ABSTRACT
The paper investigates the effects and potential of distributed generation (DG) on the operation of weak distribution networks. It focuses on the development of a new method to increase the integration capacity of DG in an existing network. The paper considers voltage issues and the load transfer capability of distribution network including windmills. The proposed method is based on ring operation of the distribution network and control of windmill active and reactive power. The applicability of the proposed method is tested with load-flow simulations on a real life distribution network and planned windmills. The studies have proved the capability of the proposed method to increase the integration capacity of DG units without major network investments.

1. INTRODUCTION
The fast propagation of DG at distribution network will have a major influence on distribution networks. This implies many new factors which are not usually considered. The experience of distribution network companies of these topics is so far slight. However, these topics will become a part of normal operation, not just special cases. This will necessitate the existing networks and operation methods in order to consider DG in the distribution network.

The voltage drop of a medium voltage network has been one of the main planning issues in rural distribution networks in Finland [1]. There are networks where the length of 20 kV feeders is as much as 100 kilometers and the demand in sparsely populated areas is very low. The impedance of these feeders is remarkably high. If a large DG unit is installed far from a primary substation, voltage rise problems may occur during low demand periods [2]. The voltage rise problem is acute in coastal and skerries areas due to wind power installations. The integration capacity of DG units on weak distribution network is limited by the voltage rise problem.

The propagation of DG may be seen either as a change of load curves when production replaces a part of the load or as an addition of production units to the distribution network. Some changes in the structure of distribution network are needed due to DG. The structure and operating principle of the distribution network will move towards a distribution system (active distribution network) with several active components along the network. Meshed operation of distribution network may allow more enhanced control and operation principles than today. These issues at least should be taken into account in most potential areas of DG in long-term planning studies [2].

2. PROPOSED METHOD
Medium voltage networks are normally operated radially although they are constructed meshed for reasons of reliability. Typically a rural overhead medium voltage network includes remotely controlled disconnectors at important nodes where radial feeders may be connected.

The proposed method is based on meshed operation of distribution network and control of DG unit active and reactive power. The meshed operation of the distribution network will divide power flows to the feeders more evenly than radial operation, losses will be minimised and voltage rise due to DG can be limited.

The integration capacity of a DG unit may also be increased by controlling the active and reactive power of the DG unit. At least for the case studied the control of the DG unit may be based on terminal voltage. The consumption of reactive power is used to limit the voltage rise problem when necessary. If this is not enough, the production of active power must also be limited. This possibility to control the integration capacity should be considered in the interconnection contract. The control of DG unit may benefit both parties when network investments are avoided. The proposed method is quite different from the “minimum load maximum production” planning principle because the integration capacity is flexible and dependent on network conditions.

In ring operation the protection of feeders may be based on existing protection devices, if extra delay is allowed for in the protection [3]. The proposed protection solution is straightforward and economically attractive. When a fault occurs the task is to indicate and locate the faulty ring. When the ring is opened the conventional feeder protection may operate. The amount of load interrupted due to the fault is the same as in a radially operated network. The proposed solution requires some changes in the feeder terminals software and replacement of disconnectors with fast switch-disconnectors at remotely controlled nodes.

3. TEST RESULTS
3.1 Test system
The method was tested with a case study on a distribution network of Fortum Sähkönsiirto Oy in south-west Finland including windmills in archipelago skerries. The distribution network in this area is relatively weak, because...
the length of medium voltage lines (20 kV) is long and the amount of load is small. There are also considerable restrictions for network expansions due to environmental reasons. The calculations are based on real hourly load curves and network data.

The network studied (Figure 1) consists of one HV/MV substation, which feeds two MV feeders (Kasnäs and Byholmen). The other short MV feeders of the substation were not included in the network model used. Calculations were carried out with an equivalent network, where some of the branch conductors of the MV network are omitted. In the PowerWorld [4] case the constant current loads were located in the middle of a certain part of the feeder. These loads were summed up from that particular part of the feeder (based on different customer groups). For the estimation of load demand customers’ annual unit consumptions and customer group based load curves are remarkable advantage compared to radial operation of feeders. The network transfer capability for the windmill studied may be increased from 1.1 MW to 1.9 MW by operating the network as a ring in the minimum load case (Table 1). The network transfer capability increases as a function of the Kasnäs-feeder load. The network transfer capability during maximum load condition is 2.0 MW and 2.9 MW for radial and ring operated networks respectively.

The voltage profile of the radial network is very different at the Kasnäs- and Byholmen feeders. The voltage of the Kasnäs feeder is very high in all cases and at the same time the voltage of the Byholmen feeder is determined by the loading of the feeder. The control of voltage at the primary substation must be a compromise between these two competing tasks. However, the ring operation of the network may be used to balance the voltage profile at these feeders. The lowest voltage appears at the primary substation.

![Figure 1. Study case “minimum load of Kasnäs feeder and maximum production of wind mill”](image)

Table 1. Network transfer capabilities.

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The network transfer capability may be determined in this case by the Kasnäs feeder load in planning (Table 1) and by windmill terminal voltage in operation. In order to calculate the amount of electricity not produced due to output power limitations a certain load duration curve (Figure 3) must be assumed. The output power of the windmills (Figure 2) is compared to the network transfer capability (Table 1) in different load conditions taken from the load duration curve. The amount of electricity not produced is the difference between the output and the capability. If the real load and wind curves are known, more precise results may be calculated than with the load duration curve and stochastic wind.

Figure 2. Distribution of annual wind speed and power output for all units.

![Figure 2](image2.png)

Figure 3. Load duration curves.

The amounts of electricity not produced are presented in Figures 4 and 5 in radial and ring operation modes for three different load duration curves and integration capacities. The distribution network operation mode has a strong influence on the amount of electricity not produced. The influence of load duration curve, however, is minor. The difference in the amount of electricity not produced between operation modes with 3 MW integration capacity is about 1200 MWh or 27400 € (using year 2001 monthly average of Nordpool elspot-price, 22.83 €/MWh). The difference in the amount of electricity not produced between 3 and 2.25 MW integration capacities is about 1000 and 300 MWh with radial and ring operation respectively. It is also interesting to note that the amount of electricity not produced is extremely low when the integration capacity is 1.5 MW in radial operation. When this is compared to the network transfer capability (1120 MW) determined by the “minimum load maximum production” planning principle, there seems to be a great opportunity to increase wind power production by changing the distribution network planning principle.

![Figure 4](image4.png)

Figure 4. Electricity not produced in radial network for three different load duration curves and integration capacities.

![Figure 5](image5.png)

Figure 5. Electricity not produced in ring operation for three different load duration curves and integration capacities.

4. DISCUSSION

The proposed method has been proved to increase the integration capacity of windmills on a weak distribution network. The requirements of the method are a possibility to operate the network as a ring with fast switch-disconnector and to control the active and reactive power of the windmill. No centralised control system or operator
interaction is needed to operate the network in this case. The integration capacity of windmills may be concluded by the windmill terminal voltage.

The distribution network planning and calculation of windmill integration capacity based on local wind statistics gives more flexibility for planning decisions compared to the “minimum load maximum production” planning principle. The decision on integration capacity may also be easily converted into financial terms. The planning decisions of the distribution network and wind power production may be based on calculations of network transfer capabilities and electricity not produced with different amounts of integration capacities, capacity factors, wind statistics, load duration curves, etc.

There are, however, a few open questions. One major question is the influence of the method on power quality. Although the number of interruptions would be the same for the whole network, the number and duration of interruptions seen from the customer side may increase. The reliability of fast switch-disconnector and protective devices also has a central role for the safety and reliability of the whole network. Voltage quality problems such as voltage dips, flicker and harmonics may also disturb a larger area than previously.

Another question is what happens when the ring of two or more feeders is switched to radial operation. There exists a danger of over-voltages at the windmill terminals if the control of the windmill is not fast enough or the switching operation is not co-ordinated with windmill operation. At the same time the voltages of other switched feeders would drop decisively. In any case there would be large and sudden changes in the voltage levels due to switching. This may stress the network operator during storms due to repeated switching operations. Thus it may be easier to operate the network in the radial operation mode during periods of repeated switching operations. In normal operation the voltage control is more precise and the voltage level is closer to nominal with the proposed method than with traditional radial operation.

The research of the method proposed should also extended to more complex systems. It is not certain that the method proposed would work properly in cases with several windmills at different locations, with different production types or with more complicated network structure. There is also a potential to improve the voltage / reactive power control of the system and enhance the network transfer capability in this way.

5. CONCLUSIONS

The proposed method based on the ring operation of a distribution network and control of active and reactive power of a windmill has been tested with a real life distribution network and planned windmills. The requirements of the method are a possibility to operate the network as a ring with fast switch-disconnector and to control the active and reactive power of the windmill. No centralised control system or operator interaction is needed to operate the network in this case. The integration capacity of windmills may be concluded by the windmill terminal voltage. The integration capacity and network transfer capability can be increased by the use of the proposed method in the weak distribution network studied.

The proposed method allows more flexibility in distribution network and windmill planning than conventional the “minimum load maximum production” planning principle. The advantages of ring operation compared to radial operation may be evaluated by comparing initial data of the analysis. In the case studied the electricity not produced with 3 MW integrated capacity respectively is 4.5 % and 19.8 % of annual energy production capability when the network is operated in ring and radial operation mode.

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REFERENCES