot})$ $=(P_{wind}(t)-NHC_{SOA}-P_{load}(t)) \cdot (1-Prob_{tot})$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS3}'-P_{load}(t)) \cdot Prob_{tot}$ $=(P_{wind}(t)-NHC_{SOB}-P_{load}(t)) \cdot Prob_{tot}$	$P_{curtailment}=\Sigma[(P_{wind}(t)-NHC_{SS3\_x}'-P_{load}(t))\cdot Prob_{case(x)}]$ $=\Sigma[(P_{wind}(t)-NHC_{SOB\_case(x)}-P_{load}(t))\cdot Prob_{case(x)}]$
Smart Solution 4 (Smart Solution 3 with DLR)	$NHC_{SS4}=NHC_{SOA\_DLR}$ $NHC_{SS4}'=NHC_{SOB\_DLR}$ $NHC_{SS4\_x}'=NHC_{SOB\_DLR\_case(x)}$	$PHC_{SS4}=NHC_{SS4}+P_{load\_max}$ $=NHC_{SOA\_DLR}+P_{load\_max}$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS4}-P_{load}(t)) \cdot (1-Prob_{tot})$ $=(P_{wind}(t)-NHC_{SOA\_DLR}-P_{load}(t)) \cdot (1-Prob_{tot})$	$P_{curtailment}=(P_{wind}(t)-NHC_{SS4}'-P_{load}(t)) \cdot Prob_{tot}$ $=(P_{wind}(t)-NHC_{SOB\_DLR}-P_{load}(t)) \cdot Prob_{tot}$	$P_{curtailment}=\Sigma[(P_{wind}(t)-NHC_{SS4\_x}'-P_{load}(t))\cdot Prob_{case(x)}]$ $=\Sigma[(P_{wind}(t)-NHC_{SOB\_DLR\_case(x)}-P_{load}(t))\cdot Prob_{case(x)}]$