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Increasing the Hosting Capacity of Distribution Networks by Curtailment of Renewable Energy Resources

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***Abstract*-- This paper applies the hosting-capacity method to a realistic distribution system. Under given circumstances the hosting capacity for Distributed Energy Resources (DER) identifies the degree of DER in power grid that can be accepted without endangering the reliability or quality of power. In this case study two limits setting the hosting capacity were evaluated: overvoltage and overcurrent. Finally it is examined to what extent the hosting capacity can be increased with use of real-time information and calculation of dynamic performance indications that govern the hosting capacity. It is shown that there is significant potential for increasing the hosting capacity without having to build new lines.**

***Index Terms*-- Distributed power generation, Energy storage, Load flow, Power generation planning, Power system management, Power system control, Power system planning, Power system simulation, Power quality, Energy resources**

I. Introduction

The introduction of distributed generation will impact the performance of the power system. With the desire to increase the production of renewable energy it therefore becomes important to develop objective means to determine the maximum amount of generation that can be connected to a power distribution system – the hosting capacity. The amount of Distributed Energy Resources (DER) the network can host depends on a number of parameters such as the characteristics of the generation units, the configuration and operation of the network, the requirements of the loads as well as national and regional requirements.

Different distributed generation technologies provide different control capabilities over both the active and reactive power. The performance of the system may either improve or deteriorate after the connection of new distributed generation. A deterioration of the performance is not directly a concern, as long as the resulting quality is within an acceptable range.

The hosting capacity is recommended by the European energy regulators [1] and by the European network operators [2] as a way to quantify the performance of the future electricity network (the “smart grid”). The latter also mention the development of methods for calculating the hosting capacity in distribution networks as a prioritized activity in their roadmap towards the future power grid in Europe.

The impact of additional generation of DER in a network can be quantified by using a set of performance indicators such as power quality measurements like voltage magnitude, voltage dips and risk of overload.

The hosting capacity is defined as the amount of distributed generation for which the performance becomes unacceptable. [3], [4]. The use of a performance index to determine the hosting capacity is illustrated in Fig. 1.

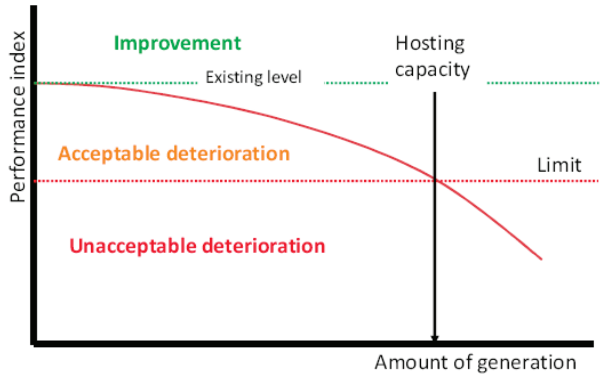

Fig. 1. In the hosting capacity approach a power quality performance index is considered. With the increase of DER an acceptable deterioration is defined. When the increase of new DER generation increases further the performance index will pass a limit after which the deterioration is unacceptable. This limit to the amount of new generation is taken as hosting capacity 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 network.

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 network.

II. Studied Network

The intention of this paper is to apply the hosting capacity principles to a real world power system. The studied network was based on an existing 130/50/10 kV regional distribution network in the centre of Sweden. The network transfers close to 1 TWh per year. A large part of the consumption comes from industrial customers. Within the network there is approximately 40 MW installed wind power and 20 MW hydropower, producing about a tenth of the consumed energy

The work is undertaken within a joint development project at the HVV (www.highvoltagevalley.se) consortium and financed by the Swedish Governmental Agency for Innovation Systems

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in the network. As can be seen in Fig. 2 the loading profile shows a strong seasonal variation with occasional in-feed of electricity to the national grid.

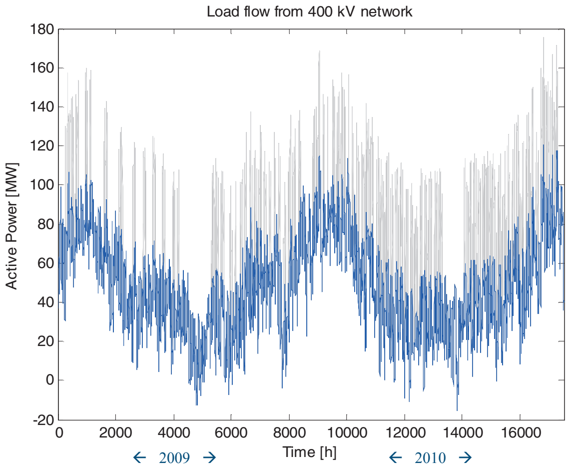

Fig 2. Active power exchange over two years between the regional and the national grid. Superimposed in grey is the load from a large arc furnace oven that is operating on a weekly schedule. For generality of the results this load was excluded from the study. The network's ability to handle such peak loads partially explains the favorable capability to receive vast amounts of intermittent energy resources as found in this study.

The parameters used in the modelling were - as far as possible - the actual values for transformers, cables and lines obtained from the network operator. The network is operated radial under normal operating conditions and reserve lines and transformers not used during the studied period where excluded from the model.

Load flows were performed using measured hourly averages of P and Q at the 50 kV side of the transformers. Measurement series covered two complete calendar years (2009 and 2010).

Additional production from renewable energy resources was based on actual measurements series for existing installations. This allows for a realistic correlation of loads with wind and hydro production. Operational parameters like voltage limits and transformer tap changer settings were as far as possible those utilized by the utility.

The load flow calculations were performed using commercially available power system simulation software. The network model is shown in Fig. 3.

III. Calculating the Hosting Capacity

A. *Hosting capacity limits*

One of the key steps in defining the hosting capacity is to define limits that are either based on power quality parameters (e.g. maximum over/under voltage) or customer service specifications (e.g. number of complaints). For transparency in evaluating the hosting capacity objective measures are needed. The first hosting capacity to be considered is the rating of such apparatus as the power rating of transformers. This was between 30 and 60 MVA in this network and often the limiting factor even if higher production was simulated to investigate the dynamic nature other hosting capacity limits.

The studied network was operated at 138/54.5 and 10.5 kV. To be within the design criteria of a standardized 132-kV voltage level the voltage increase incurred by new production

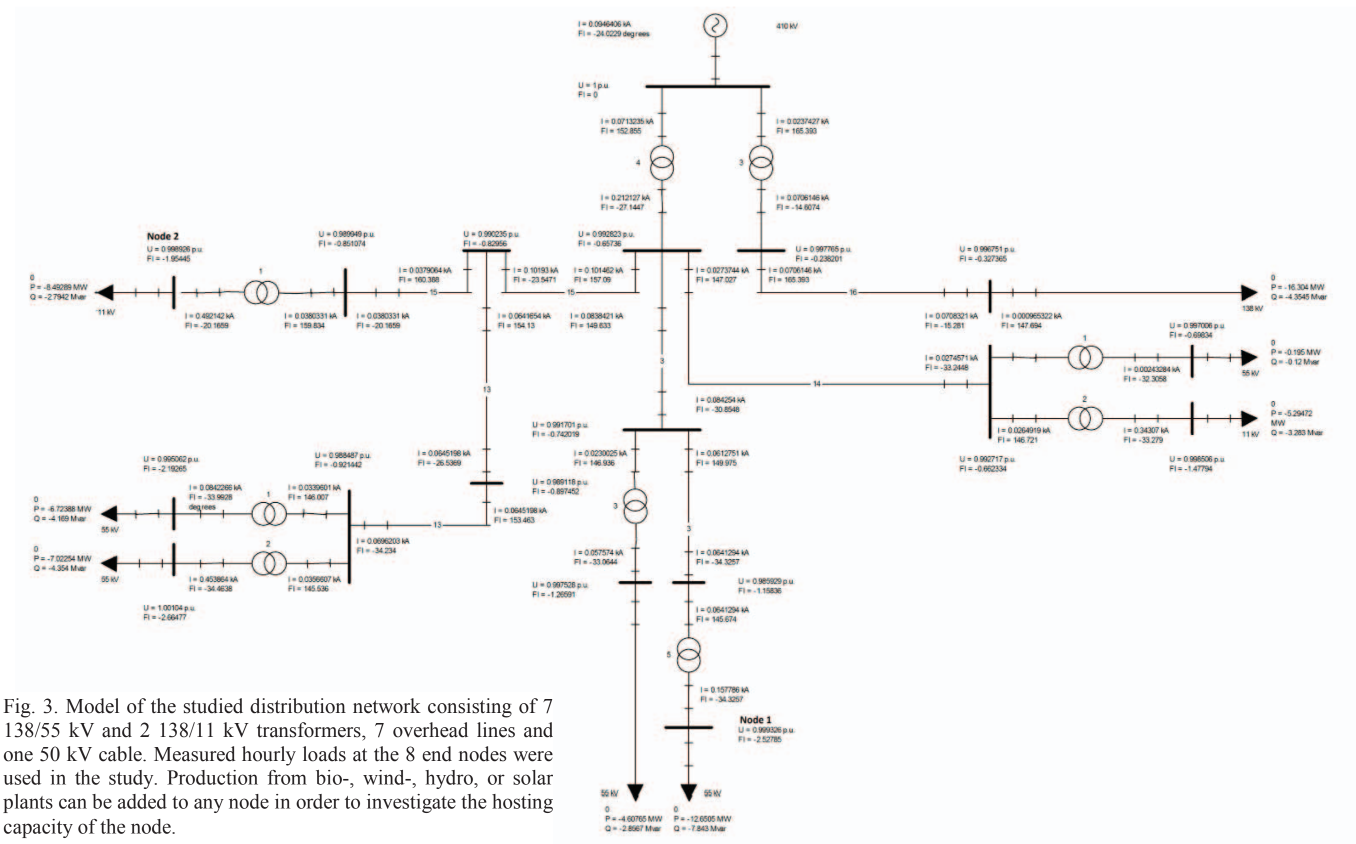

Fig. 3. Model of the studied distribution network consisting of 7 138/55 kV and 2 138/11 kV transformers, 7 overhead lines and one 50 kV cable. Measured hourly loads at the 8 end nodes were used in the study. Production from bio-, wind-, hydro, or solar plants can be added to any node in order to investigate the hosting capacity of the node.

should not be more than 5%. Therefore +-5% was taken as hosting capacity voltage limit.

Line currents were calculated and compared to maximum-permissible currents for the various line and cable types. Maximum-permissible currents were calculated with commercial line loading software. According to the Cigré technical brochure 299 [5] recommendations, values were calculated near maximum annual temperature (30 °C), with 1000 W/m2 irradiation and 0.6 m/s wind. This resulted in static current limits for the used overhead line types between 290 and 480 Amperes.

B. Addition of real and simulated production

In this study production from four different renewable energy sources is considered, namely;

- Bio energy from a combined heat and power plant which is modeled as a constant power influx.
- Wind production which is based on true measurements from an existing 17 turbine/34 MW wind farm within the network (Fig. 4a).
- Hydro power was based on a 5.4 MW plant whose power output is regulated on a daily and weekly basis, thus its production is also intermediate in its character (Fig. 4b).
- Finally the production from solar plant was calculated based on measured global irradiation (Fig. 4c). The efficiency and characteristics of the solar cell modules where taken from a 3 kW installation at STRI in Ludvika and the simulated production was verified against recorded energy production.

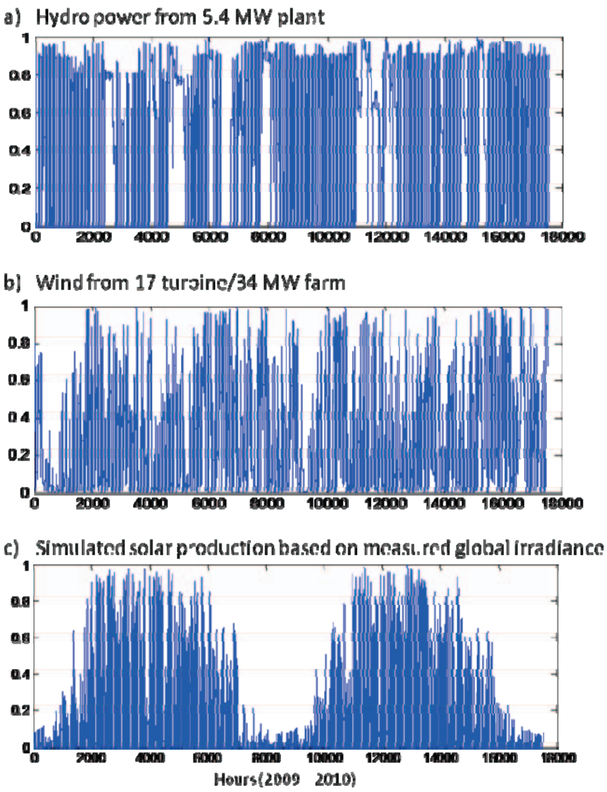

Fig. 4. Intermittent character of various renewable energy resources used in the study. The production has been scaled to allow comparison between the various energy sources.

C. Production mix

In this study the hosting capacity of the network was studied for i) constant production (bio energy), ii) the real mix of wind and hydro power present in the network today, iii) pure wind production and iv) a production mix where 50% of the produced energy comes from wind, 25% from hydro and 25 % solar energy and finally v) a mix where 50% is produced by wind and 50% by solar power. The mix of wind and solar energy is of particular interest to study as the maximum wind and solar production rarely coincide, as seen in Fig 5.

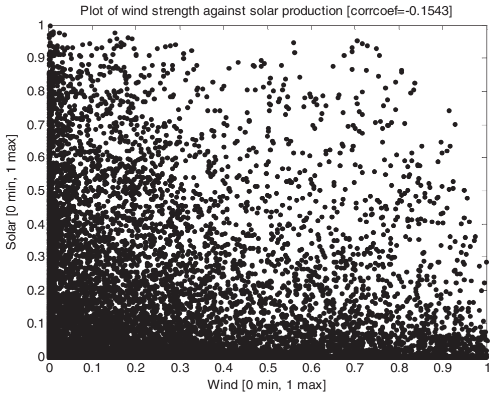

Fig. 5. Correlation between wind and solar production shows that maximum wind and solar production are unlikely to happen at the same time. Thus curtailment for the rare case of maximum production coinciding should be beneficial.

Regarding the solar production it should be stated that the production amounts to very large areas of solar cells. Using the efficiency and dimensions of the 3 kW reference installation 84 MW installed capacity the area would be equivalent to 650 000 m^2 or one hundred football fields. This would be roughly equivalent to using the south facing roof of nearly seven thousand houses of the average size in Sweden[1]. With placing also on public and industrial roofs this area would be equivalent, but not exceed, the suitable roof space available in the studied network.

D. Load flow calculations

For each hour during the two year time series a load flow is performed and the voltage at each end node in the network is stored (Fig. 6). The currents through the power line are calculated and compared to either a fixed current limit or a dynamic line rating calculated with measurements of temperature, wind and solar irradiation (Fig. 7).

[1] According to 2009 energy statistics available at www.energimyndigheten.se

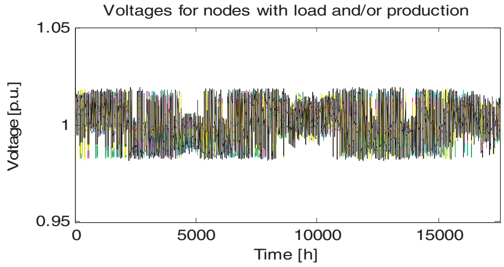

Fig. 6. Example of calculated voltage variation in per unit. Due to the tap changers the voltage is kept within limits throughout the studied loads in this study. With the used power system model the voltage is stable well after the power rating of the transformers has been exceeded, as is frequently the case in this study.

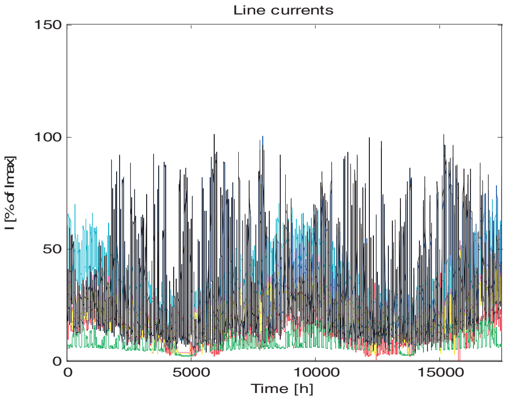

Fig. 7. Example of line currents where production is added to one node in the network. The line (black) connecting the load with the simulated production is at its hosting capacity. Hence any further increase in production will cause the overhead line to surpass its rated maximum current.

IV. Results of Hosting Capacity calculations

The study showed that in this network it is the rated power of transformers that are limiting the hosting capacity. If the transformers can be exchanged, overcurrents will be a bigger limitation to the hosting capacity than overvoltages. This is due to the consistent use of tap changers on all 138/55 and 55/11 kV transformers and their ability to maintain the voltage sufficiently close to its desired value.

The network shows a large capability to receive additional renewable energy resources; this is because some industrial loads were excluded from the network for the study in order to allow greater generality of the results. Table I and Table II show the hosting capacity for two nodes in the network. One of the nodes has today a mix of wind and hydro power and this production mix was frequently used in the hosting capacity calculations for this node.

It must however be noted that the results found in this study cannot be directly applied to the study network. Some industry loads not typical for a regional network have been omitted. The power ratings of the transformers (30-60 MVA) are also by far surpassed in many of the studied cases. Thus the implementation of these results would require new transformers, even if the overhead lines themselves did not need strengthening.

TABLE I

Hosting capacity for node number 1 of Fig. 3 for various types of renewable energy resources. Produced energy is the average of the two studied years.

Hosting Capacity :	**Current limited**	
	[Power]	[Produced/year]
Constant power (Bio fuels)	120 MW	1050 GWh
100% Wind	130 MW	330 GWh
Present prod mix: *(85% produced energy is wind, 15 % hydro.)*	130 MW *(110 MW wind, 20 MW hydro)*	350 GWh
DER mix 1: *(50% produced energy wind, 25% hydro, 25% solar)*	150MW *(58 MW wind, 21 MW, hydro. 71 MW solar).*	295 GWh
DER mix 2: *(50% produced energy wind, 50% solar)*	148 MW *(43 MW wind, 105 MW solar)*	172 GWh

TABLE II

Hosting capacity for node number 2 of Fig. 3 for various types of renewable energy resources

Hosting Capacity :	**Current limited**	
	[Power]	[Produced]
Constant power (Bio fuels)	70 MW	615 GWh
100% Wind	75 MW	190 GWh
DER mix 1: *(50% produced energy wind, 25% hydro, 25% solar)*	90 MW *(34 MW wind, 13 MW, hydro. 42 MW solar).*	170 GWh

The results show that while the installed power may increase with intermittent energy resources the total produced energy will decrease with the availability of the energy resource. As the wind showed a slightly higher availability than solar power the total production with the energy mix of wind, hydro and solar production is the lowest. As the time series is relatively long (17520 hours representing two years) it is also likely that the maximum wind and solar production will coincide for at least a few hours, effectively creating the hosting capacity if production cannot be held back for these few hours as is done in the next section.

V. Methods to further increase hosting capacity

A. Curtailment of production

Curtailment of production involves reducing the power output from certain energy resources at times when the hosting capacity otherwise would be exceeded. The ability to curtail the production will allow for a larger installed capacity of distributed energy resources. An example of curtailment can be letting water through the spill way of a hydro plant or controlling the blade angle of a wind turbine, effectively letting wind pass through without maximum power generation.

Table III and Table IV show the hosting capacity increase when the production is required to be within the current limit only 98 and 95 % of the time. For the remaining 2 and 5 % of the time the production will be curtailed. When curtailment is carried out the resources still produce energy, but only as much as the hosting capacity limit permits. For the hours where curtailment was required the amount of curtailed energy is calculated by comparing the produced energy this hour without curtailment and with curtailment.

TABLE III
HOSTING CAPACITY FOR NODE NUMBER 1 WITH CURTAILMENT. PRODUCED ENERGY IS THE AVERAGE OF THE TWO STUDIED YEARS

Hosting Capacity :	**Current limited**		
	[Power]	[Produced]	[Curtailed]
Present prod mix: no curtailment: *(85% produced energy is wind, 15 % hydro.)*)	130 MW	350 GWh	0
with curtailment: 2% (175h/year)	154 MW	410 GWh	7 GWh
: 5% (438h/year)	170 MW	455 GWh	27 GWh

TABLE IV
HOSTING CAPACITY FOR NODE NUMBER 2 WITH CURTAILMENT. PRODUCED ENERGY IS THE AVERAGE OF THE TWO STUDIED YEARS

Hosting Capacity :	**Current limited**		
	[Power]	[Produced]	[Curtailed]
100% Wind: no curtailment	75 MW	190 GWh	0
with curtailment: 2% (175h/year)	84 MW	210 GWh	2.6 GWh
with curtailment: 5% (438h/year)	90 MW	230 GWh	11 GWh

The higher the percentage of time during which curtailment is acceptable, the higher the amount of production capacity that can be connected to the grid. However, even though the hosting capacity is increased the proportion of the additional energy that must be curtailed increases quickly making additional increase in hosting capacity less and less attractive. In other words; increased curtailment gives diminishing returns.

There are two ways to allocate the amount of power that must be curtailed. Fig. 8 shows the case where the new production unit must do all the required reduction. One quickly reaches a point where it is no longer beneficial to add new production as most of the added production capability will be curtailed (wasted).

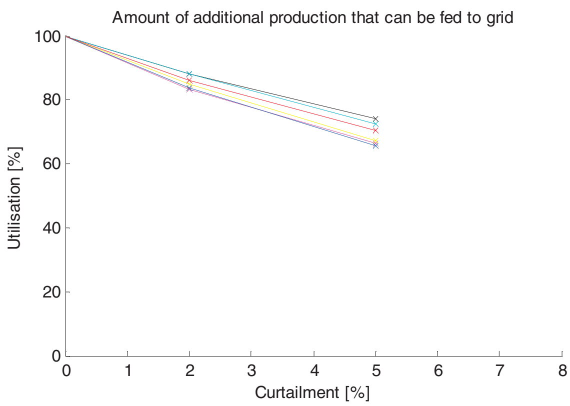

Fig. 8. As the amount of curtailment increases (x-axis) a larger and larger proportion of the additional energy must be curtailed (y-axis). Thus the returns from further curtailment quickly diminishes. The diminsishing return was similar for all nodes in the studied network.

The other extreme is that all production units will share the required curtailment equally as shown in Fig. 9.

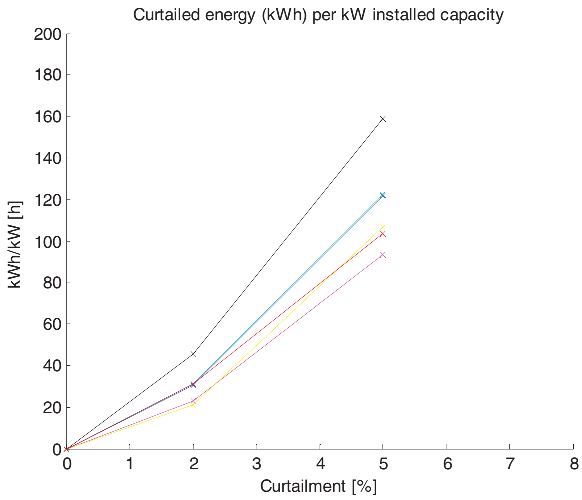

Fig. 9. The required curtailment in kWh is evenly divided among the production units. The amount of energy each production unit must curtail is ploted as a ratio kWh/kW for all nodes in the studied network.

B. Dynamic line loading

The static line limit results in a conservative estimate of the maximum current permitted. The average temperature during the two years of study was four degrees and solar radiation is sparse for much of the year. This means that the cooling of the conductor will be significantly greater than the static limit implies for much of the year. Based on true solar irradiance, wind and temperature measurements the ampacity for the overhead lines was calculated using IEEE Std. 738-2006 [6]. There where two practical hindrances to applying this method. Firstly the wind measured at a nearby wind station will likely be reduced by topology and vegetation depending on the lines height. The most sheltered line section will in practice heat the most and be limiting for the entire line. Wind measurements where made at 10 m altitude while the 130 and 50 kV lines height may only be 7 to 8 meters. Even with clearance width of 40 meters for a power line the wind will be reduced and this reduction in wind speed has to be considered. The wind was therefore reduced to half based on results of previous studies [7].

Both the IEEE and Cigré method [5] are based on solar radiation in a plane normal to the sun. Due to its relative simplicity to measure, the global irradiance on a horizontal plain is more readily available. This was the only data available in the study and thus the global irradiance needed to be scaled based on other equivalent measurement series. Fig. 10 shows the calculated ampacity which was up to 5-6 times higher than the fixed current limit calculated with recommendations from [7].

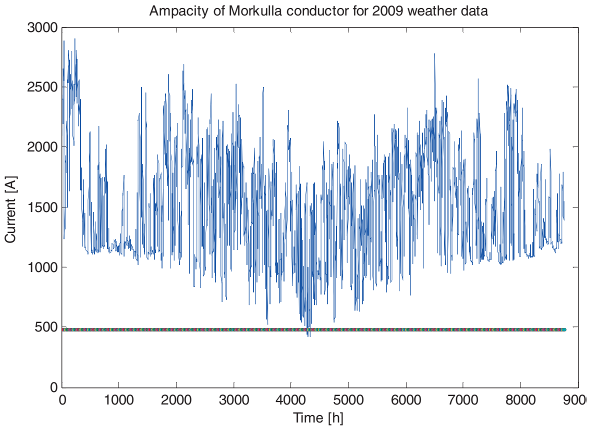

Fig. 10. Calculated ampacity used in Dynamic Line Rating model, compared to fixed limit (horizontal line] based on recommendations from Cigré technical brochure 299 [5].

Fig. 11 shows the current using dynamic line rating based on actual temperature, wind and solar radiation. Fig. 12 show for the same production how many percent of the fixed current rating the overhead line would be loaded.

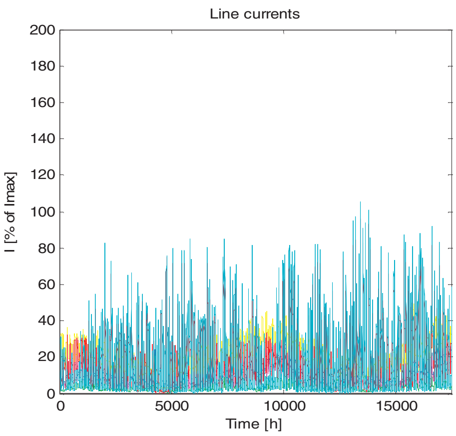

Fig. 11. Actual current as percentage of dynamic line rating from calculated ampacity. The amount of production is the same as in Fig. 12 below where dynamic line loading is not used.

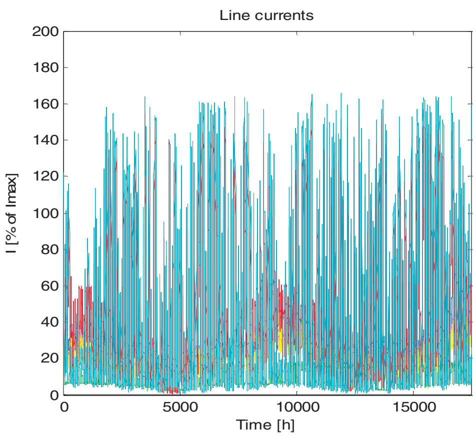

Fig. 12. Actual current as percentage of static current limit calculated according to [5]. Production is the same as in Fig. 11.

The amount of additional energy production with dynamic line rating is used can be seen in Table V and Table VI.

TABLE V

HOSTING CAPACITY FOR NODE NUMBER 1 WITH DYNAMIC LINE RATING BASED ON IEEE STD 738-2006. PRODUCED ENERGY IS THE AVERAGE OF THE TWO STUDIED YEARS

Hosting Capacity :	**Current limited**		
	[Power]	[Produced]	[Curtailed]
Present prod mix: no dynamic line rating: *(85% produced energy is wind, 15 % hydro.)*	130 MW	350 GWh	
With dynamic line rating	260 MW	700 GWh	

TABLE VI

HOSTING CAPACITY FOR NODE NUMBER 1 WITH DYNAMIC LINE RATING BASED ON IEEE STD 738-2006. PRODUCED ENERGY IS THE AVERAGE OF THE TWO STUDIED YEARS

Hosting Capacity :	**Current limited**	
	[Power]	[Produced]
100% Wind: without dynamic line rating	75 MW	190 GWh
with dynamic line rating	120 MW	350 GWh

Comparison with Tables IV and V reveals that the dynamic line rating gives much larger increase in hosting capacity than the production curtailment method. There is however no problems with combining the two methods; this increases the hosting capacity even further.

In the case of a renewable energy production mix containing both solar and wind power the peaks where both production maximums coincide will be few. Calculation of the correlation coefficient shows that the likelihood of minimum dynamic line rating (corresponding to a hot sunny day with no wind) is more likely to coincide with maximum solar production. However the extremes of all three parameters (maximum wind and solar production as well as minimum dynamic line rating) are very infrequent. For the production shown in figure 13 only 83 hour (0.5%) needs to be curtailed despite a maximum of over 150% of the dynamic line rating. The amount of curtailed energy is here relatively modest at 4 GWh/year.

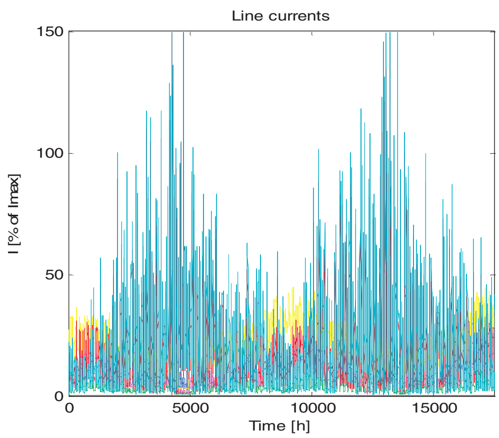

Fig. 13. Current limits using dynamic line rating for a production mix where 50% of total energy comes from wind and 25% each from hydro and solar. The peaks exceed 50 % of the dynamic line rating, still curtailment is only required 0.5 % of the time.

TABLE VII
HOSTING CAPACITY FOR NODE NUMBER 1 WITH CURTAILMENT. PRODUCED ENERGY IS THE AVERAGE OF THE TWO STUDIED YEARS

Hosting Capacity :	**Current limited** [Power]	[Produced]	[Curtailed]
DER mix 1: *(50% wind energy, 25% hydro, 25% solar)* With dynamic line rating and curtailment 0,5% (figure 13)	180 MW *(68 MW wind, 25 MW, hydro. 84 MW solar).*	350 GWh	4 GWh

Comparison of Table VII with Table II show that also a curtailment 0.5 % of the time allows the production mix with 25% of energy from the lesser available solar production to reach the same annual energy production (350 GWh) as the pure wind production. This is because of the non coincidence of maximum values discussed previously.

VI. DISCUSSION

If the alternative is a costly strengthening of the grid it can often be an attractive solution to install a larger than otherwise permissible amount of DER and instead reduce production somewhat during certain times when the over current limits would otherwise be exceeded. This is also the only solution when building new lines or substations is not acceptable or would take many years.

Communication between the network operator and the production units is essential to allow for optimal curtailment (i.e. as little as possible without resulting in an overload or overvoltage). Communication would also be required to allow DER units with reactive power generation capability to help compensate the reactive power losses created from the large increase in active power flows from lower voltage levels.

This study shows that the amount of DER could be multiplied in the studied network. However this assumes the removal of some industry loads excluded in the study and that the transformer power ratings are not, as today, limiting the hosting capacity. When studying the overall hosting capacity of real networks it is important with comprehensive network model and good power system understanding to allow a simultaneous study of all hosting capacity limits.

VII. CONCLUSIONS

In the paper the hosting capacity approach is applied to a real network in order to objectively find limits to the amount of permissible new DER. Today permission to connect new DER is often based on studies of worst case scenarios where short circuit currents and the thermal overload of transformers, lines and cables are studied at maximum load. The hosting capacity approach allows for increased transparency in such calculations through the development of methodology to objectively define performance indices and acceptable levels of deterioration.

The paper quantifies the possible increase in hosting capacity enabled by using increased communication capability that today is becoming economically viable to implement in distribution networks. Two cases have been studied to demonstrate this approach i) use of a thermal line model where ambient temperature, aggregated heating and dissipation in power lines are used to calculate the maximum permissible current through time (dynamic line loading) and ii) curtailing of DER generation when maximum consumption in the distribution network coincides with maximum wind production. In both cases the possibility to collect, distribute and process limited amount of measurement data from various parts of the network is anticipated. Later studies within this research project aim towards implementing and verifying such approaches in the studied network. Use of energy storage systems will also be studied.

VIII. ACKNOWLEDGMENT

The work is undertaken within a joint development project at the HVV (www.highvoltagevalley.se) consortium and financed by the Swedish Governmental Agency for Innovation Systems.

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X. BIOGRAPHIES

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