GENERATION CURTAILMENT AS A MEANS TO INCREASE THE WIND POWER HOSTING CAPACITY OF A REAL REGIONAL DISTRIBUTION NETWORK

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ABSTRACT

This paper represents how generation curtailment can be utilized to increase the wind power hosting capacity of an existing distribution network. The paper proposes a control algorithm that implements the curtailment and can be easily implemented as a part of the existing network management tools of the distribution system operator. The paper also presents how the amount of annual curtailment can be evaluated prior to wind farm construction.

INTRODUCTION

The amount of generation connected to distribution networks is constantly increasing. Depending on the type and size of the distributed generation (DG) units, they can be connected to any of the voltage levels operated by distribution networks operators (DSOs). Small DG units such as rooftop PV plants are connected to LV networks (400 V), medium-sized DG units such as larger PV plants or single wind turbines are connected to MV networks (in Finland usually 20 kV) and large units such as wind farms are connected to HV distribution networks (in Finland 110 kV) or directly to transmission system. Connecting generation to any of the above mentioned DSO networks can cause problems related to voltage quality, overloading of network components and protection [1]. The factor limiting the network's DG hosting capacity depends on the voltage level and the type of network (weak/strong). In weak MV and LV networks, voltage rise is usually the factor limiting the amount of DG that can be connected to the network. In stronger networks, overloading of feeders/transformers or increased fault levels are usually the limiting factors. The measures that can be used to mitigate the DG caused problems are different depending on the limiting factor and also on the voltage level. This paper concentrates on mitigating overloading problems. The work has been demonstrated as a case study considering a real Finnish 110 kV HV distribution network to which a large amount of wind power is to be connected but the proposed methodology is applicable also to other networks and generation types.

Overloading problems caused by wind power plants can be mitigated either by reinforcing the network or moving towards an active network management scheme. The cost of network reinforcement is, in many cases, very high and can make otherwise profitable wind power projects too expensive. Active network management methods can decrease the total costs significantly. [2] In this paper, generation curtailment as a means to increase the wind power hosting capacity of an existing 110 kV HV distribution network is studied. The study network is a real network operated by a Finnish DSO Elenia. The study network is located at the coast and has, therefore, good wind conditions. A large amount of wind farms is planned to be built on the area. If the current passive network management method is maintained, some of the planned wind farms cannot be connected to the existing network because the feeders would be overloaded if all the connected units would be generating their nominal power. However, due to the intermittent nature of wind power, the frequency of occurrence of these kind of network conditions can be rare. Moreover, the feeder current limits are dependent also on the ambient temperature and wind speed and, hence, during the winter time more power can be transferred than during the summer time. The average wind conditions are better during the winter time than during the summer time [3]. Utilizing generation curtailment when overloading would otherwise occur can, therefore, be a profitable option.

The aim of this paper is to study the implementation and profitability of generation curtailment in the study network. The proposed control algorithm is described in detail and also its integration as a part of the existing DSO systems is discussed. The paper will also present estimates on the amount of generation that would be annually curtailed if the control algorithm would be taken into use and all the planned wind farms would be connected to the existing network. This information is vital to wind power producers when making the investment decisions and the network connection agreement.

STUDY NETWORK

The study network consists of a 110 kV main feeder and branches. The main feeder has transmission system connection points at both ends but is radially operated. At the moment, the network feeds load substations and one wind farm. There is, however, significant interest in building new wind farms to the area. Some of the planned wind farms already have finalized connection agreements and with some negotiations are still ongoing. The network structure is depicted in Figure 1.

Only the main feeder can be overloaded since the nominal powers of the wind farms connected on the branches are

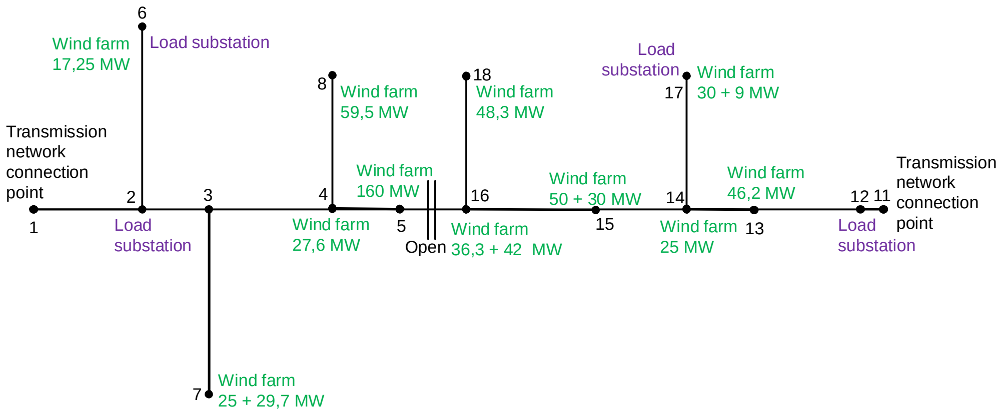

Figure 1. The example network structure.

relatively low. The current limit for the whole main feeder is 1155 A. Current and voltage measurements are available from load substations, wind farms and transmission network connection points. Also real and reactive power measurements are available from load substations and wind farms.

PROPOSED CONTROL ALGORITHM

The proposed algorithm has been designed such that implementing it as a part of the existing DSO SCADA would be as easy as possible. The algorithm utilizes measurement data that is already available and sends the control signals through standard communication channels that are available to all generation plants connected to HV distribution networks. Also contractual issues have been taken into account when defining the control principles.

Operational principle

The control algorithm curtails wind power generation when any part of the network is overloaded. At first, the algorithm utilizes measurement data and network static data to determine currents at each network section. If the current limit is exceeded at any of the network sections, the algorithm determines the amount of needed generation curtailment, selects the wind farms to be curtailed using a predefined order and sends new real power set points to the wind farms to be curtailed. The algorithm includes also a restoring part which cancels the generation curtailment commands in case they are not needed anymore. The functional diagram of the algorithm is represented in Figure 2.

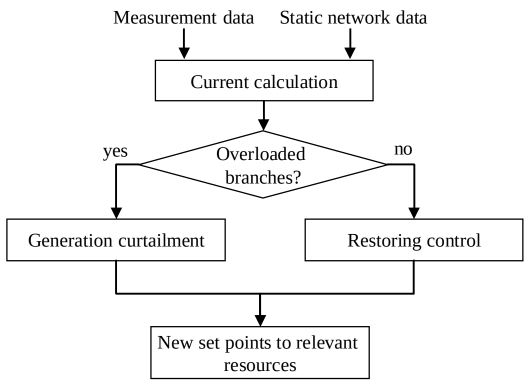

Figure 2. The functional diagram of the control algorithm.

Current calculation

There is both load and production in the network and, therefore, the maximum current can be located also elsewhere than at the transmission system connection point. Control decisions cannot be made based only on direct measurement data but currents in all network sections have to be calculated. In a radial network, currents can be easily calculated utilizing the network static data and the measured current magnitudes and angles at load and production sites. Moving averages of the current measurements should be used as input to the current calculation function instead of instantaneous values. The thermal time constants of feeders are quite long and, therefore, current transients do not require control actions to be conducted.

Generation curtailment

Generation curtailment is implemented using the last-in-first-out (LIFO) principle. From the contractual point of view, this is the simplest approach because modifying the already existing connection agreements is not a feasible option. It is the best choice also from the wind power producers' point of view because an estimate on the annual curtailed energy can be given during connection negotiations and the situation does not change even if new units connect to the network later. Moreover, in case of overloading mitigation, all units whose power is transmitted through the overloaded branch are equally effective in reducing the overloading whereas if the main problem would be voltage rise, different units would have different voltage sensitivities and, therefore, LIFO would not necessarily lead to a very efficient outcome. Other selection methods are discussed in [4].

The flow chart of the algorithm part that determines the amount of curtailment for each of the generating units is depicted in Figure 3. To minimize the amount of generation curtailment, the algorithm starts from the branch that is most distant from the substation and proceeds through all the branches. At first, the algorithm checks if the studied branch is overloaded and determines the needed current reduction. If ambient temperature measurement is available, the current limit is changed based on the measurement. The effect of ambient temperature to the feeder capacity is significant [5]. It would be possible to take also wind conditions into account when determining the current limit but the DSO operating the example network preferred not to include it because major part of the feeder is located in the middle of forest where the impact of wind speed for the cooling of feeder is unknown and is expected to vary a lot in each specific feeder section.

The algorithm utilizes a LIFO table in deciding which units to curtail. The table includes information on the order in which the units have been connected to the network but also information on which branch currents the unit can affect. The algorithm curtails as many units as necessary to obtain the current reduction target for the branch under study, saves the new calculated real power set points and moves to the preceding branch. When all the branches have been gone through, the new set points are sent to the units. If the network switching state changes, the LIFO table has to be updated. If network topology data is available in the distribution management system, this update can be done automatically.

Also other principles than LIFO can be used without changing the algorithm implementation. Since the controlled units are selected from the LIFO table, the order in which the units are controlled can be changed by simply modifying the table.

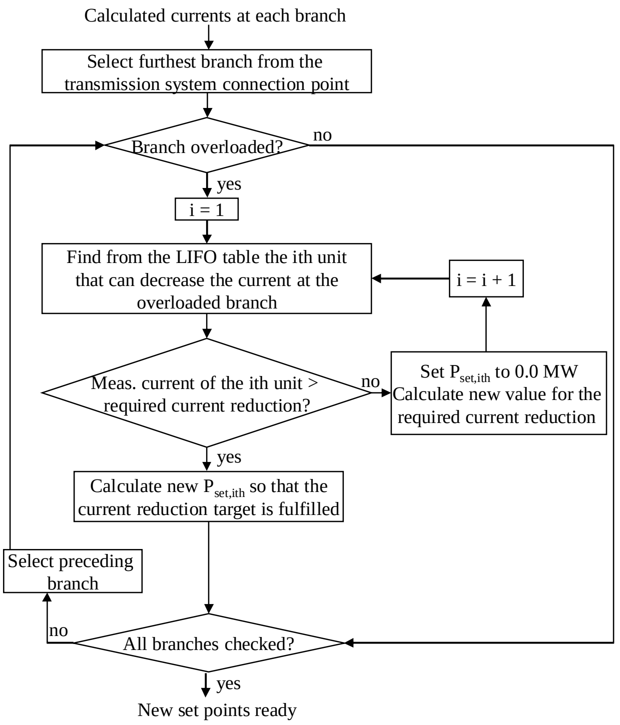

Figure 3. Flow chart of the algorithm that determines the new set points for each of the wind farms.

Restoring control

Restoring control is invoked if there are no overloaded branches in the network. At first, it checks if the maximum current in the network differs from the feeder current limit more than a predefined margin. If it does, the algorithm determines new higher real power set points using a similar operational principle as the one presented in Figure 3. The units whose real power has been curtailed are gone through in a reverse LIFO order and the set points are increased until the maximum current reaches its limiting value (feeder current limit - margin). Restoring control is needed to prevent situations where generation is curtailed although there is no need for it anymore.

Practical implementation

The control algorithm is implemented as a part of the existing DSO SCADA. The control algorithm is executed with a predefined interval. The interval cannot be too long to prevent overheating of the feeder. On the other hand, the algorithm should not be executed again before new measurement data is available and the previous control actions have been finalized. The feeder thermal time constant is in the study network approximately 20 minutes. New measurement data is available in the study network at least two times a minute and the rate of change of wind farm real power can be set between 10 to 100 % per minute [6]. Execution interval of 5 minutes is selected.

Since the proposed algorithm was planned to be as simple as possible, implementing it as a part of the existing SCADA is relatively easy. Also, it does not require a lot of calculation capacity and, therefore, does not slow down other SCADA processes. The algorithm utilizes measurement data that is already available in the SCADA with the exception of the ambient temperature measurement which is, however, not mandatory for the algorithm implementation but just improves its performance. The new set points are sent to the wind farms through existing communication channels.

The algorithm has to be able to prevent feeder overloading also in exceptional situations. In the example network, branch currents can be accurately determined also in case measurements from one node are missing because there is a current measurement also at the transmission system connection point. If measurements are missing from more than one wind farm, the algorithm assumes the powers of these units to be nominal and uses them as the primary curtailment resource.

AMOUNT OF NEEDED CURTAILMENT

It is important to the wind power producer to know an approximate value for the annual curtailment when making the investment decision. In this paper, statistical planning method [7] is used to calculate the amount of curtailed generation. In statistical planning, load flow calculations are conducted for the whole year using available load and production data. If measurement data is not available, load and production profiles can be used. In the study network, hourly load measurements are available from all the load substations. Wind speed measurement data is available from one of the wind farm sites with 10 minute interval. The production profiles for the wind farms are calculated from this measurement data by utilizing typical wind turbine power curves and by assuming that the wind speed does not differ between sites. The assumption is conservative and the real curtailment need will be somewhat smaller than the calculated one. The functional diagram of the statistical planning method is represented in Figure 4.

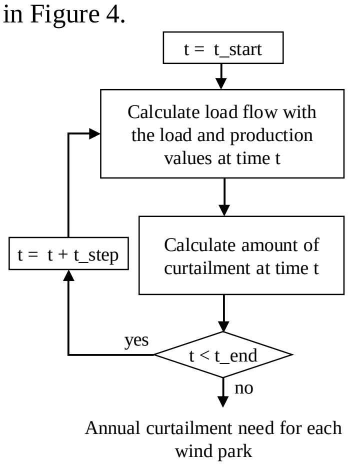

Figure 4. Operational principle of statistical planning algorithm. In this paper, calculations are conducted with a 10 minute interval for the whole year i.e. t_start = 1 min, t_stop = 525600 min and t_step = 10 min. In total 52560 calculations are conducted per study case.

Statistical planning method could be relatively easily included as a part of the network information system (NIS) that is used as the DSO network planning tool [7]. However, the functionality is not yet available in any commercial NIS. The DSO can utilize also a separate tool similar to the one used in this paper for curtailment calculations.

SIMULATION RESULTS

The operation of the control algorithm has been simulated in this paper using Matlab PST toolbox. Load flow simulations are adequate since the execution time of the algorithm is negligible compared to the feeder thermal time constant. The study network depicted in Figure 1 has been modelled using the real feeder data (lengths, impedances) so that also reactive power production or consumption by the line and the real power losses are taken into account in the calculations. The connection order of the units is not yet known but for the calculations the order shown in Table 1 was defined.

Calculations were conducted for two different wind tower heights (100 m and 120 m) and for two different transmission system voltages (110 kV and 118 kV). The

Table 1. The order in which the units are curtailed for both of the radial feeders. The uppermost is connected last to the network and will be, therefore, curtailed first.

Connection node	Nominal power		Connection node	Nominal power
7	29.7		17	30
5	160		16	42
7	25		16	36.3
8	59.5		13	46.2
4	27.6		17	9
6	17.25		18	48.3
			15	30
			15	50
			14	25

annual total curtailment is presented for these four cases in Figure 5. The wind farms operated with a unity power factor although in reality they would be operating in voltage control mode which would affect the currents also somewhat. The results shown in Figure 5 give some general idea on the network operation if all the planned wind farms would be built. For the wind power producers, however, the information is not adequate but the amount of curtailment for each wind farm is needed. Figure 6 shows the wind farm production data when the tower height has been assumed to be 120 m and the transmission system voltage 118 kV which is the typical value.

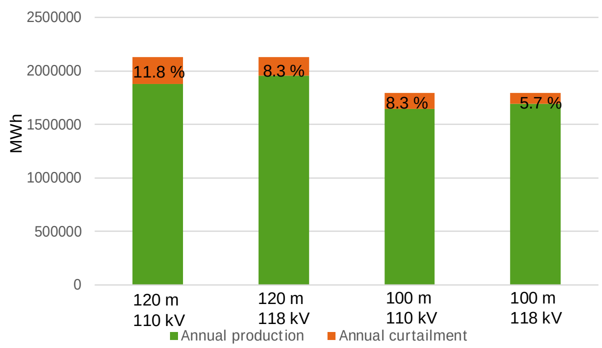

Figure 5. Total curtailment in the studied cases.

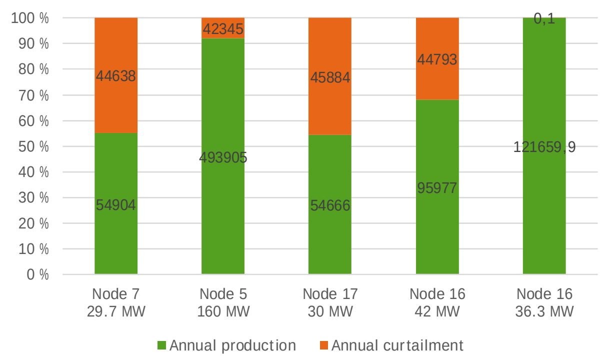

Figure 6. Production data for the wind farms that have been curtailed (tower height 120 m and transmission system voltage 118 kV).

It should be noticed that the results above assume a certain connection order of the units and the curtailed units will be different if the LIFO table is modified. However, the amount of curtailed energy will remain similar since the maximum current is for both radial feeders at the beginning of the feeder. The results show that for some of the wind farms the amount of curtailment is so high that probably they will not be built, at least with the planned nominal power. However, the real amount of curtailment would be lower since it was assumed that the wind speed is the same in all the sites and also the temperatures were not taken into account. Especially the latter increases the amount of calculated curtailment significantly compared to the real situation. The effect of temperature could be added to the calculations by using a typical yearly temperature curve as an input.

From the DSO point of view, the algorithm operated in each situation as desired. The current remained below its limit in all loading and production situations. Figure 7 shows the operation of the algorithm in one example case.

CONCLUSIONS

Generation curtailment can be an attractive alternative to network reinforcement in cases where the amount of annual curtailed generation is moderate. This paper presents a control algorithm that utilizes generation curtailment to increase the wind power hosting capacity of an HV distribution network. The paper also presents a method to evaluate the amount of annual curtailment prior to wind farm construction. Although the paper concentrates on an example network, the proposed control algorithm can be applied also to other radial networks. The statistical planning method is applicable to all kinds of distribution networks.

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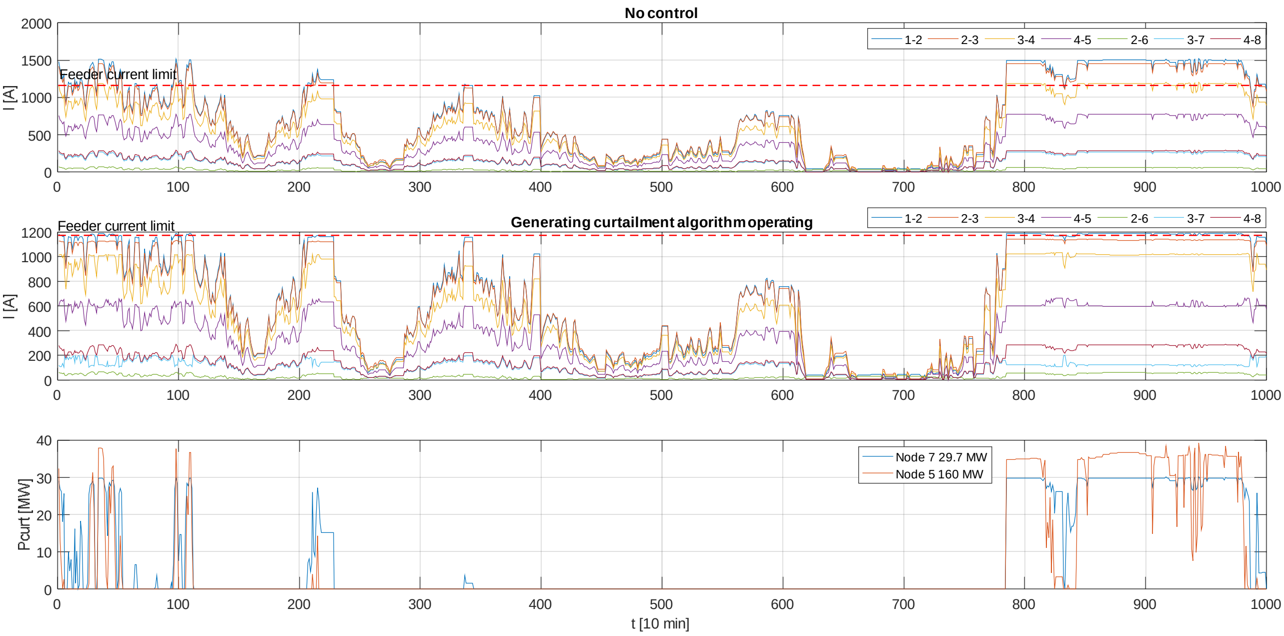

Figure 7. The operation of the proposed control algorithm in the radial feeder fed from transmission system connection point 1 for 1000 first time steps (tower height 120 m and transmission system voltage 118 kV).