Including Active Voltage Level Management in Planning of Distribution Networks with Distributed Generation

Anna Kulmala, Kari Mäki, Sami Repo and Pertti Järventausta

***Abstract*--The existing distribution networks are designed based on the assumption of unidirectional power flows. The amount of distributed generation (DG) is, however, constantly increasing which creates a need to revise the current network operation and planning principles. This paper focuses on voltage level management issues related to DG. The effect of different kinds of voltage level management strategies on distribution network planning is discussed and a planning procedure regarding voltage issues when a new DG unit is interconnected to an existing distribution network is proposed.**

***Index Terms*--Active voltage level management, distributed generation, network information system (NIS), network planning**

I. Introduction

THE amount of distributed generation (DG) is constantly increasing. However, the distribution networks are still mainly operated and designed as passive systems and the control possibilities of DG are not utilized. In future, this approach should be revised because active network management methods can allow connection of more DG in existing distribution networks and, therefore, reduce the connection costs of DG. [1]

DG can have both positive and negative impacts on distribution network operation. It can support the voltage in the network or reduce losses. On the other hand, it can also cause problems related to e.g. voltage levels, protection or increasing fault levels. In weak distribution networks, the factor limiting the connected capacity of DG is usually voltage rise caused by DG. [2]

Voltage rise can be mitigated using either passive or active methods. If passive methods such as network reinforcement for instance by increasing the conductor size are used, the operational principle of the network is not altered and the planning methods currently used are still valid. If active voltage level management methods such as controlling the active or reactive power of DG are taken in use, the distribution network is no longer passive and the operational principle of the network is radically altered. The currently used distribution network planning tools and procedures are not capable of taking active voltage level management into account in any way and can not, therefore, be used to design networks in which active voltage level management methods are used.

In this paper, the influence of active voltage level management on distribution network planning is discussed. Firstly, DG impacts on distribution network voltage quality are discussed and some active voltage level management methods are introduced. Thereafter, distribution network planning tools and procedures currently used in distribution network companies are discussed and modifications to these are suggested. Finally, a planning procedure regarding voltage issues when a new DG unit is connected to an existing distribution network is proposed.

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II. DG Effects on Voltage Quality

Voltage quality consists of many features including e.g. voltage level and its variations, fast voltage transients, harmonics, voltage dips and interruptions. DG alters the voltage levels in the network, can cause transient voltage variations and might increase or decrease the harmonic distortion of the network voltage. It also increases the network's short circuit power and, therefore, reduces the effect of network disturbances at other parts of the network on customer voltage assuming that it stays connected during the disturbance. [2]

DG raises the voltage level in the network which can be either advantageous or disadvantageous to the network depending on the size, location and time variation of the DG unit. At high load DG supports the voltage and, consequently, improves the network's voltage quality. However, if the DG unit is large enough the voltage rise can become excessive. DG can also affect the operation of existing voltage regulating devices. For instance, if line drop compensation is used at the substation automatic voltage control (AVC) relay [3], connecting DG to the network decreases the current through the transformer and, therefore, lowers the voltages of customers at adjacent feeders.

Changes in the output current of the DG unit affect network voltages. Large transient voltage variations occur especially during DG connection and disconnection. More frequent voltage changes (flicker) can be caused by changes in the primary energy source (e.g. wind) but fortunately these changes tend to be smoother than step changes and are,

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therefore, less likely to cause nuisance to other customers. Flicker can be caused also by some forms of prime mover or adverse interactions between the DG unit and other existing voltage regulators such as the main transformer tap changer or reactive power compensation capacitors. [2], [4]

DG can either increase or decrease the harmonic distortion of network voltage. The effect on harmonics depends on the type of network connection (synchronous machine, asynchronous machine, power electronics) and the design of the DG unit. [2], [4]

The planning procedure proposed in this paper focuses on issues regarding voltage levels and fast voltage transients at generator start-up and disconnection. Also the possible flicker caused by the DG unit and the unit's effect on harmonics has to be taken into account when interconnection of a new DG unit is planned. These are typically managed using emission limits defined in standards such as [5].

III. Active voltage level management

Voltage rise problems caused by DG are at present usually solved using passive methods such as increasing the conductor size or connecting the generator to a dedicated feeder or at a higher voltage level. Also active voltage level management can be used to mitigate the voltage rise. Methods of different complexity and data transfer needs have been proposed and the selection between these is made based on the structure of the network and the number of components participating in the control.

A. Methods based on local measurements

The simplest active voltage level management methods determine their control actions based only on local measurements and, therefore, require no additional data transfer between network nodes. In many cases they can, however, increase the capacity of connected DG considerably [1]. At present, DG is usually operated at unity power factor and its network connection is firm i.e. the network is designed in such a way that the unit can produce its maximum power regardless of network conditions.

Voltage rise caused by DG can be diminished by allowing the DG unit to absorb reactive power. This can be accomplished by operating the DG unit in voltage control mode. If power factor control is preferred, the DG unit's voltage controller could operate in power factor control mode when the terminal voltage is between acceptable limits and switch to voltage control when the limits are overstepped. [6]

The reactive power capability of DG depends on its network interface. Synchronous machines and power electronics interfaces are capable of controlling their active and reactive power independently whereas the reactive power of induction generators can be controlled only if some external controllable reactive power compensation device is used. [2]

Local reactive power control alters the reactive power flows in the network and, therefore, affects network losses. The additional reactive power flow can also increase the need for reactive power compensation capacitors at the substation and increase the number of main transformer tap changer operations. These effects have to be taken into account at the planning stage. [7]

Voltage rise can be decreased also by limiting the active power output of DG when the terminal voltage exceeds its limit (production curtailment). This naturally reduces also the amount of power generated but if curtailment is needed only rarely the DG owner might still find it beneficial to curtail some of its generation if allowed to connect a larger generator to the network (non-firm network connection). [1]

B. Coordinated methods

Coordinated voltage control methods use information about the whole distribution network when determining their control actions. Hence, data transfer between network nodes is needed. At present, distribution networks contain only few measurements and, therefore, precise information about the state of the network is not normally available. However, measurements in distribution networks are likely to increase in the future which makes application of coordinated voltage control methods more attractive.

Coordinated voltage control methods can determine their control operations based on simple rules (e.g. decrease substation voltage when network maximum voltage exceeds its limit) or use some kind of optimization algorithm. The first approach is most suitable in simple networks where only few measurements and controllable components exist. The latter approach should be used in more complex networks where multiple controllable components exist and determining simple control rules is difficult. [8]

Even the simplest coordinated voltage control methods can improve the utilization of an existing distribution network in case of DG interconnection substantially. For instance, if the substation voltage is controlled based on network maximum and minimum voltages instead of only the local measurement, it was possible to increase the penetration of DG by a factor of 10 in one case study [1].

IV. Distribution network planning regarding DG

In countries where the electricity market is deregulated the planning process for interconnection of a new DG unit begins when a potential energy producer makes an inquiry on connecting a generation unit to the distribution network operator's (DNO's) network. The DNO has little power on the characteristics (location, size, network connection type) of the unit and, therefore, the interconnection planning procedure focuses on assuring that the DG unit can be connected to the network safely and without violating technical constraints such as voltage limits. The aim in planning is to minimize the total costs including for instance DG connection costs, costs of possible additional losses and the reduction in transmission charges. This paper focuses on planning issues regarding network voltages. A more extensive survey on required interconnection studies is represented in [9].

Distribution networks are in Finland planned using a network information system (NIS) that combines technical, economical and geographical data and includes also network calculation functions. Network data is stored in databases and steady-state rms-values are used in the calculations. [3] In modern NIS systems also DG can be included in the calculations. However, as the calculations are based on steady-state values, DG dynamics can not be modeled.

A. Present planning principles

In weak distribution networks, the capacity of connected generation is usually limited by the voltage rise effect. At present, DG is considered merely as negative load in distribution network planning and the capacity of connected generation is determined based on two worst case loading conditions (maximum generation/minimum load and minimum generation/maximum load). It is assumed that DG does not participate in distribution network voltage control in any way and that it can produce its maximum output power regardless of the network state (a firm connection).

The planning principles for DG interconnection vary depending on the country and also DNO. In some countries simple design rules are used to determine if a planned DG unit can be connected to the desired network node (e.g. the fault level at that point has to be some multiple of the generator rating). [2] In some countries (for instance in Finland) more detailed calculations are conducted and every case is studied separately.

The studies needed for DG interconnection can not be conducted using the currently used planning tools (NIS) but usage of more advanced simulation programs is needed. This requires a lot of extra work since the network already modeled in NIS has to be modeled in the other simulation program as well. The transfer of data could be quite easily automated but software interfaces for this are not at least for Nordic NIS systems currently available. Moreover, distribution network planners are not usually familiar with these more advanced simulation tools and do not possess enough knowledge on network effects of DG and are not, therefore, able to perform the needed studies. Hence, DG interconnection studies are presently often bought as an external service because conducting them requires both expertise on DG issues and usage of new simulation programs.

In the authors' opinion, the distribution network companies should be able to plan also the DG interconnections using the tools currently used and, hence, the NIS has to be developed. Also planning procedures for DG interconnection are needed. If DG interconnection studies remain a relatively rare task, using external consultants might be profitable also in future but the DNO should still possess enough knowledge on DG issues and adequate tools to be able to assess the results obtained from consultants.

B. Statistical planning method

The utilization of distribution networks in case of DG interconnection can be substantially improved if the presently used worst case planning principle is replaced with statistical planning. In statistical planning, load flow is calculated for every hour of the year instead of the two worst cases presently used. Different voltage control possibilities (DG active/reactive power control, substation voltage control etc.) can be included in the method. As an output the method gives information on the influence of the DG unit and the selected voltage control methods on the network's operational characteristics (e.g. network losses).

In Nordic NIS systems loads are modeled using hourly load curves that give the customers' average loads and standard deviations for every hour of the year [10]. For statistical planning similar curves are needed also for DG. These are called production curves. The production curves are not accurate in the same way as load curves and can not, therefore, be used for examining the network state on a certain hour. However, they give a good guess on the average operation of the network and can, therefore, be used to compare different planning approaches. [7], [11]

Naturally, also in statistical planning some technical constraints exist, e.g. overvoltages should never occur. Hence, solutions where the network state is unacceptable even for one hour of the year need to be discarded.

C. Development needs for NIS

At present, Nordic NIS systems do not include adequate functionalities for planning of DG interconnection. Connecting DG to a distribution network changes the former radial network to a meshed one. Modern NIS systems manage meshed networks and, therefore, the actual calculation functions do not need to be modified. However, there is a need to develop more accurate models for DG as using the steady-state approach might lead to misleading results. Also models for active voltage level management methods need to be included in the planning tools. The challenge lies in making simple enough models for NIS that still model the DG effects and operation of active voltage level management adequately.

DG is presently modeled in NIS load flow calculations as a negative load with fixed active and reactive powers. With the current DG operational principles this approach is adequate as DG operation is independent of the network state. However, if the unit is, for instance, operated in voltage control mode this approach can not be used because the reactive power output of the unit depends on its terminal voltage. Thus, for voltage level studies DG models should be extended to enable modeling of different reactive and active power control strategies. The models can still be quite simple, e.g. if the DG unit is used in voltage control mode, only the droop-curve describing the dependence of reactive power output on terminal voltage needs to be used instead of constant reactive power.

For studying the fast voltage transients at generator start-up and disconnection only relatively small changes to the DG model need to be made. The fast voltage transient can be simulated by simply running two load flows: with and without the generator. At generator connection, the current to be used is generator start-up current. At generator disconnection, full-load situation is examined.

Active voltage level management methods should be included in NIS as one way to overcome possible voltage problems caused by DG (other ways are passive methods such as increasing the conductor size). The models for different active voltage level management methods can be simplified and do not need to include information on the actual implementation of the algorithms or for instance their delays. A static description is adequate. Modeling the methods that are based on local measurements is quite straightforward: only the dependences between the measured variable and the controlled variable need to be described. Modeling of coordinated methods can require more work depending on the complexity of the voltage control method. The methods based on control rules can be included relatively easily because their modeling is practically similar to modeling of the methods based only on local measurements. Methods based on optimization algorithms require more work because also the optimization algorithm needs to be modeled.

V. The Proposed Planning Procedure

The proposed planning procedure considers voltage level issues and fast voltage transients at generator start-up and disconnection when interconnection of a new DG unit to an existing distribution network is planned (short-term planning). Its operational principle is depicted in Fig. 1. When a real DG interconnection is planned also other voltage quality issues (flicker, harmonics, adverse interactions between voltage regulating devices) and protection issues need to be considered. A planning procedure for protection planning is presented in [12].

The proposed planning procedure consists of three steps and is iterative. The first two steps consider network characteristics that are critical i.e. that need to always remain within determined limits. The third step uses the statistical planning method and is used to compare the effects of different planning approaches.

A. Step 0: Initial data

Before any calculations can be made adequate data on the network and DG unit needs to be available. The network data consists of network component (feeders etc.) data and load data (hourly load curves). Both are stored in NIS databases and are, therefore, always available for the DNO. The generator data is obtained from the potential energy producer. For voltage level studies the generator's reactive power operation needs to be known. For studying the fast voltage transients the generator's start-up current is needed. Naturally, also the generator's location, size and connection arrangement have to be known.

The limiting values for network voltage level and fast voltage transients can be found in [13]. DNOs can also have planning principles of their own and national recommendations can also give restrictions.

B. Step 1: Fast voltage transients

In the first step of the planning procedure, fast voltage transients at generator start-up and disconnection are studied. If a large single generator is connected to a weak distribution network the transient voltage variation at generator connection or disconnection can become the limiting factor instead of voltage rise [2]. Transient voltage variations at generator start-up can be diminished by planning the DG unit properly. Also network reinforcement mitigates the transient voltage variations but active voltage level management methods do not affect them at all. Thus, only passive correction methods (action 1: changes in the DG unit or in the network) are available if the transient voltage variation is too large.

The transient voltage variation is determined by calculating load flow with and without the generator. All the voltage regulating devices need to be in the same state in both calculations (e.g. the tap changer position of the main transformer). If the start-up current of the generator is larger than the rated current, the transient at generator connection is larger than at disconnection. However, if the DG unit consists of multiple generation units they can be connected to the network sequentially which, naturally, diminishes the start-up transient. Disconnection study is made in full-load situation.

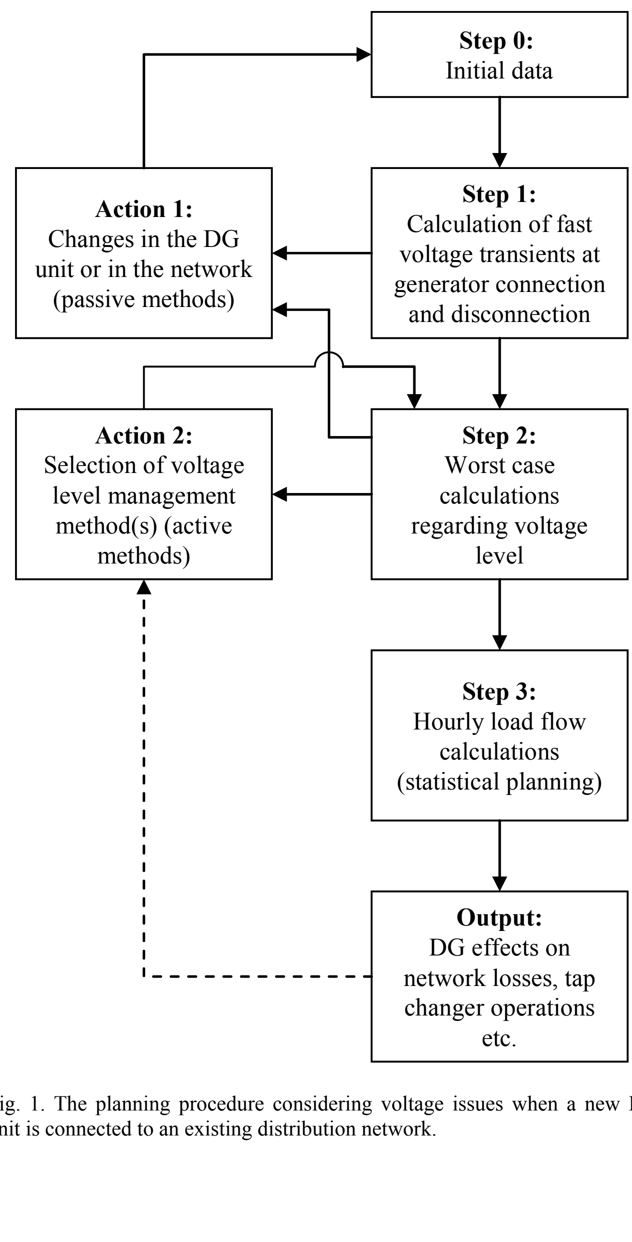

Fig. 1. The planning procedure considering voltage issues when a new DG unit is connected to an existing distribution network.

C. Step 2: Worst case voltage level calculations

If the transient voltage variations at generator connection and disconnection are acceptable, the next step is to consider voltage levels. In step 2 of the planning procedure, worst case calculations regarding distribution network voltage levels are conducted. This step is needed because using statistical planning is reasonable only after it has been verified that the network will operate in an acceptable way in every network state i.e. that overvoltages or undervoltages never occur.

At this step, load flow is calculated in two loading conditions that are maximum load/minimum generation and minimum load/maximum generation. Determining the maximum and minimum loading conditions requires load flow calculations for every hour of the year. Mean powers can not be used for network dimensioning purposes and, therefore, powers that are not exceeded or gone below with some probability are used [11]. The rated power of the DG unit is used as the active power in the maximum generation case and the reactive power is determined from the reactive power characteristics of the unit. With the currently used operational principles, unity power factor is usually used. In the minimum generation case the DG unit is disconnected from the network.

If the voltages remain in an acceptable level in both simulation cases, the DG unit can be interconnected and no actions are needed (in some cases they might, however, be advantageous in the long term). If the voltage limits are, however, exceeded, two alternatives for corrective actions exist. Passive methods (action 1 in Fig. 1) can be used solely in which case the planning procedure does not differ from the currently used planning principles in any way. Also active voltage level management methods (action 2 in Fig. 1) can be taken in use.

After the corrective actions are selected, the worst case calculations are redone and if network operation remains unacceptable, more actions need to be taken.

D. Action 2: Active voltage level management methods

Active voltage level management methods can control all components capable of voltage control. The most commonly used control variables are DG active and reactive power and main transformer tap position (i.e. substation voltage) but also for instance loads could be included in the control. For NIS modeling, the type (continuous, discrete) and control range of each control variable needs to be determined. Also the control algorithm used is needed.

NIS should include a possibility to choose the control variables used in active voltage level management and to define their characteristics. For instance DG active and reactive powers can be either continuous or discrete control variables depending on the characteristics of the DG unit whereas substation voltage is always a discrete variable.

Some commonly used active voltage control algorithms could be included in NIS. These should include at least control of DG active and reactive powers based on local measurements and coordinated control of substation voltage (see for instance [14]). Also a possibility to define own control algorithms would be useful. If active voltage level management is implemented as a part of the distribution management system (DMS), the DMS models can be directly utilized also in NIS because in Nordic countries NIS and DMS are highly integrated.

E. Step 3: Statistical planning

The third step of the control algorithm realizes the statistical planning method introduced in chapter IV.B in which load flow is calculated for every hour of the year using hourly load and production curves [7]. At this step, mean powers of loads are used because statistical planning is not used for network dimensioning but for comparing different alternatives to solve the possible voltage problems.

As an output step 3 gives information on the influence of the DG unit and the selected voltage control methods on the network's operational characteristics. Interesting characteristics are for instance network voltage level, network losses, the number of main transformer tap changer operations, the amount of curtailed production, the amount of controlled reactive power and the amount of energy taken from the transmission network. Also the investment costs are an important factor to be taken into account. The statistical planning can be conducted using different planning approaches and its outputs can be used to choose the best out of these.

F. Practical implementation aspects

The proposed planning procedure includes some features that could be easily automated. All the steps could be implemented as their own functions that would realize the functionality discussed in the preceding chapters.

In step 1, load flows with and without the generator are calculated. The function realizing step 1 should conduct the load flows using the correct generator characteristics i.e. start-up current in connection situation and full-load at disconnection.

In steps 2 and 3, load flow calculations for every hour of the year are conducted. In the current NIS systems these kinds of studies would have to be conducted by hand as only single load flows can be executed at once. As there are 8760 hours in one year, conducting the simulations one by one is not in practice possible. Moreover, even selection of the simulation hour is not possible in all planning systems but load flow can be calculated only for the peak power situation. The processes in steps 2 and 3 could be implemented as their own functions that would carry out the simulations for the whole year and store the needed data for later examination.

G. Further development

In future, the proposed planning procedure will be further developed and its operation in real NIS will be studied. If the planning procedures regarding voltage issues (proposed in this paper) and protection issues (defined in [12]) would be both implemented in NIS, almost all DG interconnection studies could be conducted by the DNO using the currently used planning tool (NIS). The procedure regarding protection issues will be implemented in NIS in project ADINE [15]. Also implementation of the voltage planning procedure would, thus, be interesting.

The proposed planning procedure covers only short-term planning issues regarding DG interconnection. In a real case also the long-term planning issues need to be considered. The DNO should try to predict the future development of the network and make planning decisions based also on the expected future developments and not only on the current situation. For instance, if it is expected that a lot of DG will be constructed near the site where the DG unit to be interconnected is located, building a dedicated feeder for the unit might be profitable even though the first unit could be connected also to an existing feeder with smaller costs. In future, the proposed planning procedure will be developed to take also the long-term planning aspects into account.

VI. Conclusions

The penetration level of distributed generation is constantly increasing which changes the operation of distribution networks in many ways. However, the distribution networks are still mainly operated and planned without consideration of the control possibilities of DG.

In this paper, the effect of DG on distribution network short-term planning regarding voltage issues was considered. The introduction of active voltage level management methods to distribution networks was discussed and their effect on network planning reviewed. Also development needs for the distribution network planning tools currently used were proposed. Finally a planning procedure regarding voltage issues when interconnection of a new DG unit to an existing distribution network is planned was proposed. The proposed planning procedure is such that it can be implemented in the currently used network planning tools relatively easily.

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VIII. Biographies

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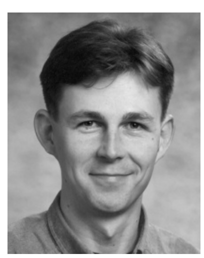

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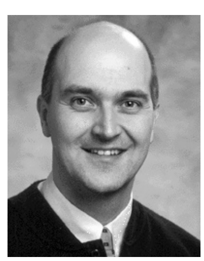

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