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Dimensioning of Energy Storage for Increased Integration of Wind Power

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***Abstract*—Energy storage can potentially allow for more production from renewable resources into existing grids. A methodology to quantify grid limitations and dimension battery energy storage systems is presented in this paper. By use of grid consumption and production data, the hosting capacity methodology is developed as a general framework for storage dimensioning that can be applied by grid operators. The method is successfully applied to an existing subtransmission grid; actual hourly production and consumption data during a two-year period is used. The role of a storage system compared to other means to handle overloading is studied. It is found that about one third of overloading instances are suitable to handle with a battery energy storage system. After this, diminishing returns per unit of storage capacity are shown to occur.**

***Index Terms*—Distributed power generation, energy resources, energy storage batteries, power system analysis computing, power system management load flow, power system simulation, power transformers, smart grids.**

I. Introduction

INCREASING the amount of distributed renewable energy resources (DER) such as wind and solar power is a challenge to the grid operator. One of the limitations set by the grid is that DER production may peak at times of low consumption creating a surplus of power in the grid causing overload of grid components [1]–[3].

There are a number of ways to increase the amount of renewables that can be integrated into a grid, where replacing a transformer or building of additional lines are the classical solutions. Several alternative solutions exist like energy storage, controllable loads, communication of real-time measurements and thermal limits, controlled real-time production curtailment, distributed semiautonomous control and protection, etc. Such solutions can represent a cost-effective complement to classical grid planning alternatives and can be important tools in the creation of a sustainable energy sector.

With the fast development of Li–ion battery technology, their energy-density and lifetime is expected to improve while the cost is reduced. Today storage in the range of up to a few megawatt hour (MWh) capacity is being commercialized

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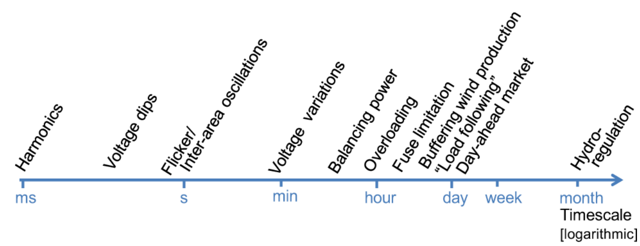

Fig. 1. Characteristic time scale of energy storage applications.

and pilot installations built in several counties [4]–[7]. The development of the methodology to allow a grid operator to dimension the storage size and power ratings (charge and discharge power) is, therefore, of importance. For a dimensioning method to be applicable by a grid operator, it is important that the method uses data that is readily available and that the results can be easily interpreted in relation to the practical planning and operation of the electricity grid. The proposed method for dimensioning energy storage is, therefore, based on load flow calculations using hourly measurements of consumption and production.

A battery energy storage system (BESS) is suitable for applications where variations to be handled by the storage range from a few seconds to a few weeks. An overview of such applications is given in Fig. 1. In practice one is today limited by the number of storage cycles per year that can be made without unacceptable shortening of the BESS lifetime. The upper bound is given by the desired degree of utilization, i.e., if energy is stored for too long only a few cycles are possible per year giving high investment cost per cycle.

A method to quantify the hosting capacity (HC) is developed in this paper and the method is applied to a real grid. The HC concept was selected due to its transparency and relative simplicity.

The extent to which a BESS can raise the HC is quantified. With a storage system to absorb peak power, the grid does not need to be designed for the full installed capacity. However, as a prolonged period of overproduction will fill even the largest energy storage, it is in practice not justified to dimension the energy storage for the worst case as its capacity would be poorly utilized the vast majority of the time. This implies that any storage to handle surplus variable production should be combined with other methods to safely spill (i.e., curtail) surplus production or match demand to production (i.e., demand-response). Alternatively, the risk associated with short periods of surpassing the HC limits may be accepted if the consequences can be determined and justified.

Following a case study approach, actual consumption and DER production measurements from a real subtransmission grid are used in this paper. Times for charging and discharging of stored energy in the BESS are taken from an existing 75-kWh Li–ion storage facility in Sweden [8]. This BESS is designed for peak load shaving and charges in three hours during the night and discharges during one hour in the evening in order to decrease peak load.

The optimum role of a BESS is ultimately a question for economic analysis; still the per unit effectiveness of storage capacity constitutes a technical restriction that will be the base for economic analysis of the feasibility of a BESS.

In Section II, the HC methodology to determine the grid performance indices is explained. Section III describes the developed methodology for dimensioning the energy storage. Results are presented in Section IV followed by discussion (Section V) and conclusions (Section VI).

II. Grid Performance Indices

A. Hosting Capacity Concept

The grid limits the amount of renewable energy that can be connected. The term hosting capacity (HC) is defined as the maximum amount of new production that can be connected without endangering the reliability or quality for other customers [9]. The HC is a transparent and objective method for quantifying and comparing the amount of DER that can be integrated into the grid. It can be calculated for individual locations but also for a larger area (e.g., the distribution grid behind an HV/MV transformer) or even for a whole country or for a large interconnected system. The HC enables a fair and objective discussion between stakeholders. The concept has been recommended by the European energy regulators [10] and the European grid operators [11] as a way to quantify the performance of future electricity grids (the "smart grid").

The impact of additional generation of DER in a grid can be quantified by using a set of performance indicators including power quality measurements like voltage magnitude, voltage dips as well as over-current limits in the distribution grid. The use of a performance index to determine the HC is illustrated in Fig. 2, and has been developed by the authors in [12] and [13].

By defining the performance indicators and levels of acceptable deterioration, a framework exists in which one can objectively determine the maximum amount of generation that can be connected to a power grid.

When determining the HC limit, the impact of the phenomenon that sets the limit needs to be considered. For overloading, short periods may be acceptable as the thermal limits will not be surpassed. The impact of the overload, and thus the definition of what an acceptable deterioration is, may also vary greatly. It could be 1) slight reduction of power from wind park through curtailment but it could also be 2) disconnection of the entire wind park if the overload protection will trip the production instead of the transformer. If the transformer in the grid must withstand the full overload consequences, the impact could also be 3) loss-of-life of the transformer insulation or even 4) trip of transformer from overload protection resulting in interruption of power delivery to consumers.

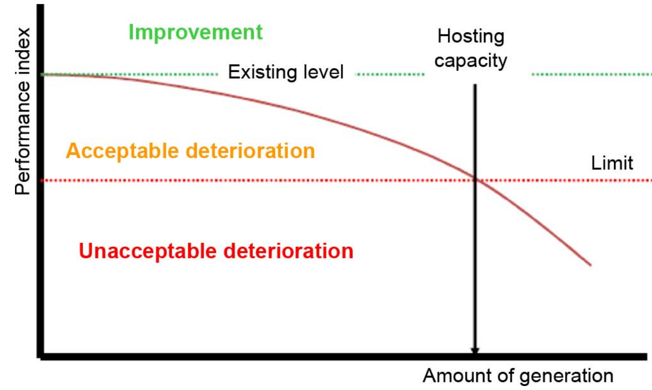

Fig. 2. In the HC approach, a power quality performance index is considered. With the increase of DER, an acceptable deterioration is defined. When the increase of new DER generation increases further, the performance index will pass a limit after which the deterioration is unacceptable. This limit to the amount of new generation is taken as HC for the studied performance index. Hosting capacities for several performance indices are to be studied to find the limits to new DER generation of a given grid.

B. Combining Storage With Curtailment to Improve Grid Performance Indices

In this case study, large-scale integration of DER is simulated in the existing connection point between the distribution and subtransmission grid. The DER will cause excessive back-feed into the subtransmission grid. Due to the variability of the DER, the overload from production is limited to short periods of time when high production coincides with low consumption in the grid. Energy storage is a way of taking care of the surplus production.

An alternative to storing the surplus energy production that cannot be delivered to the grid is curtailment. Curtailment of production involves reducing the power output from certain energy resources at times when the loading limit of, for example, a transformer would otherwise be exceeded. In the case of wind power, the pitch angle of the rotor blades can be altered to "spill wind" letting it pass through without optimum energy capture, thus reducing the power output of the wind turbine. The ability to curtail the production implies that all overloading does not have to be taken care of by the storage unit. When part of the production that would otherwise be curtailed is instead stored and later returned to the grid, the amount of nondelivered energy will decrease. This "energy not delivered" is taken, together with the avoided overloading, as measures for evaluating BESS performance.

III. Modeling Approach

A. DER Resources

The required model to be used for the DER depends strongly on the phenomenon that is creating the most severe HC limit. For thermal overload and voltage rise that were found to limit the amount of DER in the studied grid, a relatively simple model is sufficient where DER production sources are modeled as "negative loads." The developed module includes time series of DER production from solar, bio fuels, wind, and small-scale run-of hydro installations allowing for an arbitrary mix of DER resources to be simulated in any node of a grid.

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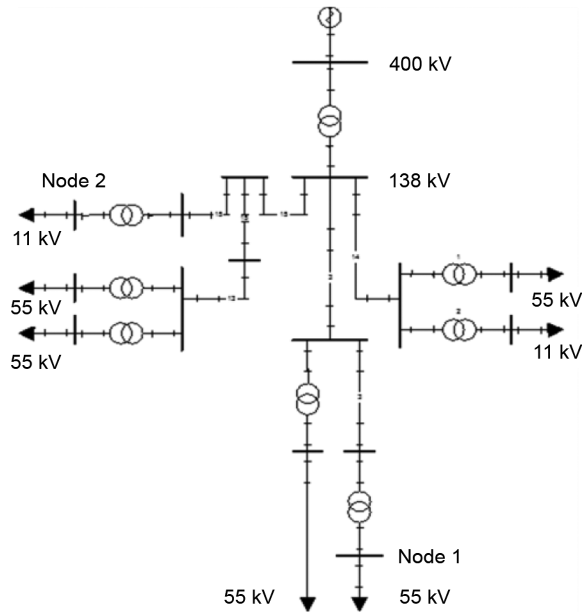

Fig. 3. Studied grid consisting of five 138/55-kV and two 138/11-kV transformers and a number of 138-kV power lines. The grid is radially operated with a single in-feed from the national 400-kV grid.

B. Studied Grid

The studied grid constitutes a typical subtransmission grid connecting a distribution system operator (DSO) with 1-TWh transferred energy per year and 28 000 customers. Industrial loads are extensive in the grid. The grid is in normal operation, a radial grid fed by a single source from the 400-kV national grid. This allows the interconnection to the EHV grid to be modeled as an infinitely strong source. Eleven transformers connected to the regional 130-kV grid are included in the grid model, as shown in Fig. 3.

Measurements of consumption and production on the 50- or 10-kV side of these transformers are included. The subtransmission grid has full $N-1$ redundancy with parallel transformers that are not included in the model as only one transformer of each pair is operated at any given time. In total, seven power lines and one cable are modeled. The power exchange with the 400-kV grid is depicted in Fig. 4, and shows a strong seasonal variation with peaks in winter due to the use of electricity for heating and a minimum in summer when many industrial loads decrease.

In this study, the amount of wind power is increased for two nodes in the studied grid. Node 1 is a rural 63-MVA 138/55-kV transformer with existing 34-MW installed wind capacity and 6-MW hydro. Consumption varied over the two years between 6 and 53 MW with a mean of 24 MW. Node 2 is an urban 40-MVA 138/11-kV transformer with only minor hydro power (3 MW compared to consumption of 1 to 26 MW with a mean of 8.5 MW). In node 1, the direction of power flow fluctuates and production surpasses the consumption roughly one hour of eight. Peak flow caused by surplus production is 55% of the peak flow from surplus consumption. In node 2 the simulated wind production will initially only decrease the net flow until the production dominates over the consumption, reaching an HC limit with reversed power flow direction compared to initial situation.

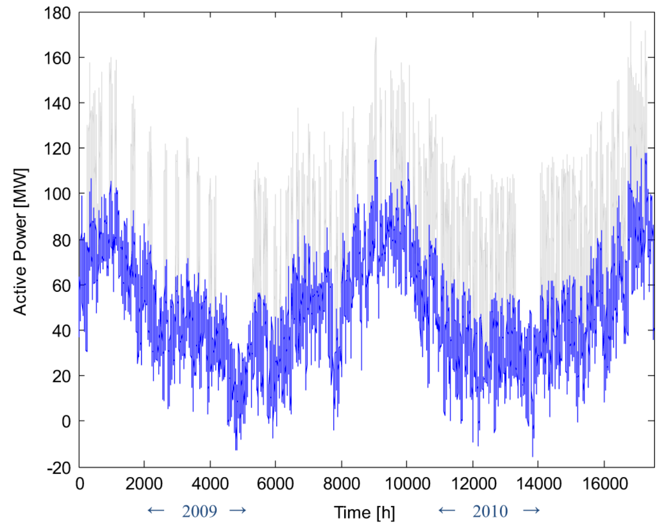

Fig. 4. Active power exchange over two years between the regional and the national grid. Superimposed in gray is the load from a large arc furnace oven that is operating on a weekly schedule. For generality of the results, the arc furnace load was excluded from the study. The grid's ability to handle this load partially explains the large HC found in this study.

C. Energy Storage

The level of DER production is selected such that the HC is exceeded a fixed percentage of the time. This constitutes a probability of overloading and the improvement of this performance indices achieved with a BESS is studied.

This study is limited to grid performance indices associated with overloading, which can be studied with hourly measurements of consumption and production. To study the effect of BESS for phenomena that are characterized by shorter time scales than one hour, the same methodology can be used, but higher time resolution of input data is required.

D. BESS Model

The requirements on the BESS model depend on the phenomena or phenomenons that are studied. For thermal overloading studied here, and also slow voltage variations, short-duration dynamic phenomena are of lesser importance and these are, therefore, not considered in the BESS model used. When the BESS discharges its energy to the power grid, it is considered as generating positive real power. When the BESS absorbs energy from the power grid, it is considered as generating negative real power.

Storage capacity is taken as the allowed depth of discharge starting from full storage capacity. (The name plate capacity of the batteries in a BESS may be larger than this amount so as to prolong the lifetime of a BESS system by avoiding maximum discharge.) The limits for stored energy C for the hour h can thus be expressed

$$0 \leq C(h) \leq C_{\max} - C_{\min}.$$

Power discharge P_d and charge P_c limits can be expressed

$$0 \leq P_d \leq P_{d,\max}$$
$$0 \leq P_c \leq P_{c,\max}.$$

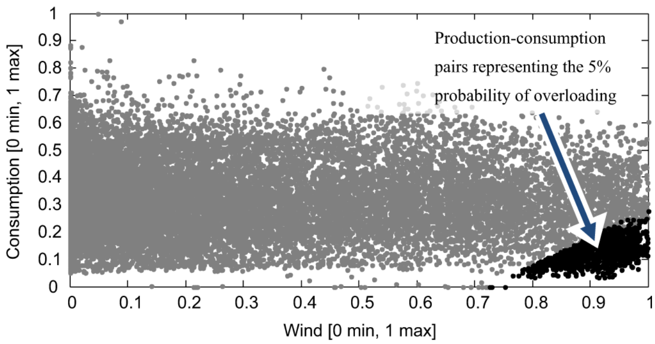

Fig. 5. Correlation between wind production and consumption for node 2 shows that maximum production and low consumption (causing highest overloading) is unlikely. The dark consumption and production pairs represent the overloaded hours when DER production is above HC.

The energy storage is modeled with grid-to-grid round-trip efficiency η during a storage cycle of 0.8. It is assumed that all losses occur during conversion. The battery state of charge is assumed proportional to charged/discharged energy. Therefore, the energy absorbed from the grid is $1/\sqrt{\eta}$ that stored during charging and the discharged energy to the grid is η times the released energy from the battery. This gives

$$\text{Discharge}: \quad C(h+\Delta t) = C(h) - \Delta t\,\frac{P_d}{\sqrt{\eta}}$$
$$\text{Charge}: \quad C(h+\Delta t) = C(h) + \Delta t\,\frac{P_c}{\sqrt{\eta}}.$$

E. Consumption and Production Time-Series

Hourly measurement of consumption for two full calendar years (2009 and 2010) for eight transformers connected to a 138-kV grid was used. Time correlated measurements from existing 34-MW wind, 5.4-MW runoff hydro, and 3-kW solar installations (all situated within the grid at 60° North and 15° East and further described in [12] and [14]) were used to ensure realistic seasonal and daily time correlation with the consumptions. The case of increased wind power was selected in this study due its highly stochastic nature requiring the here developed probabilistic study of overloading.

The capacity factor of the wind park was 29% during the studied time period. Reactive power for the wind production was measured and found to be near zero. Reactive power for loads was calculated based on a power factor of 0.95 for domestic and 0.85 for industrial consumers.

Overload of a transformer or a line in a radially operated grid occurs for high production in combination with low consumption. Any positive correlation between high production and low consumption will decrease the HC, whereas a negative correlation will increase the HC. In the case of the wind production, the correlation coefficient with respect to the measured consumption is -0.05, which implies that high production is unlikely to correspond with low consumption. This can also be seen in Fig. 5.

The BESS needs to be dimensioned after the low probability events where high production and low consumption coincide. For example, a production within 75% of its maximum will coincide with consumption within 25% of its minimum for less than 3% of the hours. A large number of data points are required to achieve a correct representation of the power flow distribution. To include annual variations, the measurements should cover at least one full year.

IV. Simulation Method

A. Degree of Wind Penetration

Load flows are performed for each set of consumption and production data in the time-series described in Section III-E. For power flow calculations, the power system is represented by a single phase model employing positive sequence parameters only [15]. The installed capacity of wind power was increased by scaling the wind power time-series data in order to simulate the addition of more wind turbines to the power system. For each additional MW of installed capacity, new load flows were performed for all 17 520 hours. The HC is exceeded when the first transformer or line exceeds its loading limit during at least one of the hours.

For installed capacity above the HC, the probability of exceeding the loading limits was calculated from the number of hours with overloading. For hours when the limit is surpassed, the power system analysis tool is used to calculate the reduction in power flow required at the location of storage to avoid the overloading. For hours after overloading has ended, the amount of discharge that is possible without the BESS causing a new overloading is likewise calculated. Based on these calculations and the modeled storage capacity and power limits, the influence of a BESS on the probability of overloading has been determined.

Some two million load flow calculations are required per node for the full analysis of voltages and overloading of transformer, lines, and cables over two years with production increase in 100 steps. This can be handled in about 6–8 hours on a powerful PC. Fig. 6 gives an overview of the procedure.

B. Time-Series Simulation of Energy Storage

The algorithm of storing and discharging energy to the BESS needs to be optimized for each application of the storage. In the study, charging commences as soon as overloading occurs. The amount of energy to be stored is limited by either 1) the remaining storage capacity, 2) maximum charging power, or 3) power flow reduction needed to avoid overloading. The time of overloading is concentrated to certain periods. Once a period of overloading has ceased, there is an increased probability for a new period of overloading to commence. With overloading occurring 5% of the time, the probability for a second period of overloading to start in the following measured hour was 23% for both studied nodes. The probability for a second period of overloading to occur within three hours was 36% for node 1 and 35% for node 2. This is 10 to 20 times the probability of an overloading to occur within the same time frame for a randomly selected hour without overloading. Thus it is a good strategy to empty the storage as quick as the grid and BESS can handle once the immediate risk of overloading is over. This control algorithm we call "quick store/discharge."

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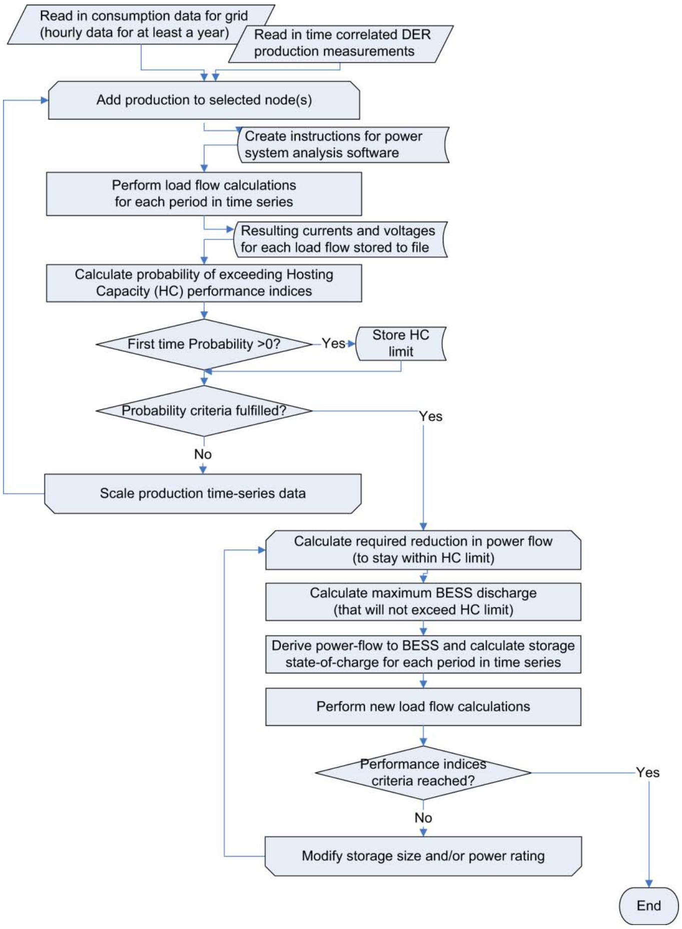

Fig. 6. Overview of procedure used to evaluate grid HC limits, performance indices, and energy storage requirements for various amounts of DER production. Each application of the BESS will result in a different algorithm for dispatch of the storage. The power flow to the battery will thus vary.

V. Results

A. Hosting Capacity of the Studied Grid

The HC relative to over-voltage, line, and transformer overloading was examined by step-wise increases of the installed wind power capacity. The first loading limit (of a line or transformer) to be reached sets the HC of the grid. In Fig. 7, the case where production causes one of the transformers to reach its loading limit is shown. This was the first HC limit to be exceeded in both examined nodes in the studied grid. This corresponded to 74-MW installed capacity in node 1 and 56-MW in node 2 (with unaltered consumption).

B. Overloading Due to Surplus Production and Effect of BESS

Installed wind power capacity beyond the HC limit causes overloading during certain time periods, as shown in Fig. 8. The surpassing of the HC limit can be expressed as a probability (percentage of hours during which overloading occurs).

For node 1, overloading occurs 5% of the time (438 hours per year) when the installed capacity reaches 97 MW (compared to an HC limit of 74 MW) and 56 MW (compared to HC of 45 MW) for node 2. In other words, if overloading during 5% of time could be tolerated or mitigated, 21-MW additional installed

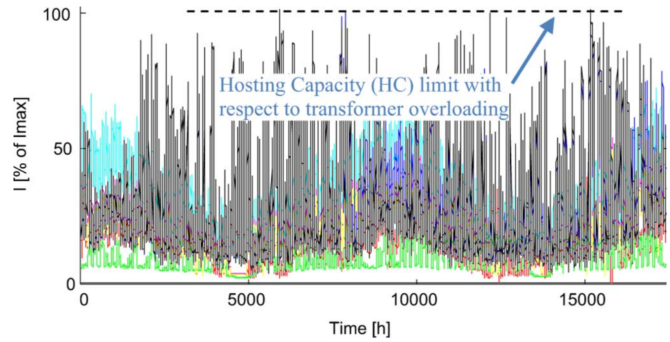

Fig. 7. Example of transformer through currents where production is added to one node in the grid. The through current of transformer (black) connecting the node with the simulated production is here at its HC, hence any further increase in production will cause overloading for at least one component and one hour during the year.

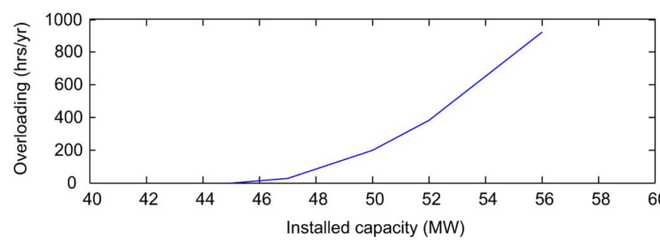

Fig. 8. Hours per year during which the 138/11-kV t transformer in node 2 is overloaded as a function of wind power on secondary side of the transformer.

capacity could be connected to node 1 and 11-MW additional to node 2.

The capacity factor of the wind farm during the two studied years was 29%. Therefore, the surplus installation of 11 MW in node 2 would yield some 28 GWh/year of additional production. Most of the time, the grid will be able to receive this additional power but 1.6 GWh/year of the surplus production needs to be removed to avoid overloading. The corresponding value for the node is 58-GWh additional production of which 3.1 GWh cannot be received by the grid.

C. Increase of HC With BESS

Due to the variable nature of the wind production, as well as consumption, the surplus energy is concentrated to periods of high production that coincide with low consumption. The worst case, a 60-hour period of near continuous overproduction during an autumn storm, is shown in Fig. 9. If the storage has required charging capacity to store all overproduction, this would for node 2 require a BESS storage capacity of nearly 160 MWh even for the case of "just" 11 MW of surplus capacity. Such a large storage is neither commercially feasible nor justifiable due to the infrequent use of the full storage capacity. Instead the avoided hours of overload and the nondelivered energy to grid is studied as a function of the BESS storage capacity.

As shown in Fig. 10, a BESS of just 1/40 of the size required to avoid 100% of overloading can bring considerable benefits, eliminating as much as a third of the overloaded hours. Fig. 10 shows a linear increase of the avoided overloading with storage size up to 4 MWh. For increasing storage size, the increase in avoided overload becomes less. The effect on the performance index per MWh capacity decreases as the storage size exceeds

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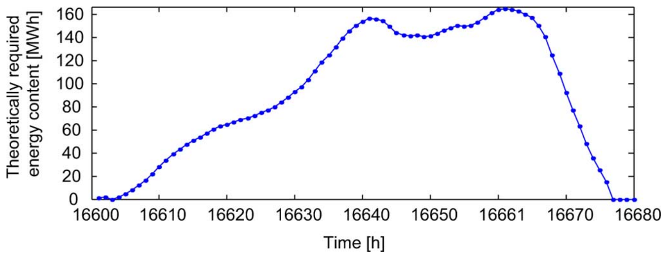

Fig. 9. Required storage capacity to fulfill the worst period of over production. Such a large storage is unfeasible both on economic grounds and due to the infrequent usage of the full installed capacity.

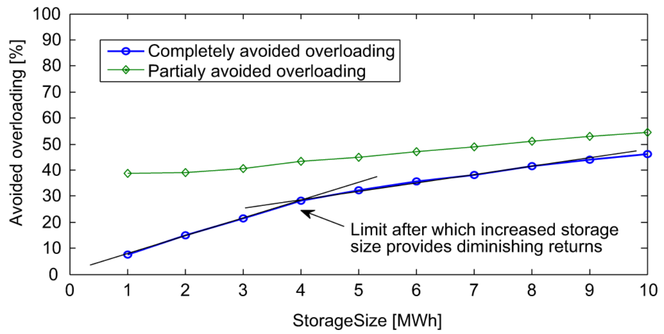

Fig. 10. Avoided overloading with energy storage in node 2. Linear extrapolation reveals a best possible size after which a given unit capacity increase would give diminishing returns.

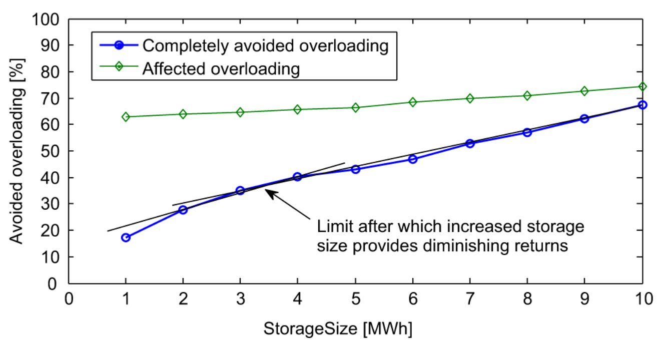

Fig. 11. Avoided overloading with energy storage in a 10-MVA 40/10-kV transformer of another grid in central Sweden.

4 MWh. Any economic returns due to the storage are related to the avoided overloading, so that the return per additional MWh becomes less with increasing amount of storage capacity. This is referred to as "diminishing returns per unit of storage capacity," a phenomenon that is found for all nodes in the studied grid and also during studies of other grids (Figs. 11 and 12). Other studies have also reported the rate of the increment of benefit getting smaller above a certain level [16].

D. Influence of Storage Efficiency

In Section V-C, an ideal storage has been assumed, with only the storage size as limitation. Due to conversion losses in the BESS (that mainly come from the ac–dc and dc–ac conversion and the associated voltage level transformations) all energy taken from the grid cannot be returned. With losses in the BESS, more energy is drawn from the grid in order to fill storage of a given capacity. This will actually decrease slightly the amount

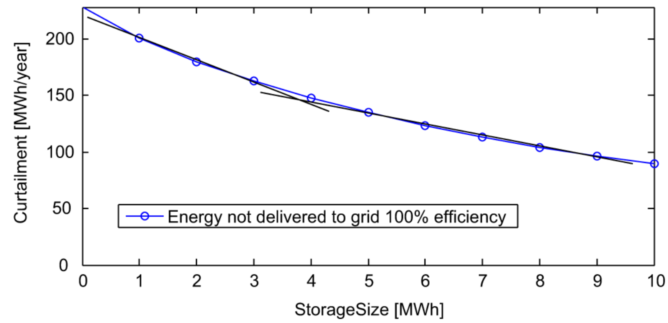

Fig. 12. Decrease in avoided curtailment with increasing storage size in a 10-MVA 40/10-kV transformer of another studied grid in central Sweden. Like in the previous figure, the point of diminishing return is shown.

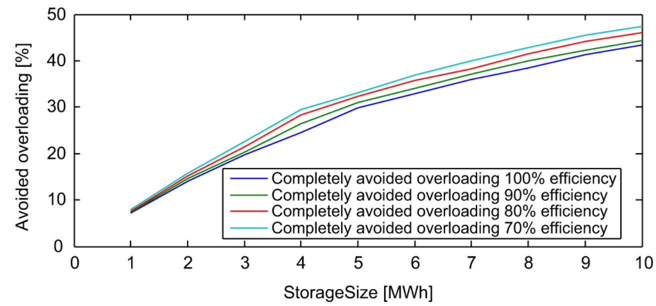

Fig. 13. Conversion losses in the BESS will draw additional power from the grid. Therefore, the same capacity of a BESS will avoid more overloading with lower efficiency. This is of cause energy that cannot be utilized (other than as heat) or returned to the grid as electricity.

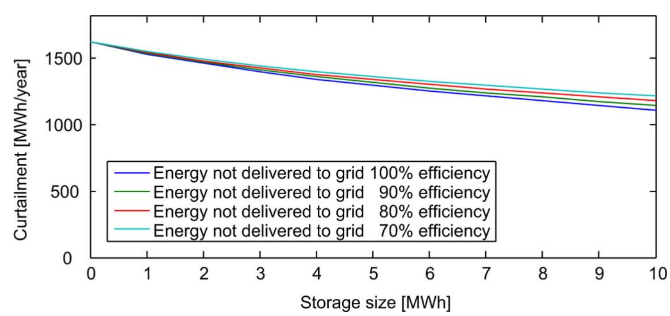

Fig. 14. BESS ability to decrease the amount of required production curtailment is influenced by its grid-to-grid round-trip efficiency.

of overloaded hours compared to the case without conversion losses, as seen in Fig. 13. However, conversion losses imply that less energy can be returned to the grid (Fig. 14).

E. Influence of Charge and Discharge Power

Due to the Li–ion, batteries in the studied BESS discharge and charge current are asymmetrical, normally allowing quicker discharge than charging. For handling overloading the priority is instead to charge quickly. The effect of varying charging power is shown in Fig. 15. The storage will frequently be hindered from reaching its full capacity when charging time is increased from one hour (left) to ten hours (right).

As the charging capacity poses an increasing limitation to the loading of the storage, the number of hours that overloading will be avoided decreases. This is shown in Fig. 16. Likewise, the amount of energy that must be curtailed (cannot be delivered

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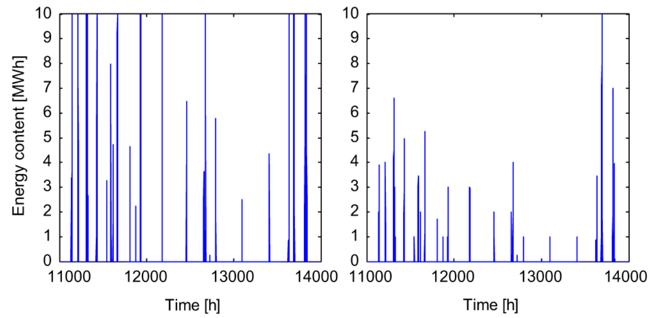

Fig. 15. Effect of charging power in node 2. In the left figure, the storage can be completely filled within an hour. In the right figure, the time to load the storage is instead 10 hours. This will prolong the lifetime of the battery but the charging power, rather than the capacity, now limits the amount of energy that can be stored. The reduced charging power means that the BESS will reach its maximum capacity less often.

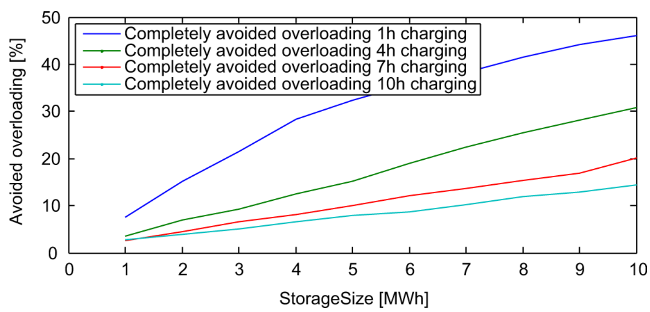

Fig. 16. Decrease in hours where overloading can be avoided for smaller power rating of the BESS charger.

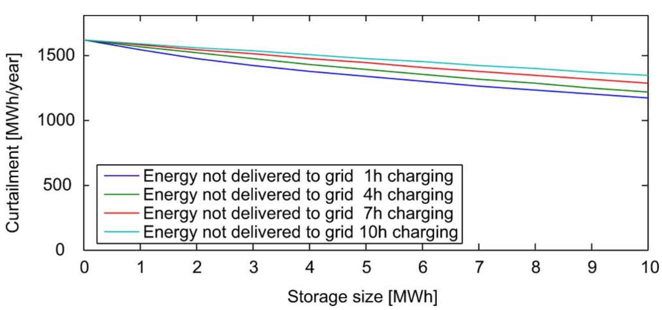

Fig. 17. Decrease in avoided curtailment with different charging power.

to grid) increases as the charging power, rather than the storage capacity, becomes the limit (Fig. 17).

In Fig. 18, the discharge time is varied from 1 to 10 hours. Because the average time between overloading peaks (68 hours) is considerably longer than the average duration of the overloading (4.3 hours), the discharge power of the BESS has less impact than the charging power but is still significant for storage size around the point of diminishing returns. The increase in nondelivered energy is only 1.3%–2% in this case and, therefore, not shown in a figure.

VI. Discussion

A. Modeling of Battery Storage

This paper studies one application of storage in order to exemplify the HC method for dimensioning an energy storage

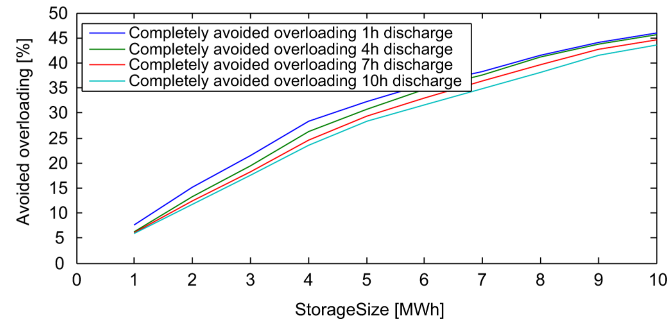

Fig. 18. Decrease in hours where overloading can be avoided for smaller power rating of BESS discharge.

thereby increasing the amount of wind power that can be connected to the grid. Other applications require a different control algorithm to govern the dispatch of the storage.

Refinement of the energy storage model used in this paper would be required for simulations with shorter time-scales where dynamic aspects need to be included in the BESS model. Other improvements could include detailed state-of-charge estimation and modeling of the varying losses depending on different charging/discharge power levels.

B. Dimensioning of Energy Storage

The aim of this study was to develop methods to dimension the capacity and power ratings of a BESS storage system using the HC approach. In order for the developed methodology to be easily applicable to utilities concern was given to limit the required input data to such information that is readily available to a DSO. This consists of hourly data for consumption and production in the point of grid connection (such metering infrastructure is today common place in Sweden and being developed or planned in many other countries) as well as basic line and transformer data required for load flow calculation. The time correlated consumption and production data need to be sufficiently long (at least a full year with hourly data) in order to be able to calculate the probabilities also for low probability events.

For a DSO, it is desirable to be able to see the BESS largely as a "black box" characterized by its capacity and power ratings. As has been shown in this paper, the power rating will greatly affect the performance of a BESS and must be selected carefully. The effect of the efficiency is smaller but will nevertheless have an influence on the results around the point of diminishing returns. Today there are suppliers of MWh capacity BESS systems guaranteeing up to 90% grid-to-grid efficiency [16]. However, this efficiency is under certain conditions and will decrease for shorter charging or discharging periods. It is, therefore, important to have the complete picture of varying efficiency during different operating scenarios when evaluating the BESS performance.

In this paper, the fast charging was found to be more important than fast discharge. Generally, the length of the time during which the storage is to be filled compared to the available time period to empty it will influence the optimal power ratings. For other applications of a BESS like load shedding, the relation between charging and discharge power may be reversed.

VII. Conclusion

The quantification of the HC for the various nodes of a grid is an important tool to scan a grid for suitable DER locations and aim investment efforts towards the true bottlenecks of the grid. This paper shows that accurate dimensioning of a BESS is possible using the HC method and readily available data about the electricity grid and from revenue metering systems. The model has been developed so that the results are applicable, for example by a grid operator, as input to grid planning. The methodology can be extended to other applications such as load shedding or other storage techniques like molten salt (for heat from solar reflectors), pumped hydro (topology permitting), or compressed air (with gas turbine).

As found in this study, the capacity per unit benefit of the BESS system decreases with increasing storage size. This phenomenon we call "diminishing returns per unit of storage capacity." For storage sizes above this size, it quickly becomes less attractive to install more capacity. The "point of diminishing returns" should not be confused with an economic optimal size. Determining such requires including a number of additional studies beyond the technical study presented in this paper. The economy of the BESS will be influenced by the selected application, market price for the ancillary services provided by the storage and regulatory framework, including ability to add investment to tariff cost base of the utility. However, any economic evaluation needs to consider the physical restrictions of the storage technology.

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