STATISTICAL SHORT-TERM NETWORK PLANNING OF DISTRIBUTION SYSTEM AND DISTRIBUTED GENERATION

Sami Repo, Hannu Laaksonen, Pertti Järventausta
Tampere University of Technology
Tampere, Finland
sami.repo@tut.fi

Abstract – The paper presents improvements on the short-term network planning of a distribution system and distributed generation (DG) on the open electricity market. The interconnection of DG is currently based on worst case principle thus great savings in network investments can be achieved by applying a statistical planning approach. An idea for flexible interconnection is also introduced which further extends the advantages of a statistical planning approach. The approach is applied to an existing network information system (NIS) used for distribution network planning. The capability of the proposed approach is presented with a real life example and with a concept for voltage level management.

Keywords: Distribution system, distributed generation, network planning, voltage level management

1 INTRODUCTION

The propagation of DG in a distribution network will have a major influence on the distribution network. This implies many new factors which are not usually considered in distribution network planning. However, these topics will become a part of normal operation, not just special cases. This will necessitate developing the existing network planning methods in order to consider the interconnection of DG to the distribution network.

The penetration of DG in the distribution network will certainly make the planning and operation of the distribution network more complex [1,2]. However, that will also offer a great opportunity for enhancement of distribution network utilisation. The advantages of modern measurement, control and management systems should be tested in order to derive full benefit from existing investments and to meet the quality requirements of power supply in the future. The structure and operating principle of the distribution network will move towards a distribution system (active distribution network [3]) with several active components along the network. Ring operation of the distribution network may also allow improved control and operating principles than today [4].

The combined planning of a distribution network and a DG is a stochastic planning approach. However stochastic planning is too complicated in practical cases on the open electricity market where power production and delivery are separated. The size, type, location and time of DG installations are unknown in long-term network planning, which compels network companies to use case by case interconnection planning.

In weak distribution networks over-voltage problems are likely to occur during low demand periods when there is a large amount of DG interconnected on a medium voltage (MV) network [5]. Due to this network planning is currently based on the worst case conditions i.e. the so-called "minimum demand − maximum production" principle.

The paper will present the advantages of statistical network planning to calculate the effects of DG interconnection on a distribution network instead of the worst case planning principle. The statistical planning of a distribution network gives more flexibility for planning decisions compared to the worst case planning principle. The paper investigates the effects and potential of DG on the operation of weak distribution networks. The paper considers voltage issues and the network transfer capability of a distribution network including DG units.

2 PLANNING OF NETWORK AND DG

The starting point of the research was the existing NIS used for distribution network planning in Finland which typically includes, in addition to network data, calculation functions for load-flow and fault currents [1,6]. The load-flow calculation is based on statistical hourly load curves defined for different customer groups. This enables the calculation of load-flow for any hour of a year. The interconnection studies of DG units are based on an existing network where the use of NIS is a practical tool. The purpose of the methods studied is to examine the capability to interconnect a DG unit in a distribution network. The interconnection requires special consideration for safety reasons but also due to possible technical and economic effects.

2.1 The Worst Case Planning Principle

Traditionally the planning of a distribution network has been based on the worst case planning principle in order to meet power supply requirements in almost all circumstances. The worst planning case of radial distribution network is the maximum demand condition which determines the dimensioning of the network. This condition is used to determine the maximum currents and voltage drops in each feeder section [1].

The interconnection of DG in a distribution network has brought a voltage rise problem in lightly loaded networks. The easiest way to take into account the voltage rise problem in network planning is to extend the existing planning principle with this new restriction. The worst conditions from the network point of view are the maximum demand condition together with minimum production condition, and the minimum demand condition together with maximum production [2].

These conditions are considered very conservatively. For example, the first planning condition is usually considered as zero production condition although there some production may exist. Correspondingly, the second planning condition is applied with total maximum production although this is less likely as the number of production units increases.

The simplicity of the worst case planning principle is both the best and the most unsatisfactory feature of this principle. It is considered to meet the requirements of network planning accurately enough and in an appropriate way when the number of DG units is small, relative unit capacity is large, and the production of units is based on the same energy source. The assumptions of the worst case planning principle are less likely to be fulfilled when the number of units is large, the unit capacity is small e.g. a photovoltaic unit which replaces part of load demand of a house-hold, DG units are equally dispersed in the network, and various energy sources are used.

2.2 Statistical Planning Method

When the assumptions of the worst case planning principle are not valid, the stochastic behaviour of DG units must be taken into account in network planning. The idea of hourly load curves used in NIS is extended as statistical production curves to consider power production in the distribution network. Due to a lack of actual measurements and heavy dependence between power production and the location of the DG unit, the production curves are based on long-term statistics of wind speed or temperature. The properties of production curves are described in Chapter 3. The correlation of power production and load demand is a very critical issue in network planning. For example, the operation of combined heat and power (CHP) unit and load demand correlates very well, hence the worst case planning principle is simply too conservative.

The application of both the load and the production curves at load-flow calculation makes it possible to simulate the hourly functioning of the distribution system including DG units. The planning of the distribution network is not restricted to certain fictive planning conditions, but a series of hourly conditions is considered in order to find the most limiting conditions and the utilisation period of limitations. For example, the results of load-flow calculations may be used to estimate the mean voltages and desired exceeding probability levels. The knowledge about network limitations and their seriousness in terms of amount (e.g. voltage level) and time (e.g. hours when voltage is above the maximum limit) provides much information for the network planner for further studies where the removal of these limitations is considered.

The load-flow simulations with production curves enable interconnection studies to see what kind of network conditions might exist and to see the differences between active network management strategies or network enforcements. When a number of different production curves are used in load-flow simulations and the simulation results are examined together, the method will converge towards probabilistic load-flow simulation e.g. Monte-Carlo simulation. The calculation of economic effects, like costs of network losses and transmission charges which are dependent on the point in time, also becomes possible. The hourly load-flow information is needed to calculate time dependent costs and income, which are further needed, for example, in the planning of distribution tariffs for DG.

The production curves are not accurate in the same way as load curves are. The load-flow simulation with production curves is more or less a good guess about what might actually happen. The results of certain hour especially would not be accurate due to uncertainty of future wind and temperature. For network operational purposes it is better to use special forecast methods instead of production curves.

3 STATISTICAL MODELLING OF LOADS AND PRODUCTION

3.1 Load Curves

The planning of an electricity distribution network is based on load-flow calculation which uses customer group based load curve models as initial data to determine network loading for every hour of the year. Due to the many load points in MV and LV networks, the load data is usually insufficient. For the estimation of load demand customers' annual consumptions and customer group based load curves are needed. The Association of Finnish Electricity Utilities has collected load curve models for 46 different customer groups in a ten-year measuring programme. Based on parameters included in these load curve models certain customers' mean power for a particular hour can be calculated.

However, for network dimensioning purposes the mean power is not enough, the peak power also has to be determined. The distribution of the load for a particular hour of the day can be approximated by a Gaussian distribution, which is characterised by its mean value and standard deviation (P_{it} and δ_{it}). In a Gaussian distribution the following relationship exists between the values of mean probability and a given excess probability level:

$$P_{p,it} = P_{it} + z_a \cdot \delta_{it} \tag{1}$$

where $P_{p,it}$= power having an excess probability of p%
P_{it}= mean power for customer i at time t
z_a=coefficient related to p
δ_{it}=standard deviation for customer i at time t

For example, in voltage-drop calculations the excess probability used is typically around 10 % (z_a=1.28) and in the calculation of losses the mean values (50 % excess probability, z_a=0) are used [1]. In order to find the minimum load conditions for voltage rise calculations, the coefficient z_a must be negative.

A load curve for a group of similar customers can be constructed by summing the individual customer load curves statistically:

$$P_{group,it} = n_i \cdot P_{it} + z_a \cdot \sqrt{n_i} \cdot \delta_{it} \qquad (2)$$

where n_i = number of similar customers i.

A load curve for two different groups of customers can also be constructed by summing the individual customer load curves statistically. The standard deviation of the summed load depends on the correlation between the loads. If there is no correlation between them:

$$P_{sum,12t} = n_1 \cdot P_{1t} + n_2 \cdot P_{2t} + z_a \cdot \sqrt{n_1 \cdot \delta_1^2 + n_2 \cdot \delta_2^2} \qquad (3)$$

where n_1 = number of similar customers *1*
n_2 = number of similar customers *2*
P_{1t}= mean power for customer *1* at time *t*
P_{2t}= mean power for customer *2* at time *t*
δ_{1t}=standard deviation (customer *1* at time *t*)
δ_{2t}=standard deviation (customer *2* at time *t*)

When the population of a certain customer group increases the total variation decreases and therefore the load curve is more likely to yield the right results [6]. When the number of customers at certain node is low the methodology may overestimate load demand.

3.2 Production Curves

Because the operation of DG units is based on weather conditions (wind, temperature, water flow), industrial or household heat consumption (district heating CHP application) or electricity market price, production curves also have to be based on the general statistical data describing them. Because at the planning stage the functioning of the production unit is unknown, the establishment of production curves for a production type which is more or less stochastic in nature could be based on the compiled statistics about monthly wind speed and temperature distributions of the planned production site or some reference site. In this paper it is assumed that the hourly wind speeds and temperatures created for the site in question do not correlate.

3.2.1 Wind Power

Wind speed is usually represented with Weibull distribution e.g. in wind atlas files. Typically the wind atlas includes yearly average wind speed and the Weibull distribution's parameters (scale and shape factors) of the site in question. The Finnish wind atlas also contains information about monthly wind speeds and therefore it is possible to get the monthly average wind speeds and Weibull distribution's parameters from it.

From the monthly wind speed distribution it is possible with random sampling to create hourly wind speed time series for that month. However, the randomness of the created hourly wind speed curve has to be restricted to a certain extent to make wind speed behaviour more realistic i.e. the wind speed of consecutive hours is not allowed to differ more than some chosen maximum value. With the above restriction the hourly wind speed curve will be created several times for the month in question until the average wind speed of the created curve differs only ± 0.1 m/s from the original wind speed distribution and also contains wind speed values from both ends of the original distribution. The latter condition can be fulfilled for example by checking that the created wind speed curve's Weibull distribution's parameters are close enough to the original distribution's parameters. The establishment of the wind generator's hourly production curve for active power requires the power curve of a particular wind turbine with information about the turbine's nominal power and cut-in, cut-off and nominal power wind speeds.

If we have many wind turbines at different locations, the hourly wind speed time series cannot be entirely the same at every location. In such a situation the wind speed curve for many wind turbines can be derived from a single wind speed curve by taking into account the smoothing effects in both time and space. A new wind speed curve can be generated from the original wind speed series by applying a moving block-average of the elements in the original time series in a timeslot around the specific time corresponding to the dimensions of the area and the mean wind speed. The smoothed power curve for wind turbines should also be used when the number of wind turbines is large and the distances between turbines are long (> dozens of kilometers) [7].

3.2.2 Combined Heat and Power (district heating)

The electric power production curve of CHP unit depends on the application. In district heating electric power production follows CHP heat production with some unit-specific ratio if no heat storage is used. CHP unit heat production is aimed to fulfil customers' heat demands which are heavily dependent on the outdoor temperature. From the compiled statistics about monthly temperature distributions of the planned production site it is possible to generate daily average temperatures in the same way as hourly wind speeds were above taken from monthly Weibull distributions. It is assumed here that the monthly average temperatures are normally distributed.

It is also presumed that it is possible to create a combined proportional standard heat demand curve for the heat customers of the particular area. The proportional heat demand curve could be, for example, daily or weekly. With the heat demand curve, daily average temperatures and initial data needed one can determine CHP nominal heat power. The initial data includes the following:

– Percentual proportion of a unit's nominal heat power of customers' peak heat demand
– Percentual proportion of yearly heat demand which is dependent on the outdoor temperature
– Customers' total heat demand
– The reference indoor temperature for heat demand (usually +17°C) which is used to calculate the heat demand number
– First and last day of the summer season (in the summer season heat demand is not dependent on the

outdoor temperature and the CHP unit is disconnected from the network)

After the CHP unit's nominal heat power has been calculated it is possible to form the CHP unit's hourly heat production curve where the summer season is also taken into account. With unit-specific electric / heat power ratio the CHP unit's nominal electric power and hourly electric power production curve can be determined.

3.2.3 Limitations of Production Curves

The method introduced above to create the production curve for wind turbines includes many simplifications which make it somewhat inaccurate. Inaccuracies of hourly wind speed curves are a result of simplifications in:

- Wind atlas files wind speed data (height dependency, terrain roughness, reference data for planned site etc.)
- Production curve creation method (wind speed variation of consecutive hours is not based on real mathematical/physical models and transition probabilities such as Markov chains or ARMA models)

In wind atlas files and the production curve creation method another possible source of errors is hourly modelling of wind speed with some average value (hides the varying nature of wind) and error resulting from Weibull fitting (appropriate in cases where average wind speed is high > 7 m/s).

One way to get wind atlas files without surface wind measurements is to create them with a so-called mesoscale model which is often more reliable when the terrain is complex and surface wind measurements are made low (< 50 m). The problem is that it needs heavy and expensive computation which also requires an expert to carry it out.

In addition with hourly wind speed curves inaccuracies the hourly production curve for wind turbines also have other simplifications like:

- It does not question the reliability of the power curve (temperature and air pressure corrections, turbulence dependency, impact of other wind turbines on wind farms etc.)
- It does not take the shadowing effect into account when wind turbines in wind farms are considered
- It does not take the limitations in availability into account (failures, maintenance etc.)

Because of all the above-mentioned inaccuracies wind turbines' yearly production and the utilization period of maximum load will become somewhat overoptimistic.

The method for creating the electricity production curve for district heating CHP units also includes many simplifications which make it inaccurate. These simplifications and assumptions include among others:

- assumption of normally distributed monthly/daily average temperatures
- hourly variation of temperature during a day is not taken into account
- assumption of consecutive days' maximum allowed difference in average temperatures
- assumption of proportional standard daily/weekly heat demand curve (can be quite hard to determine in practice)
- estimate of customers' total heat demand
- limitations in availability are not taken into account

4 INTERCONNECTION OF DG

4.1 Why Flexible Interconnection?

The whole idea is based on the fact that the network transfer capacity may be larger with flexible than with fixed interconnection when network constraints occur occasionally. The fixed interconnection is always available and calculation of interconnection capacity is based on the worst case planning principle. The flexible interconnection expects controllability of DG unit (reactive or active power), but it can utilise the capability of network more precisely. The use of flexible interconnection requires active network management to avoid occasional network constraints.

The network transfer capability from the DG point of view is heavily dependent on loading conditions in the distribution network. The utilisation of an existing MV network may be improved in the case of a DG unit interconnection if the operation of the DG unit is not totally independent of network conditions [3,5].

If the enforcements of the MV network are based on the worst case this might introduce a severe economic barrier for a DG interconnection in weak distribution networks due to excessively conservative principles. The flexible planning principle may allow higher penetration of DG in a distribution network with less network investments and connection charges than with the fixed worst case planning principle. The flexible interconnection may benefit both the network and the production companies by allowing higher penetration of DG with less network investments.

4.2 Voltage Level Management

The proposed concept for voltage level management is an example of active distribution network management. The concept includes two hierarchical levels. The first level is a local level and the second is a co-ordination level. Figure 1 explains the basic idea of the proposed concept. The local voltage control is a conventional one, where a local controller maintains a constant voltage or power factor at the DG unit terminal. This control level must be the fastest one. The co-ordination level introduces a system-wide perspective for the voltage level management of the distribution network.

4.2.1 Local voltage control

Many DG units are capable of continuous control of voltage level or power factor. This opportunity, however, is much restricted by interconnection contracts which set very narrow limits for the free-of-charge power factor, and are sometimes even lost by using DG

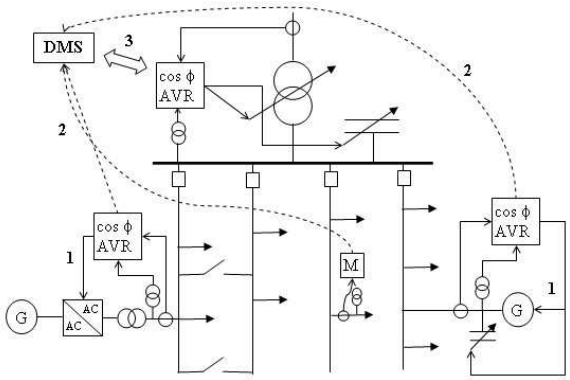

Figure 1: Concept for voltage level management.

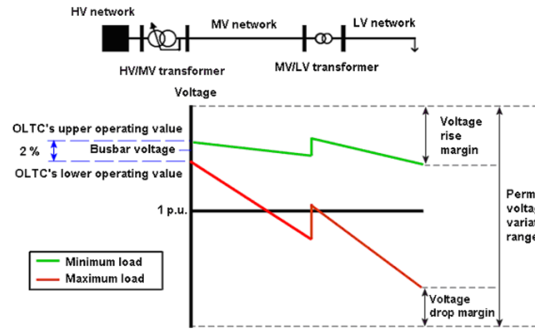

Figure 2: Available voltage rise and drop margins.

units at unity power factor. From the MV network point of view, it would be beneficial if a DG unit would take part in the voltage level management of the MV network [8-10]. That would be an ancillary service produced by a DG unit for a network company. An ancillary service contract could replace network reinforcement when the interconnection of a DG unit causes occasional voltage rise problems.

The idea of local voltage control in the case of DG is to reduce the voltage rise when necessary by controlling the reactive power of a DG unit. The controller should be able to control the excitation of the synchronous machine, power factor correction of the induction machine, or the reactive power of the frequency converter. The operation of the local controller is totally based on local measurements (indicated with number 1 in Figure 1), hence that is applicable in a whole range of DG units from wind farms to small house-hold size units.

The reactive power flows in the MV network should be considered carefully in these cases by the network company. The additional reactive power flow would increase the costs of MV network operation by increasing the losses of the MV network, increasing the need for reactive power compensation capacitors at HV/MV substations and increasing the number of on-line tap changer operations. However, the consumption of reactive power at the location of the DG unit may be an interesting choice for network enforcement, especially when voltage rise is expected to occur occasionally.

4.2.2 Co-ordination of Voltage Level Management

Figure 2 presents the basic idea of distribution network planning when the co-ordination of voltage level management is applied. The available voltage drop margin is the minimum of voltage drop margins of all feeders. The voltage drop margin is the difference between the minimum of feeder voltages and the voltage minimum limit. Similarly there is an available voltage rise margin corresponding to the maximum of feeder voltages and the voltage maximum limit.

The idea of co-ordination is to utilise the available voltage drop and rise margins if these exist and if there is a need for co-ordination. If the load demand is low, the voltage drop margin is large, and could be utilised by reducing the voltage set-value of HV/MV substation (indicated with number 3 in Figure 1). This will result in a reduction of the voltage drop margin but simultaneously it will increase the voltage rise margin, which may be utilised by allowing a rise of DG units output. When load demand decreases, there is a chance of a voltage rise problem, especially when the outputs of DG units are large. However, there is also a possibility of decrement of voltage setting at a HV/MV substation because voltage drop is less than during high load demand period. The need for voltage resetting at a HV/MV substation is mainly determined by the outputs of DG units. Therefore the output of the largest DG units needs to be measured on-line (indicated with number 2 in Figure 1).

The co-ordinated voltage level management of a MV network is based on the resetting of voltage set-value at the primary substation. The capability for the reduction of voltage set-value must be evaluated in order to avoid voltage drop problems at radial feeders. The minimum voltage setting of a HV/MV substation for lightly loaded conditions is typically determined by the voltage drop of feeders not including DG units. Therefore it is important to apply load curves in the load-flow calculation in order to pay attention to the behaviour of different customer groups on different feeders. This is done with a distribution management system (DMS), built on customer and network databases and on information from SCADA system [11]. The DMS is based on load curve based on-line load-flow calculation and will estimate the voltage level of the system. DMS also uses current measurements and device status information via SCADA from a HV/MV substation, from controlled DG units and from on-line hourly energy meters to reset load curves in order to fit the results of load-flow calculation and actual measurements [6,11].

4.3 Production Curtailment

The opportunity for production curtailment may also benefit both the network and the production company when network investments are avoided and a voltage rise problem appears occasionally. The likelihood of this kind of network condition is very rare and may be evaluated based e.g. on load curves and wind and temperature statistics or measurements. The possibility of production curtailment should be considered in the interconnection contract. Another option is a separate ancillary service contract.

Production curtailment may be easily realised at hydro plants and relatively easily at CHP plants by resetting the set-value of the turbine controller. CHP plants are more complicated because the heat demand of the plant usually dominates the operation of the plant. The heat storage device makes it possible to separate the demand for heat and electricity from each other to some extent. Otherwise the CHP plant should be operated to produce heat only or with reduced electric / heat power ratio, which would reduce the efficiency of the CHP plant.

Wind power curtailment would probably be the most important of all unit types due to the location and stochastic mode of operation of these units. The simplest method of wind power curtailment would be disconnection of the required number of units from the problematic area. The order of disconnection may be realised by voltage relays either by setting different upper voltage limits or by setting different tripping delays for units. The output of a variable speed and pitch controlled wind turbine can be controlled by a frequency converter and blade angle control, hence the unit need not be disconnected, which makes it possible to control the output of the unit continuously.

5 EXAMPLES

Examples are presented with a real life distribution network of Fortum Sähkönsiirto Oy in south-west Finland, where the voltage rise problem is acute if the planned wind turbines are constructed. The load-flow calculations were made for an average year based on hourly load demand and production estimates. The simulations cover 8760 hours.

The MV network examined (20 kV) consists of one HV/MV substation feeding five MV feeders. The wind turbines are connected 22 km away from the substation and they are equipped with permanent magnet generators and frequency converters in the stator circuit, which allows power factor control between 0.92–1.00 inductive or capacitive. In the example simulations four 750 kW variable-speed wind turbines are modelled as one 3 MW generator. It is assumed they will meet the same wind almost at the same time i.e. smoothing effect is not considered.

The network effects of wind turbines with different planning principles and voltage control methods (local and co-ordinated) are studied in a situation where the voltage at the HV/MV substation is aimed to be 20.4 kV.

5.1 Comparison of fixed and flexible interconnection

Table 1 presents the network transfer capabilities at wind turbine connection point. The results are presented regarding the load demand of the feeder including wind turbines. The results are presented for three different voltage level management concepts and for fixed and flexible interconnection. The capability of fixed interconnection is calculated based on the worst case planning principle.

The present situation, where the fixed interconnection is used with unity power factor at the DG unit site is very conservative and the utilisation of network capability is very low. The worst case planning principle is suitable for traditional distribution network planning but it is not capable of considering system-wide aspects when DG is integrated in the distribution network.

The main advantage of flexible interconnection is its capability to take into account network loading condition and enhance the network transfer capability when possible. The network transfer capability is the same as allowed production of the DG unit in this case. The advantages of voltage level management concepts are also very clearly seen in Table 1.

Table 2 shows the amounts of energy not produced by a 3 MW wind turbine. The total available production is 9109.1 MWh, which is calculated from simulated wind. The difference between fixed and flexible interconnections may also be seen in this table. Similarly the effect of voltage level management concepts may be seen.

5.2 Properties of Statistical Planning Principle

Next some further analysis of simulation results is presented. The same load-flow conditions and results as before are used. Figure 3 shows voltages of the wind turbines' connection point during one week period at January when both the load demand and the wind power production are high. Figure 4 shows power production of wind turbine.

At Figure 3 the lower dashed curve represents voltages when wind turbine is not connected and the upper one represents situation where wind turbine is continuosly producing maximum power. These curves sets limits for voltage variations. The maximum limit of MV voltage is 21 kV. The continuos thin blue curve shows the voltage at simulated wind conditions. The corresponding power production may be seen from Figure 4. At both figures blue curves are sometimes replaced by continuos thick red curve i.e. they have exactly the same

Load [kW]	*Unity power factor*		*Local voltage control*		*Co-ordinated control*	
	Fixed	*Flex.*	*Fixed*	*Flex.*	*Fixed*	*Flex.*
364	850	850	1120	1120	2000	2000
473	850	900	1120	1250	2000	2080
572	850	950	1120	1300	2000	2160
690	850	1050	1120	1350	2000	2240
825	850	1150	1120	1550	2000	2320
992	850	1300	1120	1750	2000	2400
1174	850	1500	1120	2000	2000	2500

Table 1: Network transfer capabilities [kW].

Voltage control method	Fixed Lost energy	Flexible Lost energy
Unity power factor	48.6	40.4
Local voltage control	38.0	23.3
Co-ordinated control	14.3	0

Table 2: Energy not produced [%] due to network constraints.

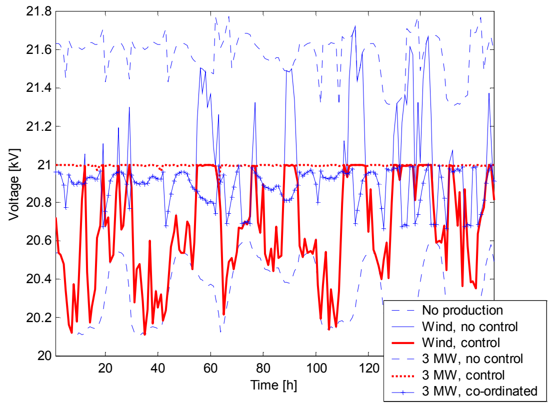

Figure 3: Voltages of wind turbine connection point.

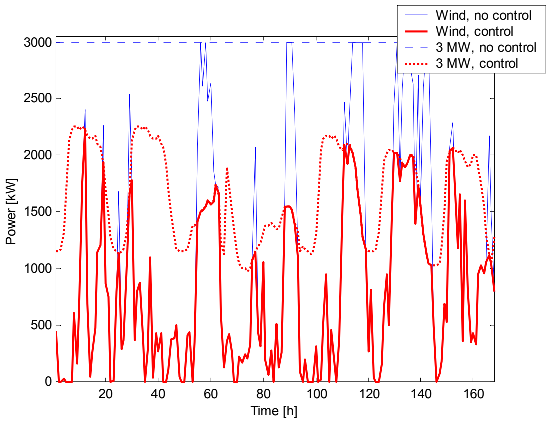

Figure 4: Power production of wind turbine.

values. Although the load demand is close to maximum, there is a severe voltage rise problem at the connection point of wind turbine several times during a week. Figures also shows the strong correlation of wind turbine output and connection point voltage. When the local voltage control (continuos thick red curve) is applied the voltage is always within a permissible range. The local voltage control means combination of local voltage control and production curtailment in this case. The dashed thich red curve represents maximum production conditions according to voltage level. The voltage of wind turbine connection point is always 21 kV in that case. The output of wind turbine has exactly the same profile as load demand of the feeder.

The co-ordinated voltage level management concept means reduction of substation voltage when necessary and possible. The co-ordinated concept is the only one which is capable of adapting to all simulated loading and production conditions. At Figure 3 the continuous blue curve with plus signs represents situations where the output of wind turbine was constantly 3 MW. The voltage of wind turbine connection point is always below the maximum voltage limit. The average of substation voltage is 19.66 kV in that case when it is normally 20.40 kV. The minimum voltage of all feeders supplied from that substation is 19.40 kV on average (minimum

	No production	Unity power factor	Local control	Co-ordinated control
Energy from HV network [MWh]	26375	20883	19329	17406
Energy from HV network [MVArh]	-7407	-7912	-4 882	-3691
Transmission charges [€]	87211	68139	62350	55775
Distribution losses [MWh]	571	549	566	779
Energy not produced [MWh]	–	3706.4	2135	0
Tap changer's yearly operations [number]	44	29	140	1 923

Table 3: The network effects of wind turbine with different voltage level management concepts.

19.07 kV) with co-ordinated concept and 19.99 kV on average (minimum 19.80 kV) with constant substation voltage. The reduction of substation voltage is remarkable, but the co-ordinated voltage level management concept is capable of controlling voltages of all nodes via DMS. Of course the uncertainty of load estimates, which may be evaluated from the standard deviation of each customer, will decrease the range of permissible voltage variation.

5.3 Calculation of financial issues

Some network effects of wind turbines are gathered in Table 3 with different voltage level management concepts. The first row of Table 3 indicates that voltage level management has an influence on wind turbine operation capability. The same row also sets the basis for the network company's financial calculations. The table also shows that reactive power feeding from the HV/MV substation to the HV network decreases with both voltage level management concepts. The MV network includes a sea cable about 40 km long which produces about 1 MVAr reactive power. The increment of reactive power consumption decreases the operational costs of the MV network in this case by decreasing the reactive power flow of the MV network. However, this will increase the requirements on reactive power compensation capacity on other neighbouring HV/MV substations.

The main advantage of a DG unit for a network company is the reduction of power transfer between HV and MV networks, which affects the transmission charges paid by a network company. When comparing voltage level management concepts, one can see that transmission charges (marketplace and use of grid fees) are 6575 € lower with co-ordinated control than with local control. However, the distribution losses are 213 MWh higher with co-ordinated control. Assuming that the price for distribution losses is 30 €/MWh the costs of distribution losses are 6390 € higher with co-ordinated control. Although in this way the co-ordinated control seems slightly more favourable (6575 € - 6390 € = 185 €) than local control, one must also note that the number of on-load tap changer's yearly operations is much higher with co-ordinated control, which may increase the need for maintenance of on-load tap changer. The financial advantage of co-ordinated control comes true for the network company when the distribution tariff for wind turbines is positive and not zero or negative as is commonly claimed.

6 CONCLUSIONS

The proposed statistical planning and voltage level management concepts were tested with a real-life distribution system. These were compared to the traditional planning and operation principles. The example clearly shows the capability of the statistical planning method to increase the network transfer capability when that is compared to the traditional worst case planning principle. The proposed voltage level management method may be applied to further increase the network transfer capability.

The proposed methods were developed for cases where the permissible voltage variation range is exceeded occasionally. When the interconnection of a DG unit is considered in a weak distribution network the combination of the statistical planning method and the co-ordinated voltage level management method may produce great advantages for both the network and the production companies. The capability of these methods can be evaluated by the load-flow simulations.

The load-flow simulation is based on a similar computational approach to those as existing commercial NIS and DMS. Load-flows are computed hourly and they are based on statistical load and production curves. Load-flow simulations are very useful, especially when the functioning of a distribution system is analysed in order to interconnect a DG unit in a network. Simulations may be used to examine both the technical and the financial issues. The interconnection of a DG unit in the distribution system will change operational costs such as marketplace fee, use of grid fee and costs of network losses. The income of the network company will also change remarkably when the production of a DG unit replaces load demand on the customer side.

7 ACKNOWLEDGEMENT

The authors are grateful to the partners of the Densy (Distributed Energy Systems R&D-program of Tekes) project "Integration of distributed generation into electricity distribution network" for the interesting real life research topic, comments, funding and research co-operation. The research also obtained funding from the Academy of Finland project "Power system security assessment and management".

8 REFERENCES

[1] E. Lakervi and E.J. Holmes, "Electricity distribution network design", London, UK, IEE Power series 21, 325 p, 1995

[2] N. Jenkins, et al., "Embedded generation", London, UK, IEE Power and Energy series 31, 273 p, 2000

[3] W.J. Laycock, "Intelligent networks", Power Engineering Journal, pp 25-29, February 2002

[4] S. Repo, et al., "Ring Operation of Distribution System in Case of Distributed Generation — Voltage Control", Proceedings of Nordic Wind Power Conference, March 2004, [On-line] http://www.elkraft.chalmers.se/NWPC/nwpc.html

[5] C.L. Masters, "Voltage rise the big issue when connecting embedded generation to long 11 kV overhead lines", Power Engineering Journal, pp 5-12, February 2002

[6] A. Seppälä, "Load research and load estimation in electricity distribution", VTT Publications 289, Espoo, Finland, 118 p, 1996, [On-line] http://www.enease.fi/asepthes.pdf

[7] P. Nørgaard and H. Holttinen, "A Multi-Turbine Power Curve Approach", Proceedings of Nordic Wind Power Conference, March 2004, [On-line] http://www.elkraft.chalmers.se/NWPC/nwpc.html

[8] E. Bompard, et al., "Voltage control in radial systems with dispersed generation", Proceedings of IEEE PowerTech, September, 1999

[9] S.N. Liew and G. Strbac, "Maximising penetration of wind generation in existing distribution network", IEE Proceedings in Generation, Transmission and Distribution, Vol. 149, No. 3, May 2002

[10] J.-H. Choi, and J.-C. Kim, "Advanced voltage regulation method of power distribution systems interconnected with dispersed storage and generation systems (revised)", IEEE Transactions on Power Delivery, Vol. 16, No. 2, pp 329-334, April 2001

[11] P. Verho, et al., "An intelligent support system for distribution network management", International Journal of Engineering Intelligent Systems for Electrical Engineering and Communications, Volume 4, Number 4, pp 219-227, December 1996