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Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy – some illustrative case studies

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ABSTRACT

This paper presents the use of curtailment to allow more wind or solar power to be connected to a distribution network when overcurrent or overvoltage set a limit. Four case studies, all based on measurements, are presented. In all cases the hosting capacity method is used to quantify the gain in produced energy for increased levels of distributed renewable energy resources. A distinction is made between "hard curtailment" where all production is disconnected when overcurrent and overvoltage limits are exceeded and "soft curtailment" where the amount of production to be disconnected is minimized. It is shown that the type of curtailment method used has a large impact on the amount of delivered energy to the grid. The paper further discusses details of the curtailment algorithm, alternatives to curtailment, the communication needs and risks associated with the use of curtailment.

1. Introduction

The amount of renewable energy that can be connected to any distribution network without endangering the reliability or quality for other customers (the "hosting capacity") is limited by the overvoltage and overcurrent limits in the distribution network. As the proportion of renewable electricity production increases so does the risk that network components get overloaded and/or the network users will experience overvoltages [1–3].

The here applied "hosting-capacity approach" has been introduced to quantify the limits placed by the grid on renewable electricity production. The hosting capacity is in this context defined as the maximum amount of new production that can be connected without endangering the reliability or quality for other customers [1]. The traditional way of connecting a new production installation is based on a kind of "worst-case approach". The maximum installed capacity is such that the risk of, for example, overload or overvoltage is sufficiently small, and therewith the impact on other network users.

Curtailment of production is a method to connect more production without impacting other network users. Other methods are available to achieve this. The reader is referred to [1,3–6] and other publications for examples of such methods. This paper is an upgrade and extension of an earlier work by the same authors [7]. The examples discussed in this paper will be used to illustrate a general method to quantify the effectiveness of curtailment. This methodology offers the different stakeholders (network operators, owners of production units, regulators, equipment manufactures and others) a tool with which they can compare curtailment with network investments in primary infrastructure (lines, cables, transformers, etc.) or other methods such as energy storage and reactive-power compensation.

The general methodology used in this paper is introduced in Section 2, illustrated through four case studies in Sections 3–6, and followed by a general discussion and synthesis of the four cases in Section 7 and conclusions in Section 8.

2. Curtailment and hosting capacity

When curtailment is in place, there is no longer any technical limitation to the amount of production capacity that can be connected. Unacceptable impact on other network users is no longer prevented by limiting the installed capacity but by limiting the actual production whenever needed. In practice it will be economic considerations by the owner of the production units that limit the installed capacity. With increasing installed capacity the utilization of the installation (e.g. expressed as the ratio of annual

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production and installed capacity, MW h/MW) will decrease and thus the return on investment.

The proposed methodology, illustrated in this paper through four examples, calculates the curtailed and the produced amount of electricity as a function of the installed capacity. This relation can be used as input to investment decisions, for the choice of technology, and to develop appropriate investment models.

During the four case studies, a distinction is made between “hard curtailment” and “soft curtailment”. Both should be viewed as extreme cases: for the hard-curtailment case it is assumed that all production units downstream of a certain location in the grid are disconnected. This is very close to the traditional protection relaying approach but instead of tripping the overloaded components, the installations causing the overload are disconnected from the electrical grid. For the soft-curtailment case it is assumed that the production will be reduced just enough to remove the overload or overvoltage situation that would otherwise occur. The actual curtailment in reality will be somewhere in between these two extreme cases, where the actual amount of curtailment depends on the details of the curtailment scheme.

This paper illustrates that risks in four case studies and discusses different methods of keeping the risks under control. How a risk-based approach together with advanced communication and control equipment increases the amount of renewable energy that can be connected to the distribution network is investigated following the approach of [1,8].

3. Solar power at low voltage, limitation in subscribed power

3.1. Description of the case

The impact of solar power on the loading has been studied for a large hotel complex located at 38°N. Measurements of the consumption (1-min averages during 1-week) have been combined with a model of the production. The consumption is high from about 10 am through 10 pm with a maximum of about 590 kW; the minimum consumption is about 230 kW. More details of this example are shown in [1, Section 4.2.6].

In this example, the limitation is assumed to be set by the subscribed power. Exceeding this limit is assumed to result either in disconnection of the installation or in high fines to be paid on top of the network tariff. Increasing the subscribed power would result in a higher network tariff and/or the need for investments in the grid. Curtailment of production is studied here as an alternative.

3.2. Overloading

The production has been calculated for a horizontal panel as a function of the time of day for 21 June. The resulting maximum loading as a function of the installed power is shown in Fig. 1. The system loading (i.e. the maximum apparent power) slightly decreases up to about 300 kW solar power (region A in Fig. 1). For higher amounts of solar power than 300 kW, the maximum occurs when the sun is below the horizon and further production will no longer reduce the maximum (region B). When more than 1000 kW of solar power is installed, the maximum loading occurs at noon and will increase linearly with the installed capacity (region C). The value of 300 kVA per phase (slightly above the original maximum) is reached for 1140 kW installed capacity. For even more solar power, the owner of the hotel runs an increased risk that the apparent power exceeds the subscribed power. The consequence of this may be a tripping of the installation by the overcurrent protection or fines to be paid by the hotel owner to the network operator. When the hotel is supplied from a dedicated transformer of three times 300 kVA rating, adding more solar power will require a larger transformer. When the hotel is supplied from a shared transformer, a higher subscribed power is needed, the costs of which will have to be discussed with the network operator.

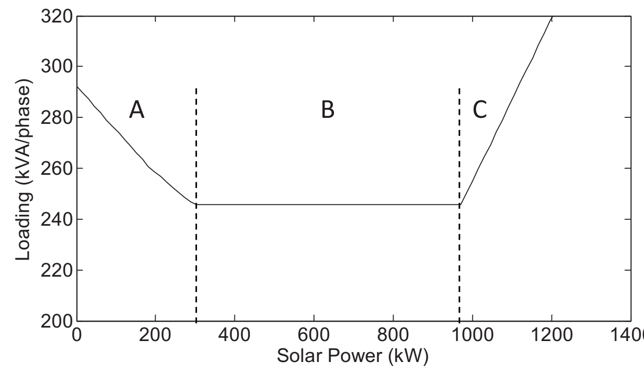

Fig. 1. Maximum apparent power per phase as a function of the installed solar capacity. (A = maximum from consumption at daytime; B = maximum from consumption in the evening; C = maximum from production at day time).

3.3. Curtailment

The impact on the amount of produced energy from solar power has been calculated for “hard curtailment” and for “soft curtailment”. For hard curtailment the whole solar-power installation is assumed to be disconnected once the supply current exceeds the subscribed power. For soft curtailment, the solar power production is reduced not to zero but just enough to keep the current below the threshold. Hard curtailment could in this case consist of an overcurrent relay at the point of connection that trips all production once the subscribed power is exceeded.

To estimate annual curtailment, solar production has been calculated for 12 weeks, spread equally through the year. Consumption has been assumed to be independent of the time of year and cloud cover assumed to reduce average solar energy production to 70% of its maximum value.

The results are shown in Figs. 2 and 3. For installed capacity below about 1150 kW no curtailment is needed, but for higher installed capacity the need for curtailment increases rapidly. For an installed capacity equal to 1500 kW, curtailment is needed for more than 600 h per year.

What matters is not the number of hours of curtailment, but total curtailed energy and total solar energy delivered to the grid. For hard curtailment (red solid curve) the curtailed energy increases as curtailed hours increases; with the annual production decreasing as installed capacity increases. So, hard curtailment is not a solution in this case.

With soft curtailment (green dashed curve) the amount of curtailed energy is reduced and the annual production continues to increase, but with a decreasing profitability. Up to about 1250 kW installed capacity the annual production corresponds to

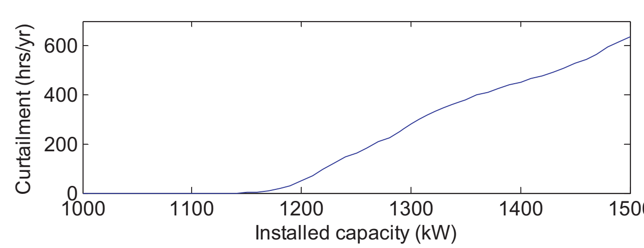

Fig. 2. Time during which curtailment is necessary to prevent the current from exceeding the supply rating.

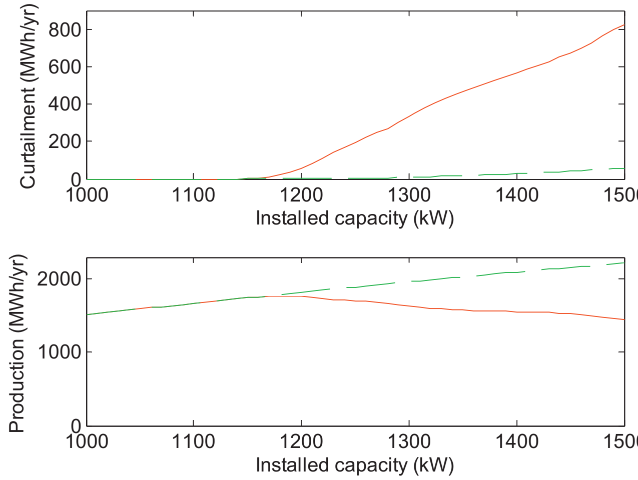

Fig. 3. Annual amount of curtailed energy (top) and annual production (bottom). Hard curtailment (red solid) is when solar power is disconnected upon detection of an overload. Soft curtailment (green dashed) is when the reduction in solar power production is the minimum amount necessary to maintain the current within the rating. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

1500 h/year at peak. The additional 250 kW up to 1500 kW have an effective utilization of only 1300 h/year. For the next 250 kW (not shown in the figures) this would drop further to 1000 h/year.

3.4. Implementation

The variable to be limited in this case is the amplitude of the current flowing between the customer and the grid. The actual value and the time window over which the current should be measured depend on the protection used and on the agreement between the customer and the network operator. When the supply current is limited by the overcurrent protection, the curtailment algorithm should be coordinated with the protection setting. We will discuss this in more detail in Section 4.4, with the next example.

When the limitation is in the amount of energy consumed per hour (kWh/h), a few samples per hour would be sufficient. A high current during part of an hour could be compensated by a lower current during another part of the hour. The need for curtailment would more likely occur toward the end of an hourly period.

Based on the measurement of the current at the interface with the grid either a trip signal will be generated (in case of “hard curtailment”) or a required reduction in production will be calculated and communicated to the solar-power installation. One possible implementation in the solar-power installation would be to have different modes for the controller: maximum power point tracking normally; constant current during curtailment.

The communication needs are limited in such a set-up. There is only one place where the current has to be monitored and the installation which power output is to be limited is located nearby.

4. Wind power behind an HV/MV transformer, limitation in transformer loading case 1 (simulated wind production)

4.1. Description of the case

During a 4-week period the power through a 130/10 kV transformer supplying a region with mainly domestic load without any distributed generation was measured every minute. Downstream of the transformer, wind power is connected to the medium-voltage grid. Random values of production have been obtained by assuming Weibull-distributed wind-speed with a mean value of 7 m/s and a shape factor of 2. A scaled version of a 600 kW wind turbine was used to translate wind speed into active power production. Reactive power production is assumed to be zero. See [1,5,6,9,10] for more details about stochastic models of wind power production.

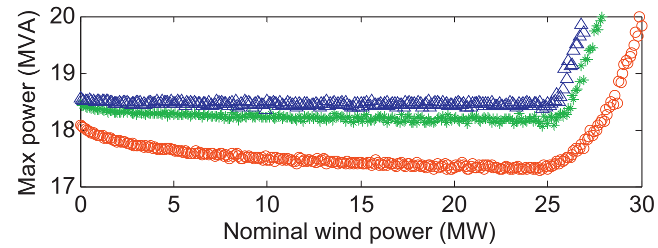

Fig. 4. High-percentile values of apparent power through a transformer with increasing amount of wind power on secondary side: 99.99% (triangle); 99.9% (star); and 99% (circle).

Apparent power through the transformer has been calculated for various nominal wind power levels, from zero to 30 MW. The results are shown in Fig. 4. For wind power values up to about 25 MW, the risk of overloading only decreases a little. The risk of overloading, due to excessive reverse power flow, increases rapidly when more than 25 MW of wind power is connected on the secondary side of the transformer.

4.2. Curtailment

Two curtailment methods have been studied: “hard curtailment” where wind power is disconnected when transformer loading approaches the maximum-permissible value, and “soft curtailment” where production is reduced by the exact amount required to avoid overvoltage or overloading.

The results are shown in Figs. 5 and 6. Up to about 26 MW installed wind power, no curtailment is needed. For installed capacity up to about 31 MW, total produced energy still increases even with hard curtailment, but profitability of the capacity above 26 MW is slight.

For soft curtailment (green dashed curve), although annual production increases with greater installed capacity, profitability decreases as installed capacity increases. Up to 25 MW the utilization is about 2700 h per year; but the additional 10 MW capacity up to 35 MW is only used for 2500 h/year and the 5 MW up to 40 MW for only 1900 h/year.

4.3. Communication

Soft curtailment in this case could be performed by sending a signal to the wind turbine controller to alter pitch angle of the rotor blades to decrease wind production. Transformer loading is derived from current through the transformer and used to calculate

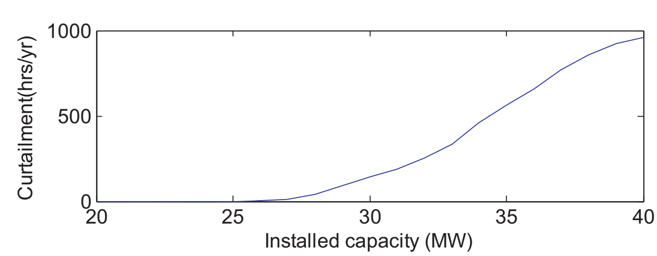

Fig. 5. Number of hours per year during which curtailment is necessary to prevent HV/MV transformer overloading due to wind power on secondary side of the transformer.

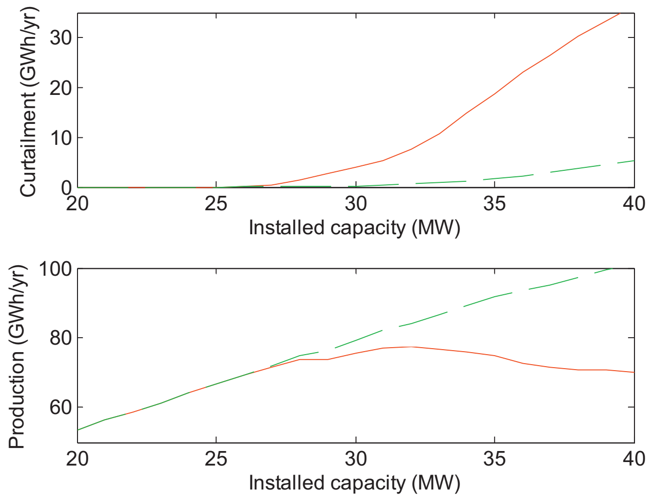

Fig. 6. Annual amount of curtailed energy (top) and annual production (bottom). Hard curtailment (red solid) is when wind power is disconnected upon detection of an overload (red solid). Soft curtailment (green, dashed) is when the reduction in wind power production is the minimum amount necessary to maintain the current within the rating. Annually curtailed energy (top) and amount of production (bottom) and soft curtailment (green dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

a maximum production (or a curtailment amount) for the wind turbines.

The required accuracy and response time of current measurement in the transformer substation is modest, so current measurement could be obtained from the SCADA system for distribution to the wind turbine operator.

A novel solution with an IEC 61850/61400-25 compatible control system for the wind turbine would allow direct information exchange with an IEC 61850 relay within the nearby transformer substation. Such a solution requires access to the metering core in the transformer substation and configuration in the SCADA systems of the network operator.

The monitoring device in the transformer substation can be completely separated from the Ethernet of the network operator allowing the wind farm owner to implement a curtailment system with a minimum of intervention with the grid operator. Thus the wind farm automatically adjusts its production to ensure that the transformer loading remains below it limits without the network operator issuing any real-time production set-points to the producers.

4.4. Implementation

The curtailment algorithm will reduce production when the current through the transformer gets too high for too long. The setting of this algorithm should be such that the curtailment is as small as possible; but fast enough that the overload protection of the transformer does not take the transformer out of service. This is a classical protection coordination problem, as shown schematically in Fig. 7.

Thermal overload of a transformer is a relatively slow process. For example, recommendations for the setting of short-circuit protection give a value of two times the rated current for 30 min and five times rated for 50 s [11,12]. The maximum-permissible overload current and time should be determined using the loss-of-life methods, described for example in [13–15]. The curve labeled “4” in Fig. 7 corresponds to the maximum overload with negligible loss of life. However, once the setting of the overload protection is known, curtailment has to be coordinated with the protection setting (“3”).

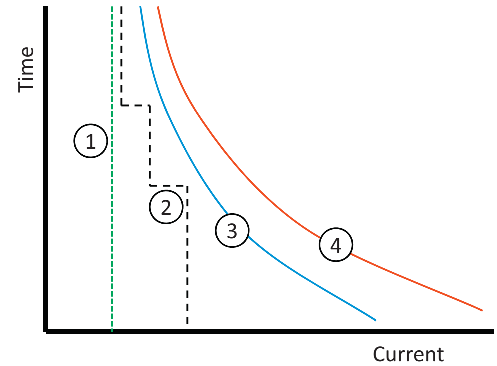

Fig. 7. Curtailment and protection settings. (1 = maximum permanent load current; 2 = curtailment settings; 3 = overcurrent protection; 4 = actual thermal limit).

A hypothetical example of a curtailment algorithm would be as follows, based on obtaining a value of the rms current at 1-min intervals; all currents are expressed as a percentage of a reference current.

- When current exceeds 150% of the reference current, reduce immediately to 150%.
- When current exceeds 130% for 3 min, reduce immediately to 130%.
- When current exceeds 120% for 10 min, reduce to 120%.
- When current exceeds 110% for 30 min, reduce to 110%.
- When current exceeds 100% for 100 min, reduce to 100%.
- When current is below 100% and curtailment has been performed during the preceding 100 min, allow the current to increase to 100%.
- When current has been below or equal to 100% of the reference current for 100 min, allow overloads as above.

The reference current would in this case be somewhat below the maximum current that the transformer can tolerate permanently without the overload protection tripping.

Another option would be for the overcurrent protection relay to issue a warning when its pick-up timer has started. This signal could be used to curtail production, following similar rules to those above. This scheme would allow set-up of curtailment without detailed knowledge of over-current relay settings. A more sophisticated option would be for the wind farm to receive curtailment commands from multiple overcurrent relays in a meshed grid or a frequently reconfigured grid as described in Section 4.3. A further advantage is that only the overcurrent relays, and not the curtailment algorithm settings, would need to be modified as the grid expands or changes its characteristics.

5. Wind power behind an HV/MV transformer II, limitation in transformer case 2 (measured wind production near transformer)

5.1. Description of the case

As was the case of the previous example in Section 4 the power through a 130/10 kV transformer is measured. However, this time actual measurements of both consumption and wind-power production were collected for two entire calendar years in a different network. The transformer is rated at 40 MVA and supplies a region with both domestic and industrial loads with only small scale hydro production. It is assumed that downstream of the transformer wind power is connected to the medium-voltage grid. Time-correlated production values from a 34 MW wind farm in the vicinity of the 130/10 kV transformer have been used. The reactive power

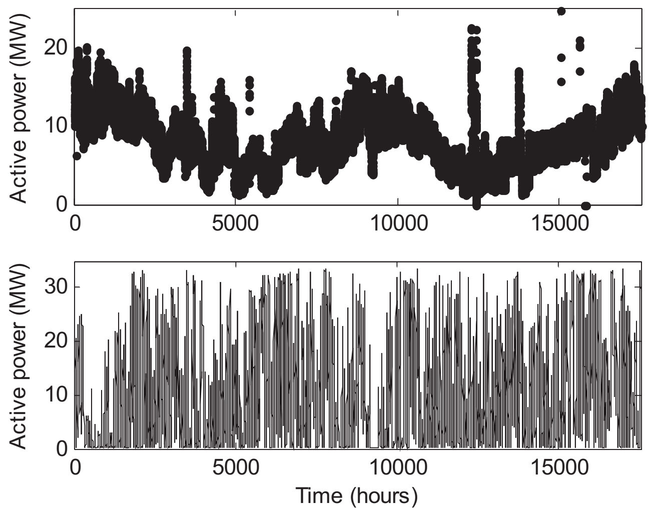

Fig. 8. Active power flow through a 130/10 kV transformer and intermittent character of nearby wind power production used in the study.

production is zero or near zero for this wind farm. The hourly loads and production of the added wind are shown in Fig. 8. The horizontal axis in Fig. 8 stretches from the first day of year one to the last day of year two.

Compared with the case in Section 4 where the wind was simulated with a Weibull distribution, this example with actual wind production time correlated to the loads shows a similar behavior. For a number of values of the nominal wind power, from zero to 70 MW, the 99%, 99.9%, and 99.99% values of the active power through the transformer have been calculated. The results are shown in Fig. 9. For wind power values up to 26 MW, the risk of overloading only marginally decreases. The risk of overloading increases fast when more than 26 MW of wind power is connected on the secondary side of the transformer.

5.2. Curtailment

Like in the previous cases, the produced and curtailed amount of energy has been calculated as a function of the installed wind-power capacity. Up to 45 MW of installed capacity, no curtailment is required, as seen in Figs. 10 and 11.

The curtailed and produced energy is shown in Fig. 11, where it has been assumed for the soft curtailment case that no more production is curtailed than needed. For hard curtailment, like before, the production is disconnected completely every time curtailment is needed, i.e. when the transformer would be overloaded

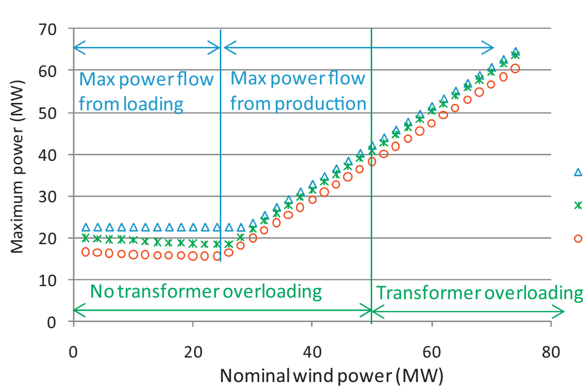

Fig. 9. High-percentile values of power through a transformer with increasing amount of wind power on secondary side: 99.99% (triangle); 99.9% (star); and 99% (circle).

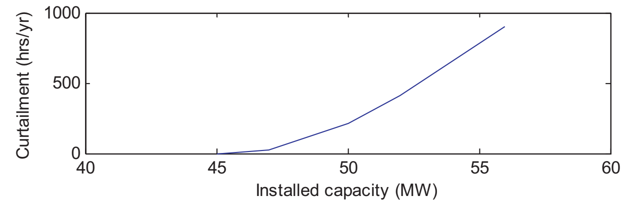

Fig. 10. Number of hours per year during which curtailment is necessary to prevent HV/MV transformer overloading due to wind power on secondary side of the transformer.

otherwise. The behavior is similar to the results from the example discussed in Section 4.

The implementation and curtailment examples would here be the same as in the case of Section 4.

6. Overvoltage due to wind power

6.1. Description of the case

Probability distribution functions of the voltage magnitude after connection of a wind-power installation have been calculated by means of a Monte-Carlo simulation. For each distribution, 100 000 samples were taken. Each sample of the voltage after connection of the wind turbine was obtained as the sum of a sample from the measured pre-wind voltage and a sample from the voltage rise. The former was obtained by taking a random value of time, within the measurement time window, and using the voltage magnitude at this random instant. The sample of the voltage rise was calculated from the wind power production, which was in turn calculated from the wind speed using the power curve for a 600 kW turbine scaled to the size of the wind power (1, 2, or 3 MW in this case). This scaling will not impact the result as the power curves are largely independent of the size of the turbine.

For the wind speed, a Weibull distribution with an average value of 7 m/s and shape factor of 2 is used. Next, four different percentiles of the overvoltage distribution have been calculated as a function of the amount of installed wind power. The results are shown in Fig. 12. The measured voltage magnitude has been scaled in such a way that the maximum pre-fault voltage without wind power is 99% of the overvoltage limit. The overvoltage limit corresponds to a value of 100% (the horizontal dashed line) in the figure. The hosting capacity is the amount of wind power for which the

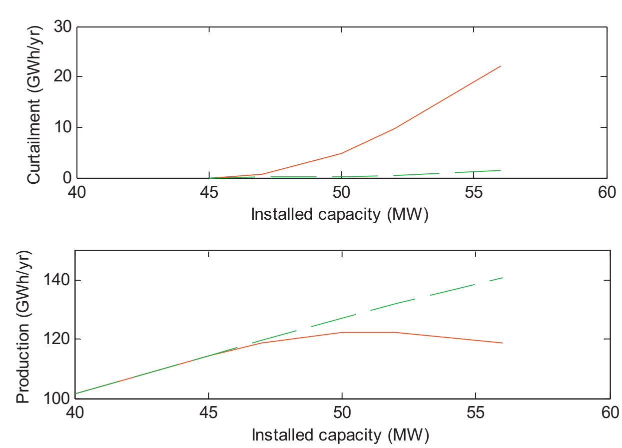

Fig. 11. Annually curtailed energy as a function of the installed wind-power capacity (top) and amount of production (bottom) for hard curtailment (red solid) and soft curtailment (green dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

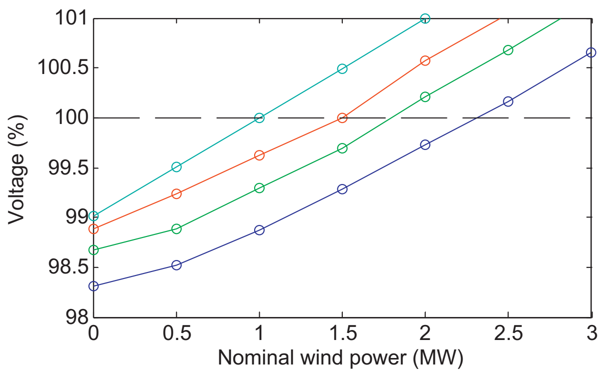

Fig. 12. Statistical overvoltage indicators as a function of the amount of wind power: (top to bottom) 100%, 99.99%, 99.9%, and 99% high-percentile values.

overvoltage indicator exceeds the 100% line. The dashed horizontal line corresponds to the overvoltage limit.

As can be seen from Fig. 12, the hosting capacity varies strongly between the indicators.

- The maximum voltage exceeds the limit for 1 MW wind power.
- The 99.99% value exceeds the limit for 1.4 MW wind power. (This corresponds to allowing overvoltage 0.01% of the time or 1 h per year.)
- The 99.9% value exceeds the limit for 1.8 MW wind power.
- The 99% value exceeds the limit for 2.3 MW wind power.

The hosting capacity thus varies between 1 and 2.3 MW depending on which percentile value is used. However, also here the occurrence of overvoltages can be avoided by curtailing the production during a small percentage of time.

The European voltage characteristics standard EN 50160 [16] gives limits on acceptable overvoltage for 95% of the time. These limits are used in several European countries, whereas other countries use more strict limits including 100% limits [17].

In Sections 6.2–6.4, it has been assumed that no reactive-power control is present, apart from the one keeping unity power factor. In Section 6.5, the same approach is applied to the case with reactive-power control.

6.2. Curtailment and produced power

Two curtailment algorithms have been applied and the results compared in Figs. 13 and 14. The number of hours during which curtailment is necessary to prevent overvoltage is shown in Fig. 13. With increasing installed capacity, the probability that the voltage exceeds the overvoltage limit increases quickly. Below 1 MW installed capacity, no curtailment is needed, with 2 MW installed capacity, curtailment of about 30 h per year is needed. For higher installed capacity the need for curtailment increases rapidly, reaching almost 1000 h per year for 4 MW installed capacity.

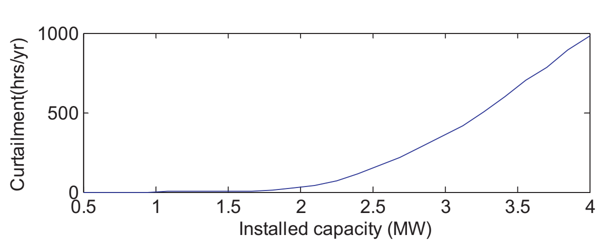

Fig. 13. Number of hours per year during which curtailment is necessary to prevent overvoltage due to wind power connected to an MV feeder.

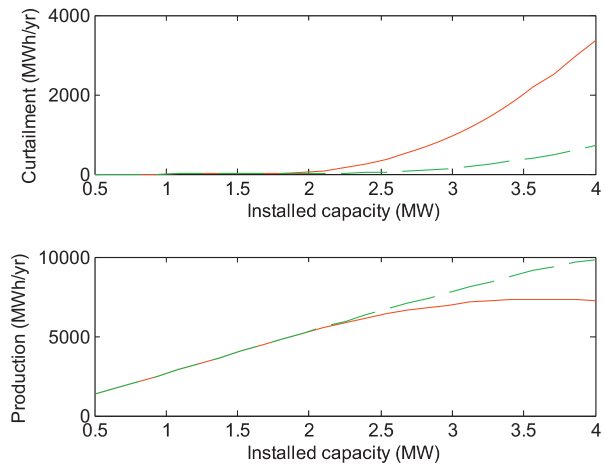

Fig. 14. Annual amount of curtailed energy as a function of the installed wind-power capacity (top) and produced energy (bottom) for hard curtailment (red solid) and soft curtailment (green dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Again, what matters is not the number of hours of curtailment, but total curtailed and total wind energy delivered to the grid per year (both shown in Fig. 14). The curtailed and produced energy has been calculated for two curtailment schemes: in the first ("hard curtailment"; indicated as red solid line) all wind-power production is disconnected when the voltage exceeds the overvoltage limit. In the second scheme ("soft curtailment"; green dashed line) the amount of production is reduced just enough so that the voltage does not exceed the overvoltage limit.

In the first scheme the amount of curtailed energy grows rapidly; above 3.5 MW installed capacity the annual produced energy starts to decrease. It therefore makes little sense to install more than about 3 MW of wind power. For the second scheme there is no comparable reduction in annual produced energy.

6.3. Implementation

One option is to accept a limited increased risk of equipment damage due to overvoltages and allow an increase on the amount of wind production.

A second option (referred to above as "hard curtailment") would be to equip the wind-power installation with overvoltage protection; and to measure at a limited number of locations in the medium-voltage network. The overvoltage protection would disconnect the wind-power installation when the production is too large. The wind production would be reconnected when the voltage is far enough below the limit for long enough. The choice of the reconnection criterion is a trade-off between amount production interruption and risk of frequent rapid voltage changes due to connection and disconnection of wind power.

A third option (corresponding to "soft curtailment") requires the presence of a smart-metering infrastructure. Here a data-base with periodically updated overvoltage measurements collected throughout the area of concern would be monitored. When overvoltages occur a curtailment command is issued to the wind plant giving it instructions to decrease its wind output by, e.g. turning blade angles to suboptimal position. The amount of production decrease could be predefined depending on the amount of overvoltage measured. The production set-point can be reduced further until the overvoltage disappears and then gradually increased when no overvoltage occurs.

6.4. Communication needs

The required communication infrastructure depends on the amount of uncertainty (risk) the different stakeholders are willing to accept. Generally speaking, a lower acceptance of risk will give a lower hosting capacity and/or more need for communication infrastructure.

When a certain level of overvoltages is accepted, there is no need for any communication. With the higher level of overvoltages, there is a higher risk of equipment damage due to overvoltages.

Tripping or curtailment of production can be based on the measurement of the voltage at the point of connection to the production unit. When this voltage is too high, the unit is disconnected or the production is reduced. Only local communication is needed in this case. For the setting of the overvoltage limit or voltage–production curve, the relation should be known between the voltage at the point of connection and the highest voltage experienced by any other network user. This might require the occasional recalculation of the settings (e.g. with reconfiguration of the distribution network and/or major changes in production or consumption) and communicating these changes to the production units.

Curtailment may also be based on the actual voltages experienced by the network users. For this an overvoltage-time curve has to be defined, and coordinated with the overvoltage limits that the network operator has to comply with as well as the immunity of end-user equipment to short-duration overvoltages: a hypothetical example based on the requirements under EN 50160 [16] and experiments on equipment immunity [2], would be:

- 114% of nominal voltage for 60 s;
- 109% of nominal voltage for 10 min.

The voltage is continuously measured with all network users. For the above overvoltage-time curve an update once every 15 s would be sufficient. No communication is needed as long as the curtailment limits are not exceeded. Once they are exceeded an alarm signal is sent from the affected customer to a central controller indicating how much the voltage needs to be reduced. The central controller translates the required voltage reduction into a reduction in production for one or more wind turbines; this curtailment signal would then be sent to all turbines involved.

A large communication infrastructure is needed, covering all low-voltage customers, and with an access time of a few seconds. However the amount of communication would be limited during normal operation.

6.5. Reactive-power compensation

In the case when overvoltage is limiting an alternative to curtailment to allow more wind power to be connected is to use the reactive-power control capabilities of the converters [18,19]. The effectiveness of this alternative depends on the ratio between resistance and reactance of the grid. The same approach will be used to evaluate the effectiveness of this method as for curtailment of active power only.

For this example the wind-turbine is assumed to have a reactive power control capability at the Point of Common Coupling (PCC), corresponding to a minimum power factor, $\cos\varphi$ of 0.9. While the voltage rise due to the active-power injected is dependent on the resistive part of the source impedance at the PCC the reactive-power compensation contributes to a reduction in voltage which magnitude depends on the reactive part of the source impedance. Curtailment is needed only when the available amount of reactive-power compensation is not sufficient to bring the voltage magnitude back below its maximum value.

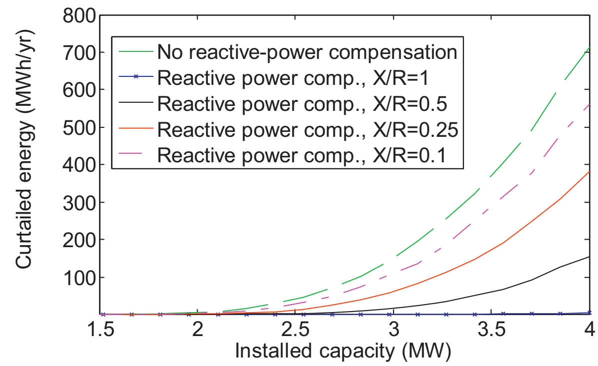

Fig. 15. Annual amount of curtailed energy with soft curtailment as a function of the installed wind-power capacity. The effectiveness of reactive-power compensation using the wind turbine capability curve depends on the electric parameters of the grid.

In Fig. 15 this remaining amount of soft curtailment is shown for different values of ratio between reactance X and resistance R of the source impedance. In all cases the resistance is kept equal to the value used to obtain Figs. 12–14. The green dotted curve ("no reactive-power compensation") in Fig. 15 corresponds with the green dotted curve in the upper plot of Fig. 14.

A lower value of X/R in the Fig. 15 corresponds to a thinner and shorter cable or line, with the total resistance being constant. With increasing X/R ratio, the reactance increases, for constant resistance, so that the ability of reactive power to compensate the voltage rise also increases. However even for X/R ratio equal to 1, some curtailment is needed when the installed capacity exceeds about 3.5 MW.

Here is should be noted that overvoltage problems are expected mainly in rural networks where feeders and transformer tend to have lower X/R ratios. In urban networks, with high X/R ratios, the length of the feeder is limited by its current rating, not by its voltage drop or rise. Thus in the networks where voltage rise is more likely to be a problem, the opportunities for reactive-power compensation are less. It should however also be noted that X/R ratios less than unity are rare and only occur in very weak parts of the grid. Also reactive-power control has limits (i.e. there is a hosting capacity associated with them) and failure of the control system could result in unacceptable overvoltages.

7. Discussion

7.1. Synthesis of the four cases

This paper shows four examples where curtailment can be used to allow an increasing amount of renewable electricity production to be connected to a distribution network. The number of curtailed hours, the curtailed energy and the actually delivered energy per year are calculated for these four examples. The gain, in the form of additional production that can be installed, varies for the four examples as shown in Fig. 16. For three of the examples the curtailment is about the same for the same normalized installed capacity. However for the voltage limit example in Section 6 (blue dashed curve close to the horizontal axis) the curtailment is much less.

A distinction has been introduced in this paper between "hard curtailment", where the production units are disconnected once a limit is exceeded, and "soft curtailment" where the production is reduced just enough to keep voltage and current within their limits. It is shown that soft curtailment results always in an increase in the total amount of produced energy, although there are diminishing returns as installed capacity increases. This is because a larger

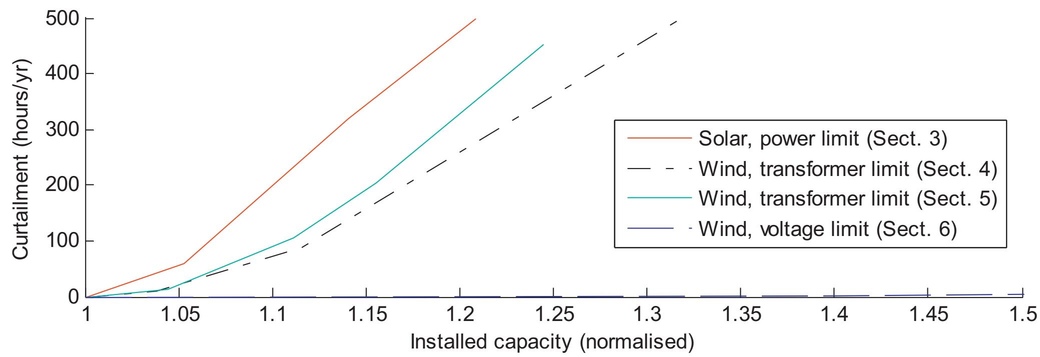

Fig. 16. Comparison of curtailed energy using so-called "soft curtailment" in the examples of Sections 3–6. Installed capacity (horizontal axis) has been normalized using the hosting capacity without curtailment. (For interpretation of the references to color in this sentence, the reader is referred to the web version of the article.)

proportion of the additional capacity will be curtailed and not possible to deliver to the grid as shown in Fig. 17.

For hard curtailment the total production decreases above a certain amount of installed capacity. For the solar-power example of Section 3, total production decreases almost immediately when curtailment becomes necessary. For the wind-power example of Sections 4 and 5 even with hard curtailment an increase in annual production is possible. This is shown to be especially the case when curtailment is used to prevent overvoltages.

7.2. Who carries the risk?

The normal dimensioning of the electricity distribution network is such that voltage and current remain within their limits for every load situation. While this approach is to the advantage of existing costumers, it could result in barriers for new customers such as installations of renewable electricity production. At present such an installation can only be connected when even the maximum production (the installed capacity) does not result in any overload or overvoltage for any load situation.

Exceeding this amount of installed capacity will result in a certain risk that the maximum current or voltage is exceeded. In the first example (solar power with a hotel in Section 3) that risk is carried by the owner of the hotel. Exceeding the current limit will either result in tripping of the overload protection or in fines for exceeding the subscribed power.

For the other examples the risk is carried by the network operator and by the other network users. An overload will result in tripping of the overload protection of the transformer, i.e. an interruption for all customers downstream of the transformer. It will also, in many regulatory schemes, result in penalties or reduced tariff for the network operator [17,20]. The impact of overvoltages is more indirect, but the higher the overvoltage, the higher the risk of equipment damage.

Using a curtailment scheme will shift the risk back to the owner of the wind-power installation. When the voltage or current exceeds the set limits, the production is reduced or completely interrupted depending on the scheme used. A minor risk remains with the network operator and other network users because there is a finite probability that curtailment will not work or will not be fast enough.

7.3. Who carries the costs?

In the first example, both costs and risks are carried by the hotel owner. This makes it easy to do an economic optimization. The hotel owner can further improve the economics by shifting consumption to periods with large production and insufficient consumption. Hot-water production could be used for this when a sufficient amount of hot-water storage is available.

The situation becomes less clear for the other examples, were different stakeholders are involved. Here we assume that curtailment is cheaper than investment in primary infrastructure (transformers, lines, etc.) or that building of new primary infrastructure will be impossible or take too long. When the overload is due to a specific customer, e.g. a wind park, the network operator will typically be allowed to charge this customer for any investments in the network. In that case it could be in the customer's interest to propose curtailment as an alternative to paying the required cost for grid connection of the entire plant capacity.

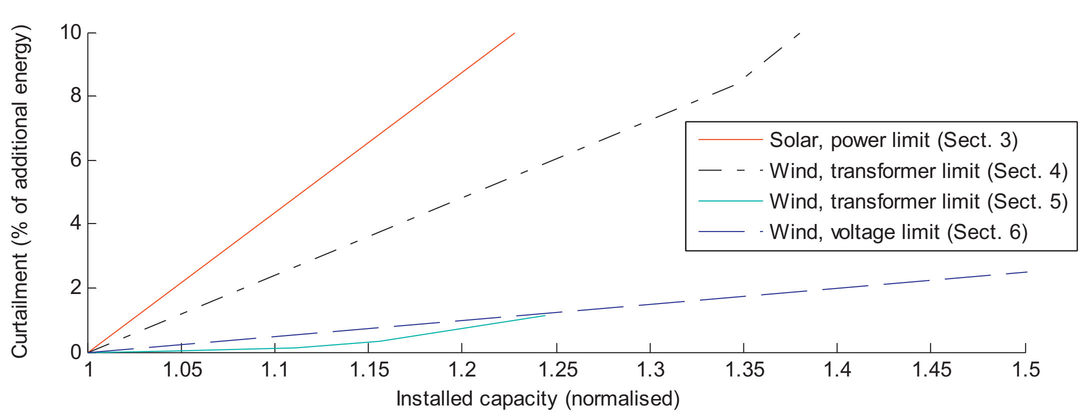

Fig. 17. With additional installed capacity a growing proportion (vertical axis) of additional capacity is curtailed. For comparison with the examples in Sections 3–6 the installed capacity has been normalized with the hosting capacity without curtailment (horizontal axis). The vertical axis shows the soft curtailed energy as a percentage of the additional energy made available with soft curtailment.

Details of this vary between countries and some network operators will not be able to charge investment costs to an individual network user. Instead of building new infrastructure, the network owner could buy a “curtailment service” from one or more producers. Different business models are possible for this; further discussion of those is beyond the scope of this paper.

If the overload is not due to one specific new customer but due to a general increase in loading (production and/or consumption), there will be differences in who carries the costs depending on the regulatory principles in use. Two main cases can be distinguished.

The regulator sets a maximum tariff based on a template calculation, e.g. considering customer density. The actual investments and operational costs do not impact the maximum tariff. This is often combined with quality regulation, either setting rules on minimum quality of supply (continuity and voltage quality) or by letting the maximum tariff be influenced by the actual performance. With this type of regulation, the network operator is incentivized to reduce costs and will choose for curtailment instead of investment in primary infrastructure. The rules on quality of supply might set a limit on the extent to which production and consumption can be curtailed. This is an issue to be discussed for future regulatory schemes.

An alternative method for tariff regulation is where the regulator approves necessary investments to be recovered through the tariffs with a reasonable return on investment. In the same way, necessary operational costs are covered through the tariffs with a reasonable profit. With this type of regulation, the investment in primary infrastructure actually results in a larger capital base and thus in a higher profit (in absolute terms). With this type of regulation, it is up to the regulator to decide whether a new transformer would be a necessary investment or not.

7.4. Curtailment and reserves

It was said at the start of Section 7.2 that the dimensioning of the distribution network is such that voltage and current remain within their limits for every load situation. For large parts of the network this also holds for the situation when a component is out of operation for repair or maintenance.

In many cases the maximum downstream load of a transformer will be about half of its rating, so as to have spare capacity available, for example, in case of the loss of another transformer. The maximum amount of wind power that is allowed to be connected is thus not determined by the actual thermal limit of the transformer but by the thermal limit minus a reserve margin. By using a curtailment scheme, this reserve margin (which could be up to half of the actual limit) could be more effectively used. Only when a nearby component is out of operation will curtailment be needed. The amount of time this will occur varies considerably between locations but will on average only happen a few percent of the time. The same holds for overvoltages, which are likely to occur first when part of a feeder is supplied from an alternative path.

The use of a curtailment scheme may make it possible to utilize the actual transport capacity to a much larger degree than is currently the case. This application of curtailment has not been studied in the literature yet.

8. Conclusions

The studies presented in this paper made use of measured voltage variations and consumption patterns. Production models have been used in three cases to demonstrate the methodology of estimating the amount of renewable energy that can be connected to a grid based on such measurements. An additional example with measured production patterns and a complete power system simulation has been included to verify the results of the here described method.

The hosting capacity approach, introduced in earlier studies, has been extended to include curtailment of renewable electricity production. The hosting capacity found from earlier studies is the installed capacity above which curtailment becomes necessary. For higher installed capacity the gain in annual produced energy should be compared with the increase in installed capacity. The result can next be compared with costs and benefits of other methods to increase integration of renewable electricity production. It has been shown that the same approach can be used for assessing the efficiency of reactive-power compensation.

It is shown that the amount of energy curtailed strongly depends on the curtailment method used. For curtailment methods related to existing overload or overvoltage protection (referred to as “hard curtailment” in the paper) the annual energy production might even go down with increasing installed capacity.

It is also shown that reactive-power compensation can reduce the amount of curtailed energy a lot. However, the reduction in curtailed energy is less for the kind of grids in which overvoltage problems are more likely to occur.

Further studies are needed, using measurements from different locations over time periods of at least 1 year, to determine if the conclusions from the studies described here are generally valid. Field trials are required to verify the behavior and suitability of proposed communication and curtailment algorithms during real grid operation.

With the practical implementation of curtailment schemes it is important that the resulting amount of curtailed energy is compared with the minimum amount of curtailed energy needs to prevent an overload or overvoltage situation (referred to as “soft curtailment” in the paper). Thus is concluded that an assessment of the consequences of the scheme, e.g. in terms of annual energy production per MW installed capacity, is necessary for every scheme.

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