“Connection of Distributed Energy Generation Units in the Distribution Network and Grid"

Project Acronym: CODGUNet

Final report

Edited by

Sauli Jäntti, CODGUNet project group

Oy Merinova Ab, 30th of September 2003

Sauli Jäntti
Oy Merinova Ab
Yrittäjänkatu 17, Vaasa Airport Park
PL 810
65101 Vaasa
Finland

CODGUNet

COnnection of Distributed energy Generation Units in the Distribution Network and Grid

Foreword

The CODGUNet project is a co-operation project between 4 Nordic countries. The financing of the work done in each country is based on a group of organizations and companies in the specific country. The coordinator would like to thank all partners for a good co-operation.

The responsible coordinator has been Oy Merinova Ab and the main partners participating in the execution VTT Processes, University of Vaasa, Research Center Technobothnia, SINTEF, Vattenfall Utveckling (VUAB), LTH, Elforsk and Eltra. The project has been supported by the project partners, Electric Power Pool, the Nordic energy associations and companies like PVO and Wärtsilä Finland Oy.

Steering committee (SC) in the project has been formed from the funding organisations: Finergy, Elforsk, STEM, TEKES, EBL-Kompetanse and Eltra. Project manager has been Sauli Jäntti and chairman of SC Kari Luoma from Merinova Oy, Vaasa, Finland.

Summary

The current penetration of Distributed Generation (DG) in Finland, Sweden and Norway is very low compared to many other countries. There is power production in small units, but these plants are most often owned and operated by power companies. Denmark, instead, has a lot of distributed generation, not only wind power.

Typical for DG is a great number of production units, which are small in size (from 10 kW up to about 10-20 MW) and located near the consumption of energy. These units produce often electricity for a certain end-user. In CODGUNet project DG does mean generation connected to the distribution network or on the customer side of the meter, size not more than 20 MW and 24 kV voltage levels.

Connection of a lot of small-distributed power generation units to the distribution network will have consequences related both to technological, economic and legal matters. Subsidies to renewable energy sources and technological development are considered as the most important drivers of DG.

Because the share of DG is expected to increase, there is a need for technical, commercial and interconnection process related rules and recommendations. Many technical issues are difficult, so it will probably take several years to have covering international recommendations of connecting consumers into the network.

Existing experience from countries with a lot of DG should be utilised when developing national or company wide instructions. Benchmarking for the best practices is a good start to develop rules and recommendations, as long as international standards are non-existent. Most of the existing regulations and requirements are only covering directly coupled rotating machines but not the DG units that are connected to the grid through a power electronic converter. The most common and prospective technologies, which are used for distributed generation, are presented in the report.

Various technical aspects relating to the network connection were analysed mainly by applying simulations with a computer model of a distribution network and DG units connected to it. The applied simulation tool was PSCAD/ETMDC, which is a commercial electromagnetic transient simulation program. The focus was on different technical solutions applied in network connection and in their performance with respect to power quality and network protection. All the tasks applied simulations with a computer model of a distribution network and DG units connected to it.

According to the simulations made, the major problem with all types of DG units seems to be that the short circuit faults on adjacent feeders may cause unnecessary tripping of the power plant. The reason for this is that in a relatively weak network the voltage drops dramatically in all feeders when there is a fault in one feeder.

One result of this study is a set of simulation models that can be applied in further studies. These models have been applied in simulations that also provide information about different technical issues relating to the power quality as well as the system protection considering the increasing amount of DG in distribution networks.

Connecting a lot of small power production units to the distribution network will inevitably have some sort of effect on both the distribution network and, if the share of DG becomes large enough, the high voltage transmission network. DG plays a special role in the power balance, since it to a great extent is neither dispatchable like conventional generating units nor predictable like the load.

CODGUNet final report

1. Introduction

The results from the Nordic co-operation project "*Connection of Distributed Energy Generation Units in the Distribution Network and Grid*" (acronym: “CODGUNet”) are presented in this final report. In CODGUNet project the main aim is to identify and specify issues related to a more common use of distributed generation (DG) in the network. Focus of the project has been the network connection and the requirements to the distribution system and generation unit equipment set by network control and operation.

1.1 Project description

Different kinds of distributed energy generation technologies are developed world wide with large R&D budgets. Typical for these technologies are a great number of production units, which are small in size (from 10 kW up to about 10-20 MW) and located near the consumption of energy. These units produce often electricity for a certain end-user. In CODGUNet project DG does mean generation connected to the distribution network or on the customer side of the meter, size not more than 20 MW and 24 kV voltage levels. One main idea of these units is that while the consumption of the end-user increases, additional electricity is taken from the distribution network and when the consumption decreases, the generation unit may provide electricity to the network.

From distributed generation technologies especially wind power has already been largely applied, but also other technologies, such as gas, diesel and biomass fired micro and mini turbines and CHP devices, solar cell systems etc., are in the phase of commercialisation.

Flexibility for the user and environmental aspects are often mentioned as the benefits of distributed energy generation. Until now, the competitiveness of distributed energy generation has been poor in electricity generation. Despite of that, many companies and interest groups strongly believe the future of distributed energy generation. For some technologies the improvement of competitiveness could be based on serial production of devices, for some on the economical benefits given by society due to environmental reasons. For most of the technologies the decisive factor for the commercialisation is, whether the distribution costs can be reduced from the price of produced electricity.

Connection of lot of small-distributed power generation units to the distribution network will have consequences related both to technological and legal matters. When distributed units become more common and the unit sizes increase, connection and disconnection effects on the net increase. The network and grid companies are especially worried on the variation of electricity generation causing problems in network balance and possible need for reserve capacity, and on the effect of different kinds of generators on the quality of electricity.

The quality of electricity has become critical by many customers, especially when it comes to changes of voltage (peaks, sags). Quality indexes and standards for electricity products are being developed. The effects of distributed electricity generation on the quality of electricity are thus more and more actual.

With the presently available simulation models and tools these effects can be evaluated more economically and easily than earlier. It is probably possible to develop a procedure with which the effects of distributed generation on the net can be calculated already in the planning phase, which could help to make proper decisions.

The economic questions are related to the tariffs, costs of connection and pricing of transmission of electricity in the trade between the network company and the generator. The expectations on these aspects are very different by the distribution network companies, the developers of distributed generation technologies and potential customers to distributed technologies. The technological and commercial questions need to be specified to proceed in the discussion.

The development of the distributed generation technologies and the positive general attitude (among politicians and people) on these technologies in many countries can change the situation and role of the DG in energy production. It is obvious that the connection and disconnection effects need to be specified and solved and the regulation and agreements related to the distributed generation in the network need to be re-evaluated.

1.2 Objectives and scopes

The objectives of the GODGUNet project have been:

- To identify and specify the issues (problems and possibilities) related to more common use of distributed generation in the network, which are of interest for the Nordic electricity utilities for their future planning. The main topics are such as quality of electricity, control system, protection, electrical safety, legal matters, connection terms, costs and tariffs.

- To provide information on technical issues related to the connection of DG in the distribution network and grid and make easier to connect/increase DG for network owners.

- To collect and to evaluate the available information from different countries (Nordic countries, Germany, The Netherlands, UK) on present and planned regulations, rules and the experiences gained by the network companies.

- To develop solutions to the technological issues such as the quality of electricity with simulation tools and other calculation methods. The case studies are specified in particular WP plans.

- To utilize DG for improving reliability of the network and network business.

- To be a step for knowledge network between specialists of electricity network and a pilot project for certain Nordic co-operation projects.

The selected generation technologies, protection and communication solutions, case study examples, network parameters and power quality demands have reflect the Nordic industrial praxis striving to fulfil also the becoming European demands.

1.3 Execution of project

Preliminary part of the project lasted app. 9 months and technological part 2 years. The research work was made partly parallel.

The main topics for the WP:s are specified below. In all WP:s there was an exact project plan for realising the WP.

The project is divided into the following independent work packages (WP's) that have been numbered according to the Nordic project.

Table 1. Work Packages in CODGUNet project

Work Package	Work package title	Work package coordinator	Participants
WP 1	General overview on the issues related to the connection of DG in the network	VTT Processes Risto Komulainen	VTT Processes
WP 2	Present status of DG in Nordic countries (possibly also Germany, Netherlands and UK)	VTT Processes Risto Komulainen	VTT Processes SINTEF
WP 3	Aspects of different distributed generation technologies	VUAB Saga Häggmark	VUAB Technobothnia Elforsk
WP 4	Network connection of different types of distributed energy generations, technological analyses	Technobothnia Kimmo Kauhaniemi	Technobothnia SINTEF LTH
WP 5	Effects on power system	SINTEF Anngjerd Pleym	SINTEF VUAB, LTH
WP 6	Analysis of large scale DG for network business	Eltra John Eli Nielsen	VUAB Eltra
WP 7	Summary and proposal for further studies Project management	Merinova Sauli Jäntti	Merinova Actors of WP's
WP 8	Dissemination of results	Merinova Sauli Jäntti	Merinova Elforsk EBL-Kompetanse

Project started on 11.2.2002 in Stockholm and will be finalized in the CODGUNet seminar on 25-26th of November in Oslo, Norway.

2. General overview on the issues related to the connection of DG in the network, WP1

In WP1 the main task was to identify the problems and opportunities related to the most common issues in grid connection and operation. The survey based on a questionnaire study to Nordic network companies. A total of 44 answers were received, so the results give a rather good overview on the current opinions. The collected information can be used when the network companies, producers and authorities will make future plans and strategies for DG. One of the most valuable results of the survey was the identification of major barriers to DG, seen by network companies. The results gave also input for WP 3 in the project, and they can be utilised for European projects where VTT Processes is participating, bringing the Nordic view to the EU-projects.

2.1 Definition of Distributed Generation (DG)

The definition was asked in order to find out the current conception of DG of network companies. As an example, the definition given by CIGRE working group was given, and it was generally well accepted both in Finland, Sweden and Denmark.

The definition of DG given by Working Group 37-23 of CIGRE is
- not centrally planned
- today not centrally dispatched
- usually connected to the distribution network
- smaller than 50-100 MW

Many people think that the power limit could be smaller than 50 MW, e.g. 10 MW. Because different forms of DG have very different characteristics, e.g. PV and CHP, further definition is recommended when speaking about DG.

2.2 Generation technologies

The prevalence of different DG technologies was roughly estimated using the following question: ”Do you have the following types of DG units connected in your network? or “Do you have the following type of DG in your production?” The percentage of ”yes” answers is shown in Figure 1.

Figure 1 presents the comparison between Denmark, Finland and Sweden.

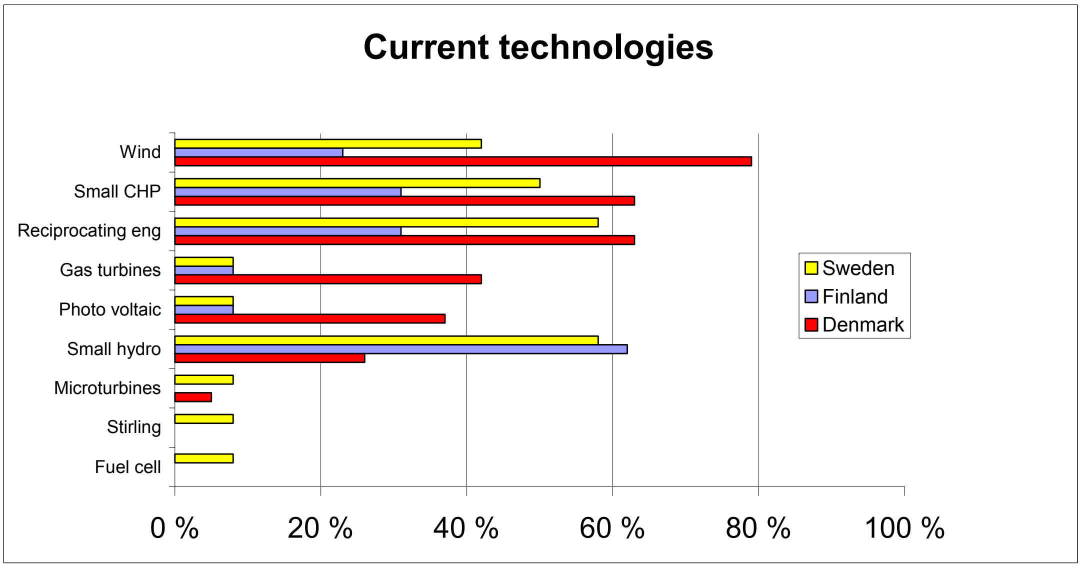


Figure 1. The comparison of the prevalence of DG technologies in Denmark, Finland and Sweden.

Remarks:

- Most of the units are owned by utilities. This is true to small-scale power plants also in Norway.
- Some of the power plants reported are probably reserve power (diesel, gas turbine) for peak clipping and maintenance/emergency purposes.

2.3 Identification of problems and opportunities related to the most common issues in grid connection and operation

At present, DG seems not to be regarded very beneficial. Only ”good total efficiency (especially with CHP)” is almost generally recognised to be a significant benefit, and this question is not very relevant when thinking of the interests of network companies. Interestingly very few companies think that they could defer network reinforcement with help of DG. Figure 2 presents a graph created from the answers.

Figure 3 illustrates that network companies believe there are several technical challenges to wider implementation of DG. Protection issues are regarded problematic almost unanimously. One interesting finding is, that according to the study the Danes, who have more experience with DG than the others, see DG more problematic.

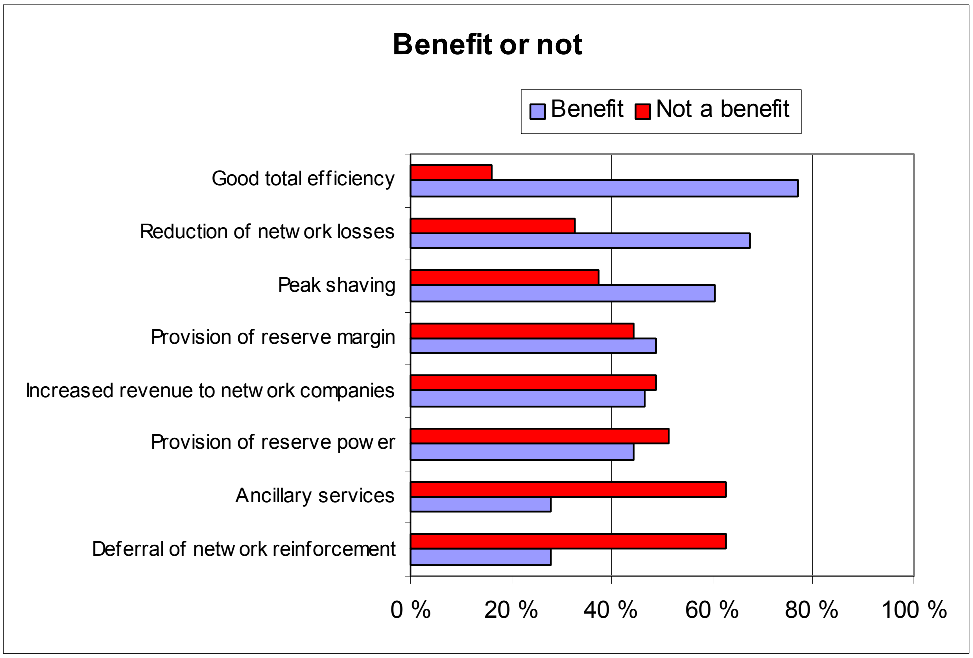


Figure 2. Benefits of DG.

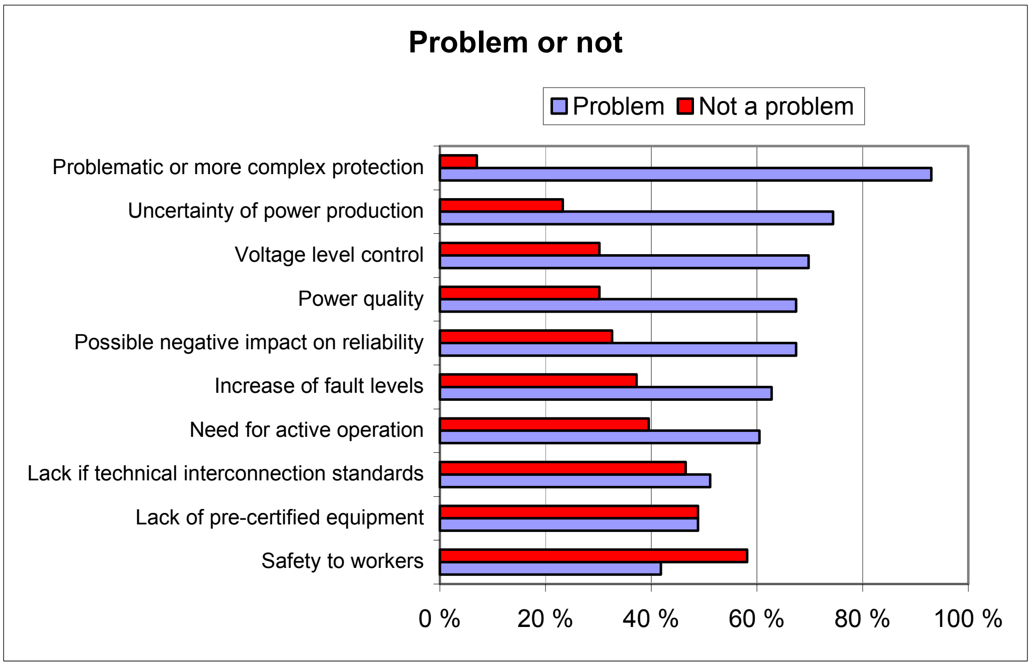


Figure 3. Problems related to DG.

Figure 4 illustrates, which of the suggested items were considered as drivers and which not. The conclusion is that subsidies to renewable energy sources and technological development are the most important drivers.

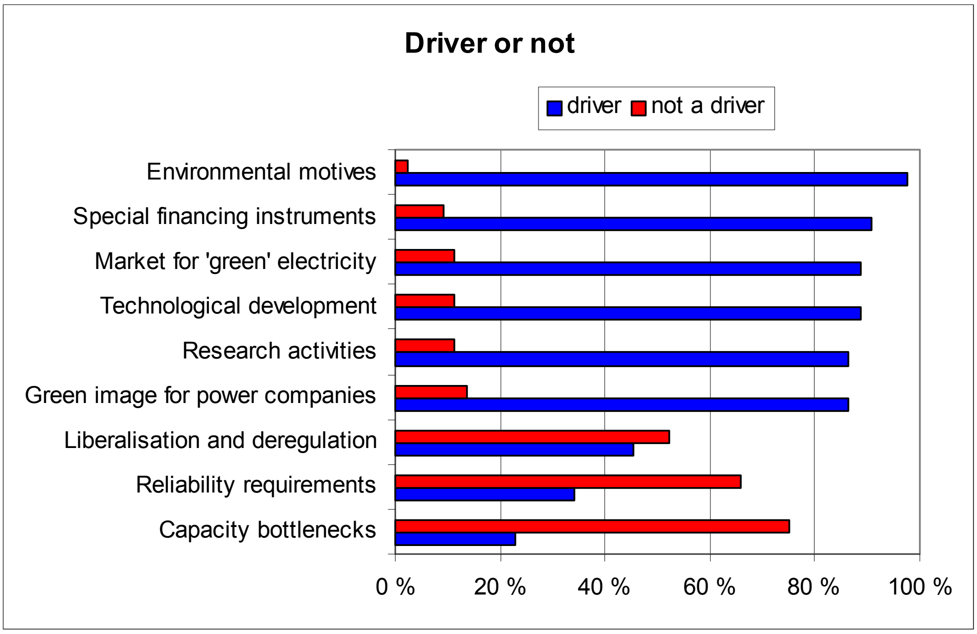


Figure 4. Drivers / not drivers / DK, FI, SWE.

2.4 Conclusions

The current penetration of DG in Finland, Sweden and Norway seems to be very low. There is power production in small units, but these plants are most often owned and operated by power companies. Denmark, instead, has a lot of distributed generation, not only wind power. Subsidies to renewable energy sources and technological development are considered as the most important drivers of DG.

Because the share of DG in power production is so low, network companies in Finland and Sweden don’t have much experience in the area. From their point of view, real benefits of DG are difficult to recognize. Penetration of DG in Norway is also small, and the experience with DG accordingly low, just as for Finland and Sweden.

The companies are, however, to some extent aware of the possible technical problems that DG may cause, e.g.

- problematic or more complex protection,
- uncertainty of power production,
- voltage level control problems,
- power quality,
- reduced reliability,
- increase of fault levels and
- need of active operation.

Denmark has a lot more experience of DG, but the attitudes of the Danish network companies don’t seem to be very positive towards DG. In fact, the survey indicated that Danish network companies’ see slightly less benefits and more problems than Finnish and Swedish companies.

Business related and interconnection process related barriers to wider implementation of DG were not as obvious as most of the above mentioned possible technical barriers. The uncertainty of future regulatory environment was considered as the most significant barrier, while there were different opinions on other possible barriers.

Finnish, Swedish and Norwegian network companies expect that network design and network management and operation are going to be more complex due to increasing share of DG, and the Danish answers to the survey affirm this viewpoint.

3. Present status of DG in Nordic and other valid countries, existing recommendations, WP 2

In WP 2 the main task was to collect information on recommendations, instructions and guidelines in different countries and experience of network companies on the functionality of the rules. The focus has been in the Nordic countries. The results have given input for WP 4 and WP 5. These results can also be used for European project where VTT Processes is participating, so that results from the EU- project will be to the maximum extent in a harmony with the Nordic practice.

3.1 Legislation

In each country there are several laws, statutes or decrees that affect DG. The legislative regulations can be classified into the following categories:
- Electricity market,
- Electrical safety, and
- Environmental issues.

Laws in different countries have naturally national characteristics. EU will probably try harmonizing legislative issues, which will have to be taken into account in most Nordic Countries. One significant step in this direction is Directive 2001/77/EC, so-called RES-E Directive. It is the EC directive on the promotion of electricity produced from renewable electricity sources in the internal electricity market requires the network operators to set up and publish their standard rules relating to the bearing of costs and grid reinforcements, which are necessary in order to integrate new procedures feeding electricity produced from RES into the interconnected grid. The directive shall put into legal practice by 27th of October 2003.

3.2 Existing national and company wide recommendations

Today there are some local recommendations in the Nordic countries, which, in principle, have common principles with local adaptations. Many of them discuss wind power. Wind power units are becoming larger and larger (2 ...4,5 MW) which drives these units out of national recommendation scopes in the future, if the recommendations are not updated.

For the time being there has not been an urgent need for recommendations dealing with other production technologies, because the penetration of DG, especially not owned by utilities, has been very low. The situation seems to be changing due to development of technologies and governmental subsidies to renewals.

3.3 Need of rules and recommendations

Because the share of DG is expected to increase, there is a need for technical, commercial and interconnection process related rules and recommendations. Many technical issues are difficult, and it will probably take several years to have covering international recommendations in the same way as when connecting consumers into the network.

In the open energy market companies are operating in several countries. International activities would be easier if the rules were the same. Thus it is important that the Nordic countries will bring their needs and requirements into the European standardisation process. This way we can ensure that the output will be in a harmony with our needs. The goal could be to have comprehensive international recommendations in the same way as when connecting consumers into the network.

Existing experience from countries with a lot of DG should be utilised when developing national or company wide instructions. Benchmarking for the best practices is a good start to develop rules and recommendations, as long as international standards are non-existent. Most of the existing regulations and requirements are only covering directly coupled rotating machines and not DG units that are connected to the grid through a power electronic converter.

Recommendations must often be adjusted to local practices, legislation and electricity market. This is especially true with the commercial issues of grid connection. In most countries the success of DG lies so far mainly on governmental subsidies, and only a few countries have liberalised their electricity market.

Topics where recommendations are possibly needed have been listed below.

- Interconnection process
  - Procedures: technical, commercial, environmental
  - Charges
  - Responsibilities
  - Information exchange between network operator and DG developer.
- Testing: commissioning and maintenance testing
- Tarifs: Feed-in tarifs
- Metering
- Protection and safety
  - Loss-of-mains protection of various types of DG
  - Relay settings
  - The impact of autoreclosing on protection of DG and the impact of DG on autoreclosing
  - Island mode operation
- Power quality
- Voltage control
- Reliability – perhaps not a recommendation, but a study how DG will influence on network reliability:
  - complex network – less reliable?
  - prevention of autoreclosing
  - unintended operation of protection
  - impact on restoration times
  - emergency power
- Control and operation
- Requirements to inverter-based interconnection – many of the new DG technologies can be connected to the distribution network with inverter technology.

4. Aspects of different distributed generation technologies, WP 3

4.1 Introduction

The goals for WP3 have been to supply the other CODGUNet work packages with characteristics of different DG technologies and to identify the barriers for extensive introduction of DG. Only existing information on characteristics was collected in this WP. It was decided that various aspects of DG implementation should only be formulated and described but not analysed. Other WP's should perform relevant analyses necessary for the project results.

The following objectives were given priority in order to reach the goals of WP3:

- Description of characteristics of different DG technologies from the networks point of view such as power quality, production capabilities, economy, technical solutions etc.

- Description of obstacles, barriers and opportunities when implementing DG.

Key results were:

- Information on technical and economic aspects of different forms of generation

- Characterisation of electrical properties

- Barrier description

- Basic definitions for WP4

The most common and prospective technologies, which are used for distributed generation, are presented in WP3, which summarises the main characteristics of different DG technologies, describes technical solutions for their network connection and the possible impact from DG on network operation is also discussed. WP3 also contains a brief discussion concerning environmental issues for each DG technology and economic aspects regarding e.g. investment costs. Finally the barriers and opportunities associated with utilisation of each technology are highlighted and also an overview over existing energy storage technologies.

4.2 Characterisation of electrical properties

4.2.1 Distributed Generation

Wind power

Wind turbines have developed rapidly from unit sizes below 20 kW (fixed speed, stall control) in the seventies to the present sizes of up to 4 MW. In order to withstand the mechanical stress, most wind turbines above 1.0 MW are equipped with variable speed system incorporating power electronics in combination with pitch control. If advanced enough these systems are capable of decoupled active and reactive power control on the grid side and of decoupled torque and generator excitation control on the generator side.

Single wind power units are normally connected to the distribution grid 10/20 kV. The present trend though is that wind power is being located off shore in larger parks that are connected to higher voltage levels (even to the transmission system). For such large installations the transmission system owners in several European nations recently have written new connection regulations that imply e.g. that the wind turbines shall survive prolonged periods with low grid voltage and in some cases even frequency support is a requirement. This is a challenge that requires new concepts to be designed by the wind turbine manufacturers and will definitely rule out the uncontrolled systems. An uncontrolled wind turbine may however be used if a DC connection system is used where the rectifier is capable of controlling the generator speed and thereby allowing generator speed to vary and thus controlling the mechanical stress of the turbine.

Reciprocating engines

Reciprocating engines, developed more than 100 years ago, were the first among DG technologies. Both Otto and Diesel cycle engines have gained widespread acceptance in almost every sector of the economy. They are used on many scales, ranging from small units of 1 kVA to large several tens of MW power plants.

Smaller engines are primarily designed for transportation and can usually be converted to power generation with little modification. Larger engines are most frequently designed for power generation, mechanical drive, or marine propulsion. Reciprocating engines are usually fuelled by diesel or natural gas, with varying emission outputs. Reciprocating engines are currently available from many manufacturers in all size ranges. They are typically used for either continuous power or backup emergency power. Co-generation configurations are available with heat recovery from the gaseous exhaust. Heat is also recovered from the cooling water and the lubrication oil.

Photovoltaic

Photovoltaic (PV) systems convert the sunlight directly to electricity. PV-systems produce direct current and a power electronic converter is necessary for connection the PV unit to the grid. PV technology is well established and widely used for power supplies to sites remote from the distribution network. Photovoltaic systems are commonly known as solar panels. PV solar panels are made up of discrete cells that convert light radiation into electricity connected in series or in parallel.

Micro-turbines

Distributed generation with micro-turbines is a new and fast growing business. The market is worldwide. If there is a demand of power there is a possible market for distributed generation with micro-turbines. In the Nordic countries distributed generation with micro-turbines are expected to be operated in combined heat and power mode. The reason for this is that the cost of power is close to the cost of heat. For each produced kilowatt-hour of electricity the micro-turbines will produce two kilowatt-hour of heat. With inexpensive fuels the power could be produced without taking care of the heat. Example of inexpensive fuel is landfill gas. The micro-turbines could also be used for peak shaving stand-by power, capacity addition, stand-alone generation and others. In the case of capacity addition the short time from decision and order to operation will be a heavy argument for DG with micro-turbines in the future.

Fuel cells

Fuel cells generate power through the electrochemical reaction between hydrogen and oxygen. The conversion is highly efficient and leaves only water and heat as by-products, which is the main motivation for the increasing interest in the technology. For DG purposes fuel cells from 0,5 kW and upward are developed. Proposed applications include continuous generation, cogeneration or power only, remote power, backup power etc. As hydrogen usually not is directly available most DG fuel cells are fuelled with hydrogen, which is processed from available hydrocarbons, e.g. natural gas. Normally the fuel processing is an integral part of the fuel cell system.

As of today there is only one fuel cell system that can be seen as at least semi-commercial. This is a 200 kW phosphoric acid fuel cell of which some 200 units have been sold worldwide. On the other hand there are numerous activities on-going with the objective of putting fuel cell systems on the market in the 2005-2010 time frame. While the development covers the entire range up to 1 MW an emphasis can be seen on so called residential fuel cells. Residential fuel cells are systems in the 0,5-10 kW range that are targeted against single or multi-family houses, small enterprises etc and planned to be produced in very large numbers.

Stirling engines

Stirling engines are powered by the expansion of a gas when heated followed by the compression of the gas when cooled. The gasses used inside a Stirling engine never leave the engine. There are no exhaust valves that vent high-pressure gasses, as in a gasoline or diesel engine, and there are no explosions taking place. Because of this, Stirling engines are very quiet.

The Stirling cycle uses an external heat source, which could be anything from gasoline to solar energy to the heat produced by mouldering plants. The best working gas in a Stirling engine is hydrogen. Helium is working nearly as well as the hydrogen, but it is much more expensive. The cheapest alternative is air, but it has properties inferior to the other two gases.

In spite of its long history, Stirling engines are still mostly used in some very specialised applications, as auxiliary power generators, where quiet operation is important.

4.2.2 Energy storage

The demand for electricity is seldom constant over time. Excess generating capacity available during periods of low demand can be used to charge an energy storage device. The stored energy can then be used to provide electricity during periods of high demand, helping to serve power system loads during these times.

The share of renewable electricity production is expected to increase by extension of intermittent generation. The extension of wind power plants will accentuate the need of electric energy storage. Power production variations in hours, days and even longer periods require some kind of adjustment. Use of energy storage can also reduce the need of investments in reinforcements in the network and grid.

From the network owners perspective there are several positive aspects with distributed generation in combination with energy storage. Increased network utilisation ratio, availability, transfer capacity and power quality are some examples. By reducing peak demands for power generation and offering greater flexibility among power supply options (including renewable), energy storage systems not only can help utilities by improving their cost-effectiveness, reliability, power quality and efficiency, they also may reduce the environmental impact of electricity generation, transmission, and distribution.

Benefits of energy storage:

- provide electricity during periods of high demand
- reduces the need of investments in reinforcements
- increased network utilisation ratio, availability, transfer capacity, power quality
- improve efficiency and reliability of the electric utility system
- reduce the environmental impact of electricity generation, transmission and distribution

Energy storage technologies:

- Batteries
- CAES (Compressed Air Energy Storage)
- Flywheels
- Pumped Hydro
- Supercapacitors
- SMES (Superconducting Magnetic Energy Storage)

4.3 Information on technical and economic aspects of different forms of DG generation

4.3.1 Technical aspects

There are different ways to classify the different DG technologies. The most important are the following criteria:

- Location: energy based or customer based
- Controllability and availability
- Energy conversion system: rotating machines or static inverters.

Energy based sites with hydro, wind, solar, biomass, geothermal, waves and other energy sources, as a rule, are situated far from the load centres. Therefore, the problems related to the network connection are not an exception.

The CHP technologies such as micro-turbines, reciprocating engines, Stirling engines as well as fuel cells and photovoltaic can be placed at the customer site. The important condition is availability of fuel infrastructure for the DG units.

Another important feature of various DG technologies is their availability and as a result the possibility to control power output. Thus, wind and solar energy are non-controllable and uncertain. Furthermore, the experience shows that days without wind and sun often correlate with peak load demand. Therefore, it can be concluded that these technologies have no or little installed capacity value, since the reserve power units are needed in order to provide power supply when there is no wind or sun.

Most of the new DG technologies are connected to the network via an electronic interface. The class of rotating machines is represented by reciprocating engines, gas turbines and some wind turbines. There are several substantial differences in application and influence on the network from the two different systems. For example, short circuit current for the induction and synchronous generator can reach 500-1000% of rated power current, while converter connected generator at the same site will produce only about 100-400% current. Most generators are operated with a power factor between 0.85 lagging and 1. However, some inverter technologies can provide reactive compensation and thus perform the voltage control.

Distributed generators may introduce harmonics. In case of inverters there has been particular concern over the possible harmonic current contributions they may cause. Fortunately, these concerns are in part due to the older line commutated inverters. Most new inverter designs are self-commutated and use pulse width modulation to generate the injected sinusoidal wave. These newer inverters are capable of generating a very clean output, furthermore, they are able to perform the function of harmonic filter. Synchronous generators can be another source of harmonics. Depending on the design of the generator windings (pitch of the coils), core non-linearity, grounding and other factors, there can be significant harmonics.

4.3.2 Economic aspects

The investment cost for wind power is decreasing with size and time, but increases when going to off shore sites. Rough estimates for present factory delivery costs are in the range 650 – 900 €/kW. Transportation, building and grid connection costs in the range 300 – 500 €/kW and the yearly operation and maintenance cost is around 1,7 % of the total investment cost. For off shore sites the cost may increase with 50% for the building and grid connection part. The total production cost is believed to decrease 15 – 25 % until 2010.

Cost targets for fuel cells are commonly given as 1000-2000 $/kW with O&M costs in region of 0,005 - 0,010 $/kWh. Today’s costs are in order of magnitude larger but is on the other hand for small, more or less hand built, series.

The values given for the installed costs of reciprocating engines varies greatly depending on the source; the overall range is from 250 to 1500 $/kW. For the operation and maintenance costs values from 0,005 to 0,015 $/kWh are given. As an example, the investment cost for a complete micro-CHP from SOLO-Kleinmotoren is about 1800 €/kWe. Annual operation and maintenance costs are estimated at about 6% of the total investments cost.

Particular investment costs for the boiler with steam turbine depends very much on the utilised fuel. Thus, the turbine unit with boiler based on natural gas or fuel oil costs around 1000 €/kW$_e$. Units based on bio-fuel combustion are more expensive, for example investment cost for the unit with electrical capacity 10 MW can lie around 2000 €/kW$_e$. Smaller units are usually more expensive.

4.4 Barriers and opportunities when installing DG

4.4.1 Technically related barriers

Requirements

Experiences from the wind power production in Denmark, and from the Swedish island Gotland, are that it is important to follow the technical requirements for keeping the stability in the network. The grid operator must be sure that the technical requirements are followed and be sure of the quality of the equipment.

Power quality

Reverse power flow may cause over-voltage problems. The voltage at the customer's terminals may exceed statutory limits. Selection of a proper power factor of the DG unit is one countermeasure. It is necessary to conduct further studies on the effect on distribution line voltage variation. Short-circuit current from a DG unit may cause malfunction of over-current relays and fuses. It may be necessary to develop a new fault detection system. One obstacle may be the need of ensuring safety of DG units: Should there be regular safety inspections of the equipment?

The possibility to operate as active filters reducing distribution system harmonics could make DG units with electronic interface more attractive from the point of quality service.

Islanding

Islanding seems to be the most controversial topic with grid-coupled DG units. However, theoretical studies show that islanding can only occur under very special and unlikely circumstances if basic safety methods are implemented. These methods are:

- Monitoring of grid voltage
- Monitoring of grid frequency.

Distribution networks with DG are presently not designed to operate in island mode. If islanding occurs it presents a number of hazards and thus needs to be avoided. Common international guidelines addressing the problem of islanding do not yet exist. Dangerous situations are very unlikely, but the consequences could be grave. One of the main questions is: "Which measures lead to an acceptable degree of security?" To reach an international consensus the following aspects have to be clarified:

- Definition of voltage and frequency limits for the operation of DG units
- Definition of the allowable duration of islanding
- Definition of standard test methods for islanding-prevention devices.

Location

Some DG technologies can be placed both indoors and outdoors. In the case of indoor solution it might be a problem to find space inside in buildings for example in the boiler room. In the Nordic countries, for example the micro-turbines can be placed outdoors or in a container. Low temperature can cause freezing problem during stop in wintertime for outdoor units and even for container solutions.

Regarding photovoltaic systems it should be noted that in the north the annual yield is far less than in countries closer to the equator. It is possible to integrate PV into residential and commercial buildings.

Availability

In the Nordic countries we have a very high availability of power from the grid. This is a barrier for many DG installations. A DG-unit might decrease the power availability for the DG-owner if he is dependent on one single unit.

A clear benefit of fuel combustion technologies is that the power is available practically always in opposite of e.g. wind power or PV, which are available only in windy and sunny weather. From operational point of view the engine genset is superior in many ways. It can be started very fast and the power output can be controlled to give the required output at any time. Due to this diesel gensets are in many cases used for back-up or peak-shaving purposes. Thus, an opportunity might be to apply for example a diesel genset combined with e.g. a wind power plant. These kinds of hybrid applications can be found in the literature.

4.4.2 Economically related barriers

Grid connection

In Sweden, The Company, which has the concession for electricity distribution, has an obligation to connect all types of customers (both consumers and producers) in the area. The distribution company has the right to take a connecting fee corresponding to the cost of the specific connection.

Small-scale producers with plants smaller than 1500 kW and wind power units with generators smaller than 1500 kW, have today favour special conditions for connection and power transmission on the grid. If connection of the small-scale generators and wind power parks leads to reduction of the operation cost for the distribution system e.g. by reducing losses, the producers can receive compensation. On the other hand, if the connection increases the operation cost, the distribution company have no right to demand compensation from the producers.

A proposal has been put forward on “green certificates”, which also include a proposal to remove the special rules for production sources with a nominal power less than 1500 kW from 2003.

When the producer starts planning the new DG unit he has to be sure that it is possible to connect the unit for a reasonable cost before spending too much money on the environment permission. The network company gives an offering for the specific connection. Getting permission may take several years. During this time both the situation in the network and the legislation can change. This may be a problem for the network company to handle and give the relevant information. The investment is big and the situation is uncertain. Furthermore, the technology for the plant may be changed during the process of getting permission, which also is a problem for the network operator.

At the same time the costs for connection differs according to the grid situation. The first plant may have to pay for new lines and transformers etc, while the next project only pays for additional costs that can be several times less for the same maximum power. It could be difficult to co-ordinate the permission for two projects in order to optimise the investment and solution and get an altogether lower connecting cost.

In Denmark there are similar technical rules for connecting wind power to the network. The difference is where the responsibility is divided. All investment costs in the grid and all transmission costs are included into the price for the customers. It means that the grid operator has to pay these costs in the first place. Hereafter the costs are equally distributed among all customers. The economical problem related to the network connection does not concern the producers.

In Germany regulations for grid connection are sometimes a barrier. One example is that an external disconnection switch is required, but this is often very expensive compared to the total system cost. This is referring to small plants and probably this will be a fact even in the Nordic countries.
Rates and metering are barriers, before there is proper standardization of these issues.

Heat load demand

In the Nordic countries the fuel combustion technologies have their main market for combined heat and power production. The unit needs to be connected both to the electric grid and to a heat distribution system. Only electricity may be produced, but in this case the heat created in the generation unit has to be stored for later use or to be cooled away. The heat from the unit can as an alternative be used for cooling system (air conditioning) but the cooling period is (normally) short in the Nordic countries. There are however projects for cooling in connection with micro-turbines in Norway and in Finland.

One interesting opportunity is Virtual Power Plant, which means that many DG units together can operate as a larger power plant and have a very high availability. This will give an excellent opportunity to use several small heat demands. One opportunity is to operate them in combination with heat storage that can store the heat produced for later use. The hot water in the storage will take the peaks in the heat load. An obstacle for this may be the cost of heat storage. Another aspect with gensets is that units can be made so compact that they can be moved easily to desired location, e.g., in containers.

Development

There is a possible huge market for micro-turbines especially on the European continent. But to reach the market the manufactures have to produce cheap and cost efficient standard engines. The new micro-turbines should have low maintenance and low investment costs. They must meet environmental demands. The units should not require special permits. A small unit cannot carry the cost for an expensive handling with engineering, permit and other costly questions. There are expectations that micro-turbines shall have low maintenance cost. But this has to be shown. To have costly engineering work will be an obstacle for the technology.

The short time from decision until a micro-turbine or other DG technology can be in operation is one other important opportunity. A traditional power station need years until it produces power and heat. In the future it is expected that new power from CHP DG can be in operation a couple of weeks from decision. The capacity can be increased in many small steps.

As a highly efficient, versatile and environmentally compatible new technology there is an abundance of opportunities for fuel cells. The potential market for stationary fuel cells in DG applications has been estimated to billions of dollar in various studies, which of course is a major attraction for the involved companies.

Obvious obstacles or rather uncertainties are the economic and technical challenges that lie ahead for fuel cells. If these are solved there are also questions regarding installation, technical support and business model that needs to be addressed. The first two items is about building up a new service structure and the last is how to handle the at least initial technology risk. For residential fuel cells there is a need for standards and codes with regard to the installation in buildings.

Today there are developed Stirling engines available for commercial application. However the interest for Stirling engines for co-generation is still low. For a wider commercial application of Stirling engines more documented experience from the installed units is required. Right now this experience is still insufficient in order to get serious attention to the technology. If Stirling engines are considered to be interesting for future applications, it is important to continue research concerning application of Stirling engine for co-generation and to perform more tests on real installed units. Price of electricity produced by for example PV systems is an obvious barrier. Many countries have programs to promote residential PV installations, and new programs are being launched. Many government-subsidised projects are going on in various countries.Steam boiler is instead a mature, well-tested technology with more than 100 years operation and development experience.

4.4.3 Fuel related barriers

At most sites the micro-turbine or engine needs to be connected to a chimney and sometimes also to the gas grid. This can be costly and time consuming. Installation of a new chimney can be costly so connection to an old is recommended or to have an out door unit without chimney as for example the Capstone (a micro turbine supplier).

If the micro-turbine is connected to low pressure (and a gas compressor increase the pressure to the demanded level of the combustion chamber) the barrier with permits may be reduced. To have a gas grid with natural gas is an opportunity but not necessary for micro-turbines. Denmark has an opportunity with a large gas grid but also Sweden and Finland have natural gas grid. The use of different fuel is an opportunity for the micro-turbine. Natural gas, town gas, biogas from landfill or sewage, oil, methanol are some of the fuel that can be used.

The low emissions are an opportunity and it is possible to find cases when the exhaust gas from the micro-turbine or engine is used in greenhouses. The carbon dioxide in the exhaust gas is used as fertiliser for i.e. growth of cucumber in greenhouses.

A barrier for fuel cells is the availability of fuel, primarily natural gas although other fuels as propane, biogas and diesel are feasible. An obvious barrier for gas engines is the availability of the gas. For making the plant operation economical a gas pipe is required. For engines using diesel or other fuels the availability of fuel is generally good.

For Stirling engines an important research field is related to the fuel. One of the promising alternatives is bio-fuel. Thus in Denmark there is a test installation where the combustion chamber is replaced by the bio-fuel boiler. The engine is 35 kWe and has the electrical efficiency 19% and total efficiency 87%.

Almost any fuel can be used in steam boiler; for example in Sweden bio-fuel and waste are used more often. However, combustion of waste is very demanding. The fuel must be prepared for combustion – turned into a homogeneous mass, otherwise the fuel properties, particularly moisture content, will differ considerably, which will influence the thermal value of fuel.

4.6 Overview in table

Table 2 summarises the main features of the principal DG technologies used today or having the potential application in the nearest future. The table also gives rough margins for the installed and operation and maintenance costs for each technology. In the table the characters are for each DG technologies and lines for describing the qualities of the technology. Fuel cells are a very promising technology, but they are presently very expensive. Micro-turbines presently are more expensive than the traditional combustion engines, but they are smaller, lighter, and operate with no vibration and less noise.

Table 2. Overview of different DG technologies

	Wind generators Landbased	Wind generators Offshore	PV	Micro-turbines	Fuel cells	Stirling engines	Recipro-cating engines	Steam cycle
Size, kW	10-3000	3000-6000	<1-100	25-500	5-3000	2-500	50-25000+	10000
Installed costs, €/kW$_e$	950-1500	1100-1650	6000-10000	1000-1800	1000-2000	~1800	250-1500	1000-2000
Operation and maintenance costs, €/kWh	0.008	0.01	Little	0.008-0.015	0.005-0.01	0.018	0.005-0.015	0.005
Emissions	No	No	No	Low	Almost no	Low	Fairly low	Fairly low
Availability on demand	Low*	Low*	Low*	High	High	High	High	High
Location	Energy-based	Energy-based	Energy / customer-based	Customer-based	Customer-based	Customer-based	Customer-based	Customer-based
Commercial status	Available well established	Available well established	Available	Available coming into commercial application	2005	Available newly introduced	Available well established	Available well established
Application	Green power Remote locations	Green power Remote locations	Green power Base load	Co-generation Back-up Peak reduction	Power quality Base load	Co-generation Back-up Peak reduction	Back-up Co-generation Peak reduction	Co-generation
Fuel	-	-	-	Natural gas	Natural gas	Any heat source	Natural gas, diesel, biofuel	Natural gas, diesel, biofuel

5. Network connection of different types of distributed energy generations, technological analyses, WP 4

5.1 Introduction

In WP4 various technical aspects relating to the network connection were analyzed mainly by applying simulations. The focus was on different technical solutions applied in network connection and in their performance with respect to power quality and network protection.

The tasks in WP 4 were as follows (the responsible participant is mentioned in the parenthesis):

1. Performance of DG relay protection (Technobothnia)
2. Voltage behavior at DG start-up and shut-down (LTH)
3. Voltage and current harmonics caused by converter based DG units (SINTEF)

All the tasks applied simulations with a computer model of a distribution network and DG units connected to it. The simulation tool applied was PSCAD/ETMDC [Manitoba HVDC Research Centre]. It is a commercial electromagnetic transient simulation program that enables accurate analysis of dynamic events of power systems. It suites especially for analyzing fault or switching events but it can also be used to study the behavior of systems including power electronics with high switching frequency. The algorithm applied is based on trapezoidal integration of the differential equations representing the power system.

Since it is a time domain simulation program the state of the system is calculated over a specified period with extremely short time steps – even up to some picoseconds. The output of the software consists of the waveform of current and voltages in the system as well as any derived quantity. In addition to the actual power system a detailed model of the associated control systems can be created with various data signals.

The application of electromagnetic simulation needs always a special expertise. In this case the other major reason for the selection of applied tool – in addition to its suitability for the problems studied – was the existing competence of participants and some earlier related studies that can be utilized. This concerns especially the team in Technobothnia who has focused its research activities on various power system simulations. Also other participants had earlier experience on using the tool.

5.2 Performance of various DG protection schemes considering coordination with network protection

5.2.1 Simulations

A suitable approach for analysis was verified by making first a pilot case study where only one DG type was studied. After the pilot case other DG types were studied by applying an approach that was based on the experience gained from the pilot case. For the pilot case, the wind power was selected. In addition to the **wind power** (case 1), the studied technologies were **diesel generators** (case 2), **solar power** (case 3) and **microturbines** (case 4).

The DG units were connected to a configurable network model representing a typical rural medium voltage network. The term "configurable" means that the model could be easily changed to represent alternative network arrangements. This includes the possibility to select the method for neutral earthing.

The DG units were modelled as accurately as possible considering the time frame to be simulated. Since only the behavior during the operating time of the protection was interesting in this study, the phenomena with longer time constants need not to be considered.

With all the DG models a set of simulations was made. The following fault types were studied:

- 3-phase short circuit
- 2-phase short circuit
- earth fault (single phase-to-earth fault).

For the earth fault studies different types of earthing practices were studied: isolated, compensated and resistance earthed network. The possible location of the fault and the location of the power plant in the network were also varied. For the power plant location there were two alternatives: either at the end of the feeder 1 or at the beginning of the feeder 1. In the former case the possible fault locations are given in the following figure. The fault locations are numbered from 1 to 4 for further reference.

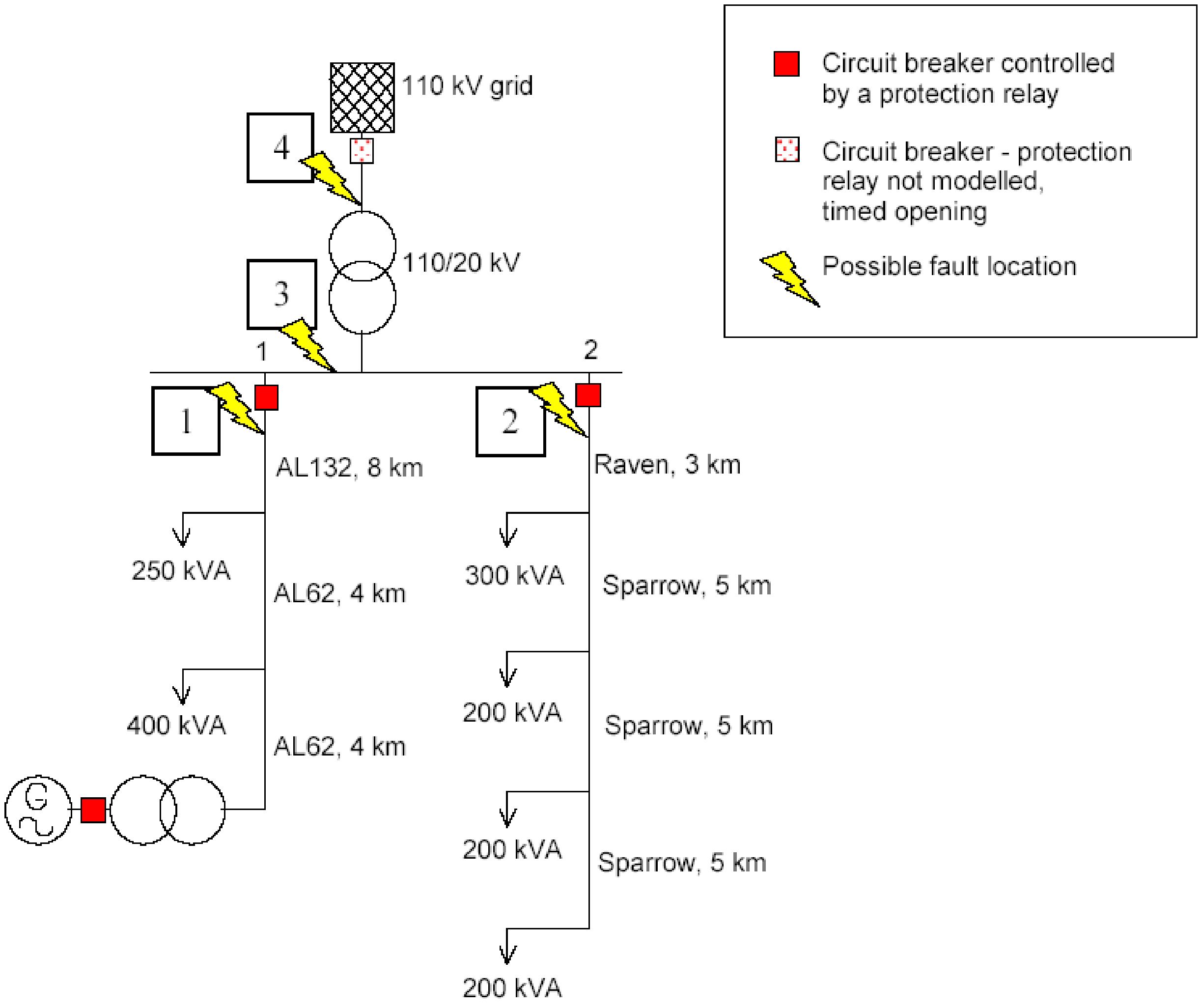


Figure 5. Fault locations in the case where power plant is located at the end of feeder 1.

In case shown in figure 5 there was still one more parameter to be varied. The last line section of the feeder 1 was either 4 km (like in the figure above) or 30 km. This made it possible that the fault level at the connection point of the power plant has two quite different values. Especially with the wind power plant this means that the fault level was either above or below the limit given in some recommendations: 5% of the rated power.

Considering the fault locations 3 and 4 in the figure above the fault is always cleared by opening the grid connection 100 ms after the fault initiation. In practice this means that in these cases DG units always remains feeding an island with a fault in it.

In a case, where power plant is located at the beginning of the feeder 1, the possible fault locations are shown in figure 6. In this case only the alternative where the last line section is 30 km is interesting since it gives the lowest short circuit currents at the end of the feeder.

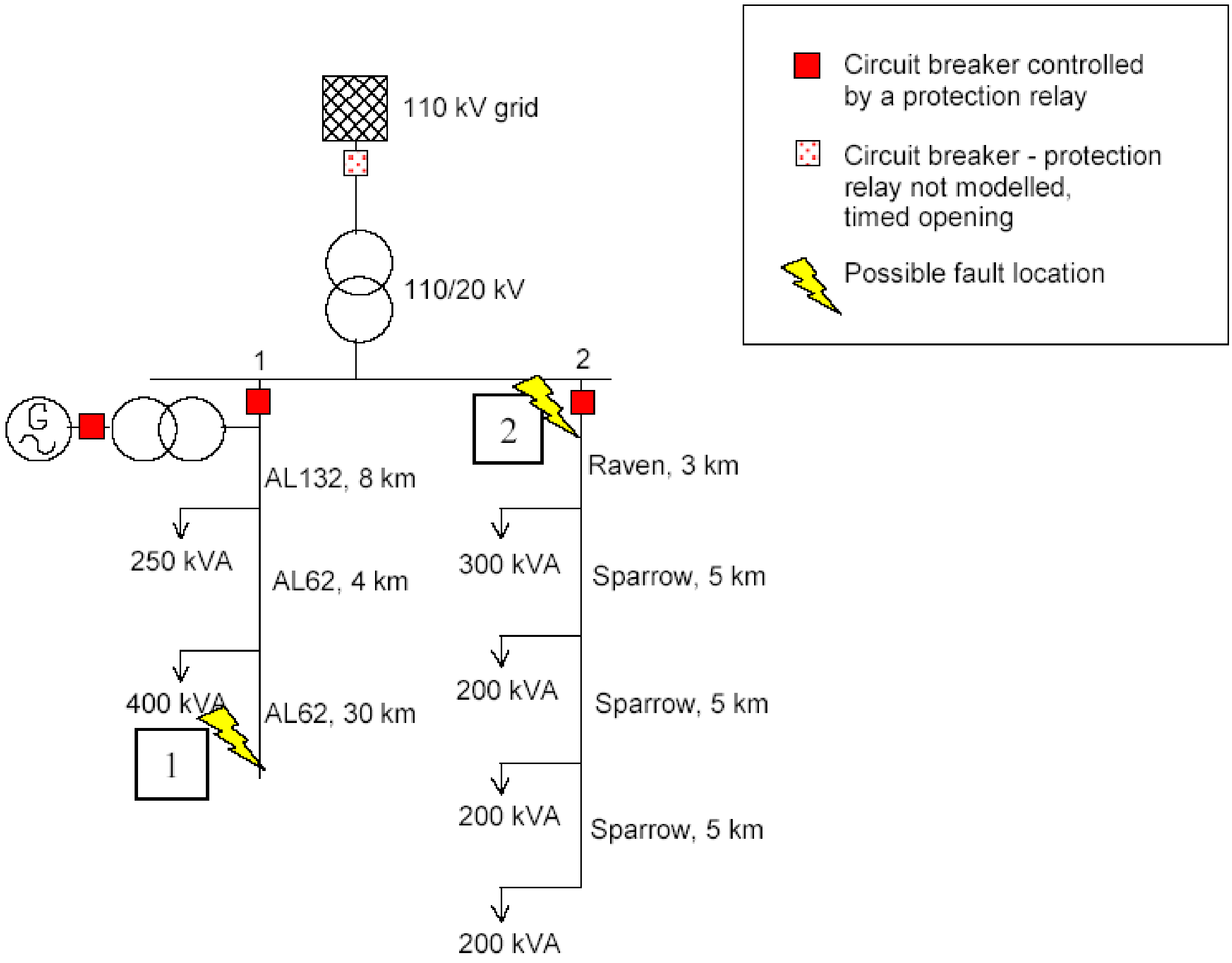


Figure 6. Fault locations in the case where power plant is located at the beginning of feeder 1.

With isolated system, all the three fault types were simulated for both of the network arrangements presented above. The earth fault simulations were repeated by applying resistance earthed and compensated network.

In addition to fault simulations, also a case where feeder 1 is disconnected without a fault was simulated. In this case the power plant is left running on island, which is generally not acceptable. In order to have the islanding situation appear the some adjustments was made in the network model in order to have favorable situation from the islanding point of view. This means that the load in the islanded part of the network must be closely matched to the power output of the DG unit before the disconnection from the grid.

5.2.2 Results

The primary goal of the simulations was to analyze the impact of DG units to normal protection of the distribution network. The analyzed fault situations were 3-phase and 2-phase short circuit faults and single-phase-to-earth faults in various locations on the network. The DG types simulated were wind power plant, diesel power plant, photovoltaic unit and microturbine.

According to the simulations, the major problem with all types of DG units seems to be that the short circuit faults on adjacent feeders may cause unnecessary tripping of the power plant. The reason for this is that in a relatively weak network the voltage drops dramatically in all feeders when there is a fault in one feeder. By default the undervoltage limits are relatively high and the time delays are short. In order to avoid unnecessary trippings there are two alternative actions that can be done:

- the time delay applied in feeder overcurrent protection is made shorter than the delay in DG units undervoltage protection
- the delay of the DG unit's undervoltage protection is increased above the delay of feeder overcurrent protection.

In principle this means that the selectivity is achieved by proper timing of the relay operations. In addition to this it is also possible to lower the undervoltage limit. For the feeder overcurrent protection the lower limit for the possible values of the time delay is determined by the features of the relay and associated devices (e.g. current transformers) so that the minimum achieved with the latest technology is around 0.1 s. On the other hand the allowed increase of the delay of DG units undervoltage protection is mainly dictated by the generator or inverter tolerance against voltage dips. Recently there has even been increasing demand toward some specific ride-trough capabilities especially for larger set of generators. However, relating to typical DG units it is enough that delays can be set so that suitable coordination with network protection is achieved.

An interesting finding with the wind power plant was the formation of the healthy island that continued operation. Although this is obviously a rare event, it seems to be possible with directly connected induction generators, too. In practice the island operation would not be possible more than few seconds since there is not any frequency control in the island created and loads in the real network are usually constantly changing. On the other hand in this study the synchronous generator driven by a diesel engine was not able to run in island for a longer period due to the power based control and relatively tight speed limits. With other types of control schemes a successful island operation would have been possible. It should also keep in mind that in this case the speed relay also serves as the loss-of-mains protection.

Considering the two inverter applications in these simulations it was verified that they could be operate in island if the power is closely matched with the power output before the grid disconnection. A major distinction between the PV unit and the microturbine was that the former has also a specific loss-of-mains protection based on grid impedance measurement. It turned out to be efficient in this case although the time delay seems to be unnecessary long.

Loss-of-mains protection may be very challenging, if all the possible cases must be covered. If there is no loss-of-mains protection, there is a risk of network re-connection without synchronization, which can cause damage to the power plant and to the components of the network.

The diesel power plant, which was rather large in proportion to the total load of the feeder it was connected to, causes protection problems to the network especially in short circuit faults. Unnecessary tripping of both feeder relays and power plant turned out to be possible. The situation where the feeder 1 relay is unnecessarily tripped in a fault at feeder 2 is illustrated in the figure 7. This situation can only be avoided applying directional overcurrent relay in feeder 1.

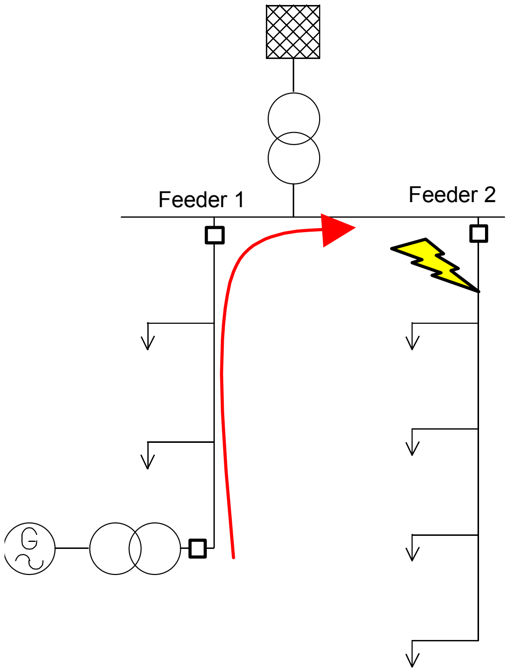


Figure 7. Unnecessary tripping of feeder 1 relay in case where the fault is in feeder 2

The other problematic situation is illustrated in the figure 8. In this case the share of the fault current from the generator is so large that the relay at the beginning of the feeder does not see the fault and does not operate at all or operates only after the generator relay is operated. There is no simple way to handle this situation. A solution may be found by properly adjusting the current and time delays of both the feeder and generator relay. If the generator is large and the feeder is long, like in this case, the only realistic solution could be major network rearrangements so that the generator is connected by a separate feeder directly to the substation bus.

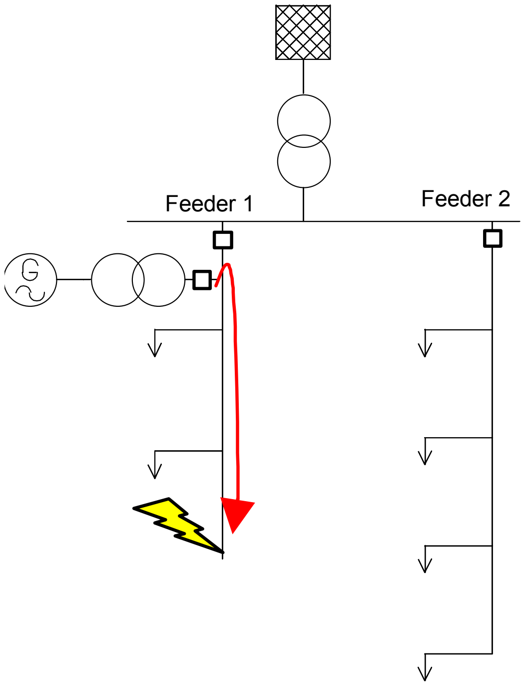


Figure 8. Generator prevents the correct operation of the feeder relay

Because the DG unit models did not include earth fault protection, the tripping time in earth faults may be too long when thinking about the safety regulations. The earth fault relays in the DG units could be based on the residual current measurement in the medium voltage side of the transformer. In order to have selective operation the time delay applied should be longer than in the feeder earth fault relay. As can be seen in the simulations also the loss-of-mains protection can be applied but this requires that the time delay is set to suitable low value considering the safety requirements. Furthermore it should be noticed that, e.g., the undervoltage relay is not secure enough for detecting the island operation.

Considering these simulations it should be noticed that almost all of them were made only at one operating point. Only in the special cases where the islanding conditions were surveyed with healthy network, different levels of power output were investigated. Alternative levels of both load and power output from the power plant might have led to different results in some cases. Varied real and reactive power levels could also have given more information about the output ranges enabling the unwanted island operation.

Synchronous generators increase the fault level of the network. This impact of the generator was not analysed in this study. If the location of the generator was at the beginning of a MV feeder, the thermal protection of all the feeders should be checked. At the end of the feeder the impact would probably be more local, but more serious because of smaller conductor cross-sectional areas. Thermal protection should of course be analysed case by case, but a general study of the impact of DG on fault levels is justifiable.

Necessary topics for further studies are protection including automatic re-closing, studies on thermal protection especially with large units, various load and production levels and simulations with various network configurations.

5.3 Voltage behaviour at DG start-up and shut-down

5.3.1 Introduction

As a result of increasing environmental concern, more and more electricity is generated from renewable sources. One way of generating electricity from renewable sources is to use wind turbines. As a result of this, in the near future wind turbines may start to influence the behaviour of electrical power systems. Therefore, adequate study of the impact of wind turbines on electrical power system behaviour is needed. The use of squirrel-cage induction machines in wind generation is widely accepted as a generator of choice. The squirrel-cage induction machine is simple, reliable, cheap, lightweight, and requires very little maintenance. Generally, the induction generator is connected to the utility at constant frequency. With a constant frequency operation, the induction generator operates at practically constant speed (small range of slip).

One very important issue when wind turbines are installed is the power quality influence that the wind turbine has on the grid. Fixed-speed wind turbines can cause large voltage fluctuations.
With the emergence of computers, a high level of automation with sensitive loads and modern communication, reliable electricity supply with a good voltage quality has become a necessity. Electricity is fundamental to economic activity, to the standard of living and quality of life. Over the last ten years the customers' perception of reliability has changed. Outage times of a few cumulative hours per year are no longer considered as a characteristic of an extremely reliable supply for an increasing number of sensitive customers, in particular industrial and commercial customers. A few cycles interruption or a voltage reduction to less than 90 % may cause serious problems for industrial customers. The number of voltage dips and swells and their duration becomes more important than the cumulative outage time per year.

The fact that some wind turbines produce strongly varying output power and some other problems has lead to high connection costs for wind turbines. Today, in Sweden, the cost for grid connection is up to 20 % of the total cost of the wind turbine [Thiringer, 2001]. Using more grid-friendly turbines and demonstrating that these can be connected to weaker grids would, in many cases, give a substantial cost reduction for the connection of wind turbines to the grid.

With microturbines recent development has been focused on technology as a stationary power source for the distributed generation (DG) market. In most configurations, the turbine shaft spinning at up to 100000 rpm drives a high-speed generator. This high frequency output is first rectified and then converted to 50 Hz.

The systems are capable of producing power at around 25-30% efficiency by employing a recuperator that transfers heat energy from the exhaust stream back into the incoming air stream. In CHP applications the use of the heat approximately triples the total efficiency. Microturbines are appropriately sized for commercial buildings or light industrial markets for cogeneration or power-only applications.

5.3.2 Simulations

The model of the distribution network applied here is the same that has been developed at task 1 of this WP. The main attention here is devoted to developing the sequence of action during start-up and shutdown of DG units.

The wind power plant is the same that was applied in task 1. In normal operating conditions the torque generated by wind is modelled simply by applying a constant input to the machine, but for complicated time sequence modelling which includes the rotor acceleration before start-up and deceleration after shut-down a block capable to output the desired sequence to output the desired sequence is applied.

Each part of the system which is involved in the process of start-up and shut-down of the wind power plant has its own timer block to set up some time sequence and investigate the various aspects (normal and emergency) of voltage behaviour in the network.

The following sequence for start-up is considered:

1. Applying a mechanical torque that accelerates the rotor to nominal speed in 60 seconds.
2. Applying zero torque during a few seconds and close the generator breaker during this time.
3. Waiting for the electrical transients to disappear. Increase the torque from zero to nominal value in 60 seconds.

Shutdown is represented as follows:

1. Decreasing the torque from nominal value to zero in 60 seconds.
2. Opening the generator breaker.
3. Applying a negative torque (with a brake) that reduces the speed from nominal down to zero in 60 seconds.

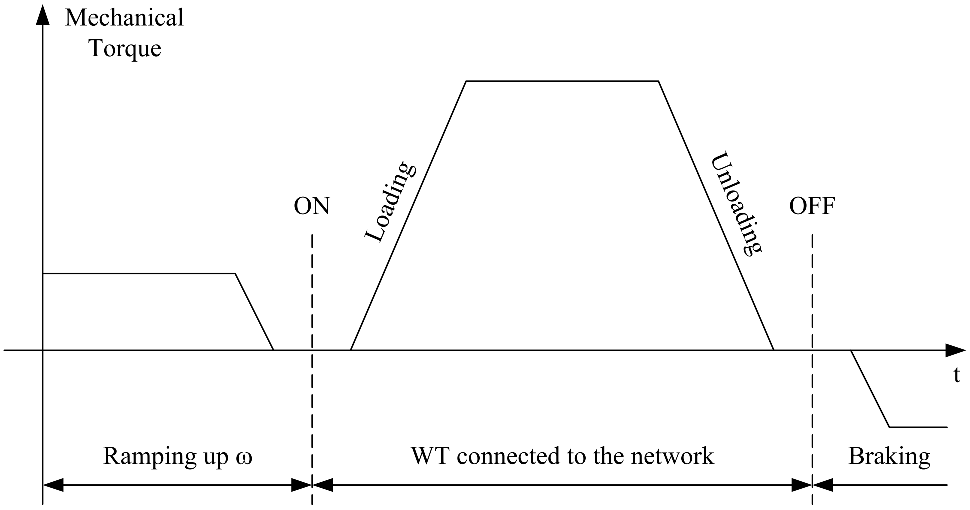


Figure 9. The sequence of wind turbine start-up and shutdown considered.

In order to compare the impact of different DG units correctly and to develop the set of recommendations for further application of DG the model of the distribution network for microturbine studies is identical to the network model which was considered during the investigation of wind power generator. It is to be noted that so called “weak” connection of DG units is more typical for wind power plants which are sited away from the bulk supply points and nearer to the ends of the network whereas microturbines are appropriately sized for commercial buildings or light industrial markets for cogeneration or power-only applications (“strong” connection).

According to manufacturer recommendations and simulation experience surveyed the microturbine is based on the current or power control and its model in normal operating condition and in the time scale exceeding about one cycle can be represented as a controllable current source.

The microturbine dynamics during start-up can be simulated with a sequence divided into three stages. At first, microturbine consumes the power from network through a single phase in order to spin up the rotor of the permanent magnet generator. Then, there is a 5-10 seconds pause for turning on fuel, igniting combustor and switching on microturbine into the network. And during the third stage the power of microturbine is ramped up smoothly with the maximum normal speed of change equal to 2 kW/sec. This process is fully controlled by power electronics systems (six phase bridge rectifier, DC-DC converter and DC-AC power inverter).

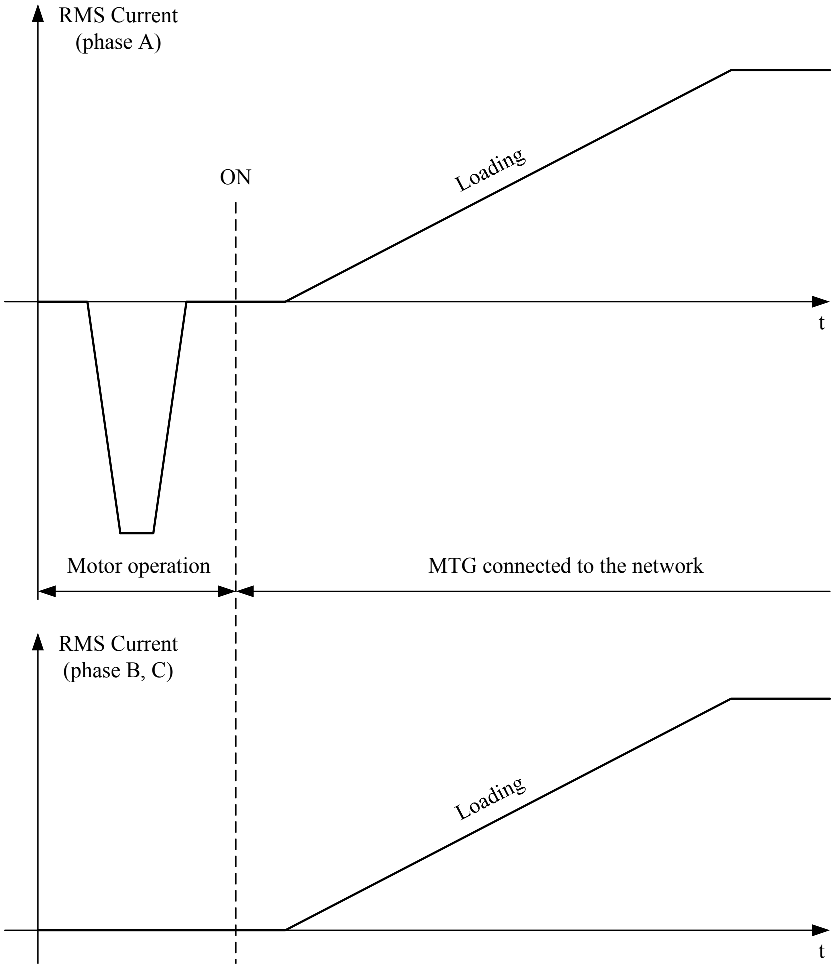


Figure 10. The start-up of microturbine

5.3.3 Results

The voltage behaviour during start-up and shutdown of a wind turbine with an induction generator directly connected to the network and the microturbine which was represented as controlled current source was investigated by the example of the model, which represents a typical medium voltage network. For this purpose, the network model created at PSCAD/EMTDC (Version 3.0.8) was used.

The long-term sequences of actions during start-up and shutdown for wind power DG unit and microturbine separately according to manufacturer requirements were proposed and then investigated using the PSCAD simulations and simplified calculations.

Two different locations of DG unit in one outgoing feeder of the network were studied during the simulations – at the end of the Feeder 1 and at the beginning of it, directly at a load bus (weak/strong end of the feeder). It is to be noted that it is more typical for microturbine to be located in the places of so-called “strong” connection whereas wind power plants are sited away from the bulk supply points and nearer to the ends of the network (“weak” connection).

For this reason when using the microturbine it is much more important to maintain local voltage level within the boundaries recommended by distribution companies. Being behind the power electronics interface the generator dynamics of microturbine does not influence on network since voltage profile along the distribution feeder (regardless of the connection place) is within 0,5% of its nominal value.

During start-up of an induction machine the voltage at the 20 kV side of the main transformer (so called main network) is within the boundaries recommended by utilities in all cases.

According to standard recommendations it is possible to skip the flicker estimation in microturbine studies since the connection of a fluctuating load may be accepted without further analysis if the power variations are within the limits of 0,2% of short circuit apparent power.

When the wind turbine operates without local load, but with the compensation capacitors on, self-excitation with relatively high stator voltages occurs almost always during switching-off the generator from the network.

The simulation results indicate that dynamic voltage fluctuations at the load buses due to wind turbine start-up and shutdown are within the limits recommended by utility guidelines, whereas the voltage at the generator bus can be changed considerably.

Without application of the wind turbine brake it is necessary to switch-off at least 40% of the capacitor banks to prevent overvoltages at the generator bus as a result of self-excitation of induction machine. At the same time, applying the brakes requires only 15% of capacitor banks to be tripped.

The small pause (approx. 300 ms) between the start of braking and tripping the generator breaker is strongly recommended to prevent overvoltages in the case of switching-off the induction generator with capacitance compensation, but without local load.

5.4 Voltage and current harmonics caused by converter based DG units

5.4.1 Simulations

In task 3 simulation models for two different converters that can be used to connect distributed energy generation to the mains are presented. One converter is a switched modulated (PWM) converter with 3 kHz switching frequency and the other converter is a forced commutated thyristor converter.

The network model applied here is the same created in task 1. For analysis purposes of this work, low voltage loads are added, both in feeder 1 and in feeder 2.

There are several parameters that influence on the harmonics introduced in the mains currents and voltages by the converter. The most important are:

- Converter switching frequency
- Filter capacitor
- Filter inductor
- Power delivered by the converter

In addition, the characteristics of the network, to witch the converter is connected, will influence on the generated harmonics. In a real converter other details like turn-on and turn-off times of the IGBT transistors and switching overvoltages will influence on the current and voltage waveforms as well. The filter values used have not been optimized, and different simulated cases are used to illustrate the influence of different parameters on the harmonic content of the current and voltage waveforms. In the case of thyristor converter also the firing angle and commutation inductance affects on output waveform. For both of the converter types simulations were made in low and high load situations.

5.4.2 Results

The main goal of this task has been to present the two simulation models for future studies of harmonics. Some analyses was included to illustrate the harmonics generated by the two power electronic converters, and how the harmonics are influenced by different parameters. No filter optimization has been done in order to minimize the harmonics.

The PWM converter generates harmonics at multiples of its switching frequency, here set to 3 kHz. In a high power situation the harmonics at switching frequency measured at the 20 kV converter connection point are 0.8 % of the fundamental for the line current and 1 % of the fundamental for the line voltage. It is shown that the filter between the converter and the mains network connection point is of importance. There have traditionally been no limits or recommendation to the harmonics at switching frequencies in question for a converter like this (between 2 and 10 kHz). Harmonics at and below 1% of the fundamental should be acceptable in this case. With careful filtering it should be possible to reduce the harmonics.

The thyristor converter generates 5th, 7th, 11th, 13th (and so on) harmonics of the 50 Hz. In a high power situation the 5th harmonic measured at the 20 kV converter connection point are 20 % of the fundamental for the line current and 2 % of the fundamental for the line voltage. The total harmonic distortion (THD) of the current is 23 %. In this case, without proper filtering, only the voltage harmonics are below the IEC limits. The current limits depend on the short circuit current at the connection point.

It is shown that resonance between the network and the thyristor converter can occur, causing harmonics at around 4250 Hz and 4450 Hz larger than the 5th harmonic.

Two low voltage (400V) loads are analyzed, one close to the converter connection point and one as far as possible from the converter connection point. With the thyristor converter the largest harmonic measured at low voltage level is about 2 % of the fundamental for the line voltage.

5.5 Conclusions

In WP 4 various technical aspects relating to the network connection were analyzed mainly by applying simulations. The focus was on different technical solutions applied in network connection and in their performance with respect to power quality and network protection. WP4 was divided into three separate tasks so that each of them was mainly executed by one participant of the WP.

In task 1 the aim was to find out criteria and arrangements that enable proper operation of the protection both in the DG unit and in the associated network. The proper operation of protection arrangements was studied in various short circuit and earth fault situations. For this purpose simulation models representing the different types of DG units and a configurable network model were constructed. The same network model was applied also in other two tasks while in task 1 the model for microturbine is created basing on models from task 3.

According to the simulations made, the major problem with all types of DG units seems to be that the short circuit faults on adjacent feeders may cause unnecessary tripping of the power plant. The reason for this is that in a relatively weak network the voltage drops dramatically in all feeders when there is a fault in one feeder. Because the DG unit models did not include earth fault protection, the tripping time in earth faults may be too long when thinking about the safety regulations. For these issues correction might be found applying suitable timing and settings of relays and in some cases other types of relays.

Also false tripping and blocking of the correct operation of the feeder relay was detected in simulations. This indicates that careful planning with perhaps some new approaches is needed in order to fully utilize the possibilities related to DG.

An interesting phenomena was the islanding situation where the DG unit remains feeding a part of the network without grid connection. For safety reason this situation is usually not allowed and thus so called loss-of-mains protection arrangements should be applied. In simulations it was verified that islanding is possible with induction generators and inverter units at least for a short period.

The task 1 showed that protection is a problematic issue and further studies are needed in order to find solutions that are more complete for the protection considering the whole system.

In task 2 one of the power quality issues relating to the DG is studied: the voltage disturbances caused by the DG start-up and shut-down. Two types of DG units were considered: wind power plant and microturbine. Basing on a detailed literature survey about the topic the behavior of these two DG units was studied by simulations. Simulation models of the DG units studied were connected to the network model developed in task 1. The results showed that dynamic voltage fluctuations at the load buses due to wind turbine start-up and shutdown are within the limits recommended by utility guidelines, whereas the voltage at the generator bus can be increased considerably after the grid is disconnected. As a result of this some recommendation for suitable sequence for shut-down are proposed considering the switching of capacitors and timing of braking.

In task 3 the harmonics generated by two different types of converter units were studied. One converter was a switched modulated (PWM) converter with 3 kHz switching frequency and the other converter was a forced commutated thyristor converter. The main goal of this task has been to present the two simulation models for future studies of harmonics. Some analyses were included to illustrate the harmonics generated by the two power electronic converters, and how the harmonics are influenced by different parameters. In simulations made the converter models were connected to a network model that was based on the model applied in task 1. The PWM converter generates harmonics at multiples of its switching frequency, here set to 3 kHz. In a high power situation the harmonics at switching frequency measured at the 20 kV converter connection point are 0.8 % of the fundamental for the line current and 1 % of the fundamental for the line voltage. The thyristor converter generates 5th, 7th, 11th, 13th (and so on) harmonics of the 50 Hz. In a high power situation the 5th harmonic measured at the 20 kV converter connection point is 20 % of the fundamental for the line current and 2.7 % of the fundamental for the line voltage. The total harmonic distortion (THD) of the current is 23 %. In this case, without proper filtering, only the voltage harmonics are below the IEC limits.

The main result from WP 4 is a set of simulation models that can be applied in further studies. These models have now been applied in simulations that also provide valuable information about different technical issues relating to the power quality as well as the system protection considering the increasing amount of DG in distribution networks. Basing on this information some recommendation were given relating to the network connection of the DG, but it also turned out that there are still many more things that need to be investigated. In this study the DG connection issues were studied with only one typical network model were studied while in order to have a complete picture of the observed topics a large number of various network arrangements as well as load and DG unit combinations must be analyzed.

Remarks

The studies showed that protection is a problematic issue and further studies are needed in order to find solutions that are more complete for the protection considering the whole system.

The major problem seems to be that short circuit on adjacent feeders may cause unnecessary tripping of power plants. Earth fault protection is another issue that may require correction of settings of relays and in some cases different types of relays.

Also false tripping and blocking of the correct operation of the feeder relay was found in the simulations. This indicates that careful planning with perhaps some new approaches is needed in order to fully utilise the possibilities related to DG.

Both short-time and long-time islanding was found in the simulation studies. Loss -of-mains protection should thus be applied.

6. Effects on power system, WP 5

The main topics of the WP 5 report were

- A vision for the new distribution power system, which is a system that facilitates the integration of distributed generation.

- Relay protection for networks with distributed generation. New ways of thinking with respect to protection in the distribution network is required.

- Controlled island operation as a means for increasing the reliability of the network.

- Impact of distributed generation on dispatch and frequency control. With a high penetration of distributed generation it is desirable that the DG units contribute to the network operation and security.

6.1 Introduction

Connecting a lot of small power production units to the distribution network will inevitably have some sort of effect on both the distribution network and, if the share of DG becomes large enough, the high voltage transmission network. Such effects are investigated in WP 5 of the project. The available resources for this work were limited, and it has not been possible to investigate all kinds of effects in detail. It is chosen to look into the following topics:

- A vision for the new distribution power system, which is a system that facilitates the integration of distributed generation.
- Relay protection for networks with distributed generation. New ways of thinking with respect to protection in the distribution network are required.
- Controlled island operation as a means for increasing the reliability of the network.
- Impact of distributed generation on dispatch and frequency control. With a high penetration of distributed generation it is desirable that the DG units contribute to the network operation and security.

6.2 Vision for the new network

Through the history of electricity the power systems in the Nordic (and other) countries have evolved to the systems we see today. These systems can be characterized by a unidirectional power flow from generation to the consumers as described below (paradigm 1):

Generation → Transmission → Distribution → Consumers

This paradigm will change when (and if) large-scale integration of distributed generation in the MV and LV network takes place. The new paradigm (paradigm 2) is a situation where bi-directional power flow is possible:

Generation → Transmission ↔ Distribution ↔ Consumers

In order to manage an electric power system with a large amount of distributed generation, a new approach to organization and operation of the network will be required. A vision for such a new approach is based on "active management" of distribution networks. A bottom-up approach is used. Small cells, which are in fact local control areas, are autonomous units with responsibility for power balance in their own area. If they do not have the necessary resources to assure power balance resources must be traded between cells at the same level or with a cell on a higher voltage level. The concept of cells and the accompanying hierarchical control structure are described in figures 11 and 12:

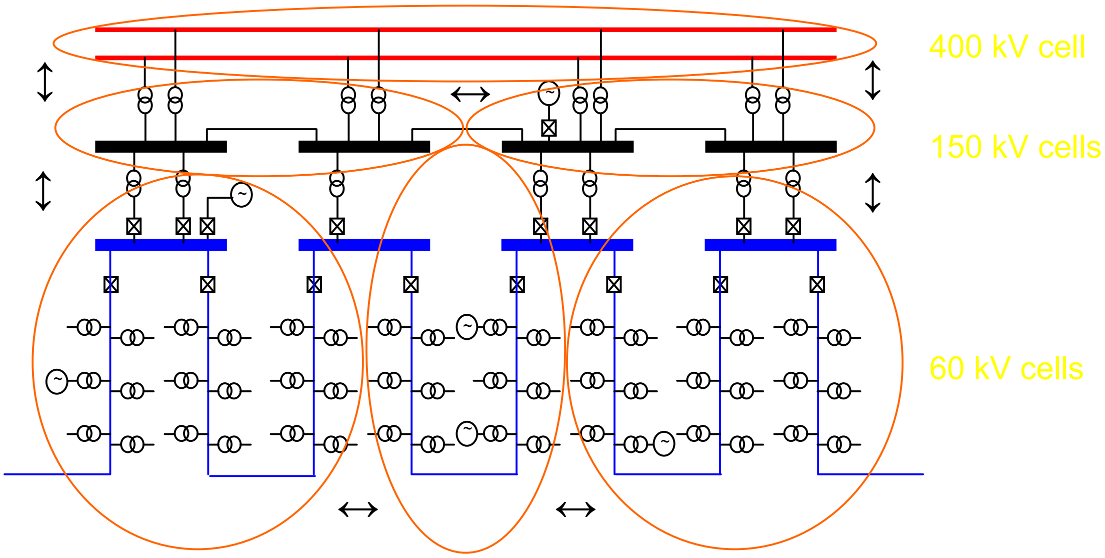


Figure 11. Concept of cells

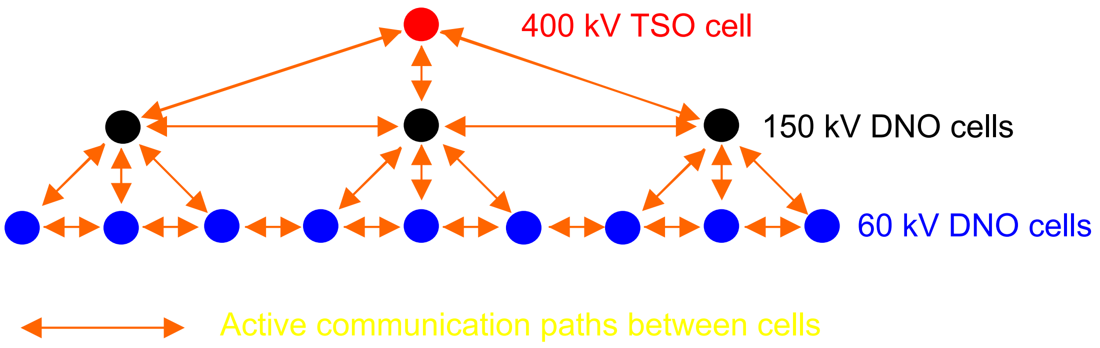


Figure 12. Accompanying hierarchical control structure

To implement this kind of network more communication and control equipment is needed, but large investments in the electricity network itself is not foreseen. The actively managed distribution network represents a radical change compared to how the distribution network is planned and operated today, and it must be implemented in steps if it is to be realized.

6.3 Relay protection for networks with DG

For reasons of simplicity and economy, operation and protection of distribution networks today is to a large extent based on a radial design with single-sided infeed of load and fault current (paradigm 1). The introduction of distributed generation (DG) in a radial network leads to a situation with multiple infeed of load and fault current. Operation and protection must somehow adapt to this. Today's situation lies in the beginning of the development towards active distribution networks, where operation and protection need not change much. Short-circuit faults are still handled with existing non-directional overcurrent protection, but DG units are required to quickly disconnect in all abnormal situations. When a fault occurs and the infeed from the upstream system is interrupted the downstream system must be de-energized. This is accomplished by the loss-of-mains protection of the DG units that either detects the fault or that an island network has been formed. In both cases, the DG units are disconnected resulting in a conventional distribution network without generation. At this point of the development, efficient loss-of-mains protection is most important. Due to the size of DG units low cost is mandatory.

As DG penetration increases, co-ordination of non-directional overcurrent protections gradually becomes more and more difficult and may even be impossible. The first measure suggested here to solve this problem is to employ directional distance protection. This is used in meshed networks today and thus allows also the distribution networks to have multiple in-feed and to be meshed. The next step to simplify co-ordination of overcurrent protections is to use current-differential protection.

Increased DG penetration makes it desirable to involve DG units in the power balance on the highest system level. Tripping of DG units can no longer be standard procedure for all sorts of disturbances. Instead DG units must be able to withstand much greater variations in voltage and frequency than today. This discrepancy can already be seen in Sweden when comparing requirements on small production units suggested by the TSO, with those used by the distribution network companies**.**

6.4 Controlled island operation as a means for increasing the reliability of the network

One way to motivate network companies to embrace DG is to exploit the benefits it may have on security of supply for the customers. This requires island operation to be allowed and not avoided as today. The island network must then be equipped to handle many of the issues dealt with on transmission level today. If a power system with massive use of DG would be designed today, island operation may even form the starting point, which leads to so-called active distribution networks. This may be viewed as the complete transition of distribution networks to fully independent systems and requires all the changes in protection mentioned in this report.

Island operation is a broad term including the operation of parts of the system isolated from the main grid at all levels of power system. The WP 5 report "Connection of distributed generation – effect on the power system" reviews the different types of islands in power systems, describes the circumstances when island operation becomes advantageous, identifies the necessary conditions, difficulties and possible solutions, as well as collected experience. In an island system there is no concept of an infinite bus with a constant voltage and frequency. The frequency in the isolated system is dependent exclusively upon the speed of the prime mover and the load determines the power to be generated.

The following main problems general for all types of isolated islands have been identified.

- Loading of the generator during a black start
- Frequency and voltage control during the island operation
- Power supply of communication and automation systems during the blackout
- Design and settings of the relay protection.

The first two problems are to a high degree associated with load behavior. Load should be connected in smaller steps; otherwise the frequency swing may cause generator protection to be activated. Such a moderate loading is not always possible due to the network design and nature of the load. Furthermore, due to the cold load pick-up phenomenon the load during the restoration process may be considerably higher than before the blackout. In a small system spontaneous load variations can be relatively large compared to the interconnected system. The cold load pick-up phenomenon will make it even more difficult to predict the load. Thus, the frequency fluctuations will be much higher compared to a normal situation.

In case of blackout, the ability or the equipment to maintain automatic functions is limited by the capacity of the batteries, which usually does not exceed several hours.

In an island grid there will be different conditions for the relay protection compared to the normal operation. In case of an earth fault the earth fault current will probably be less, and therefore there is a risk that the delayed steps instead of the instantaneous one may activate the earth fault relay. At the lower voltage levels where the overcurrent protection with inverse time characteristic is usual, the time delay will increase due to the lower short-circuit power.

Island operation is currently seldom used on a main grid level. Modern regulators in the large power stations are designed to operate in the interconnected mode, island operation is considered to be an emergency mode to be used in extreme circumstances. On the other hand, industrial generators and reserve power systems at hospitals and office buildings are designed to handle extreme situations.

To illustrate the problems related to establishing, operating and reconnecting an island, an example from a Norwegian network is used. This network contains two small hydro power plants, which are equipped for operation without connection to the main grid. The largest challenge seen is the protection system. With today's protection equipment automatic transition into island operation is not possible. Communication between relays, more sophisticated types of relays and some degree of logic in the protection system will be required. The necessary technical issues should preferably be solved already on the planning stage. If not, large investments might be necessary if it is desirable to allow for island operation at a later stage.

Automatic transition into island operation can be a safety risk. To handle safety for the staff it is very important to have clear instructions on where there might be a live network even though the main grid is disconnected. The routines have to be properly described and well known to all people involved with working in the grid.

In addition to the technical and safety issues there is also an economic part of this problem. Who should pay for the necessary investments, and will this be profitable? The primary goal for establishing a DG cell that can be operated in island condition is to reduce the number and duration of outages. This will give advantages to all parties involved:

Advantages for the grid company:

- The goodwill is dependent of the quality of the supply, better quality can result in better goodwill
- Energy not supplied means loss of income
- Reduced CENS costs (in Norway only)

Advantages for the power plant owner:

- Loss of electricity production might not be possible to regain, especially wind and hydro power plants can loose electricity production that will never be returned due to wind or water passing the power plant without being utilized.
- Stop and starts implicates losses in the process

Advantages for the customer:

- Reduced cost due to short interruptions. Many industrial processes stop during a short interruption. This gives restart costs and can also give wrecked products. Computers will stop possibly causing loss of data and time to restart.
- Reduced cost due to the duration of the outage. The modern society is very dependent on electricity to function. Loss of power often means stop of work. A survey on outage costs in Norway concludes that costs for energy not supplied are approx 40 NOK/kWh on average.

6.5 Impact of distributed generation on generation dispatch and frequency control

In an AC power system, the balance between total load and total generated power governs the frequency. A vital part of the daily routine of the system operator is to manage this balance between generation and load. This is done by requiring that the predicted load demand is covered by sufficient amounts of distributed generation. Mismatch between load and generation changes the frequency and generating units participating in frequency control respond to this by changing their output. All the units in a synchronized system react regardless of their location in the system. The power balance in an interconnected system is thus a matter of common interest to all parties involved in operation of the system. Each system operator is therefore required by coordinating organizations like Nordel to share the responsibility by having certain amounts of reserves available for frequency control, both on-line spinning reserves and off-line reserves that can be quickly put on-line.

Distributed generation (DG) plays a special role in the power balance, since it to a great extent is neither dispatchable like conventional generating units nor predictable like the load. Different types of DG, however, have different characteristics. Recordings of the electric power production of local combined heat and power (CHP) units and wind power in Denmark exemplify this. CHP units are mainly operated to produce heat, but by using heat accumulators, the heat production can be shifted in time. In Denmark a time-varying tariff is used to make CHP production follow the load and thus become predictable. Wind power is uncorrelated with load, which is illustrated by recordings from Denmark and Germany. Occasionally the wind power production covers the entire load, while at other times it is zero. In contrast to conventional generating units, wind power thus increases the need for control reserves. Simulation results for a case with high wind power penetration in northern Germany are reproduced and demonstrate the impact on dispatch. If the reserves are remotely located, wind power also increases the demands on power transmission. Recordings from Denmark illustrate how variations in export to Norway, Sweden and Germany balance wind power production. For this reason, hydropower in Norway and Sweden is important for the operation of wind power in Denmark.

With recorded load and wind power variations available, the corresponding frequency variations can be simulated. It is shown that predicted and unpredicted variations in load and generation affect frequency differently. Frequency graphs from the German dispatch simulations show that the wind power variations reduce frequency deviations. This is quite unexpected and further studies are suggested.

To better handle the power balance with high penetration of DG, system operators want the DG units to behave more like conventional generating units. Recently issued requirements on DG and wind farms show that the first priority is to avoid tripping of generation. This is reflected in strict demands on what deviations in frequency and voltage that the units must withstand without tripping. The next priority for system operators is to get access to real-time information about production level and status of all generating units and also to be able to reduce the output and thereby gain dispatchability. The idea is that all units, including wind turbine generators, should belong to the control reserve. Control reserves on-line are necessarily associated with part-load operation. Part-load reduces efficiency of thermal units, while it may increase efficiency of hydropower units. Reduction in output of wind power should be avoided, as it is a waste of free energy. Handling the variations using energy storage is better. To this end, the hydropower resources in Norway and Sweden are important assets for wind power in Scandinavia already today and will be used more in the future. This may, however require transmission system expansion.

7. Analysis of large scale DG affects network business, WP6

7.1 Introduction

Technological advances in other industries are dramatically impacting the electric utility industry at both the macro and micro level. At the macro level, the aerospace industry has delivered the highly efficient, inexpensive, quickly constructed turbine-based technologies, which have been a driving force behind electric utility industry restructuring. The turbine in a GE combined-cycle power plant has as its origin an aircraft jet engine.

Less well known but even more dramatic are the small and micro-scale power plants, technologies born in the military (the electric power source used in M-1 tanks and Patriot missile launchers are powered by new micro turbines) and automotive industries (fuel cell car engines will be fuel cell power plants).

These distributed generating resources are located in the utility's distribution system and can be on either side of a customer's electric meter. Along with better-known and proven energy efficiency and load management technologies, these distributed generators are ready to revolutionize the electric utility industry.

The key to understanding the problem distributed generators pose to utilities is having a clear answer to a deceptively simple question: How do utilities make money? Utility economics differ from the economics of an ordinary competitive business. The details of regulation have a profound, but usually not obvious, effect on the answer.

How utilities are regulated is the most important determinant of whether they have an incentive to deploy or obstruct cost effective distributed generators.

When one wants to analyse how large scale DG affects network business, it is naturally to look at the power system in the Western part of Denmark. The Eltra area has experienced a large-scale introduction of distributed generation (DG). The situation here can be used as a case study for the future development elsewhere.

Present status for RES and DG in the Eltra area are given 1.570 MW of local CHP units and 2.315 MW of Wind turbines are introduced in a the system where the minimum demand in 2002 where 1.189 MW and the maximum demand in 2002 where 3.685 MW. This means that for large portions of the year the distributed generators will be the main source of electricity.

Key information and economic figures are collected from Eltra and the Network Operators in the area. All companies have a substantial number of Distributed Generators installed in their networks.

Technical impacts from, flow towards the transmission system, regulating power, short circuit power, dispatching the CHP units and the system protection are given.

Operational impacts are also reported. Positive and negative experiences are gained from this "experiment". The most significant positive experience is that is has been technically possible with such a penetration of DG in a conventional grid. With the caveat, that strong international connections have been necessary to balance the system.

This work package also reviews the economic aspects for the Network Operators when the number of Distributed Generators increases in their networks.

The work in this work package includes no modelling or simulation. Existing data are used.

7.2 Recommendation for network operators to utilize DG

DISTRIBUTED GENERATION

DG technologies are not all revolutionary. Some have existed for over hundred years, such as generators driven by gasoline and diesel fuelled reciprocating engines. These are mature technologies whose cost and performance characteristics are well known.

Others, such as micro-turbines and fuel cells, are cutting edge technologies borrowed and adapted from the defence (the electric power source used in M-1 tanks and Patriot missile launchers are powered by new micro-turbines), automotive (fuel cell car engines will be fuel cell power plants), and aerospace industries (the turbines in a GE combined-cycle power plant has as its origin an aircraft jet engine).

The location of the distributed resource is critical. Distributed generators installed on the utility side of the meter do not jeopardize profitability. The primary and negative impact on utility profitability of distributed generators deployment occurs when these resources are installed on the customer side of the meter.

This is true for both demand-side and supply-side resources. From the utilities' perspective, demand- or supply-side resources installed on the customer side of the meter produce the same effect: sales go down and as a result revenues and profits go down.

Locating distributed generators in high-cost areas has significant potential benefits. The significant distribution cost savings resulting from distributed generators located in high-cost areas can reduce utility financial losses or even add to profits if the distributed generators are deployed only in high-cost areas.

HOW DO UTILITIES MAKE MONEY?

The key to understanding the problem distributed generators pose to utilities is having a clear answer to a deceptively simple question: How do utilities make money? Utility economics differ from the economics of an ordinary competitive business. The details of regulation have a profound, but usually not obvious, effect on the answer. Utility profits are ruled by a simple formula:

Profit = Revenue - Costs

As the regulation in the Nordic countries is based on revenue caps, the Revenue part of the formula is easily computed (allowed Revenue). So if profit must go up the cost must go down.

The fundamental formula for work is:

Work = Knowledge x Money

This formula is familiar to all, who instinctively know that work can only be accomplished through the application of knowledge and the expenditure of money. Applying this formula to power networks helps us to understand some fundamental truths regarding both developing and mature networks.

In order to apply human intelligence to produce advanced solutions as described in the report, drivers for the future development of active networks must be well understood. These will naturally vary with time but at the moment they are:

- Continued changes in ownership
- Responsibility for risk
- Increased generation from smaller gas fired plant
- Increased generation from renewable sources
- Responsibility for service provision
- Control and communication technologies
- Penetration of power electronics

The next few years will see an avalanche of new opportunities, some of which we can predict, others have yet to emerge. However, there is now a need to carefully consider the design and management of electrical power networks to better fit them for the emerging business opportunities. These networks will require the manifold application of intelligence both from their human owners and in the use of interlinked devices to enable them to become active networks.

ELECTRICITY MARKET OPERATION

The establishment of electricity markets have had major implications for network management.

Even though the Nordic countries have co-operated in the area of electricity for more than 80 years, it was not until the establishment of the Nordic electricity market that electricity could flow freely across the Nordic borders.

Allowing customers to choose supplier freely will force power stations and electricity utilities to reduce their costs. To make this pressure more efficient a more active public price control has been established. This contributes to improved efficiency in the monopoly side of the business: the network operators.

ECONOMIC REGULATION OF NETWORK OPERATORS

How utilities are regulated is the most important determinant of whether they have an incentive to deploy or obstruct cost effective distributed generators. A survey of current practices in the Nordic countries reveals that all have introduced an incentive based regulation based on revenue caps.

A key element is assessing potentials for efficiency improvement is to establish benchmarks for efficient operation. A standard definition of benchmarking is a comparison of some measure of actual performance against a reference performance.

In the Nordic countries different models are used with respect to evaluate the efficiency of distribution utilities:

- Norway : Data Envelopment Analysis (DEA)
- Finland : Data Envelopment Analysis (DEA)
- Sweden : Performance assessment model for electricity networks, "grid Value Model"
- Denmark : Grid Volume Model

In the study it has been found that the Grid Value model does not take into account the technical requirements for connection of the distributed generation. Therefore the majority of cases DG units connected to the network will deteriorate the performance of the Network Operator assessed according to the Grid Value Model. The regulators in Sweden will on this background try to modify the "grid Value Model".

In Norway work are undergoing to establish the effects of the benchmarking model on DG.

There has not been found similar work in Denmark or Finland.

7.3 Large scale integration of DG

When one wants to analyse how large scale DG affects network business, it is naturally to look at the power system in the Western part of Denmark. The Eltra area has experienced a large-scale introduction of Distributed Generation (DG). The situation here can be used as a case study for the future development elsewhere.

PRESENT STATUS FOR RES AND DG IN WESTERN DENMARK

Being the System Operator in the Western part of Denmark, ELTRA faces a great number of new challenges derived from an ambitious energy and environmental policy and a new market concept due to the liberalisation. New paradigms characterise the electricity market for generation and the transmission system since the framework and the conditions have changed dramatically within few years. The structure of the transmission grid in the Eltra area can be seen from the following figure:

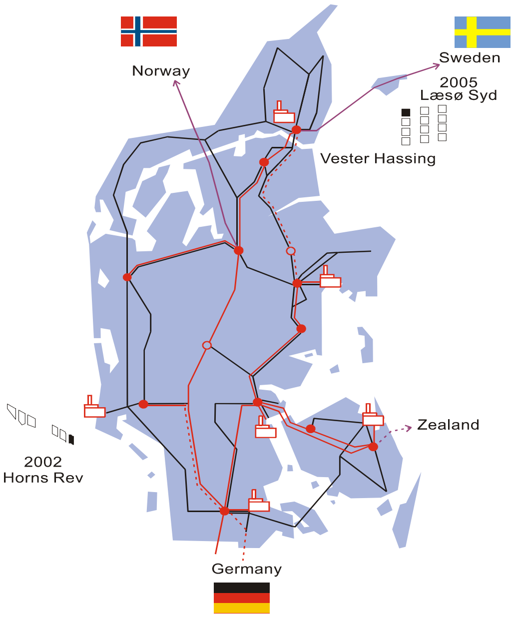


Figure 13. Transmission grid in the Eltra area

ELTRA has the job of balancing the power system taking into consideration that:

- the wind power production is unpredictable
- the CHP production is based on the district heating
- congestion must be managed in a transparent way
- the security of supply is ensured
- the market must function well, based on correct pricing.

Non-dispatchable production in Denmark may influence the market in the Nord Pool area by the amount of bound production.

The transmission grid in the Eltra area covers 712 km of the 400 kV lines and 1.739 km of the 150 kV lines. The Eltra area is connected to Norway and Sweden by HVDC links and to Germany by AC links (400 kV, 220kV, 150 kV, 60kV).

The connection to the neighbouring countries has a total capacity of about 3.000 MW. The Eltra power system forms a link between the Nordel area and of the UCTE area being a member of both organisations.

Table 3. Key figures for the ELTRA system 2002.

Customers	1.600.000	
Network System Operators	49	
Regional Transmission System Operators	6	
Transmission System Operators	1	
400 kV lines	712	[km]
150 kV lines	1.739	[km]
Combined Heat and Power, Central units	3.196 45 %	[MW]
Combined Heat and Power, Local units	1.570 22 %	[MW]
Wind Turbines	2.315 33 %	[MW]
Total	7.081 100 %	[MW]
Energy consumption, including losses	20.858	[GWh]
Peak Load	3.685	[MW]
Off-peak load	1.189	[MW]
Utilization time	5.660	[h]
CHP production, Central units	12.928 55 %	[GWh]
CHP production, Local units	6.723 29 %	[GWh]
Wind production	3.825 16 %	[GWh]
Total	23.476 100 %	[GWh]

TECHNICAL IMPACTS

Flow in 150/60 kV transformers

The flow towards the transmission system level causes problems with regards to regulating tap changes of the transformers and with regard to voltage profiles in the distribution network having lower voltages, at the points of transformation than at the points of infeed of the Distributed Generators. Network Operators therefore often connect the generators at separate outlets where consumption is not connected.

Offshore Wind farms

The energy efficiency is expected to be much better for offshore wind farms than for onshore wind farms. Measurements indicate that the same amount of energy can be produced by half the capacity offshore than onshore. Utilisation time in the order of 4.000 hour is expected.

The control functions for a offshore wind farm in the Eltra area are as follows:

- **Production limitation** set output to a maximum
- **Reserve** operate with a certain reserve downward and/or upwards
- **Balance control** set output downwards or upwards in steps
- **Grid protection interventions** set output to a lower value, in critical situations
- **Gradient limitations** adjust output gradient limit upwards and/or downwards

Each turbine handles its own frequency control. In addition, the reactive power can be controlled locally or centrally so that the wind farm's total consumption/intake of reactive power is kept within certain limits. Disconnection of the turbines in case of grid faults or too strong winds is also controlled individually.

Regulating power

Wind power and local CHP plants have displaced central units, which are being decommissioned, as there are no longer commercial basis for them. It means that the regulating units disappear in areas where the need for regulating capacity is growing. The regulating must then be effected by the local CHP plants and the wind power. Eltra is therefore working on getting these services from the DGs.

Short circuit power

The short-circuit power level has been reduced. The result has been:

- increased limitations on the use of HVDC links especially to Sweden
- increased risk of harmonics
- increased risk of voltage steps when connecting and disconnecting lines
- a risk that faults can be seen at a longer distance.

Priority to CHP and WT production

The energy policy has resulted in approximately 50 per cent of the energy production in the Eltra area now being prioritised. This means that the Danish small-scale CHP production and the wind power cannot be regarded as secondary production and it cannot be closed down when needed.

Complex system

An obvious price for the Danish energy and environmental policy has been a very complex power system to operate. Balancing a power system like ELTRAs can for the time being only be done if it is connected to areas with other types of production. This is not a situation that can be accepted in the long run.

CHP generation

From the very start the direct coupling of heat and power production was a major concern of the power utilities. A situation in which many CHP units made the base load electricity production and the large extraction and condensing power stations were to be dispatched by the power pool at peak load was not considered a satisfactory solution, neither by the utilities nor by the society. The planning tool to overcome this problem has been a three-rate tariff.

System Protection

On the basis of experience, Eltra has set some requirements on relay equipment and settings at local CHP units. Units ranging from 0 to 50 MW must satisfy the requirements.

However, in case of fast 3-pole re-closure local CHP units may be islanded during the dead time, and to avoid unit damage affected units are tripped before re-closure (0.3 s). It is impossible to apply time selectivity. Therefore, as primary protection an under-voltage relay is used, which measures the positive-sequence voltage, possibly supplemented with a ROCOF relay.

The ROCOF relay has given rise to quite a lot of forced outages of local CHP units. The reason is partly that some types of relays are sensitive to the phase shift resulting from short circuits and couplings in the network and partly that Eltra originally recommended too sensitive settings on the ROCOF relay ($df/dt > 1.5$ Hz/s and $df/dt < -0.7$ Hz/s)

However, the strategy for system protection may have to be revised. 10-12 times per year Eltra experiences simultaneous forced outages of many local CHP units.

OPERATIONAL IMPACTS

Positive and negative experiences are gained from the Eltra “experiment”. The most significant positive experience is that is has been technically possible with such a penetration of DG in a conventional grid. With the caveat, that strong international connections have been necessary to balance the system.

As the overflow situation can become critical within the next few years we have to find ways of balancing the system by means of internal Danish measures. An analysis made in co-operation with the Danish Energy Agency states that the following devices are of interest:

- closing down wind turbines
- closing down local CHP plants

- introducing flexible loads
- installing heat pumps

At the moment Eltra is analysing the possibility of dispatching the local CHP's. The use of these measures will need changes in the taxation system.

A new strategy

After the mixture of production and consumption in the same local networks the operational tasks have become far more complicated, particularly under emergency conditions.

The present control structure is based on a division of the electrical network into two parts: a distribution network connecting end-users to the electricity supply system and a transmission network connecting power plants and cross-border lines to the network. So far, little operational co-ordination has been required between the two networks, both under normal conditions and in emergency situations.

Therefore, the most important basis for a new strategy is the recognition that the distribution networks no longer can be considered as passive appendages to the transmission network, but that the entire network must be operated as a closely integrated unit. Organising cooperation on this task is a major challenge.

Furthermore, a number of technical improvements have to be developed and implemented. Conditions for central and local electricity production must be equalised bringing all power plants to contribute to system stability and flexibility.

Electricity production and consumption must be measured and switched separately. The quality of the current system analyses must be improved, and manual system control necessary during emergency operations must be organised in cooperation with the distribution network operators.

New principles

A systematic elimination of the weaknesses demonstrated above is possible, but considerable time and some new equipment will be required for supervision, measurements, analyses and control.

Several international studies have presented ideas for the integration of distributed electricity production. Some principles for use in the Eltra area have been identified as the basis for a long-term solution:

- A control hierarchy consists of a central control centre (at Eltra) and 3-6 regional control centres. Each region consists of a number of local areas. Each local area is connected to the transmission system via one 150/60 kV substation. An unambiguous operational responsibility must be defined for each local area.

- The prioritising of electricity from local CHP plants must be cancelled, so these power plants can be operated in the same way as conventional power plants in accordance with price signals from the day-ahead market and the real-time market. This principle offers network access on equal terms for all producers and opens up for a better utilisation of the network.

- The balance of reactive power within each local area must be kept within certain limits to be defined in a new set of rules. There must be a local responsibility for observing these rules and the control of local reactive resources (including condensers and local CHP plants) must be local as well.

- New rules for measuring must provide all necessary data for the regional control centres and to the extent necessary to Eltra. Reliable information on the state of the system and data for accurate system analyses must be available at any time.

- During emergency operation it must be possible to switch loads and production units separately. The principle applies to both automatic load shedding by frequency relays and to the manual restoration after serious power failures.

- During normal operation only Eltra's control centre will be manned 24 hours per day. In other system states (from alert to emergency) it must be possible to man the regional and local control centres concerned. Restoration after a complete system collapse will be the ultimate challenge. Procedures for this situation must be trained, but hopefully never used.

Cooperation required

A number of tasks must be solved together with the regional transmission operators and the distribution network operators in preparation for the implementation of these principles.

Mapping of production and consumption

From the very beginning a mapping of the distribution of production and consumption for all 60/10 kV terminals and of the equipment for measuring will be required.

Rules for Measurements, Generators and Communication

Furthermore, new rules must be prepared for a number of areas, including measurements, reactive power, local power plants and communication.

Procedures for Reactive power balance, curtailment of load and restoration

Finally, new procedures for local control of reactive balance, manual curtailment of load and production and for the restoration after system failures must be developed.

ECONOMIC IMPACTS

Network reinforcement

The appearance of local CHP units has influenced the network expansion of recent years. At 10 kV and 60 kV level the task of the network is no longer just to distribute energy - the CHP units and wind turbines also mean that the network must be able to collect the energy where it is produced. All things considered, this has increased the network expansion at the 10 kV level, and in a few cases also at the 60 kV level.

Socialized costs

In the ELTRA area some of the costs for network reinforcement due to connection of CHP and WT turbines (with a capacity greater than 1.5 MW) are socialized. In the period from 1992 to 2002 these socialized costs amount to 706 MDKK.

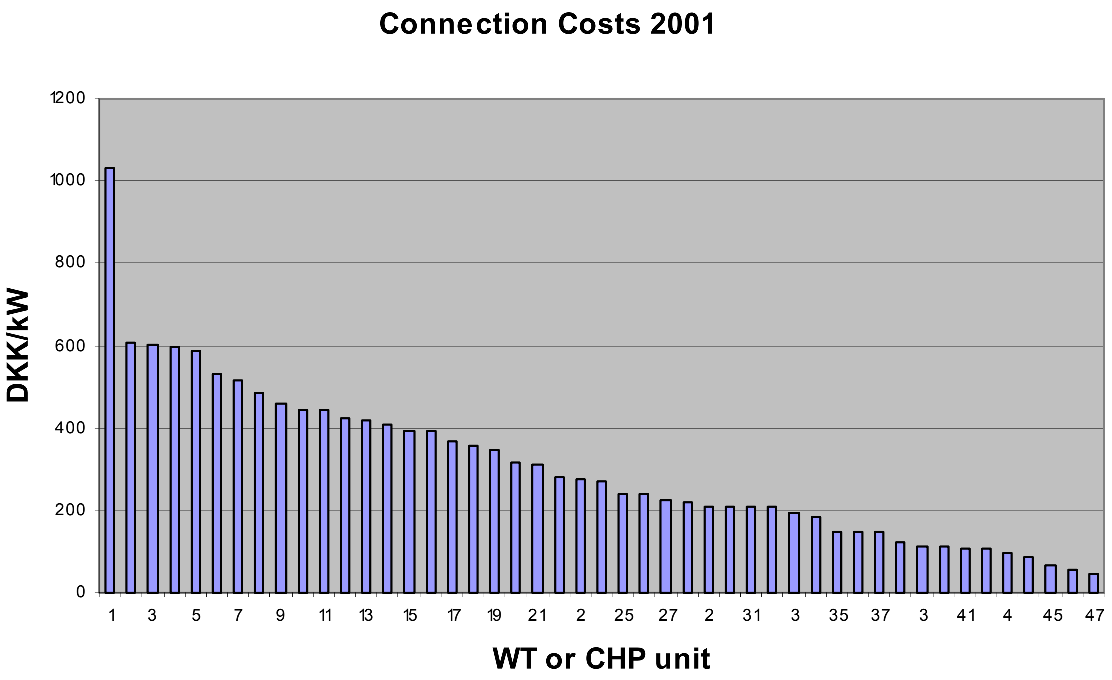


Figure 14. Connection costs of DG in Eltra area

Cost models

The socialized costs were in the beginning based on the real project costs, but the administration of this system was connected with high costs. It was then decided to estimate the project costs by a cost model. The accuracy of this model is +/- 20%. The model has been calibrated by use of 156 real cases. The connection costs for 2001 can be seen from the previous figure.

Regulation

The interest in benchmarking arises from the widespread trend of incentive-based regulation in which efficient companies are rewarded and inefficient companies must implement cost cuttings. The allowed revenue consists normally of Operating Costs, Depreciation Costs, Return on Capital and Costs to other activities:

Allowed revenue = Operating Costs (OPEX)
+ Depreciation Costs (CAPEX)
+ Return of Capital

But it is only the **OPEX** and the **CAPEX** that are subject for the benchmarking.

Benchmarking

The factors that drive the cost of operating and maintaining a distribution grid are different from company to company. However, there is one common driver for all the companies - the grid. There is a clear correlation between the size of the grid and the cost of operating and maintaining it. Therefore, the size of the grid is basis of the Grid Volume Model.

The benchmarking is done in six steps:

- Computation of Grid Volume
- Computation of Cost indexes
- Definition of "Best practice"
- Computation of Total cost index
- Computation of Efficiency
- Computation of Revenue cut

In the following figure the efficiencies for the Network Operators in ELTRA's area 2001, can be seen.

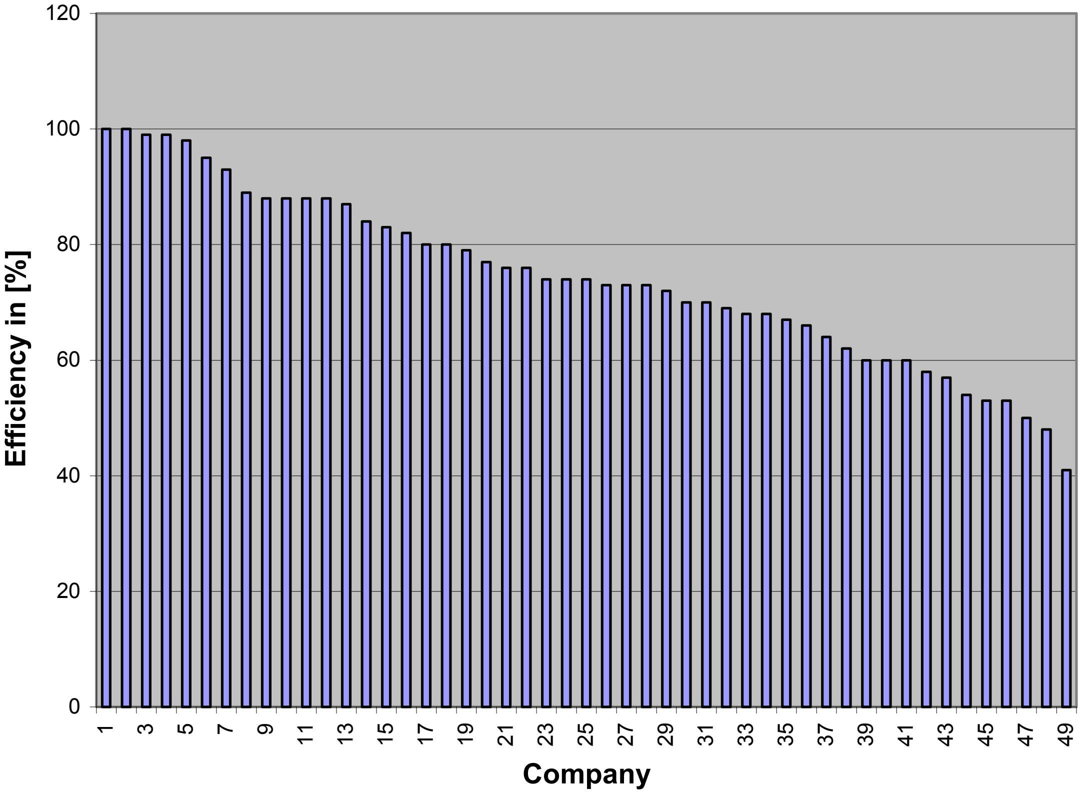
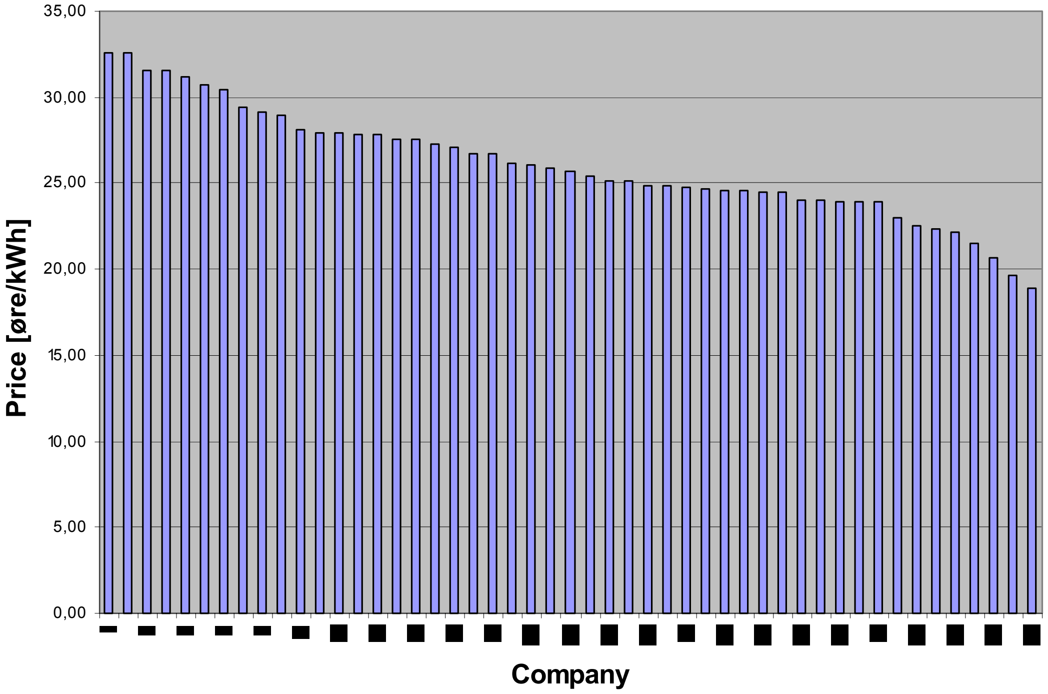


Figure 15. Efficiencies for the Network Operators in ELTRA's area 2001

In the figure 16 the price distribution of the Network Operators in the Eltra area 2001, can be seen.



[redacted]

Figure 16. Price distribution of the Network Operators in the Eltra area 2001

Figure 17 shows the efficiency as a function of the price. This figure is a little surprising, even when the estimated line says: that higher prices gives lower efficiencies.

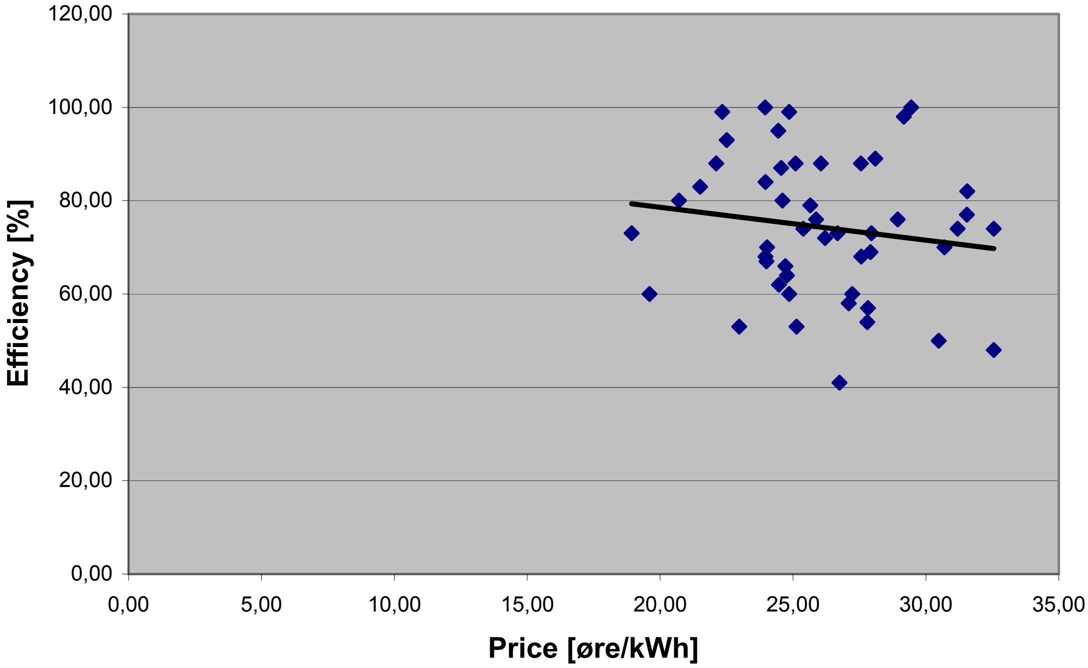


Figure 17. Efficiency as a function of the price

Figure 18 is showing the price versus the "Share of DG". With a very good will it could be said that the price is going up when the share of DG increases,

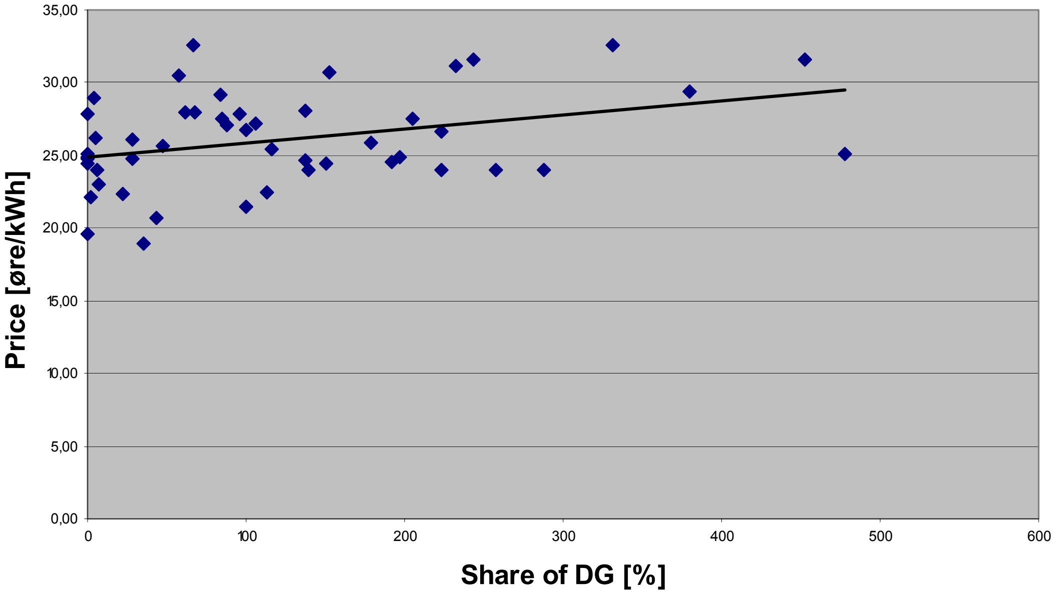


Figure 18. The price of electricity versus the "Share of DG".

8. Summary and proposal for further studies, WP 7

8.1 Connection of DG in the network

Connection of a lot of small-distributed power generation units to the distribution network will have consequences related both to technological, economic and legal matters. When distributed generation become more common and the unit sizes increase, connection and disconnection effects on the network increase. The network and grid companies are especially worried about the variation of electricity generation causing problems in network balance and possible need for reserve capacity, and on the effect of different kinds of generators on the quality of supply and the protection of the system.

One of the main results of the project was a set of simulation models that can be applied in further studies. These models have been applied in simulations that also provide information about different technical issues relating to power quality as well as system protection, when the share of DG increases. In spite of a number of simulation studies, it has turned out that there are still many more things that need to be investigated.

Operation and protection of distribution networks today is to a large extent based on radial design with single-sided infeed of load and fault current. The introduction of DG in a radial network leads to a situation with multiple infeed of load and fault current. Operation and protection must somehow adapt to this.

Requirements for independent island operation have been studied with examples of different types of islands in power systems. The circumstances when island operation becomes advantageous have been documented as well as the necessary conditions for island operation, difficulties, possible solutions and collected experience.

8.2 Conclusion of results

There are a number of technical, economical and legal issues, which needs to be clarified when the penetration of DG increases. Dynamic simulation proved to be a useful tool to investigate the technical issues. A number of challenges were identified, and there is still a lot of work to do in creating feasible solutions, e.g. in the fields of protection, control and operation, as well as in the commercial matters.

It is necessary to conduct further studies on the effect on distribution line voltage variation. Short-circuit current from a DG unit may cause malfunction of over-current relays and fuses. It may be necessary to develop a new fault detection system. One obstacle may be the need of ensuring safety of DG units by safety inspections of the equipment.

The most important basis for a new strategy is the recognition that the distribution networks no longer can be considered as passive appendages to the transmission network and the entire network must be operated as a closely integrated unit. Organising cooperation on this task is a major challenge.

To better handle the power balance with high penetration of DG, system operators want the DG units to behave more like conventional generating units. Recently issued requirements on DG and wind farms show that the first priority is to avoid tripping of generation. The location of the distributed resource is also critical. Distributed generators installed on the utility side of the meter do not risk profitability. Potential to locate distributed generators in high-cost elctricity areas has significant benefits. The quality of the current system analyses need to be improved and during emergency operations the manual system control necessary must be organised in cooperation with the distribution network operators.

Connecting a lot of small power production units to the distribution network will inevitably have some sort of effect on both the distribution network and, if the share of DG becomes large enough, the high voltage transmission network. DG plays a special role in the power balance, since it to a great extent is neither dispatchable like conventional generating units and nor predictable like the load. Tasks of needed arrangement would be useful to be solved together with the regional transmission operators and the distribution network operators.

8.3 Project and research area in DG

There is a lot of work to do in creating standards and requirements for DG interconnection in the same way when connecting consumers into the network. Both technical and commercial issues are challenging. For international operations (Nordel cooperation and business culture of multinational companies) it would be good to get a common basis to generate common concepts and regulations for DG questions. In the future this could be promoted for example by larger EU-wide project.

With a low level of DG penetration, system operation is in no way critically depending on the generated power. On the contrary, in case of abnormal situations all DG units are required to trip. This immediately leads to a distribution system with single-sided in-feed of fault current and where conventional philosophies for protection and restoration are valid. Assuming a sizable penetration of DG, the units should be considered an important security asset and then need to be treated differently. Further steps to increase security of supply would be to allow DG units to feed island networks and to use meshed distribution networks. This requires that a number of issues be properly dealt with. The ultimate future scenario is to redesign system operation completely to handle islanding and meshed networks.

Basing on information from simulations some recommendation was given relating to the network connection of the DG, but it also turned out that there are still many more things that need to be investigated. The DG connection issues were studied with only one typical network model, while in order to have a complete picture of the observed topics a large number of various network arrangements as well as load and DG unit combinations must be analysed.

References

1. CODGUNet project plan

2. Work Package reports from WP 1-6 of CODGUNet

WP 1 General overview on the issues related to the connection of DG in the network, VTT Processes Vaasa, Finland

WP 2 Present status of DG in Nordic countries, VTT Processes Vaasa, Finland

WP 3 Aspects of different distributed generation technologies, Vattenfall Utveckling Sweden

WP 4 Network connection of different types of distributed energy generations, technological analyses, Technobothnia, Vaasa Finland

WP 5 Effects on power system, SINTEF Norway

WP 6 Analysis of large scale DG for network business, Eltra Denmark