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INTEGRATION OF MICROGRIDS INTO ELECTRICITY DISTRIBUTION NETWORKS

Examiners: Prof. Jarmo Partanen
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ABSTRACT

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Integration of microgrids into electricity distribution networks

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Existing electricity distribution system is under pressure because implementation of distributed generation changes the grid configuration and also because some customers demand for better distribution reliability. In a short term, traditional network planning does not offer techno-economical solutions for the challenges and therefore the idea of microgrids is introduced. Islanding capability of microgrids is expected to enable better reliability by reducing effects of faults. The aim of the thesis is to discuss challenges in integration of microgrids into distribution networks. Study discusses development of microgrid related smart grid features and gives estimation of the guideline of microgrid implementation. Thesis also scans microgrid pilots around the world and introduces the most relevant projects. Analysis reveals that the main focus of researched studies is on low voltage microgrids. This thesis extends the idea to medium voltage distribution system and introduces challenges related to medium voltage microgrid implementation. Differences of centralized and distributed microgrid models are analyzed and the centralized model is discovered to be easiest to implement into existing distribution system. Preplan of medium voltage microgrid pilot is also carried out in this thesis.

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Hajautetun tuotannon lisääntyminen ja asiakkaiden tarve paremmasta käyttövarmuudesta asettavat muutospaineita nykyiselle sähkönjakelujärjestelmälle. Perinteinen verkostosuunnittelu ei kykene lyhyellä aikavälillä tuottamaan teknistaloudellisesti järkeviä ratkaisuja haasteisiin ja on siten rajoite tuotannon liittämiselle. Älykkäiden sähköverkkojen on tarkoitus luoda uusia ratkaisuja kyseisiin ongelmiin. Saarekekäyttöön kykenevät mikroverkot voisivat mahdollistaa hajautetun tuotannon tuoman potentiaalin hyödyntämisen myös käyttövarmuuden parantamisessa. Diplomityö tarkastelee mikroverkkojen potentiaalia osana sähkönjakeluverkon kehitystä. Työssä luodaan arvio mikroverkkojen yleistymismahdollisuuksista sekä tuodaan esiin eri vaihtoehtojen haasteita. Tuotantokeskeisen mikroverkon havaitaan sopeutuvan paremmin nykyiseen jakelujärjestelmään suojaus- ja mitoitushaasteiden vuoksi. Saarekekäyttöön kykenevät ja hajautettua tuotantoa hyödyntävät mikroverkot herättävät kiinnostusta ympäri maailman ja työssä esitellään tärkeimpiä mikroverkkopilotteja. Kirjallisuustyössä havaitaan, että maailmalla tehty tutkimus painottuu pienjännitemikroverkkoihin. Tässä työssä laajennetaan ajatusta keskijännitemikroverkkoihin ja käsitellään niiden käyttöönoton haasteita. Työssä luodaan myös alustava suunnitelma mikroverkkopilotista suomalaisessa jakeluverkossa.

PREFACE

This thesis was carried out as a part of "*Smart Grids and Energy Markets*" -research program. The topic was provided by Fortum Sähkönsiirto Oy.

I am grateful to Kari Koivuranta and Oleg Gulich for providing me this interesting subject. Kari retired during my working period and therefore I want to wish him happy retirement days. I would also like to express my compliments to Pekka Vierimaa who has worked as my boss and helped me with the microgrid pilot preplanning. In addition, special thank goes to the "coffee break visionaries" who have knocked on my door from day to day and have cheered me up with all those stories.

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Espoo, March 2012

Jukka Ihamäki
Life is not about finding yourself. Life is about creating yourself.

CONTENTS

ABBREVIATIONS AND SYMBOLS

ADA	Advanced Distribution Automation
AMI	Automated/ Advanced Metering Infrastructure
AMM	Automated/ Advanced Meter Management
AMR	Automated Meter Reading
BESS	Batter Energy Storage System
CAN	Controller Area Network
CB	Circuit Breaker
CHP	Combined Heat and Power
DER	Distributed Energy Resource
DFIG	Double Fed Induction Generator
DG	Distributed Generation
DMS	Distribution Management System
DR	Demand Response
DSO	Distribution System Operator
EV	Electric Vehicle
FPC	Full Power Converter
G	Generator
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HV	High Voltage (>36 kV AC)
ICT	Information and Communication Technologies
IED	Intelligent Electronic Device
INCA	Interactive Customer gateway
IG	Induction Generator
IMB	Intelligent Microgrid Breaker
INCA	Interactive Customer Gateway
IP	Internet Protocol
LAN	Local Area Network
LOM	Loss Of Mains -protection
LV	Low Voltage (≤ 1 kV AC)

LVDC	Low Voltage Direct Current (≤ 1.5 kV DC)
MCU	Microgrid Control Unit
MG	Microgrid
MMS	Microgrid Management System
MV	Medium Voltage (> 1 kV and < 36 kV AC)
NIS	Network Information System
PCC	Point of Common Coupling
PLC	Power Line Communication
PN	Positive-type and Negative-type -junction
PQ	Power Quality
PV	Photo Voltaic
RTU	Ring Terminal Unit
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
SG	Smart Grid
SGEM	Smart Grids and Energy Markets -research program
STS	Static Transfer Switch
TSO	Transmission System Operator
VPP	Virtual Power Plant
WT	Wind Turbine

f	Frequency
P	Active power
Q	Reactive power
R	Resistance
V	Voltage
X	Reactance

1. INTRODUCTION

High share of Finnish distribution networks are in 50's and 60's. These grids have exceeded their lifetime (40 a) and they need to be rebuilt. Technology used today is almost the same as fifty years ago but now there is a chance to build better grids for next decades. So called smart grids (later SG) might be an answer to the problems. Single smart grid features might not always be applicable but the total advantages of smart grids are expected to be greater than the sum of separated parts.

Development of smarter grids has recently produced thousands of studies about different smart grid features that could be implemented into distribution system. One interesting entity is microgrid concept. Microgrid utilizes smart grid features in a small part of distribution system and makes it capable for autonomous operation. Although, microgrids are not yet ready for large scale implementation because of the high costs of the technology, they need to be studied now to guarantee that the smart grid technology will also be applicable for microgrid operation. Microgrids develop distribution system to the direction where quality of supply is secured near the customers instead of making high investments into the main network. Overall advantages of microgrid operation are better energy efficiency, smaller environmental effects, and better reliability.

Customers demand for better reliability and power quality is one of the most obvious drivers for smart grids. Another important driver is increase of distributed generation (later DG) which acts not only as a challenge but also as an enabler. At the same time customers want both lower electricity and distribution costs. Requirement of higher demands and lower costs creates pressure to improve cost structure and to use new techno-economical technology. New innovations are needed to enable both lower costs and better services.

This thesis discusses microgrids and their implementation into distribution grids. The main focus is on technical challenges of medium voltage microgrids in Finnish distribution system. Aim of the thesis is to scan the backgrounds of microgrid operation and to discuss enablers and barriers of microgrid implementation. Thesis creates a scenario of microgrid implementation by combining the development of smart grid features with microgrid functionalities.

Thesis begins with literature study which points out the most valuable research studies of microgrid operation. Development of smart grids and microgrids include lots of uncertainties which cause that the final microgrid or smart grid model cannot be literally defined. Nevertheless, a good scenario can be created with knowledge of the backgrounds and visions of the future. Thesis examines existing and planned microgrid pilots around the world. Thesis also points out the main challenges of microgrid operation which are mainly caused by low inertia and low fault currents. Finally thesis presents a preplan of medium voltage microgrid pilot.

1.1 Relationship with other studies

A lot of microgrid research is done and several research projects are established around the world. Literature study is made to clear out the findings of the most interesting and relevant research projects. The study also points out the focus of the research and which issues need to be discussed further. More detailed version of the literature study is in appendix I and the short version is presented in Table 1.1.

Table 1.1. Literature study related to microgrid and smart grid issues. The amount of X-marks describes how well the study in question discusses the subject. (X = a bit and XXX = Well)

	Smart grids					Low voltage microgrids					Medium voltage microgrds				
Source	SG visions	Distributed energy resources	SG components	SG communication	Business opportunities	Microgrid models	Protection	Control/ stability	Pilot	Business opportunities	Microgrid models	Protection	Control/ stability	Pilot	Business opportunities
(ETP 2010)	XXX				XX										
(Commission 2010)	XX	X	X												
(VTT 2006)	XXX					X									
(Biomeri 2009)	X	XX			X										
(IEA 2010)		XXX			XX										
(INCA 2010)	XXX		XX	XXX	XX			X							
(VTT 2009)	X	XXX			X										
(Sahay & Dwivedi 2009)	XX	XX						X					X		
(Löf 2009)	X	XX	XXX	X	X										
(Pasonen 2010)	XXX	XX	X	X		X	X	XX	X	XX					
(Laaksonen 2011)			X	X		XXX	XX	XXX		XX					
(Elias-Alcega & al. 2011)				XX		XX	X	XXX	XXX						
(Lasseter & al. 2011)				XX				XX	XXX						
(Johnson & Ducey 2011)									XXX						
(Khattabi & al. 2009)				XXX		XX	XX	XXX	XXX	XX					
(Antikainen & al. 2011)	X	XXX	X		X							X	X		
(Keeyoung & al. 2009)		XX	X	XX				XXX	XXX			X	X	XX	
(Schawaegerl & al. 2009)						XX		XXX		XXX	X		X		X
(Sortomme & al 2010)						X	XXX	X			X	XXX	X		
(Voima & al. 2011)											X	XXX	X		

It has to be borne in mind that the publications presented in the table above do not fully cover the research area of smart grids. However, results show that smart grid features are widely studied already today. Many issues, such as interactive customer gateway, are really advanced. Literature study also reveals that smart grid is a current topic. Microgrid operation as a part of distribution system is relatively new subject, even though islanded operation was obviously the only choice in the beginning of electrification. The idea of low voltage microgrids has emerged due to the smart grid visions, and now the idea is extending to medium voltage microgrids. Many referred studies discuss LV microgrid piloting and it seems to arouse interest around the world. Nevertheless, results are still missing and many pilots only resemble microgrid operation instead of being a real solution as discussed later in this thesis.

Small circle in the right corner of Table 1.1 presents the most interesting studies about MV microgrids. MV microgrid subjects are less examined than LV microgrids which mean that especially MV microgrids need to be discussed further. Also the lack of MV microgrid piloting or plans of implementation can be noticed. This thesis studies MV microgrids and points out the main challenges of MV microgrid operation. Literature study also shows that business opportunities and business models need further development. However, in this study business models are discussed only superficially. Germany is often used as an example case in this thesis because Germany has a lot of renewable energy sources deployed in the networks already. Thus, many of the challenges, which are expected to be encountered in Finland, are already acute in Germany.

2. OVERVIEW OF MICROGRID FUNCTIONALITIES

Microgrid is not a specified term that is used similarly everywhere. More or less common for all definitions is that microgrid is a part of future smart distribution grid which has island operation capability. Microgrid is also expected to enable new opportunities for customers and business stakeholders. The bases of microgrid are local distributed energy resources (DER). DER can consist of distributed generation, energy storages, or demand response, all of which have impact on power balance. One purpose of microgrids is to improve distribution reliability by reducing the amount and duration of distribution interruptions with island operation. It is good to understand the variations of microgrid definitions before diving into a more detailed study of microgrids. The following list sums up the main differences in different microgrid visions. However, small alternation can be found from all of the studies. Microgrid can be:

- a part of distribution network which has islanding capability and reduces outages. Microgrid works as a part of future self healing smart grids. (Laaksonen 2011)
- *"an integration platform for supply-side (micro-generators) and demand-side resources (storage units and (controllable) loads) located in a local distribution grid"* (Schawaegerl & al. 2009).
- *"an autonomous power system, which is able to provide itself with power and all necessary services".* Islanded operation is only a special emergency case. (Fette 2011)

The list above shows that the idea of microgrids is still incomplete and different research groups have different views. Laaksonen (2011) considers microgrids as technical entity that can provide better distribution reliability. In the study Schawaegerl & al. (2009) microgrid is seen more as a local distribution system that enables easier connection of DER units. Professor Fette (2011) considers microgrids as a self managed and self serviced power system where islanded operation is only a special case. Differences in definitions can be explained with different drivers for microgrid operation. For instance, operating environment and network structure varies in different countries. The fact that electricity transmission and distribution are regulated monopoly businesses has own impact too. In Germany the amount of distributed generation has grown a lot within last few years which has caused stability and transmission problems. These kinds of problems have not been seen in Finland, at least not yet. In Finland, the drivers for microgrid operation are more closely related to better outage numbers, such as lower system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI).

In addition to variation in microgrid functionalities, the way how the wanted functionalities are achieved can vary a lot. Grid configuration can vary from simple radial to complicated meshed grid. Control and intelligence can be either centralized or decentralized. The amount of generators has an impact on the microgrid system too. In this thesis, the word microgrid describes a network that has the following features:

- System has islanding capability but is normally connected to distribution network
- DER units produce major part of the consumed electricity
- Power flow can be multidirectional but the grid is operated as a radial network

In this thesis, the islanding capability is seen as a base of microgrid operation because it enables also most of the other microgrid related functionalities. For instance, microgrid needs to include enough electricity production units to enable island operation. Microgrid is expected to be autonomous power system that is self-sufficient in energy production and is able to reduce outages.

There are still many uncertainties related to microgrids, such as what are the roles of different stakeholders, how fast will the technology develop or implement, and whether microgrids are going to be cost effective way to limit outages or not. The future of microgrids is highly dependent on development of other smart grid features, such as fast, reliable, and inexpensive communication, cost effective energy storages as well as implementation of distributed generation (DG). In Germany, the distribution business and the role of distribution system operators are developing from grid building and network operating monopoly towards service provider for network owners. Therefore in future, the owner of the grid might no longer be distribution system operator (Fette 2011).

In the beginning of microgrid implementation, it might be reasonable to implement microgrids for critical customers who are willing to pay a premium for more secure electricity supply. When the microgrid technology develops, it can be expected that the system costs come down and microgrids becomes reasonable choice for wider customer segment. It is also good to understand that cost efficiency is not always the key for everything. It has been noticed in the business life that if customers want something, they might invest in it even though it is not economically reasonable. Good examples of this kind of behavior are expensive cars, smart phones, or tablets. In other words, small scale or one-customer-type LV microgrids may have potential because they can offer independency and image of environmental friendly values. On the contrary to small scale LV solutions, large scale MV microgrids will probably be techno-economical solutions operated by DSOs. This means that the technology needs to develop before implementation of MV microgrids. Timeframes are more closely discussed later in this thesis.

2.1 Existing distribution system from microgrid perspective

Before going into the details on microgrids, it is good to understand what kind of environment existing electricity networks offers for microgrids. First of all, existing grids are quite passive. In Finland, lots of electricity grids are built during 1960-1970. As a result, many parts of local and regional networks need to be renovated in the near future. Networks build today will be a part of distribution system for another 40-50 years which means that decisions of future smart grids needs to be done now. Today, grids do not offer much real time information about loads, faults, or voltage quality, especially from the low voltage grid. In future, more information will be available due to implementation of smart meters and other sensing devices. However, exploitation of the information provided by automated meter management (AMM) is still under development.

The society is more and more dependent on electricity therefore there is a growing need for better distribution reliability. Nowadays, better reliability in electricity distribution is reached with automation at medium voltage network and using cabling instead of bare overhead lines. In other words, reliability is often enhanced by investing more into passive distribution system. However, this might not be enough to satisfy customers and society's needs. In addition, electricity customer base gets more and more segmented over time. Some customers want better reliability and are ready to pay for it, while others are satisfied to existing reliability with lower costs. Society has certain requirements for the distribution system for instance one need is to secure the operation of telecommunication link stations during long lasting blackouts. Microgrids have potential to solve these problems with a solution that reviews the problem from a new perspective. Microgrids can enhance the reliability near the customer instead of securing the whole distribution system. (Antikainen & al. 2009)

2.2 Functionalities and operational conditions

This section sums up the main functionalities that are expected from microgrid operation. These issues are more closely studied later in this work. Microgrid is often wanted to be flexible system where new things can be implemented as if plug-and-play devices (Schawaegerl & al. 2009; Laaksonen 2011). It is not an easy task to create such a microgrid that is a flexible platform for large amount of different DER units and able to operate in islanded mode at the same time. Basic requirements of electricity system need to be fulfilled also in microgrid operation. This means that operational conditions, such as power balance, voltage quality, and electrical safety need to be taken into account. Microgrid features are sorted into three categories in Figure 2.1.

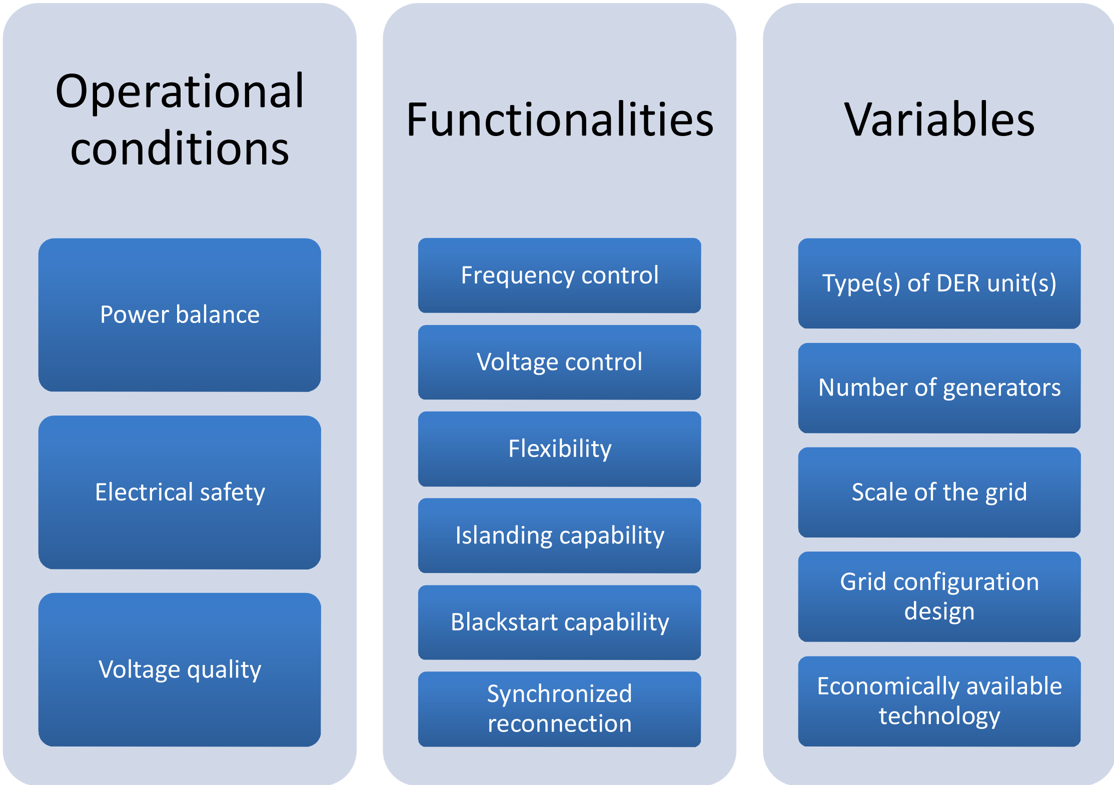

Figure 2.1. Operational conditions, functionalities, and the main variables in microgrid operation.

Operational conditions of microgrids have to be fulfilled all the time. Required functionalities depend on many variables and the final solution is a complex combination of choices and system elements. Different DER units have different control capabilities and may cause advantages or disadvantages in island operation. Flexibility means capability to adopt changes in the grid, such as the amount of accommodated distributed generation or increase the amount of customers. Flexibility of the microgrid is highly dependent on the network configuration design and the used set of technologies. In addition, the existing number of the generators influence on flexibility.

Implementation of distributed generation into existing grids has already caused problems in voltage and frequency control (Fette 2011). Problems can be clearly seen in Germany where aggressive support actions have led to fast growth of renewable energy production. Increase of DGs is not a problem but it has indirect effects. There is discussion about 50.2 Hz -problem because the protection of DGs used to be planned so that all old DG units disconnect when the 50.2 Hz is exceeded. Disconnection leads to instability in production and consumption which in worst case might cause a blackout to whole network. Table 2.1 shows what kind of impacts different DG units have on microgrid functionalities.

Table 2.1. Impacts of different generation units on microgrid functionalities. +++ means significant positive impact and --- significant negative impact.

	Wind power			**Solar**	**Load control**	**CHP**	**Hydro**	**Diesel**	**Battery**
	DFIG	FPC	IG	FPC					
Power balance	--	-	---	-	++	+++	+++	+++	+++
Voltage quality	+	+++	--	+++	+	++	+++	+++	+++
Frequency control	+	+	---	+	+	+++	+++	+++	+++
Voltage control	+	+	---	+	+	+++	+++	+++	+++
Flexibility	+	+	-	+	+	++	++	+++	+++
Islanding	+	+	---	+	++	+++	++	+++	+++
Blackstart		+	-	+	+	+++	+++	+++	+++
Synchronized reconnection	+	+	---	+		+++	+++	+++	+++

It can be seen from the table above that wind and solar production have negative impact on power balance because of their nature. Full power converter (FPC) connected production units have positive control features but they can be used only if the unit is generating power. Combined heat and power (CHP) production, hydropower, and diesel generators can be equipped with frequency and voltage control systems which means that they then have good control functionalities. The growth of diesel or hydropower can be seen limited in the future which limits the use of these control capabilities. Thus, optimal production types for microgrid functionalities might be CHP and battery storage. Use of battery storages might also enable larger share of intermittent production in microgrids and potentially solve the issues identified above.

2.4 Properties of different microgrids

In theory, microgrid can be formed in any area of the network, based on different control methods and even on different voltage levels as long as there is enough local production and controllability. More detailed information about required control capabilities and other prerequisites of microgrid operation are discussed in Chapter 5. The main principle of microgrid operation remains the same despite the above mentioned variations. The main principle is that microgrid is a part of distribution system and capable to operate in islanded mode. Electricity production is based on distributed resources. Different microgrids are presented in Figure 2.2.

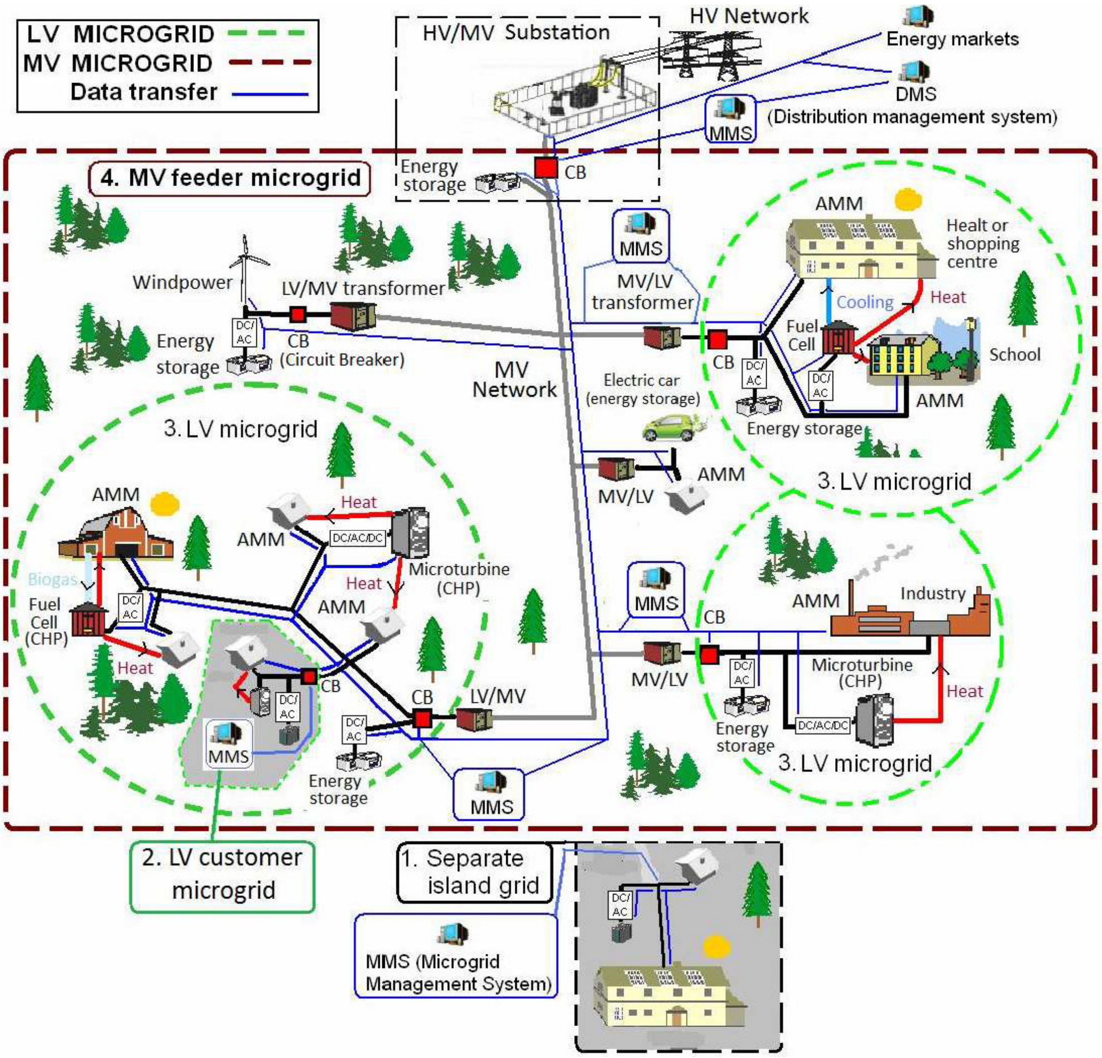

Figure 2.2. Different microgrids (Laaksonen 2011).

Laaksonen (2011) has separated different microgrids into four cases which are separated island microgrid, low voltage customer microgrid, low voltage microgrid, and medium voltage microgrid. The first one in Figure 2.2. expresses separate island microgrid where DER provides electricity to one customer or small community outside the utility grid. Suitable places could be distant islands and small villages far away from the utility grid. Summer cottages outside of the utility grid could also be electrified with this kind of microgrid. (Laaksonen 2011)

Second case in Figure 2.2. presents low voltage customer microgrid. In this case for instance, one farm or detached house have own DER unit(s) to provide needed electricity. Low voltage customer microgrid operates normally parallel with utility grid. However, in case of fault in the utility grid, the microgrid is operated as island microgrid. In this case, solar and wind power production need energy storage to offer constant electricity source. (Laaksonen 2011)

Case number three is a low voltage microgrid that consists of a group of low voltage customers. LV microgrid can include anything from few consumption points to whole low voltage network fed by a MV/LV transformer. Power production of this kind of microgrid can be based on many small scale production units and types. For instance, solar panels on the roof of detached houses and microturbine that provides CHP. (Laaksonen 2011)

The fourth case is a medium voltage microgrid. In medium voltage microgrid, bigger production units can be applied to MV network. MV microgrid can consist of a part of HV/MV substation output or the whole output. It can also be possible to use all outputs of the HV/MV substation as a microgrid. Medium voltage microgrids offer an opportunity for wind power parks and other big production systems to produce electricity during interruption in the utility grid. This is advantage also for the producers. (Laaksonen 2011)

The basic principle is the same in all microgrid types. The general ideas and protocols related to microgrids are the same for LV and MV microgrids but, when it comes to more details, separating factors can be found. In addition to technical issues, separating factors are related to present day market structure and ownership of the grid. The solution should be feasible for all business parties. The first question is how to realize this technically. The second and the biggest challenge, related to all of the problems, is how to do things economically.

As mentioned in previous sections, there are many variables related to microgrid operation. In addition to differences in voltage level, there can be differences in the number of generators. Type and nominal power of the DER units has an impact too.

Higher number of generators increases the complexity of the system and requires communication to enable same control capabilities that are achieved in the case of couple of units. On the other hand higher number of generators increases the reliability because the whole system will not collapse if one unit is not working. Different generator types are compared in different microgrid (MG) environments in Table 2.2.

Table 2.2. Comparison of different generation types in different microgrids. + useful and +++ very useful solution in microgrid operation.

Number of generators	Separate island MG		LV customer MG		LV MG		MV MG	
	One	Many	One	Many	One	Many	One	Many
Wind (DFIG)	+	+	+	++	+	++	++	++
Solar (FPC)	+	+	+	++	+	++	++	++
Hydro	++	++	++	+++	++	+++	++	+++
CHP	++	+++	++	+++	++	+++	++	+++
Diesel	+++	+++	+++	+++	+++	+++	+++	+++
Battery	+++	+++	+++	+++	+++	+++	+++	+++
DR	+	+	+	+	++	++	++	++

Table above shows the fact that intermittent production types have the lowest flexibility. This can also be seen as low reliability and unsatisfactory control functionality. More constant power sources, such as hydro power and CHP, have better controllability than intermittent production. The best flexibility and controllability is with diesel generators and battery energy storages. Demand response (DR) has positive effect on system flexibility but it can be seen as additional control reserve in addition to power production.

2.4.1 Low voltage microgrids

Low voltage microgrids can vary from a single customer to several customers. Small scale low voltage microgrids can satisfy customers' needs for more reliable electricity distribution. Low voltage microgrids can give extra benefit for customers who invest in DG. Instead of network operator interest, small scale low voltage microgrids can rather be seen as customers' interest. Customers, who are willing to pay a premium for better reliability, can invest into DGs and microgrid equipment, such as microgrid main switch and control system. Microgrid that consists of the whole low voltage network of a secondary substation can be interesting also for distribution system operators but the costs are still excessively high. However, separated customer microgrids or single customer microgrids could be interesting for some customers even though they would not be economically competitive.

2.4.2 Medium voltage microgrid

Medium voltage microgrid consists of medium voltage (mainly 20 kV in Finland) network and several secondary substations (20/0.4 kV). Medium voltage network is usually owned by distribution system operator (DSO), and therefore the logical owners of the MV microgrids are DSOs. DSOs are obligated to connect all paying customers into the grid but this might be difficult to handle in private owned grids. Nevertheless, it is not reasonable to build alternative grids at the same area. It might be possible to solve the problem with legislation but it might be time consuming. Medium voltage microgrids are interesting from the DSO point of view because the highest share of the outages that customers observe, are related to faults in medium voltage network. If the fault place could be separated and health parts operated as microgrids, the outages experienced by the customers would reduce. This would also mean lower outage costs for DSO.

Electricity grid is traditionally operated as a radial network. In a radial network, power flows from HV/MV substation to MV/LV distribution substation. In the present day grid, there is at least one medium voltage circuit breaker on each substation feeder. The circuit breaker is controlled by relays. In microgrid operation, the circuit breaker in the point of common coupling (PCC) is opened. In the current networks, the opening action of circuit breaker leads to situation where the DG units are detached if the first reconnection fails. This usually means that the whole substation feeder is without power. In microgrid planning, the loads and distributed generation are studied more closely. The island can be planned with the detailed knowledge if the balance in production and consumption is possible. For safe operation, MV microgrid might need own management system that cooperate with the control and protection units. Management issues are further discussed in section 5.3. (Voima & al. 2011)

2.4.3 DC microgrid

DC microgrid is also one solution under research. In Kaipia & al. (2009), impacts of low voltage direct current (LVDC) system is studied from the reliability point of view. The study shows that LVDC distribution might improve the reliability of electricity distribution and the power quality experienced by a customer. LVDC grid is system where alternative current (AC) is rectified to direct current (DC) and then distributed as DC and finally converted back to AC near the consumption. The system allows easy connection for DC based DG units, such as photo voltaic units. Drawback of the LVDC system is that more power electronics need to be added into the system. Lifetime of the power electronics is relatively short when compared to traditional network components, such as transformers. Therefore, fault frequency of the power electronics might be an issue. In addition, other critical components might be switches and capacitors. In distribution grid operation, power electronics have to withstand for instance different temperatures, humidity, varying loading conditions, and over voltages. However, the study in question shows that in some cases, the disadvantages caused by power electronics can be compensated with the better overall reliability. Study uses low reliability networks, such as rural overhead networks, as an example. This gain is partly based on the idea that LVDC system also replaces parts of the medium voltage branch lines. The advantages of LVDC system decrease when the reliability of the existing system is better. AC microgrid is more probable alternative if microgrid operation is implemented into existing network. However, DC concept can be considered if the grid is totally rebuilt. DC system does not face similar frequency, stability, and synchronization problems as AC systems. However, the protection or loss optimization might be even more difficult in DC system. (Kaipia & al. 2009)

2.4.4 Multi-microgrid scheme

Multi-microgrid scheme is a vision that theorizes how different microgrid possibilities fit together. Multi-microgrid scheme is presented for instance in Zheng & Li (2010). Multi-microgrid is a system which consists of several small microgrids that can be operated separately on their own or together as multi-microgrid. In the scheme, microgrids are considered as plug-and-play systems that together make the overall system flexible. Principle of multi-microgrid network is presented in Figure 2.3.

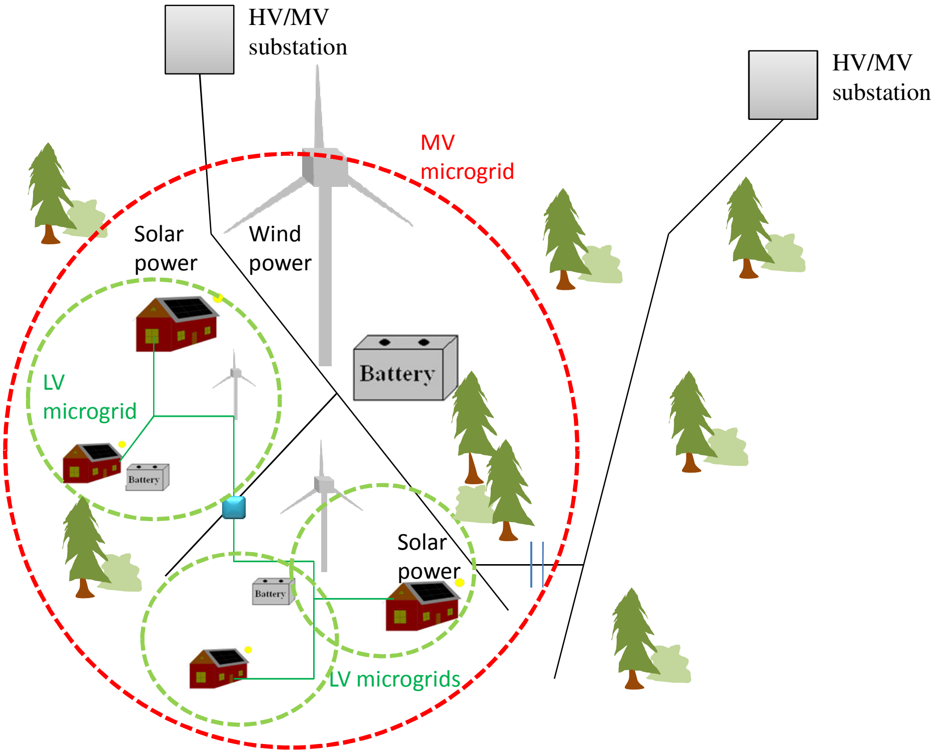

Figure 2.3. Example of multi-microgrid scheme.

The smaller microgrids inside multi-microgrid system can differ in size, power, and technology. Multi-microgrid can include for instance LV microgrids, LVDC microgrids and MV microgrids. In case of a fault, the faulted part of the grid is separated and the remaining parts are operated as smaller multi-microgrid or separated microgrids. Multi-microgrid with this kind of capabilities can be seen as a self-healing network which is one of the intended smart grid functionalities. Multi-microgrid might also ease the use of variable network topologies. To enable multi-microgrids, lots of distributed energy sources, controllable loads, and reliable high speed communication between control and protection units are needed. (Zheng & Li 2010)

2.5 Network configuration designs

In both microgrids and traditional grids, the structure of the grid has impact on the physical, technical, and operational properties of the grid. Therefore, it is important to understand the differences between different grid types. Issues, such as voltage level or geographical location have influence on the grid layout. Next some advantages and disadvantages of different network types are discussed.

Radial grid is the most common grid type in Finland today. Radial grid is based on one main line where consumption and possible generation are connected in parallel. The basic idea is presented in Figure 2.4.

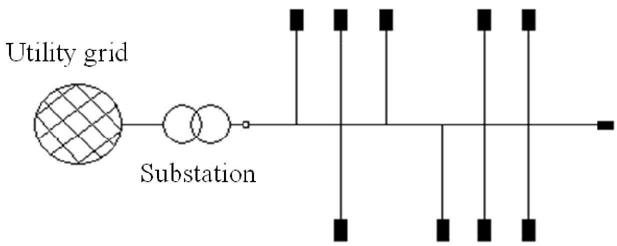

Figure 2.4. Example of radial grid.

In Figure above, there is only one main line supplying power from the substation. In real life, there can be multiple distribution lines connected in parallel at the substation. Radial networks are the most obvious choice for the base of a microgrid, especially in rural areas. Configuration design, where energy storage and DG are located near the substation, is the simplest and technically easiest to implement. In this configuration, the direction of power flow remains the same and the highest currents exist near the substation where dimensioning of the grid is the highest. A good place for microgrid control and protection system is at the substation. (Pasonen 2010)

In residential areas, networks are built as ring grids but they are still operated as radial grids. Ring grid is illustrated in Figure 2.5.

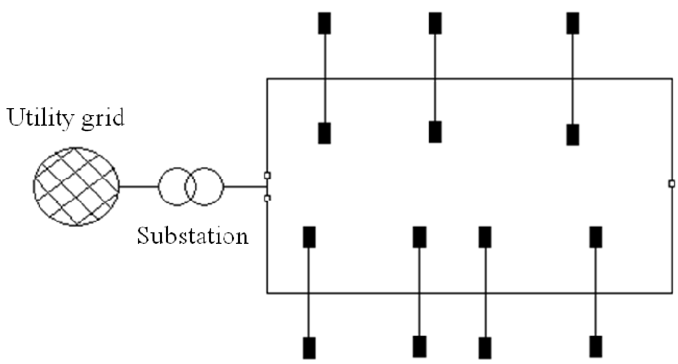

Figure 2.5. Example of ring grid.

Nowadays in Finland, ring grid is divided as two parallel lines with an open connector at the connection point of two main lines. In some big cities of North America and Europe, grids are operated as ring and several secondary substations feed the same network. In ring grid, there are two routes for power flow. Thus, protection is easier to execute in parallel grid than in ring grid because fault current goes only to one direction. This is the main reason for radial operation even though the ring operation is available. Advantages of ring operation are better voltage stability and lower power losses. Short circuit currents are higher in a ring grid which is a disadvantage in utility grid operation but might be an advantage in microgrid operation. In North American ring grids, the more complicated protection is solved with so called "*network protectors*" which are relay controlled switches. (Löf 2009)

Meshed grid is an electrical network which includes many alternative connections between nodes. Example of meshed grid is presented in Figure 2.6.

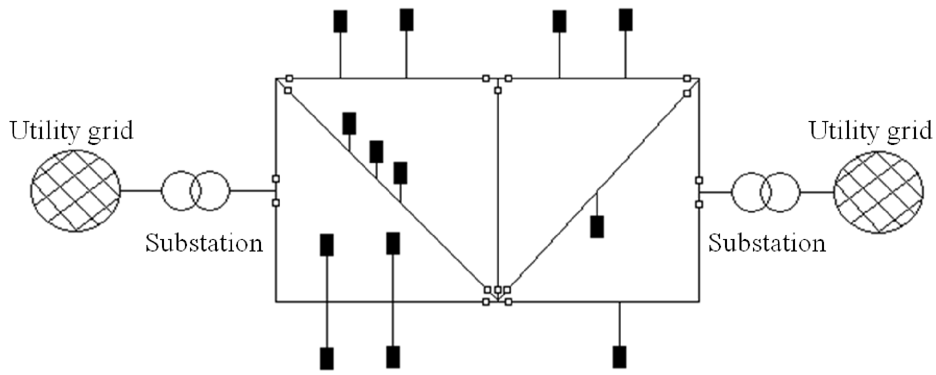

Figure 2.6. Example of meshed grid.

Operation and protection of meshed grid are challenging and that is why this kind of grid model is usually avoided in low and medium voltage networks. With development in control and protection strategies, it might become possible to have LV or MV meshed grids. Experiments of the meshed grids are limited in low and medium voltage networks but high voltage transmission grids are usually operated as meshed grids. The main advantage of the meshed grid is flexibility in operation but the main disadvantage is the difficulty of protection. HV grids do not change a lot which makes possible to use protection system that is planned only for the grid in question. In MV and especially in LV grids, more flexibility is needed also in protection. (Pasonen 2010)

It can be concluded that simple but not that flexible network structures are most often used today. Differences in operation between countries can be explained with different distribution systems. In areas, where LV grids are operated as a ring, distances are short (100 m or less) (Löf 2009). In Finland, distances are remarkable longer and the operation is more practical to execute with radial grid. Similar obstacles can be noticed when different grid structures and microgrids are discussed. DG changes the current direction in the network and sets challenges for protection.

2.6 Microgrid in this study

Because the definition of microgrid is quite loose, it is important to emphasize, what microgrid means in this thesis. Additions LV and MV are used with the term microgrid to describe the voltage level and the type of the grid. LV microgrid refers to case 3 in Figure 2.2. Small, one customer solutions are not discussed in this thesis. MV microgrid in this study means a part of medium voltage grid that usually operates as a part of utility grid but is capable to operate in islanded mode when needed. The microgrid is not expected to continue operation if the fault occurs during microgrid operation. In other words, microgrid does not include self-healing features other than transition from the utility grid operation to the microgrid operation. The power production is assumed to consist of few DER units from which the main energy comes from intermittent energy sources, such as wind turbines. The microgrid is also assumed to include an energy storage and/or diesel generator which can be adjusted rapidly. Energy storage or diesel generator works as the main unit of the microgrid operation. Therefore, control of the microgrid is expected to be centralized so that the main unit includes also the main intelligence. Topology of the microgrid is expected to be rather simple which means that the grid is operated as a radial grid. The microgrid is expected to include MV relay protection devices that can detect faults also in the microgrid mode. Described microgrid model is chosen to be the main interest because it suits best to begin the integration of microgrid into distribution network. Although, the thesis is focused on the presented microgrid scenario, it also discusses other alternatives and points out pros and cons of different alternatives.

2.7 Summary

Term microgrid can be understood differentially in different contexts. Structure of microgrid can vary a lot and many variables, such as types of generator, number of generators, and grid topology have impact to the final solution. Figure 2.7. presents microgrid related issues in a layered form where key issues are in the middle surrounded by some variables.

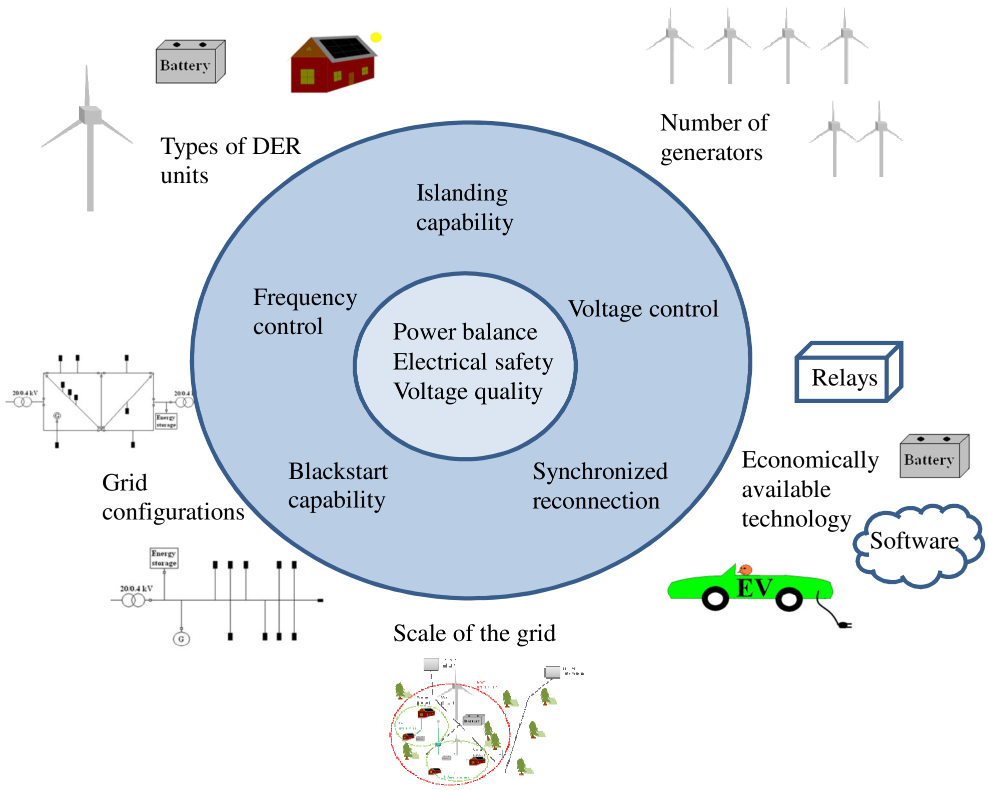

Figure 2.7. Review of the microgrid related issues.

Issues inside the inner circle in the figure above are necessities that need to be fulfilled under all circumstances. Issues inside the big circle are microgrid functionalities that can be implemented in microgrid operation. Surrounding issues and figures show some variables related to microgrid operation. All of the variables include own uncertainties which makes it challenging to predict the final, integrated microgrid model. The capabilities of microgrids can also vary according to the needs. For instance, sometimes blackstart capability is necessary and sometimes it might not be needed as discussed in section 5.3.5. In this thesis, the main idea of the microgrid is islanding capability which can reduce outages and offer independency for customers. This study focuses on MV microgrids but because there are so few MV microgrid studies available, also LV microgrids are discussed. Universal principles are expanded from LV microgrids to MV microgrids.

3. MICROGRIDS AS PART OF A SMARTER GRID

Smart grid is a vision of future electricity grid that can provide better service with reasonable cost. Large share of electricity networks in Europe were built up forty or fifty years ago. The replacement of these grids has to be done now or at least in the near future. The question is, do we build similar networks that were built fifty years ago, or do we want to improve things and make more modern grids. At least the society and its' needs have changed significantly during the last decades. Building a modern grid does not only mean replacement of old overhead lines with cables but also developing the whole infrastructure, including communication. Better communication can provide new interaction between business parties and enable new benefits of smart components, such as smart meters and hourly based billing. Smart grid also provides solutions to change the topology of the grid from centralized production and operation to more distributed one.

3.1 European energy strategy

Climate change and green values have become a part of everyday life. This is enabler for smart grids because of better resources and higher media interest. The main priorities in energy sector are presented to the European Parliament in the paper "*Energy 2020 - A strategy for competitive, sustainable and secure energy*" by European Commission. The paper is a part of Europe 2020 strategy which includes also climate objectives. The Parliament accepted the Energy 2020 strategy in November 2010 (Commission 2010).

The main priorities of the European Commission energy strategy are (Commission 2010):

1. Achieving an energy efficient Europe
2. Building a truly pan-European integrated energy market
3. Empowering consumers and achieving the highest level of safety and security
4. Extending Europe's leadership in energy technology and innovation
5. Strengthening the external dimension of the EU energy market

The strategy of Europe's leadership is ambitious because the development in energy sectors happens also in the other continents. Good example is solar technology, where Germany was a market leader of the world only five years ago. In 2009, China overtook Germany. Currently China has the clear leadership in solar technology, despite the fact that national market for solar technology is still limited in China. However, resources for research and development (R&D) are increased to support the Europe 2020 strategy. In a consequence, many research programs have been started across the Europe and numerous universities, research centers, and companies are involved. The drive to unite European energy market requires unification of electricity transmission systems and high investments are needed to avoid the bottlenecks. Nevertheless, the decisions seem to favor environmental friendly acts and similar trend can be expected to continue. (Commission 2010; IEA 2010)

3.2 Definition and targets of smart grids

Term smart grid does not yet refer to some specific type of the grid. Instead it reminds more an open vision and therefore it is difficult to say when a grid is smart grid and when not. It could be better to talk about smarter grid because the technology develops all the time. The use of definition smart grid (SG) varies a bit but the main idea is to provide better and more secure service with reasonable price. Smart grid is also planned to offer a platform for easy installation of distributed generation. In practice, the smarter grid might include better communication, better system operation, and possibilities for new production units, customer participation, and business models. The main differences of smart grid and traditional grid are presented in Table 3.1. (ETP 2010; VTT 2006)

Table 3.1. The main differences between traditional grid and smart grid.

	Traditional distribution grid		**Smart grid**	
	LV	MV	LV	MV
Communication	None	Some	Some two-way	Two-way
Production	None	Centralized	DG	DG + centralized
Interruptions	Blackouts	Reconnections + blackouts	Islanding + adaptive	Self-healing + islanding
Restoration	Manual	Manual + Semi-automated	Manual + Semi-automated	Self-healing
Power flow	One-way	One-way	Two-way	Two-way
Monitoring	None	Low level	Low level	High level
Relays	None	Some digital	Some digital	Digital

As can be seen from the table above, the development is expected to happen in several functionalities. Smart grid can be seen as much more flexible than traditional distribution grid. In addition to two-way power flow, the most eye-catching changes are the characteristics of monitoring, communication, and self-healing. (VTT 2006)

The European Technology Platform (ETP) defines Smart Grid as *"an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies"* (ETP 2010). However, existing electricity grids differ a lot because they are planned with different principles by different companies and by different planners. When different population densities are added to the picture, it causes that the platforms, where smart grids are built on, differ a lot. Therefore, it is difficult to create credible vision which would be precise enough and still fit into all circumstances. However, one good example of visionary network can be seen in Figure 3.1.

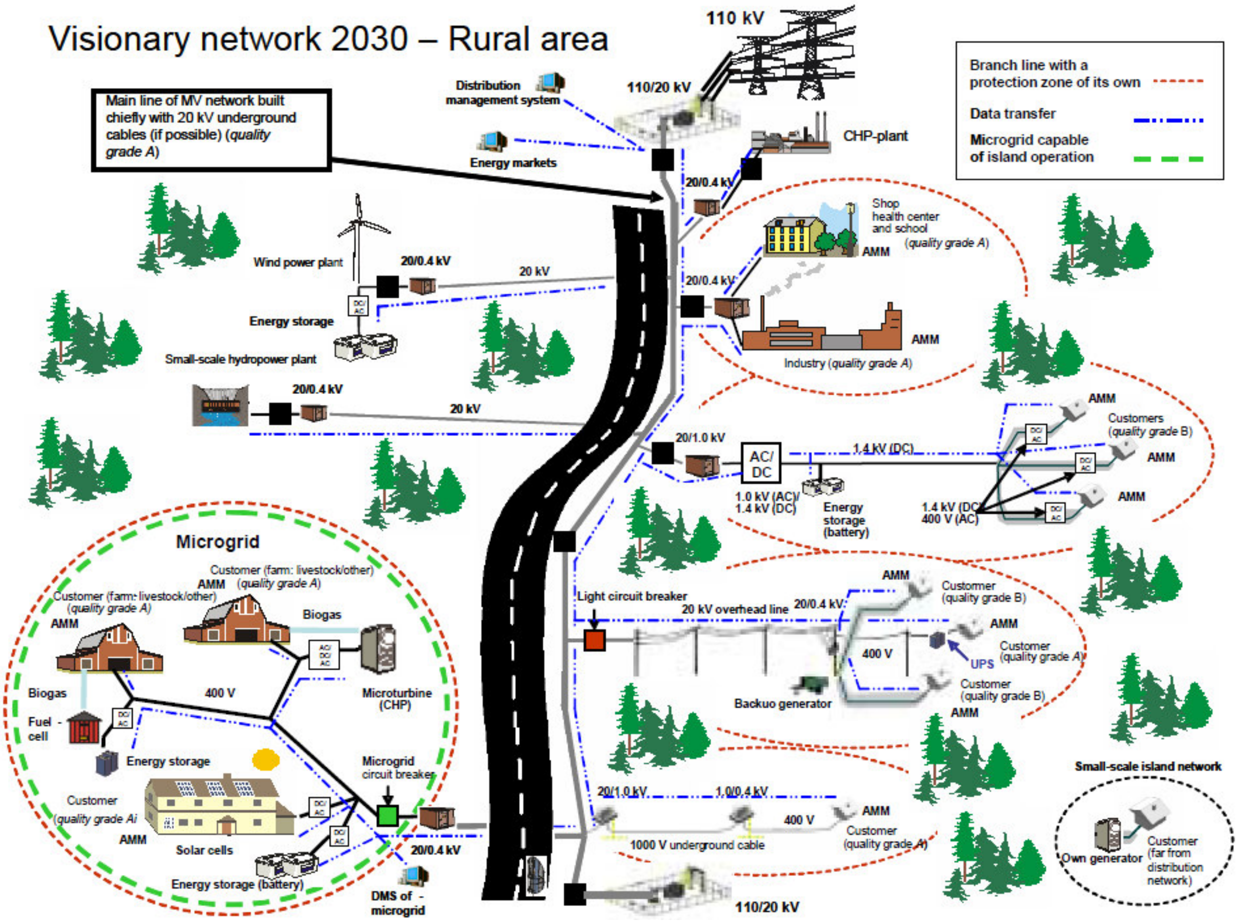

Figure 3.1. Vision of smart grid 2030 (VTT 2006).

Figure above shows the role of low voltage microgrid in the whole system. It is good to notice the importance of data transfer around the grid because existence of communication infrastructure enables new opportunities also for microgrid operation. Microgrid communication is further discussed later in this thesis.

The idea of smart grid programs, such as smart grids and energy markets (SGEM), is to enable implementation of the smart grid visions with new solutions, products, and services. What is remarkable in the SGEM research program is that 50% of the funding comes from industry sector. This means that both research institutes and industry play significant role in the research program. During the program visions are tested in real life pilot tests and the goal is to achieve solutions that are applicable worldwide. (Cleen 2011)

3.3 Distributed energy resources

Distributed energy resources (DER) are important parts of the future smart grids. DER unit can be an energy production unit or an active load. Distributed production units are the base of microgrids and without growing penetration of distributed generation, the whole idea of microgrids can be forgotten. Traditionally electricity is produced in large, centralized units and the power levels per unit are high. However, nowadays the role of renewable energy sources is growing because of the targets to degrease CO_2 emissions and use of fossil fuels. Power levels of renewable energy units are significantly lower than in traditional coal or gas plants.

In future, some of the big centralized power generation units might be replaced with several small and distributed units. For instance in Germany, this is already happening. However, traditional CO_2 free energy sources, such as nuclear power and hydro power, are still going to be the base of electricity production for a long time although, Germany has decided to replace nuclear power with other energy sources. Nuclear power is not discussed in this paper because nuclear power plants cannot be adjusted and the power levels in are too high for microgrid operation. Power levels of the distributed energy resources vary from couple of kilowatts to dozens of megawatts. In Finland, the amount of installed distributed generation is still small compared to other European countries, such as Germany, Denmark, or Spain but the prediction is that it will grow (Parkkinen & al. 2011). To support the growth, the Finnish government offers financial support for new wind and bio production units. For instance in Germany, aggressive financial supports have led to growth of distributed generation, which is especially based on wind and solar.

Distributed energy resources can be divided into separate categories according to the nature of the energy resource. Intermitted renewable production includes wind power and solar power. Wave energy has intermittent nature too. Typical for intermitted production is variability of output power which sets some challenges for the system operation and power balance. Thermal driven production and hydro power are more constant and the output power can be adjusted according to the needs. Energy storages include rotating masses, such as flywheels, and storages, such as batteries or fuel cells.

They all are adjustable power sources. Different DER units have different impacts on the system flexibility and complexity, as described in Figure 3.2.

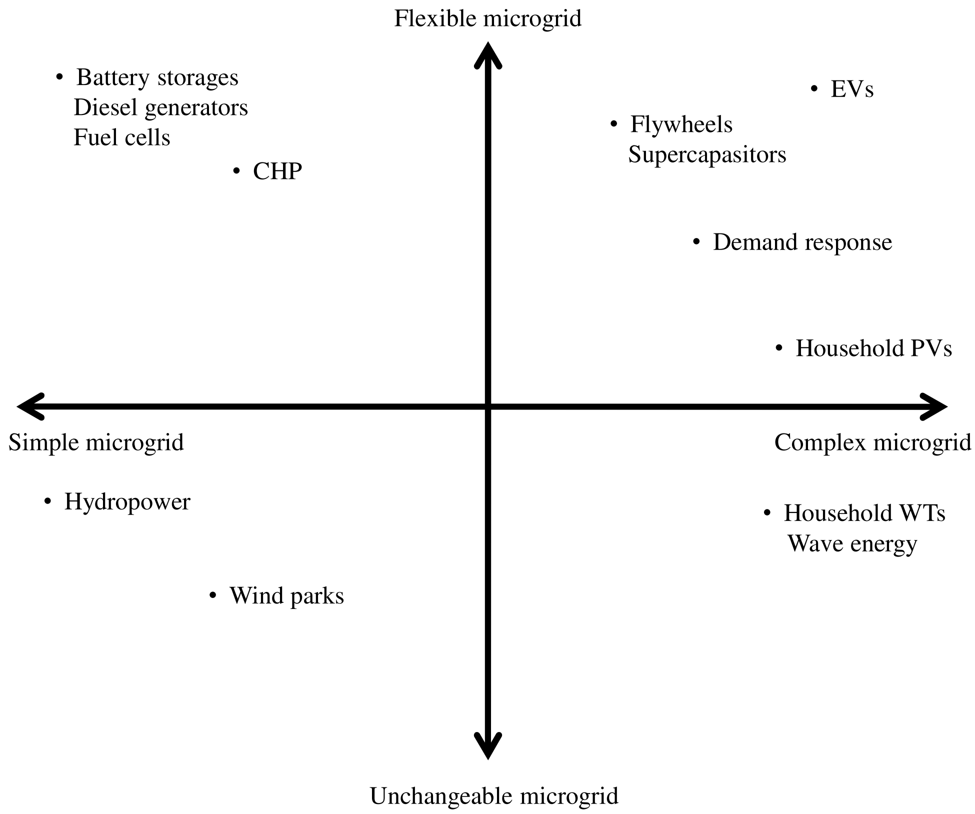

Figure 3.2. Different DER types as the base of microgrid operation.

Figure above points out the strengths of storable energy resources. It is good to notice the complexity of the system when it consists of several small units. On the other hand, many small units increase flexibility because the lack of one part does not necessarily cause problems to the whole system. Photo voltaic (PV) panels are rated to be more flexible than wind turbines (WT) because PVs can be installed where wanted. WTs need good wind conditions that vary a lot in different areas but the sun radiates similarly in large areas. Hydropower and wave energy are also strongly place dependent energy sources which weakens the flexibility. Many of the above mentioned production categories include both new and old technology. Because integration of microgrids is not possible without much higher penetration of DG, the backgrounds, future visions, and properties of different distributed energy resources are more closely studied in the following paragraphs.

3.3.1 Intermittent renewable production

Wind and solar power are examples of intermittent renewable production. These two production types are also the most popular in small scale electricity production. From the producer's point of view, they have to become more interesting because investment price has decreased and financial support is offered by governments. The greatest challenges related to wind or solar productions are the variation of output power and lack of control capability that storable resources have. In other words, when the wind speed varies, also the output power varies. The variation sets many challenges and causes that other power sources or loads need to compensate the variation of intermittent renewable production. Variation is especially challenging in microgrid operation where the amount of supporting production is limited and the system is more sensitive to changes. However, the total amount of intermitted power is increasing because the power levels of production units are increasing and the amount of production units is increasing. Thus, intermittent renewable resources seem to be the most realistic DER type for microgrid operation within the near future. Therefore, challenges and questions behind them need to be discussed.

Wind power

Wind power is the most popular intermittent energy resource in Finland. In the case of one or few wind turbines the variability has high impact to the total output power. In case of several wind turbines, the variability moderates but it can still be seen. The variability of wind production is presented in Figure 3.3.

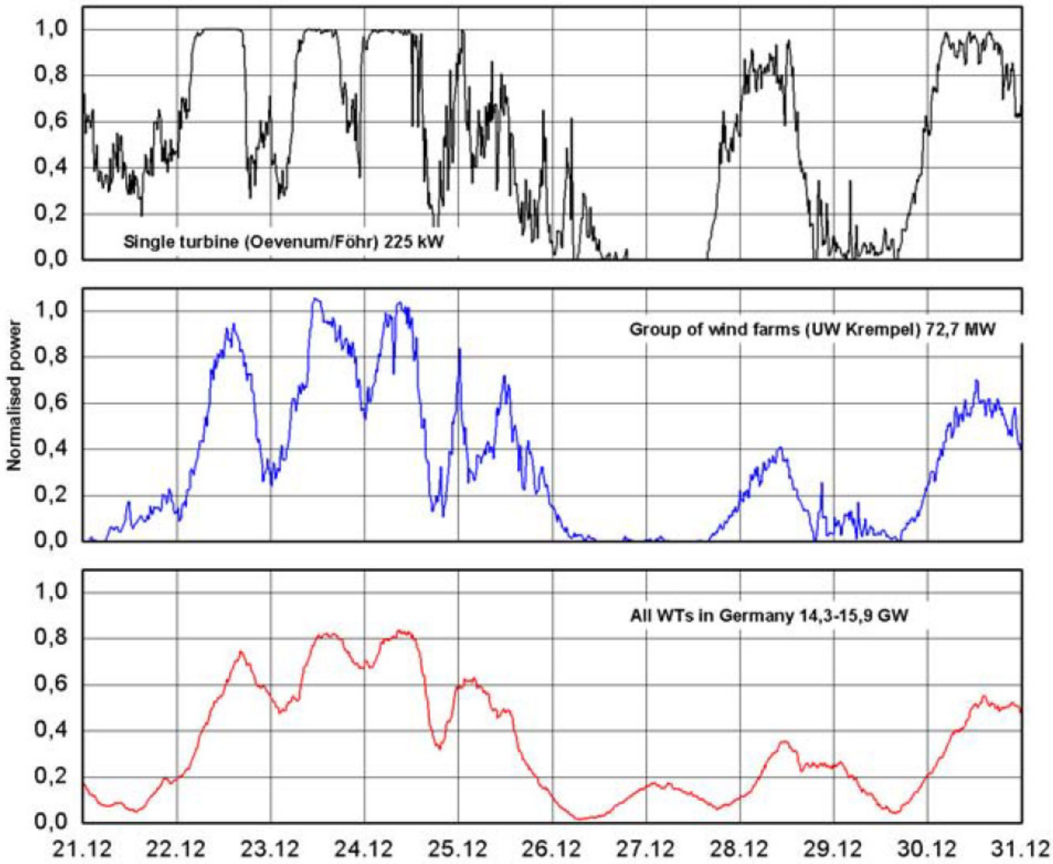

Figure 3.3. Examples of wind production from year 2004 (VTT 2009)

It can be seen from the figure above that the short time variability smoothens when more units are added to the system. What is remarkable is that in the case of all turbines the full normalized power level (1.0 p.u.) cannot be achieved even during the best wind conditions. In other words, maximum power levels of intermittent production cannot be compared to maximum power levels of traditional adjustable production units. However, if the wind turbines are distributed on a large area, it is rare that the production goes to zero because there is wind at least somewhere. From the national wind statistics can be noticed that the wind conditions in Finland are better in winter than in summer season (VTT 2011). This is good because in winter the consumption of electricity is higher than in summer season, although the short term variability has remarkable role in both consumption and production.

The development of technology in wind power has been fast. The statistics show that the average power of the wind turbines have more than doubled (700 kVA → 1519 kVA) in Finland between 2004 and 2011. At the same time, the total installed capacity has almost quadrupled (52 MVA → 197 MVA) and the amount of yearly produced wind energy has grown from 9 GWh to 371 GWh. It can be estimated that the growth will be similar or even faster in the near future because of new feeding tariffs that favor wind power and because the technology develops. However, wind power suffers from "not in my backyard" principle. People want more wind turbines to be installed but they do not want that turbines are built near their home or summer house. Despite the obstacles, wind turbines seem to be the first DER type available in large scale. If the first steps of trying microgrids operation would be started now, the first microgrids would probably be based on wind turbines. Nowadays, the trend is to build bigger and bigger wind turbines, which means that without a change in the trend, their potential in LV microgrids is limited. (VTT 2011)

Solar power

Solar energy is a primary energy source that generates many other energy sources, such as wind. Electricity can also be produced directly from sun radiation with photo voltaic (PV) modules. Another option to use solar power is to collect the energy as heat and then produce electricity from the heat with traditional steam turbine system. This kind of collector system is adapted in some large scale test plants. PV modules are more common in small scale usage and there are several different photo voltaic technologies in the market. Operation of PV module is based on PN-connection between semiconductors that convert the solar energy into direct current (DC). As the intensity of the sun radiation increases, the current increases but effect to the voltage level is small. In other words, PV panel is a current source where the voltage remains almost unchanged but the current varies according to sun radiation. The controllability of the solar power is limited because of its nature, although the DC to AC conversion enables some adjustability of the AC output power. (IEA 2010)

PV modules are common in private customer electricity production solutions. The most common ones are crystalline silicon modules that represent about 85% of global annual module sales. Thin films have 15% market share. Thin films are new solar cells that consist of thin layers of PV material. Weakness of the thin films is their lower conversion efficiency which usually means that larger area is needed to achieve the same power levels as with crystalline silicon PV modules. (IEA 2010)

New PV solutions combine crystalline silicon cells and thin films. Development of products and increase of demand will probably lower the costs of PV modules in the near future. One estimate is presented in Figure 3.4. (First Solar 2011)

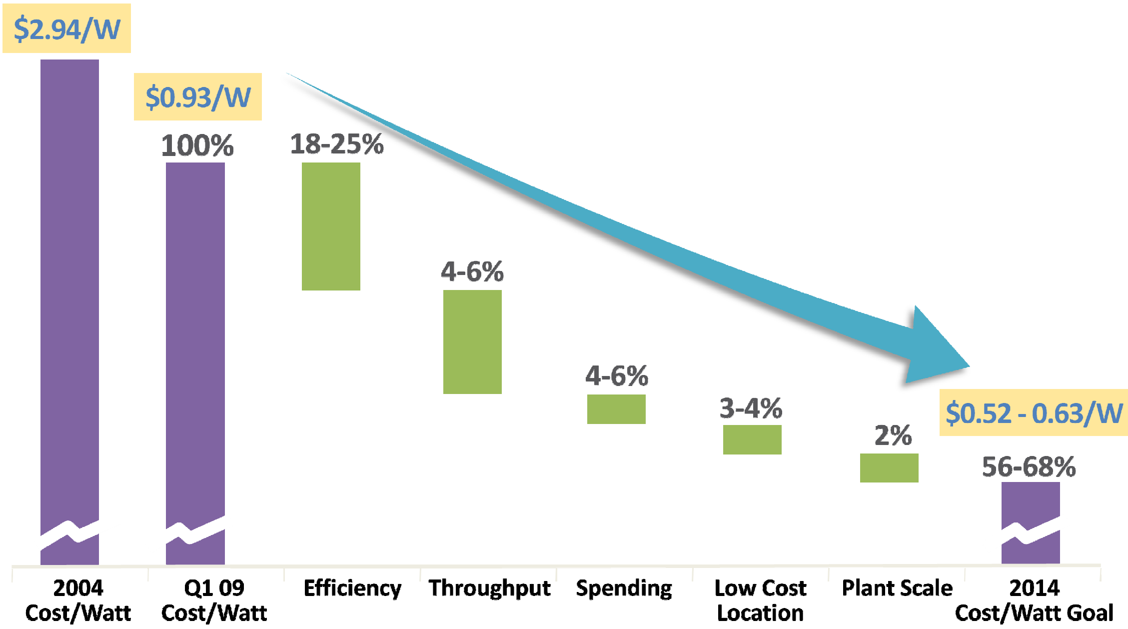

Figure 3.4. Estimate of thin film module manufacturing cost reduction (First Solar 2011).

As can be seen from the figure above, the manufacturing costs of PV modules have reduced remarkably between 2004 and 2009. In fact, the manufacturing costs have lowered into one third just in five years. In future, the cost reduction might not be as fast but some reduction can be expected. The cost reduction potential can be seen from the figure above. However, it is good to remember that the figure above describes costs of one technology from the module manufacturer's point of view. Thin films are often advertised to have the lowest investment costs per watt but this is partially offset because of higher area-related system costs. Mounting and larger required space might raise the costs significantly. (IEA 2010)

Although the amount of solar power is limited today in Finland, the potential is significant. One advantage that solar power has compared to wind power is that sun radiation is not as much dependent on the location. Sun radiation is approximately same at the same area or latitude. Therefore, solar modules can be installed anywhere if there is enough sun radiation and free space. This enables better flexibility in microgrid system planning. Nowadays, wind power is focused near coasts and high lands which causes that the greatest existing microgrid potential is also there. Nevertheless, solar power can be seen as an important part of future smart grids because of its huge potential and development in technology. It can be possible that the scale of the solar power units will increase and solar power will also have potential for MV microgrids. Other option is that high amount of small units can cover the needs of MV microgrid operation. However, this kind of distributed system sets extra challenges, as discussed later in this thesis.

3.3.2 Energy storages

A lot of research has been done and a lot is still ongoing related to energy storages. Demand for energy storages exists not only because of electrical vehicles but also because of smart grids. The need for cost efficient energy storage has become important part of future solutions because of renunciation of fossil fuels and expanding use of intermittent renewable energy resources. Industry is interested about energy storages because of the business opportunities that they might offer. Energy storage can offer control features that enable bigger use of intermittent distributed generation. Central energy storage can act as the main unit of microgrid operation. Other option is to have DG as the main unit and have distributed storages for instance next to intermittent DG units or use electrical vehicles as energy storages. In microgrid operation, energy storage units might be needed for power balancing purposes. Spinning inertia of conventional generators does not exist in microgrid which set challenges for power balance. If the costs are neglected, the energy storages have potential in all types of microgrids from small LV microgrids to large MV microgrids. (Jussila 2010)

Batteries

Penetration of electrical vehicles (EVs) is totally dependent on the development in battery technology. Energy density and power density as well as the lifespan are critical issues in the battery technology. So far the combination, where the issues mentioned above and low price could be combined is unreachable. In 2010, the manufacturing costs of lithium-ion battery were about 1000 USD/kWh, but the estimation of the study Biomeri (2009) is that the price will be 750 USD/kWh in 2015. These prices are still too expensive for many purposes but if significantly lower costs can be achieved, it might be reasonable to use batteries as energy storage, not only in microgrid operation but also in utility network operation. If batteries with reasonable costs and good features can be achieved, the use of battery storages will probably increase exponentially. Inexpensive battery technology can enable the implementation of EVs. In addition, storage systems can be connected to the distribution system to smooth the power variations and enhance the power quality. This would be good also from the microgrid point of view because energy storages could enable easier island operation and reduce the disadvantages caused by the intermittent energy production.

Supercapasitors

Supercapacitors are energy storages that can provide high peak power but only for a short time. Supercapasitors have ten times higher power density than batteries and supercapasitors are also lighter than batteries. Both discharging and charging processes are fast. Supercapasitors cannot be used for a long periods of time as energy sources because of their low energy density. Instead, they can be used for short duration energy releases to improve for instance voltage quality. Supercapasitors can also compensate switching transients and voltage sags. Some studies have even proposed control principles that use supercapasitors as dynamic voltage restorers to improve the power quality. One interesting use for supercapasitors could be next to the distributed generation units because supercapasitors could improve fault ride through capability of distributed generation. This kind of features that enable flexibility and better stability are more than welcome also in microgrid operation. However, all additional components come with a price and therefore costs and benefits need to be carefully considered before implementation. (Sahay & Dwivedi 2009)

Fuel cells

Fuel cells are energy storages where basic components are anode, cathode, and electrolyte. In fuel cells, electricity is produced based on electrochemical reactions. The difference between batteries and fuel cells is that in fuel cells the power level is determined by the fuel cell and the amount of energy by the fuel storage and fuel itself. The vision is to use hydrogen as fuel for fuel cells. Hydrogen can be manufactured from water with electrolysis. Hydrogen is clean fuel and the only reaction product is water.

The total emissions of hydrogen fuel cells depend on how the electricity, which is used in electrolysis, is produced. If electricity is produced with fossil fuels, the emissions are remarkable but if electricity is produced with renewable energy resource, hydropower or nuclear power, the emissions are small. Today, fuel cells are expensive (investment costs are about 4000 USD/kW) and the lifespan is short. In northern climate, one problem is winter because the electrochemical reactions slow down at low temperatures and the catalyst might freeze. Fuel cells work best with steady power because current spikes shorten the life time of the cells. Fuel cells are interesting topic but so far any breakthrough is not expected. If the breakthrough happens, the most remarkable change from the electricity grid point of view would probably be the increasing amount of fuel cell powered electric cars. From microgrid point of view, fuel cells have similar positive effects as batteries but the costs are too high for implementation. (Pasonen 2010)

3.3.3 Other distributed energy resources

In addition to energy storages and wind and solar power, there are also many other distributed energy resources. If traditional hydropower is forgotten, the number of these other DER units is limited in the today's network. In future, the role of other distributed energy resources, such as wave energy, electrical vehicles or fuel cells might be much bigger than today. Therefore, also following energy resources should be considered when future grids and microgrid operation are planned.

Hydropower

Hydropower that is based on dam in the river is one of the oldest energy resources. Electricity production is based on potential energy of water that is reserved into upper reservoir. When the water is released from the reservoir, it flows through a turbine which then rotates a generator. In larger hydroelectric plants, which use synchronous generators, the total efficiency is relatively high, even over 90%. However, in smaller plants that use asynchronous generators, the efficiency is lower. In addition, asynchronous generator needs reactive power which might create need for compensation devices. Besides of high efficiency, hydroelectric power generation has positive features compared to many other ways to produce electricity. The control possibilities in hydropower are good which means that power levels can be easily and quickly adjusted. Water can also be reserved which means that the electricity can be produced when needed. These are good features for microgrid purposes. In Finland, the additional potential of hydro power is limited due to the strict environmental legislation and lack of elevation changes. Small amount of new hydropower can be harnessed from existing dams by replacing the old plants with new and more efficient ones. Small amount of new potential and location dependency are the most limiting factors of the use of hydropower in microgrids. However, some MV microgrid solutions could benefit from hydropower. (Pasonen 2010)

Wave energy

One relevant and actual topic in the energy sector is wave energy. Waves have lots of kinetic energy but it is difficult to harness. There are many attempts to techno-economically harness power from the ocean waves. Here are some examples of them:

- *Attenuators* are long floating structures that move on the top of waves. This movement is then captured with hydraulic pumps in the joints. Attenuators need lots of space.
- *Point absorbers* are floating buoys that include cylinder which generate power from the up and down movement. Point absorbers are also tested in Nordic countries.
- *Oscillating water columns* generate electricity from the tide or wave. In this solution, the tide or wave hit the shore and compress air inside a large building called capture chamber. The compressed air pressure is then released through a turbine which starts to rotate and produce electricity. Also this solution needs visible installations that can be accused of spoiling the view.
- One way to produce power from waves, without spoiling the view, is to use *wave rollers*. Wave rollers are plates that stand in the bottom of the sea and move back and forth. The movement is collected by a piston pump and converted to electricity.

Wave energy systems still need some development before they can compete techno-economically with traditional power units. However, the fact is that also wind and solar power units are profitable only because of financial supports. Implementation of these technologies depends also from the support politics. Wave power has similar intermittent nature as wind and solar power which is not the ideal choice for microgrid operation. Wave power is also place oriented which cause limitations for microgrid implementation. Possible implementation of wave power units would increase the amount of energy production at the coast which might lead to need for reinforcements in the electricity grid. (Minerals 2006)

Diesel generators

In Finland, diesel generators are often used as backup generators but not for permanent electricity production. Advantages of diesel generators are low investment price, easiness to acquire, reliability, and fast response for changes. Biofuels can also be used in some diesel generators but problems with the usage and preservation of biofuel have limited the usage. One limiting factor is the warranty because some manufacturers abort warranty if biofuels are used. From microgrid point of view, diesel generators can offer good functionalities, such as fast adjustability, secure electricity production, and blackstart capability. Because of the emission trade and other environmentally friendly acts, the use of diesel generators can be seen limited also in the future. However, in some special purposes, such as backup power, the role diesel generators can be remarkable. Even though the diesel generators have superior functionalities for MV microgrid operation, the large scale usage will probably not happen due to environmental reasons. The use of diesel generators might have potential in small LV customer microgrids, although diesel powered islands are closer to intended island operation than microgrid operation. In addition, diesel generators can be useful in the beginning of microgrid implementation because they can secure stability quite well. However in future, the stability and control challenges need to be solved with emission free power sources. (Pasonen 2010)

CHP

Combined heat and power (CHP) production is common in large heat kettles that burn fossil fuels and also peat, wastes, or biofuels. Sort of new things in CHP production are micro turbines. Micro turbines are small gas or steam turbines that can be used for distributed energy production. The turbines work with heat that can be produced with multiple energy sources, such as wood chips, other biomass fuels, wastes or natural gas. Heated steam or burned gas rotates the turbine and then the turbine rotates power generator which generates electricity. Electricity production creates also some waste heat because the system has a quite low efficiency. Therefore, combined heat and power production is recommended and usually applied at least in larger units. With combined heat and power production, the total efficiency can be improved. Efficiency in electricity production is usually about 25% but in CHP system the overall efficiency can be over 80%. (Pasonen 2010)

Energy self-sufficiency is often related to microgrid operation and many studies have added district heating as a part of microgrid (Laaksonen 2011). In this thesis, the districted heating is not considered as a part of microgrid operation. Nevertheless, it is a good addition if CHP production is used and distances are suitable for district heating. In Finland, the distances are often remarkable and the residential density low, especially in rural areas, which causes that district heating is not always a suitable solution. In addition, one drawback of CHP plants is that they release emissions. Emissions can be reduced with emission filtering or carbon capture but it causes extra costs. Emissions and lack of district heating infrastructure are the reasons why the use of CHP can be seen limited in Finnish microgrids. When it comes to micro turbines, the efficiency is lower in smaller units. Cost efficiency might also be an issue. If micro turbines become economical solution, they might be used as domestic solutions without connection to larger district heating grid. From controllability point of view, CHP is a good choice for microgrid operation. (Pasonen 2010)

3.4 Smart technologies

Smart grid is not only a grid where new production types and network models are presented. Smart grids include many smart components that improve both operator and customer awareness of the grid status. This means that more measurement, communication, and self adjusting devices might be added to the grid. This leads to the need for a system that controls and analyzes large amount of data in real time. Development in software systems is at least as important as the development in hardware technology. Figure 3.5. explains the meaning of smart grid components for microgrid implementation. Estimations of the years, when the mentioned features might be available, are done partially based on the study "*Smart Grids RoadMap*" by Parkkinen & all. (2011). Study is based on questionnaire survey which was made in autumn 2011. In Figure 3.5., year 2020 means that these features might be available sometimes after year 2020.

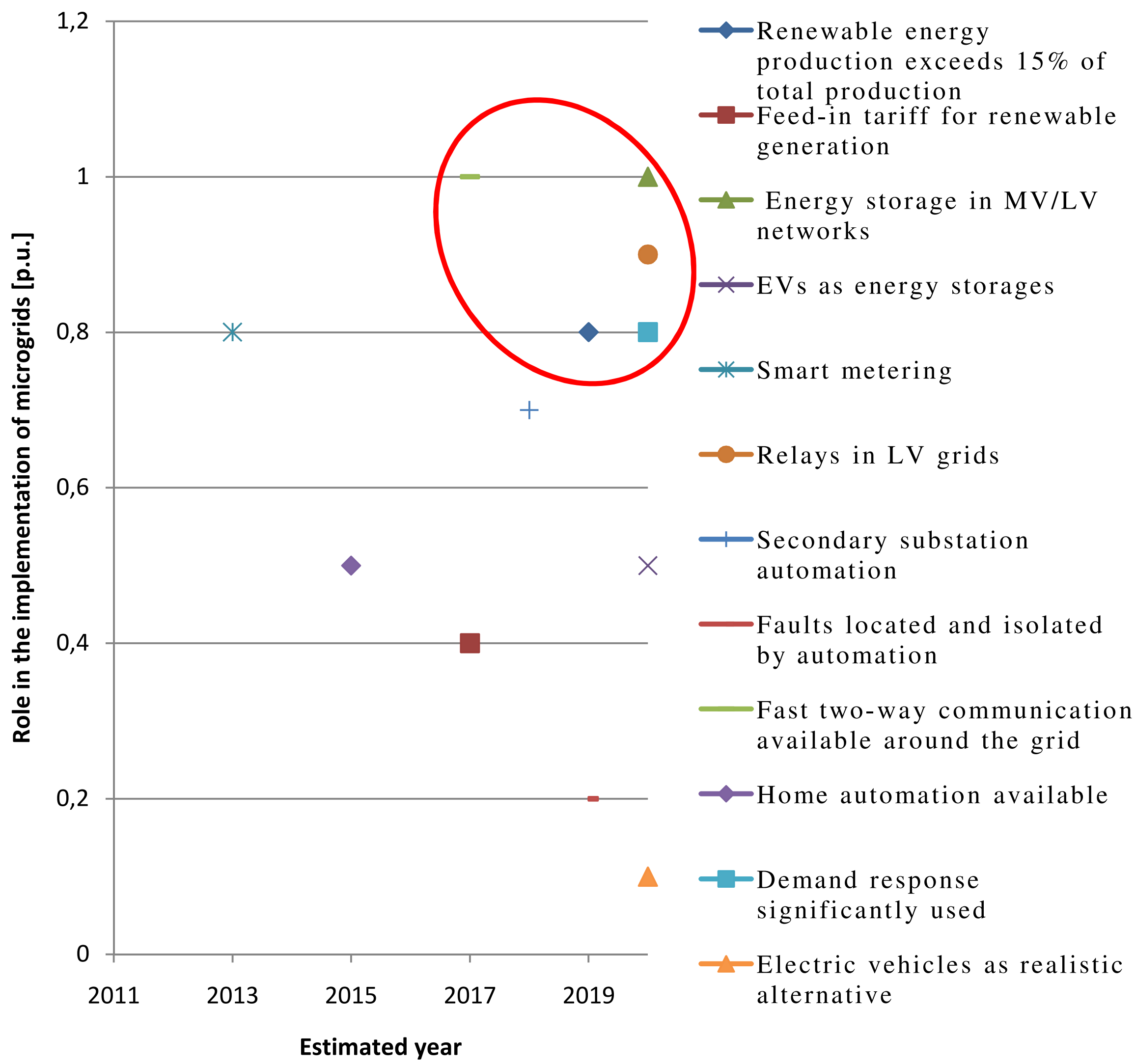

Figure 3.5. Estimations when the smart grid features will be available in such scale that they have impact on existing network.

Implementation of the microgrids is highly dependent on the development of other smart grid features and change in electricity prices. Circled group of features in the figure above can be seen as essential and limiting factors of microgrid implementation. The figure states that these features are not going to be available in the near future. Therefore, it can be concluded that the large scale implementation of microgrids cannot be expected before 2020. However, later it might be possible to start large scale implementation of microgrids. Therefore, development of smart grids needs to be observed carefully. Following paragraphs discusses smart grid features that are interesting from the microgrid point of view.

3.4.1 Smart metering

Smart meters are the first visible smart grid component that is going to be widely installed into the Finnish grids and hundreds of thousands of smart meters are already installed. Smart meters enable hourly based meter reading and communication with the utilities. Exact definitions of smart metering vary in different contexts and different meter suppliers use different definitions. Following terms are used when smart metering is discussed: automated meter reading (AMR), automated/advanced meter management (AMM), and automated/advanced metering infrastructure (AMI). In this study, the definitions are separated with differences presented in Figure 3.6. The idea is that next definition is more sophisticated method than previous one and therefore includes also the benefits of previous one. (Löf 2009)

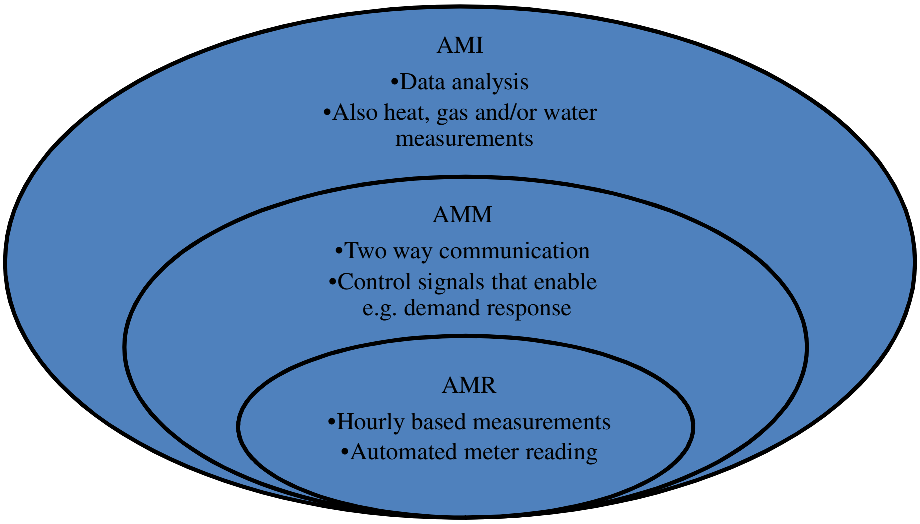

Figure 3.6. Relation of different smart metering definitions.

AMR technology enables remote reading on hourly basis. This enables that the billing is based on real time consumption and therefore use of hourly tariffs. Remote reading can be done for example via power line communication (PLC) and/or GSM/GPRS connection. Both methods are used worldwide but PLC and GSM/GPRS combination is more popular in Europe. AMM is a variation of AMR that include also two way communication which enables more sophisticated functions, such as demand response.

AMI refers to overall system that measure, remotely read and analyze the consumption. Different meters, such as electricity, gas, heat, and water meters can be added to the AMI. The system can also remotely manage measured data and send commands with two way communication. AMR is implemented to over 80% of Finnish consumption points by the end of 2013. The most significant advantages, which smart metering can offer for microgrid operation, are communication link and demand response. Communication and demand response are more closely discussed later in this thesis. (Löf 2009)

3.4.2 Protection units

Safe operation is an important part of electricity distribution in existing grids, smart grids, as well as microgrids. Nowadays, power flow is unidirectional and protection is typically planned to work with unidirectional fault currents. As discussed earlier, the role of DG will probably grow significantly in future. This might lead to situation where the power flow in the grid is multidirectional. Safe operation has to be achieved also in this situation. Protection has to detect all faults also in the case of multidirectional power flow. In future smart grids, the operation is planned to be self healing which means capability to autonomously identify, localize, and separate an unforeseen fault. In visions, this is made possible by improved information and communication technologies (ICT) and new protection protocols. It might be necessary to handle multidirectional power flow and win the challenges related to it also in microgrids. Microgrid development goes hand in hand with smart grid development also in protection issues. (ETP 2010)

In traditional radial operated medium voltage networks, the power flows from HV/MV primary substation to distribution network and onwards to MV/LV secondary substation. The protection of MV network is traditionally based on relay protection at the HV/MV substation. In smart grids, the amounts of protection devices grow. DG units will have own protection devices. Remote controlled switches and disconnectors are also added to the grid to reduce the effects of interruptions that customers experience. In addition, fault detectors and other measurement devices might be installed. In future, more precise picture of the grid operation can be created from larger amount of devices that are capable to communicate with the distribution management system (DMS). Also, faults can be detected more precisely. The existing MV protection devices or protection terminals, as the latest microprocessor relays are called, are highly developed, programmable, and capable of two way communication. Therefore, there is no need for major improvement in the hardware side of medium voltage protection devices. However, new protection protocols need advanced management systems which culminate as a need for development in software and planning. Microgrid operation highlights the need of careful planning and flexibility in software because additional protection settings are needed to enable microgrid operation. (Ihamäki 2011)

Today in Finnish low voltage network the protection is based on fuses. Traditional fuse protection is simple, inexpensive, and techno-economically the most reasonable protection device. Costs are the main reason why relays and switches are not used in low voltage grids. In fuse based protection, each phase of each output of secondary substation have own fuse. In urban cable networks, fuses are also placed into distribution cabinets. Fuses are also used to divide long overhead lines into smaller protection zones. In future smart grids, where lots of DER units are connected also to the low voltage grid, the old fashion fuse protection might not be good enough. In other words, use of effective and adaptive low voltage relays will probably increase in future. (Lakervi & Partanen 2008)

3.4.3 Secondary substation automation

Automation of secondary substations (MV/LV) should be considered in both smart grids and microgrids. Automation of secondary substations can include monitor of power flow and quality, fault indication, relay protection, automatic tap-changing, temperature measurements etc. Above mentioned monitoring, controlling and automation possibilities are not new innovations but they are not used because of the additional costs. In smart grids, some of them might become a reasonable option due to lower communication costs. Power flow measurements and on-load tap-changers are interesting, especially in rural networks because voltage level problems are more common in rural areas where the grids are narrow and distances are long. With on-load tap-changers, secondary voltage of the transformer can be adjusted actively when needed. This kind of automation, which enables better flexibility and at least partially override the problems caused by the lack of background grid, are good for microgrid operation. Nowadays, tap-changing is done manually which means that it is done seldom. With on-load tap-changers, it can be possible to solve some of the problems related to the low voltage levels in low voltage grids. Drawback of on-load tap changers is the motor drive that drives the tap changer because it is a moving mechanism and needs maintenance. This causes higher maintenance costs in addition to higher investment cost. The monitoring of secondary substations enable faster fault repair due to faster knowledge about faults. However, implementation of secondary substation automation has not started in large scale because existing solutions are not techno-economically reasonable. (Werner 2011)

3.4.4 Smart management and software

Management of the smart grids and microgrids is one of the main challenges. Existing management systems are quite sophisticated and more automated protocols, such as automatic fault isolation, could be used already with the existing technology. Accordingly, one of the problems is the human mind. People might be afraid of new technology and do not easily rely on new protocols. For instance in the case of medium voltage fault, automated and preplanned coupling sequence could separate the fault but still the work is done manually by network operators at control room. On the other hand, many new management protocols and also microgrid capabilities need new features from the management systems. One open question in smart management is the use of automated metering infrastructure in large scale. The amount of data that new metering systems can provide is enormous which causes that data management has an important role. Lots of work needs to be done before all the visional benefits can be achieved. For instance, use of real measured values in network planning needs cooperation of many systems, such as AMI, SCADA/DMS and NIS (network information system). These systems might be provided by different manufacturers which mean that the smooth cooperation of the systems might not happen easily. In many cases, the algorithms are not that difficult but they need to be reliable. Therefore the software should to be carefully tested before implementation. However, testing without a real life operation environment is difficult. In addition to improved operation or control, flexibility and security can be seen as the key features of future management software.

3.4.5 ICT infrastructure

One challenge in smart grid development is the need for cost effective ICT infrastructure. ICT infrastructure has developed a lot during last years. Use of communication (both wired and wireless) has increased a lot in people's everyday life. However in distribution systems, the development has been more composed. New kind of ICT infrastructure is needed for smart grids. Smart metering is the first large scale smart grid feature that needs new ICT because hourly based measurement results need to be transmitted from meters to database. In smart metering, power line carrier (PLC) method is one option to transfer data from meters to central unit. From the central unit, data is sent forward via GPRS (General Packet Radio Service) or some other wireless technique. In microgrids, communication between protection devices, energy resources, loads, management system, and control units might be needed. Therefore, it has been determined in Jimeo & al. (2009) that lower than 100 Mb/s link will not be appropriate to handle the information traffic when IEC 61850 standard is used in microgrid operation. It is also recommended in the same study to notice the future traffic growth that will have slowing influence on critical operation traffic. (Jimeo & al. 2009)

Different purposes need a bit different ICT infrastructure. Because the variety of different microgrid solutions is so wide, it is difficult to say which ICT system would be best for all solutions in all cases. For instance, communication based protection need ICT infrastructure that has short latency and ICT protocol that supports short processing times. Latency depends on both distance and protocol. The best option for fast communication is optic fiber which can transfer lots of information at the same time. Costs of optic fiber are high because of the fiber installation expenses. From wireless options, GPRS has too long latency for protection purposes but it suits well for other communication purposes. Reliability and security are also issues that need to be considered when appropriate ICT infrastructure is chosen. To achieve best results, the ICT infrastructure of microgrid should be planned in parallel with the microgrid system planning. (Laaksonen 2011; Pasonen 2010)

3.4.6 Standard IEC 61850

One challenge of smart grid technology, as often in new technology, has been lack of standards. IEC 61850 is a standard which was originally introduced for substation automation but which has been developed for a communication standard for microgrids. In many studies, IEC 61850 standard has been suggested to be a base of microgrid communication (Laaksonen 2011; Pasonen 2010; Elias-Alcega & al. 2011). That is why IEC 61850 is sometimes even called as the microgrid standard. The purpose of the standard is to get different equipment work together without additional data modification. The standard determinates for instance architecture, protocols for connections, and data models. IEC 61850 supports different ICT infrastructures, such as PLC, GSM/GPRS, and LAN. The standard uses Ethernet technology in which low and high priority information can be transmitted in the same wires. (Liang & Campbell 2008; Laaksonen 2011)

IEC 61850 is a mixture of application and node communication. This means that separate system parts, which are based on IEC 61850, have to have similar application logic for successful implementation. Although, the IEC 61850 can be used for microgrid communication, there might be some problems in real life solutions. It is concluded in Liang & Campbell (2008) that definition of IEC 61850 is quite unspecific. The standard is complicated and it includes some open questions in detail planning. The object oriented approach, on which the standard is based, requires intelligence and flexibility from implemented devices. Thus, only the label of IEC 61850 standard compatibility will not guarantee successful operation. Manufacturers have adopted IEC 61850 standard well and new protection devices are usually IEC 61850 compatible. Because the intelligence is software based, the software can be updated which helps to solve possible suitability issues. (Liang & Campbell 2008)

3.5 INCA

INCA (Interactive customer gateway) is a concept presented in the study *"INCA - Interactive customer gateway for electricity distribution management, electricity market, and services for energy efficiency"* (2010) made in TUT (Tampere University of Technology), LUT (Lappeenranta University of Technology) and VTT (Technical

Research Centre of Finland). INCA concept is a platform for smart functions, communication and electricity distribution. Principle of INCA is presented in Figure 3.7.

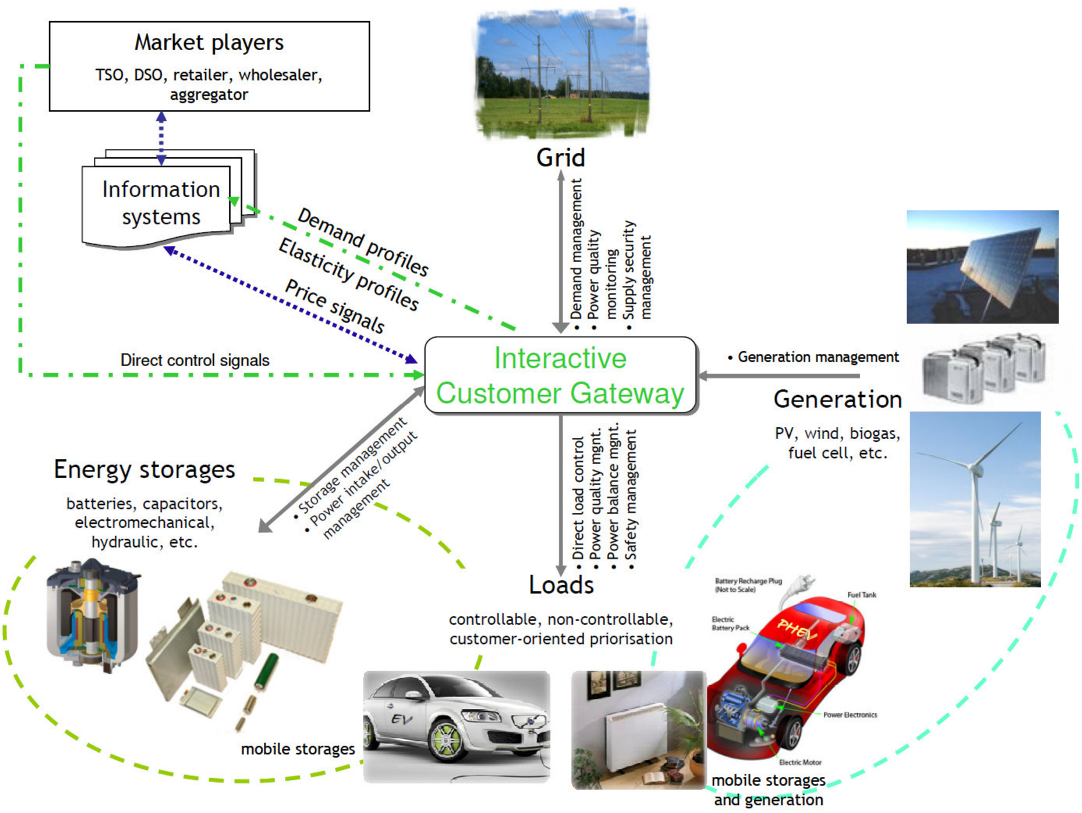

Figure 3.7. Principle of interactive customer gateway (INCA 2010).

INCA modifies old, static customer grid and introduces an active gateway for active resources and market. Important parts of INCA are smart metering which gives information about loads, communication which shares data between customers, DER units, market parties, and system operators. The targets of INCA concept are to provide a platform for active electricity usage and for new business activities which can benefit all parties. Although, the concept gives good examples how things could be done, it includes many uncertainties. The large scale implementation will probably happen step by step and the whole concept is not realistic within few years but maybe later. Some parts of interactive customer gateway, such as AMR and use of measured data, can be implemented in the near future. On the other hand, demand side management has still many techno-economical and attitude barriers. Customers might need high monetary benefits before they get interested. This makes techno-economical operation difficult without significant raise of prices. Nevertheless, interactive customer gateway is important part of future smart grids because without it many smart grid applications cannot be carried out. For microgrid operation, INCA concept can offer adjustability and flexibility. Also, the intelligent use of electric cars would be positive addition for microgrid operation. (INCA 2010)

3.6 Demand response

As the term describes, demand response means that electricity demand responses to the control signal by changing the consumption. The control signal of demand response (DR) can be high wholesale electricity price or high power fluctuation in the network. The idea of demand response is to avoid peak prices and to even out loading variation. With more even consumption profile, more energy can be distributed through the same network. Demand response can be used for power balancing purposes so that the loads response to the power fluctuation. In microgrids, where low inertia is usual, demand response can be essential part of power balance. However, it is also possible to have microgrids without demand response. With active customer behavior, less important loads can support the power balance by responding to changes of voltage or frequency level. Demand response can be important part of microgrids, especially if the power production is based on intermittent power production. Reason for this is that demand response increases adjustability and by that way helps to maintain the power balance. Technical development of demand response is almost ready but business models and customer awareness still need some work. Test implementations of demand response also show that customers' attitudes or incentives are not yet ready for large scale implementation. (Perälä 2011)

3.7 Summary

Smart grid is an extensive concept where targets of energy efficiency and environmentally friendly values are combined with the latest technology. Smart grid visions are ambiguous but most of the ideas can be technically achieved. However, cost structures need to be improved so that the smart grid solutions can compete techno-economically with existing ones. Some of the smart grid features are dependent on development of technology. For instance, penetration of electric vehicles depends on the development of battery technology. In addition, many smart grid features need each other to achieve techno-economically reasonable solution. Many smart grid features have also impact on microgrid operation. Therefore, estimations of the future penetrations of smart grid features are needed also in microgrid planning. Microgrid related smart grid issues and an estimation of their availability are presented in Figure 3.8.

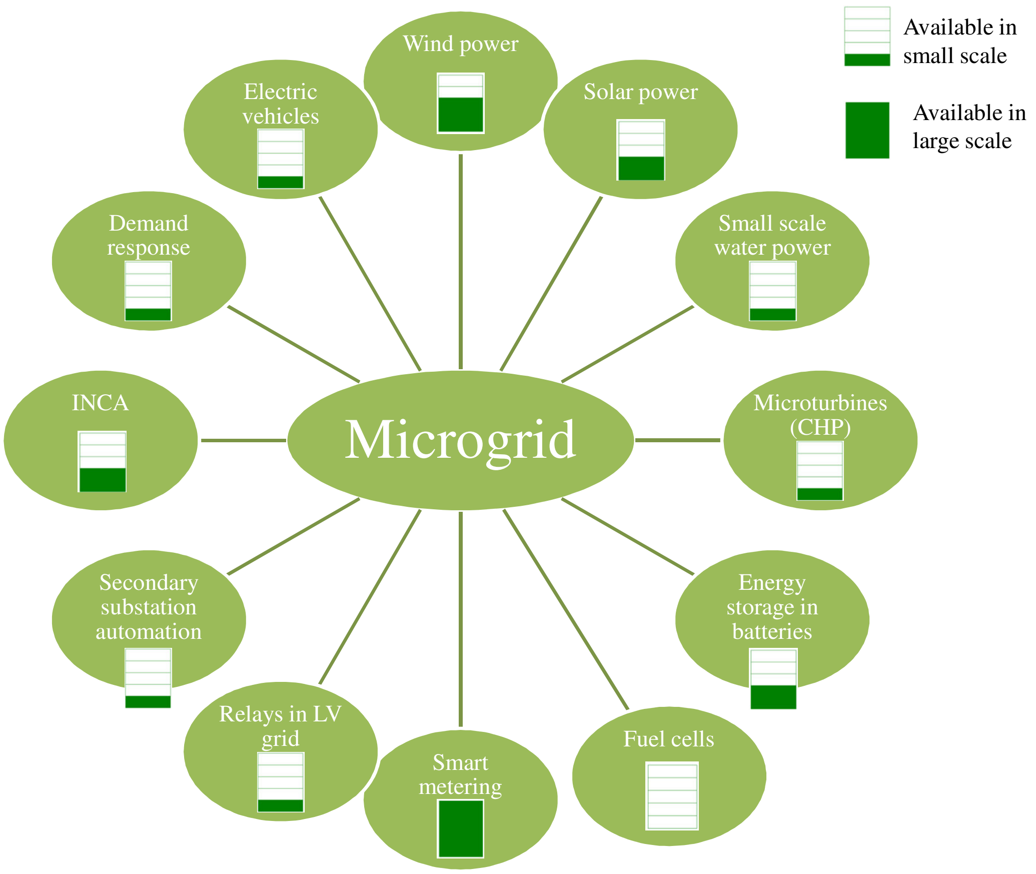

Figure 3.8. Microgrid related smart grid issues and an estimation of their availability in 2020.

As the figure above shows, many features, which are important for microgrid implementation, are still in the starting point in year 2020. Large scale implementation of microgrids is realistic even later because microgrid implementation cannot be expected to happen without high penetration of distributed generation.

4. EXISTING MICROGRID PILOTS

Due to several ongoing smart grid and microgrid programs, many pilots are planned and some even executed around the world. However, detailed information and real test results of microgrid pilots are only limitedly available. In some cases, it is also good to notice that term microgrid is used from grids that include some smart grid or microgrid features but do not have real microgrid functionalities presented in this work. A few examples of existing smart grid and microgrid pilots are described in this chapter.

4.1 Malaga Smartcity, Spain

In Malaga, Spain large "Smartcity" pilot is planned to be build. The group of 11 companies and 14 research centers are involved in the project. The Smartcity system includes MV and LV generation, energy storages, grid automation, demand response features, and smart metering. Communication has also significant role in the system. Communication will be carried out mainly with PLC through electricity lines but also optic fiber is used. Internet protocol (IP) addresses are used for information delivery. Malaga, Smartcity includes most of the needed microgrid features but it is not a microgrid pilot because it does not include capability for autonomous operation. However, these kinds of pilots are important to increase people's interest about new grid technology. The experiences of communication system are interesting from the both smart grid's and microgrid's point of view. The main smart grid features of the Malaga project can be seen in Figure 4.1. (Carillo 2011)

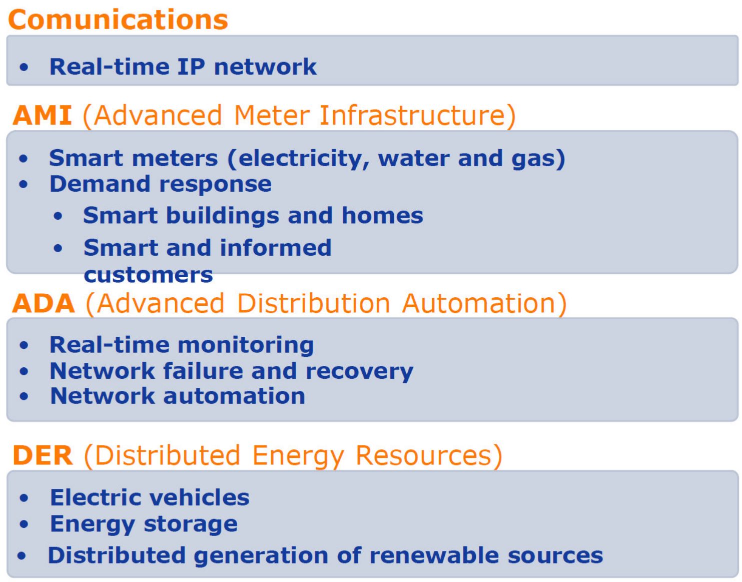

Figure 4.1. The main smart grid features of Malaga Smartcity (Carillo 2011).

4.2 U.S. Army microgrid efforts

Microgrids are interesting issue for critical customers that need high level of energy security. Good examples of this are U.S. Army microgrid efforts. Target of U.S. Army is to improve energy efficiency and reliability with new technology and also enable use of renewable energy sources. To test the potential of new technology, many pilot projects are being started. Islanding capability is also included into U.S. Army microgrid definition. Features like intelligent load shedding and advanced control techniques are tested in microgrid demonstration of Fort Still, Oklahoma. Cyber security is obviously important issue especially for Army installations and therefore it is tested in Joint Base Pearl-Hickam, Hawaii; Fort Carson, Colorado; and Camp Smith, Hawaii. In addition, issues like distributed droop control and conceptual design for islanded system are researched. Exact details about these microgrid projects are not available but the interest of U.S. Department of Defense and the issues that they study indicate the potential of microgrids. Tested systems can be considered as LV microgrids by the definition used in this thesis, although they seem to include only one customer. Islanding capability and conceptual design are interesting research subjects and hopefully test results and some analysis will be available after the tests. (Johnson & Ducey 2011)

4.3 Hailuoto, Finland

In Finland, real microgrid pilots are not established but intended island operation is being tested in Hailuoto. Hailuoto is an island at the sea near Oulu. The idea of the test is to start island operation in the case of fault in utility grid. During the islanding, also the customers at Hailuoto will experience power outage. However, island grid is automatically created by using diesel aggregate and wind power generators. Different protection settings are used for normal utility operation and for island operation. Goal is to synchronize the island back to utility grid without an outage. Results from Hailuoto intended islanding tests are not yet available. The intended island operation does not fulfill the criteria of microgrid operation but test includes many similar features as microgrid operation. In addition, island operation is tested in MV grid which is an interesting feature. However, information about Hailuoto case is limitedly available and the studied materials do not discuss for instance LV protection in MV island operation. (Cleen 2010)

4.4 Mannheim field test, Germany

LV customer microgrid was tested in Mannheim, Germany as a part of More Microgrids -project in 2009. Larger microgrid test was planned in the test project but because of some barriers, the test was finally accomplished in the Kinderhaus day-care center. The main barriers were lack of higher energy storage capacity but also legal, psychological, and contract issues with land owners and expected "*prosumers*" (pro-consumers). All distributed generators and loads in the area are privately owned. Difficulties were encountered in buying a piece of land for devices or making contracts with people. (Khattabi & al. 2009)

Transition between grid connected and island operation was tested in the Kinderhaus. In the island operation test, Sunny back-up energy storage system was used for frequency control. The islanded operation lasted 15 minutes and in that time, the frequency increased from 50 Hz to 52 Hz because of low loads in the microgrid. Load control was not used during the island operation test, although it was successfully tested in separate test. In addition to frequency control, interesting findings of the report are also next statements *"Benefits of microgrids and win-win situations are hard to realize under the* *current regulatory framework."* and *"Social acceptance by real prosumers requires more efforts than expected"*. The report gives realistic picture about the implementation of the microgrid field test. Things that sound simple might become the greatest barriers because of people's attitudes and lack of interests. Similar barriers can be encountered also if microgrids are integrated into distribution network in large scale. (Khattabi & al. 2009)

4.5 IREC's Laboratory microgrid, Barcelona, Spain

Catalonia Institute for Energy Research has made a laboratory microgrid in Barcelona, Spain. The laboratory system is a low voltage microgrid lab test. The tested system includes power generation, energy storage, and loads. System is grid connected and power can be generated with wind turbines and photovoltaic generators. Energy can be stored in lithium-ion battery, ultracapacitor storage, or charged into electric vehicle. 3-layered hierarchical management is used in IREC's microgrid. Functional schematic is presented in Figure 4.2.

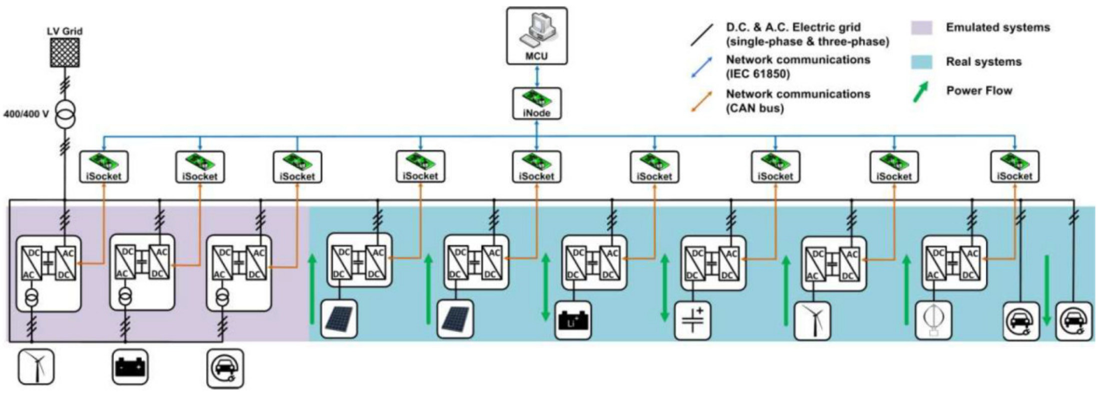

Figure 4.2. Function principle of IREC's microgrid (Elias-AlceGa & al. 2011).

Figure above shows the main components of the test microgrid and the hierarchy of "*iNode*", "*iSocets*" and microgrid control unit (MCU). All power producing units are connected to the grid via converters as can be seen from the figure. Line-frequency phase-controlled AC/DC back-to-back converters are used so that the emulator part of the converter controls active power level. Control is based on measurements of DC bus voltage. The system supports IEC 61850 standard and controller area network (CAN) protocol is used for communication. SCADA is also applied to the microgrid and it helps to configure and supervise the grid. (Elias-AlceGa & al. 2011).

4.6 CERTS, Ohio, U.S.

CERTS microgrid laboratory test bed is an example of LV microgrid that is done in a real life conditions, although real customer loads are not used. The microgrid includes all features that are expected from LV microgrid in this work but it is good to remember that the power systems are not exactly similar in U.S and in Nordic countries. CERTS microgrid include several microgenerators and a storage unit. It can operate parallel with the utility grid but it can also be isolated without interruption. According to Lasseter & al. (2011), the CERTS concept can reduce the need for custom field engineering. These kind of near plug-and-play features are also target of many smart grid visions. Relay protection of CERTS microgrid is carried out without high fault currents and both voltage and frequency stability can be achieved without high-speed communications. However, central communication is used to dispatch new set points for distributed generation units when needed. Load shedding is also used in the test bed if the frequency of the grid drops below normal operational range. The system has no "master" controller or main energy source which is advantage in reliability. This kind of protection and control system seems advantageous, although detailed information about the relays or protection settings is not provided. Nevertheless, CERTS microgrid test bed seems to be advanced entity where both system level operation and small details are considered. (Lasseter & al. 2011)

4.7 KERI microgrids, Korea

Korea Electrotechnology Research Institute (KERI) has participated in many studies related to distributed generation, energy storages, and microgrids. KERI microgrid system is planned to be established in two phases between 2007 and 2012. The first phase concentrates on small scale (100 kW) LV microgrid testing and the second phase on the evaluation of megawatt class MV microgrid. The first phase solution is similar to the definition of LV microgrid and the second phase similar to MV microgrid presented in this thesis, although they are only test solutions. The first pilot was simulated in PSCAD/EMTDC and more detailed results can be found from Keeyoung & al. (2009). Characteristics of KERI microgrid components are presented in the Table 4.1. (Keeyoung & al. 2009)

Table 4.1. Characteristics of KERI microgrid components. (Keeyoung & al. 2009)

Components	Contents of Technology to develop	Performance Evaluation factor
PCS (Power Conditioning System)	•Grid-connection/island mode Operation PCS •PQ compensation type PCS •Remote control & supervision, standard communication network	•Remote power dispatch •Self protection
IED (Intelligent Electronic Device)	•Preventing stand alone mode •Re-Sync •PQ monitoring, Grid connection standard, Protection	•Protection •Domestic/Foreign standard based
MMS (Microgrid Management System)	• Prediction load/generation, PQ compensation • Management of storing devices & load/DG • Power trading, reconfiguration islanding operation	• Safety/security/ economy etc.
STS (Static Transfer Switch)	• Static IED type high speed breaker •When fault in utility gird, fast switching performance to stand alone mode and self diagnosis functions	•Switching performance • Diagnosis
Gateway/ RTU	•Communication network & interface device standardization for various DG, storage devices and PQ devices	• Reliability

Lab results of LV test microgrid are presented in the study Keeyoung & al. (2009). The tests are made based on dummy loading so real customers were not used. The results of KERI microgrid show that in test circumstances the microgrid can control frequency and voltage quite well. In addition, disconnection of distributed generation can be avoided even when the microgrid is established. Smooth transition is possible because of quick changes in diesel engine control mode. The control is changed from active/reactive power (P/Q) control to frequency/voltage (F/U) control. The real field tests are planned to be executed based on this pilot. KERI microgrid efforts are sophisticated and try to give answers to many open questions. If the goals are fulfilled well, it seems that the KERI microgrid demonstrations can show the way for future microgrid demonstrations and real life pilots. However, it is highlighted in Keeyoung & al. (2009) that *"the establishment of pilot plant system requires enormous money and endeavor"*. In other words, microgrid piloting is so multidimensional task that it requires lots of both monetary and personnel resources. This is good to be kept in mind when microgrid piloting is planned. (Keeyoung & al. 2009)

4.8 Summary

Definition of microgrid is used differently by different researchers which causes that different solutions are called as microgrid pilots. Nevertheless, most of the pilots include many similarities, such as implementation of renewable DG and capability of autonomous operation. It is also good that different combinations and features are tested because it increases the awareness of island operation. Figure 4.3. shows how above mentioned pilots fit into the microgrid definition, presented earlier in this study.

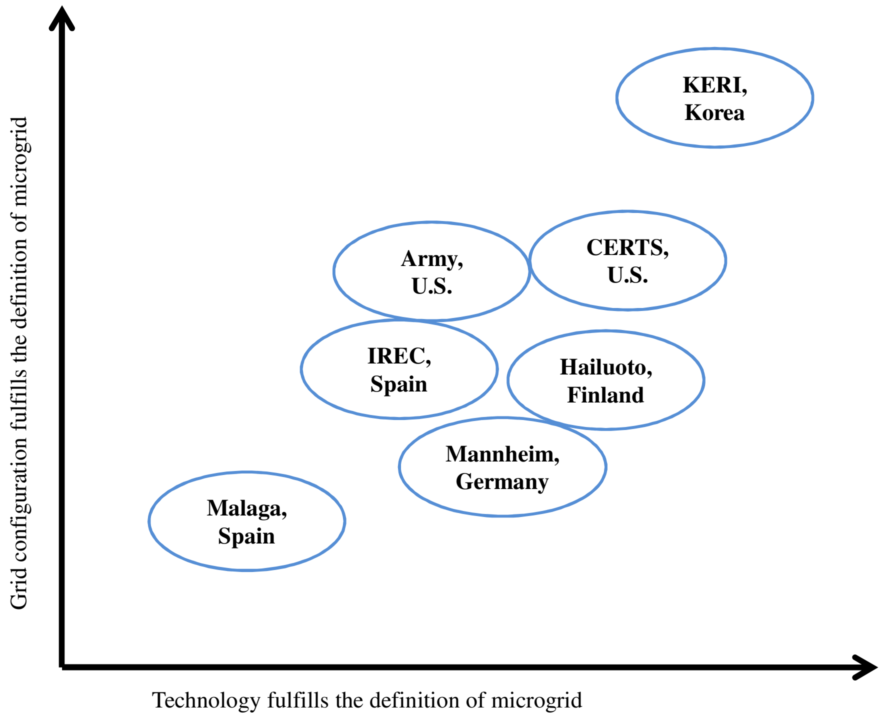

Figure 4.3. Estimation of the relation between microgrid definition and pilots.

Figure above shows that only KERI microgrid pilot and CERTS test bed are even close to fulfill the definition of microgrid presented in this study. This is not surprising, because development and research of microgrids are just in the beginning. In addition, most of the pilots or test beds discuss LV microgrids instead of MV microgrids which are the main interest of this thesis. However, microgrid piloting can be expected to multiply when other smart grid features develop and costs become lower. Even though most of the pilots are only laboratory tests, it does not matter because principles are scalable.

5. MICROGRID OPERATION

As mentioned before, microgrids combine many smart grid features into one entity. This sets a lot of challenges because many of the needed smart grid features are still under development and the final form or even goals vary. In this chapter, needs of microgrid operation are more closely described. Studies, which are related to microgrid operation, usually discuss low voltage microgrids. In this thesis the main focus is on medium voltage microgrids. Main principles of microgrid operation are scalable, despite the voltage level. However in real life, several differences exist. Operation of microgrid is a complex entity and change in one issue can lead to changes in overall system. Operation environment also influences the final solution. In a consequence, protection, control, management, and communication issues need to be considered together. However, it is difficult to create one scheme that works as a target microgrid because of the uncertainties related to each of the issues mentioned above.

Existing networks, safe operation, customer needs, technology, costs, and legislation set some barriers or boundaries for microgrid operation. Some of these can be overcome but some will remain. For instance, Finnish legislation or existing market structure does not allow microgrid operation but laws can be changed if there is enough will (Pasonen 2010). Safe operation, protection, and power quality are issues that need to be taken care of under all circumstances. Some microgrid features, such as islanding or blackstart set challenges for power quality. It can be noticed that microgrid operation is a multidimensional optimization challenge, where boundary conditions have significant role. One challenge is that existing networks work well with simple technology. It is challenging to beat them techno-economically. Nevertheless in some cases, green values and independency of corporations can be more important than techno-economical review. Next some boundary conditions and existing challenges of microgrid operation are discussed.

5.1 Power quality

Power quality is important issue in electricity distribution. Power quality can be divided to interruptions and voltage quality. Idea of microgrids heads to reduce interruptions by lowering the number and duration of interruptions. Even though microgrid operation can reduce interruptions, risk for worse voltage quality becomes higher due to the lower inertia. Growth of risks happens also in traditional grid due to distributed energy resources, especially if intermittent production is used. Maximum output power of DER unit can raise voltage near production unit, especially during low consumption. This can be avoided with the use of compensation devices or by consolidating the grid but these come with high costs. Microgrids, which are based on intermittent production, are sort of a worst case scenario from power quality point of view because of low inertia and high volatility. On the other hand, it is mentioned in Braun & Notholt-Vergara (2008) that in microgrid operation, the voltage quality can be improved significantly with inverter coupled DER units because they can compensate disturbances. Therefore, the real effects of microgrid operation are not that clear and both better and worse voltage quality might appear. It might also be possible to use different standard values in microgrid operation than in utility grid operation. For instance, traditional aggregate systems might not always fulfill voltage quality standards but it is accepted because they are used only temporarily. Voltage quality limits are presented in Table 5.1. (EN 50160; Repo & al. 2005)

Table 5.1. Voltage quality limits in standard EN 50160. (EN 50160)

	Limits	**Of the time**
Frequency	49.5 - 50.5 Hz (10 s average) 47-52 Hz (10 s average)	99.5% always
Frequency in island	47 - 52 Hz 42.5 - 57.5 Hz	95 % always
Voltage (LV grid)	207 - 253 V (10 min. average measurement) 195.5 - 253 V (10 min. average measurement)	95% always
Harmonics	THD max 8% + Own limits for each harmonic: E.g. 3(5%), 5(6%), 7(5%), 11(3.5%), 13(3%)	95 %
Voltage sags	Total amount between dozens and thousand	in a year

Table above shows the limits of standard EN 50160. Even in normal operation the limits are quite loose and much better quality is achieved in Finnish distribution grids. In addition to normal limits, worse voltage quality is allowed temporarily as the second values in the table show. If island operation is considered as temporary action which happens seldom enough, it is possible to allow these worse voltage quality limits. However, poor voltage quality is also a risk for microgrid operation because protection units might disconnect grid parts or distributed generators if the fluctuation is too high. This would worsen the voltage quality even more and could lead to collapse of the network. Although there are challenges in microgrid operation, there are also some new opportunities. For instance, use of energy storages due to microgrids enables more constant power production and voltage quality improvement. Energy storages reduce voltage fluctuation also in the utility grid mode. After all, increased smartness in distribution network and especially in protection will probably decrease disturbances. (EN 50160; Repo & al. 2005)

5.2 Protection

Safe operation is always major issue in electricity distribution. Protection devices and careful planning are in key role to enable safe operation under any condition. Fuse protection is used in traditional low voltage networks, but many studies suggest that use of relay protection is needed to enable low voltage microgrid operation (Laaksonen 2011). In medium voltage network, protection devices have developed a lot. Development has led from old, mechanical relays to microprocessor relays, which are also called as numerical relays. The second generation numerical relays include several capabilities, such as several different measurements and setting groups, 2-way data transfer, and self control. This kind of measurement, control, communication, and protection units are called as feeder terminals. They are widely used for medium voltage network protection at HV/MV substation. Feeder terminals can communicate with supervisory control and data acquisition -system (SCADA). Table 5.2. shows the main requirements for electricity network protection. (Ihamäki 2011)

Table 5.2. Requirements of protection.

Requirement	Reasons
Selectivity	Fault affect minimum amount of customers
Fast operation	Human safety, stability, minimal damages for grid components
Reliability	Protection works when needed and as wanted
Simplicity	Settings can be easily adjusted by a technician
Flexibility	Protection can be modified when the grid changes, different setting opportunities
Testing	Easy to test onsite
Low price	Cost effectiveness, limited investment resources

The requirements are partially overlapping or controversy. For instance, superior protection features usually lead to higher investment cost or fast operation might lead to worse selectivity or reliability. Sometimes usability can suffer because of multifunctional but complicated settings. The optimum solution usually combines good features and reasonable price. Selective operation means that right protection device, which is usually the closest, separates the fault so that minimum amount of customers suffers from the outage. Usually selective operation can be achieved with current, voltage, time, and/or directional parameters. Interlocking signals can also be used.

5.2.1 Challenges of existing protection

In addition to protection of feeder outputs, also protection of distributed energy resources needs to be considered because they are the foundation of microgrids. What is nowadays expected or required from the DER protection, is partially controversy to that what is required from DER protection in microgrids. However, similar challenges can be confronted in both utility and microgrid operation. Following challenges might be encountered in existing protection solutions:

- Unwanted island operation
- Unnecessary disconnections (lack of selectivity)

- Reconnection failures
- Slowness of protection

Reconnection failure might happen because also DG feeds short circuit current and electric arc will not go out fast enough. Problem can be solved with longer reconnection times but this causes other problems, such as voltage sags for healthy grid parts. The fact that also DG feed short circuit current causes that fault currents become lower at the primary substation. Lower fault currents might make protection slower because faults are not detected similarly as before. Other challenges, related to protection of the grid with DG, are more closely described in the following.

LOM protection

Nowadays, DG units are required to disconnect themselves from the utility grid when a fault occurs (Pasonen 2010). This is called as Loss of Mains (LOM) protection. The idea is to avoid unwanted island operation and quarantine safe operation. The role of LOM protection is described in Figure 5.1.

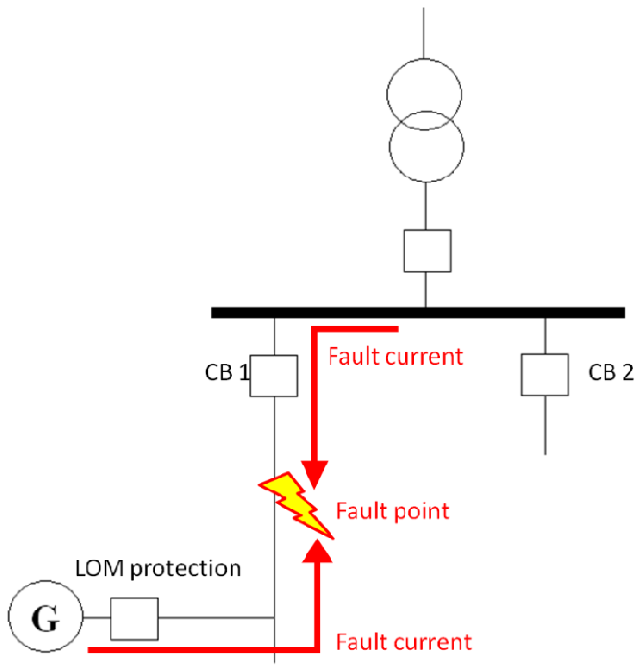

Figure 5.1. Lost of mains protection in the case of fault in MV grid.

The distributed generator (G) and utility grid feed fault current to the fault place. Due to over current, circuit breaker 1 (CB 1) opens up and the feed of fault current from utility grid stops. DG is usually protected with over and under voltage and over and under frequency protection. Usually, islanding causes that some of these voltage or frequency limits is exceeded and also the DG disconnected. However in some situations, DER unit might be able to maintain the voltage in the remaining grid. Therefore, LOM protection is needed to stop the fault current feed from distributed generator (G). Nevertheless, late disconnection of DER unit can lead to failure of automatic reconnection of CB 1. To avoid failure in automatic reconnection and guarantee the action of LOM protection, longer reconnection times for CB 1 might be needed. In worst cases, automatic reconnections cannot be used at all. This obviously has negative impact on distribution system interruption times and causes harm for the customers and higher interruption costs for DSO. (Repo & al. 2005; Pasonen 2010)

Unnecessary disconnection

Distributed generation increases the risk of unnecessary act of protection devices. Unnecessary disconnection happens if selectivity do not realize. In other words, healthy part of the network is disconnected. In addition, DG might be disconnected because of voltage dip or spike. An example of unnecessary disconnection is presented in Figure 5.2.

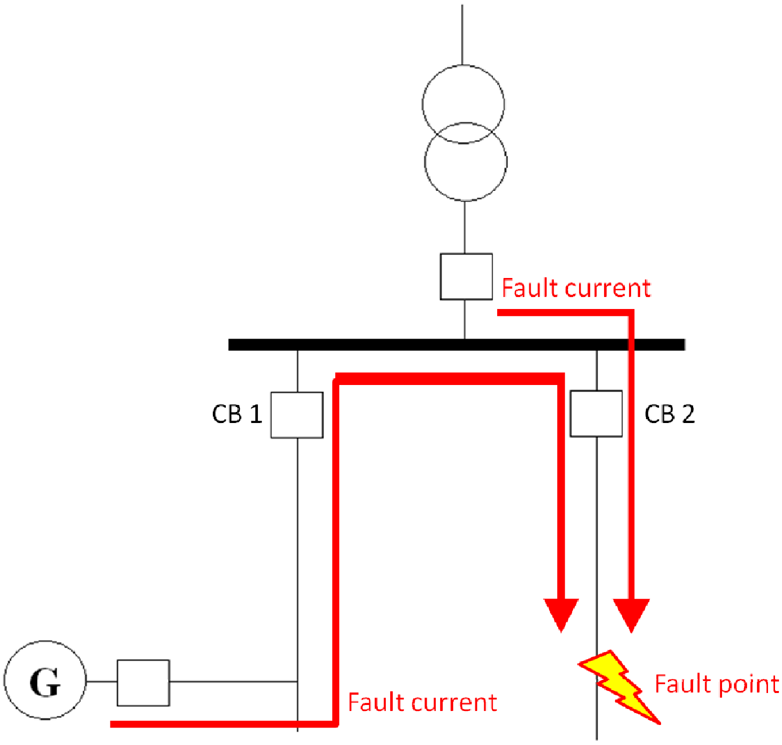

Figure 5.2. Unnecessary act of CB 1 when the fault happens behind CB 2.

Figure shows how unnecessary disconnection might happen if CB 1 acts when the fault happens behind CB 2. In this case, distributed generator (G) feeds fault current backwards through CB 1. If the current is high enough, it makes CB 1 act. This can be avoided with relays that define the direction of current. However, they cause extra costs. Unnecessary disconnection of DGs can be avoided with selective protection settings. For instance, longer disconnection times for DGs can be used if it does not cause problems elsewhere in the grid. If voltage dips cause problems for the DG unit, effects can be avoided with fast protection settings elsewhere in the grid.

Blinding of protection

One unwanted feature in the protection is blinding. Blinding of the protection might happen if the fault current from utility grid remains small. In this situation, distributed energy resource usually feeds main part of the fault current. Example is presented in Figure 5.3.

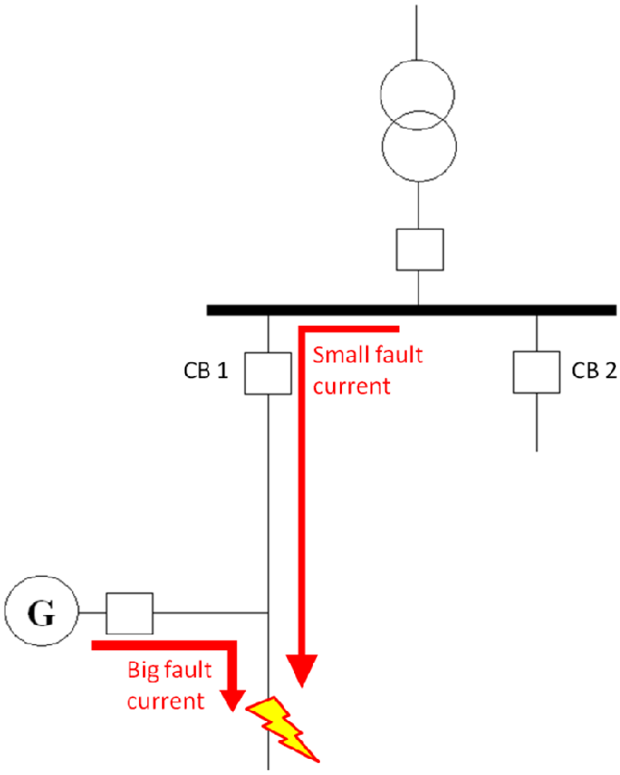

Figure 5.3. Blinding of protection device CB 1.

In figure above, the distributed energy resource feeds main part of the fault current to fault place and the fault current from the utility grid remains small. Protection device (CB 1) does not detect small fault current and it will not act. This leads to hazardous situation where human safety and grid components are under danger. Protection needs to be planned carefully to avoid blinding. Capability to provide fault current depends of the production unit and therefore the type and features of the energy resource need to be noticed in protection planning. For instance, power electronics can provide only limited amount of fault current but directly connected rotating generators are capable to provide at least double of the fault current provided by converters. In converter connected DGs the capability to provide short circuit current is about 2-3 times the nominal current. (Repo & al. 2005)

Examples show that distributed energy resources set challenges for the protection already in the normal network. Same challenges exist in microgrid operation and the situation might be even more challenging because of smaller fault currents and low inertia. Low inertia makes higher transients and variations possible. This might cause malfunction of protection devices. Especially, islanding might cause fluctuations which can danger frequency stability and voltage quality. Higher fluctuation in voltage or frequency and tight protection settings might lead to disconnection of DER unit which might collapse the whole microgrid. This is obviously unwanted and therefore protection settings need to be adjusted or low fluctuation guaranteed. Also, use of separated protection settings for utility grid operation and microgrid operation can be recommended. (Laaksonen 2011)

5.2.2 Microgrid protection

In microgrid protection, both low voltage and medium voltage protection need to be studied. In this work, the main focus is on MV microgrids and MV protection but it is also necessary to consider the protection of LV networks in MV microgrids. This is often neglected in other MV microgrid studies. Next there are some open questions in MV microgrid protection:

- Is feeder terminal protection enough?
- Is communication between protection units needed?
- Is the low voltage protection based on fuses or relays?
- What is the best solution techno-economically?

These features are also dependent on other microgrid features, such as amount of DER units and configuration of the network. It has also an impact whether the power generation is focused on medium voltage or low voltage side. A MV microgrid, in which power generation is based on small LV units such as solar panels, differs a lot from a microgrid, in which MV wind park is connected to the primary substation. Not to mention the use of high power gas or water turbines which have good controllability. The same solutions might not be applicable in all cases. This might be the reason why existing studies focus on one specific scheme and try to solve problems related to that. Solution, where large energy storage and big main power production unit is used, is easier from the protection point of view, because the current goes mainly to one direction and fault currents can be more easily determined. In this case, also the need of communication and extra costs can be expected to be more limited.

DG's capability to provide short circuit power is important in over current protection. Large share of intermittent production do not achieve its nominal power at the same time as described earlier in this thesis. Therefore in microgrid operation, the nominal power of intermittent production has to be higher than the consumption. This increases the amount of short circuit power. If the fault current levels are high enough, traditional feeder terminals can be used, although own microgrid settings are probably needed. When the power generation is connected to medium voltage grid, the power flow in low voltage grid is unidirectional, which in right conditions might enable use of traditional fuse protection. Dimensioning of the grid has also a significant role. In rural areas, where the long radial low voltage grids typically are located, the sufficient fault current is a challenge already now. In microgrids, the problem is even more significant. Therefore, it can be difficult to achieve sufficient fault currents for fuse protection in rural microgrids. As a conclusion, it can be stated that there is not a single techno-economical solution that would fit for protection of all kinds of microgrids. Nevertheless, low cost solutions need to be favored because high costs might undo the benefits of microgrid operation.

5.3 Microgrid management

Microgrid management is needed to achieve the expected functionalities, such as transition between on-grid and off-grid modes, synchronization, control of power balance and blackstart. In Laaksonen (2011), it is concluded that in practice, a microgrid management system (MMS) is needed to control the LV microgrid system as entity. In MV studies, these kinds of exclusive models are not created. Therefore, both MMS based and self-sufficient management strategies can be recommended. However, intelligence of MMS is mainly software based which increases formability. Main questions of microgrid management are:

- Whether MMS is needed or not?
- Whether control and management are distributed or centralized?
- What kind of communication is needed?
- How the power balance is controlled?

The intelligence of management can be centralized or distributed. There are some pros and cons in both alternatives. Also, some kind of combination is possible. Some simplified and aggravated differences of centralized and distributed management strategy are described in the Figure 5.4.

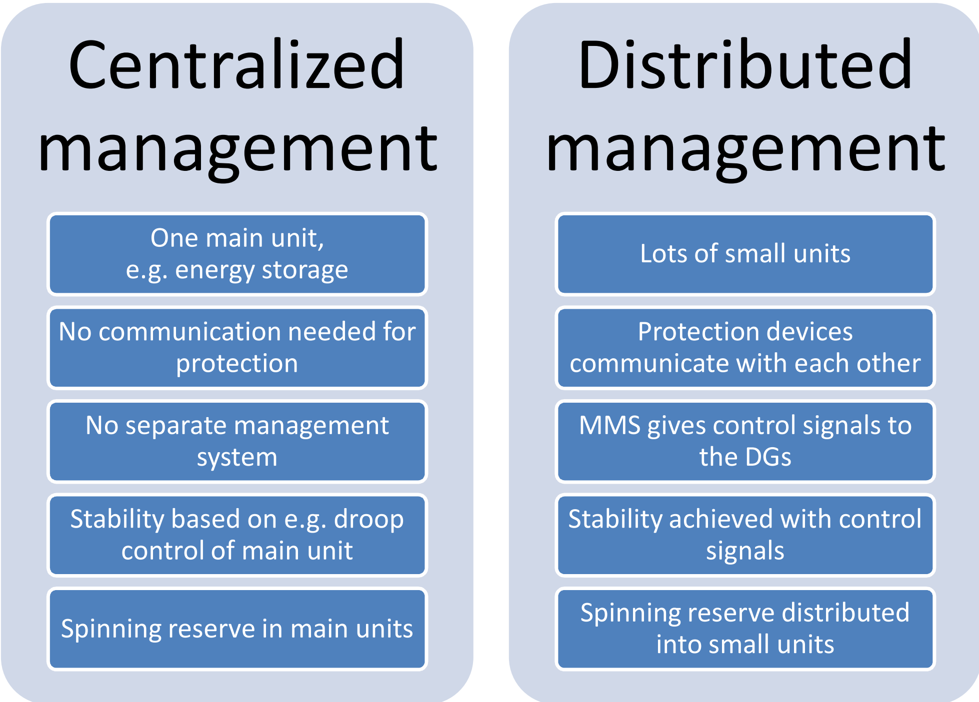

Figure 5.4. Comparison of centralized and distributed microgrid management system.

As a bit aggravated figure above shows, there are lots of differences in management strategies. Distributed management and control strategy has advantage in reliability, because lost of one part does not affect remarkably to other parts. On the other hand, centralized control might need less modification in existing devices, because most of the devices are only supporting the operation. This is significant advantage when microgrids are implemented into existing distribution system. Also, need of communication might be an issue because it has impact on system costs and reliability. Distributed control usually needs more communication than centralized one. Reliability and cost of communication are the main challenges in communication based management. In addition, it needs to be solved, what happens, when the communication fails. Opportunities and challenges of different microgrid management solutions are more closely studied in the following chapters. (Laaksonen 2011)

5.3.1 Power balance and control

Power balance is traditionally achieved by controlling the power production and in extreme conditions by controlling the loads. In transmission system, control of active power has impact on system frequency and control of reactive power has impact on local voltage level. Frequency is the same around the grid, but voltage can vary locally. In Finnish distribution grid, frequency is kept in 50 Hz by adjusting the powers in Nordic transmission system. In microgrid, the system and inertia are much smaller and the frequency needs to be controlled locally. Therefore, fast control methods are needed to avoid fluctuation in frequency or voltage. Most of the distributed energy sources are not planned for this kind of control so the most problematic questions are:

- Which units participate in control and how much?
- Is communication needed for sending control instructions?
- How the required frequency/voltage control reserve is defined?
- How the costs of power balance are divided?

As in protection or power generation, also in control, the question to begin with is whether the control is centralized or distributed. It cannot be said, which one is better because it is almost impossible to make reliable and comparable techno-economical calculations at this point of the development. From the implementation point of view, simpler strategies that do not need communication are easier to implement to the grid where ICT infrastructure do not exist. Nevertheless, if the communication infrastructure exists or can be installed with low costs, communication based management might be more reasonable option. Two main control strategies are P/Q control and V/f control. P/Q control is a control strategy where frequency and voltage level are determined elsewhere in the grid and the P/Q controlled unit adjusts its output power. In other words, P/Q controlled unit can be seen as voltage source where current and angle are controlled. In V/f control, the controlled unit can be seen as voltage source where magnitude and frequency can be adjusted. (Dobakhshari & al 2011)

In grid connected operation, all distributed generators can be P/Q controlled, because frequency and voltage are determined by the transmission network. In microgrid mode, some unit needs to be the grid forming unit. In other words, some unit needs to set the frequency and voltage level. To sustain stabile island operation, at least one main unit need to be V/f controlled. In addition, it has to be noticed that transmission and distribution system differ a lot because the ratio of resistance *R* and reactance *X* differ. In transmission lines *X*>>*R* but in distribution lines *R*>>*X*. With transmission system, the frequency and load angle are controlled with active power and the voltage with reactive power. In distribution microgrid, the grid forming unit sets frequency to 50 Hz and controls the voltage. Other units can be P/Q controlled so that they adjust the current and angle based on measurements or according to the commands of MMS. If the control strategy is based on droop mechanism, where control reference is determined by local measurements, no communication infrastructure is needed. Whether the control is distributed or not the control needs to be accomplished under strict boundary conditions. These boundary conditions come from stability and voltage quality. In addition to control of distributed generation, also demand side management is planned to be possible in microgrids to increase adjustability (Laaksonen 2011). (Dobakhshari & al 2011)

5.3.2 Control of distributed generation

Control capability of DGs is important especially in microgrid operation. In grid connected mode, distributed generators can be seen as support units that support voltage control by adjusting their output power. In addition, distributed generators reduce grid losses because the power can be produced locally. However, reactive power transmission might be needed which increases losses. Different DER units have different features as described in chapter 3. In microgrid operation, at least one DER unit needs to be the grid forming unit that sets the frequency and voltage level. In practice, the grid forming unit is the largest unit in the terms of capacity. Controllability is also an important criterion, when suitable main unit is chosen. If some adjustable energy source, such as CHP, water turbine, or large energy storage is available, it is the most considerable option for the main energy source.

Although, the control principle is simple, it is complex task to decide which units participate in frequency control and which are P/Q controlled. As a part of control strategy, spinning reserve is needed to enable stabile operation. The amount of needed spinning reserve in microgrid operation was studied in Wang & Gooi (2011). Spinning reserve is unused capacity of power production that is already synchronized with the grid and can be taken into use within given short period of time. It is mentioned in the study that the estimation of sufficient spinning reserve is complex to define in microgrid operation. In addition to economics and reliability, mix of different sources and use of intermittent DG units introduce significant uncertainty into planning. Study in question sets economical targets of control so that the total costs are minimized in microgrid operation and profits are maximized in grid connected operation. Excessive capacity of the network is the easiest way to solve the problem of uncertainty in system planning but it increases costs. (Wang & Gooi 2011)

Control of the distributed generator depends of the generation type and machinery. Therefore, control strategies need to be flexible and suitable for different generation types. Next some basic features of the control are discussed. Control of the active power level is generally well known because it needs to be handled already today. In intermittent production, the active power level depends, for instance of the wind speed or sun radiation. However, some adjustability can be achieved because the active power can be limited during good weather conditions. CHP, hydropower, and batteries can be controlled so that the active power level can be adjusted according to the needs. Also, the capability to control reactive power is highly dependent on the generator and machinery. For instance, synchronous generator can control reactive power level quite well. On the other hand, in permanent magnet asynchronous generator the flux remains almost the same. Therefore, the capability to control reactive power is limited, although some adjustability can be achieved with stator current control. In full power converter based systems, the reactive power level, as well as other features, can be adjusted well. Even though the reactive power can be controlled well, it does not mean that voltage can always be controlled. In distribution grid, the problem might be the reactive power flow. Problem is presented in Figure 5.5.

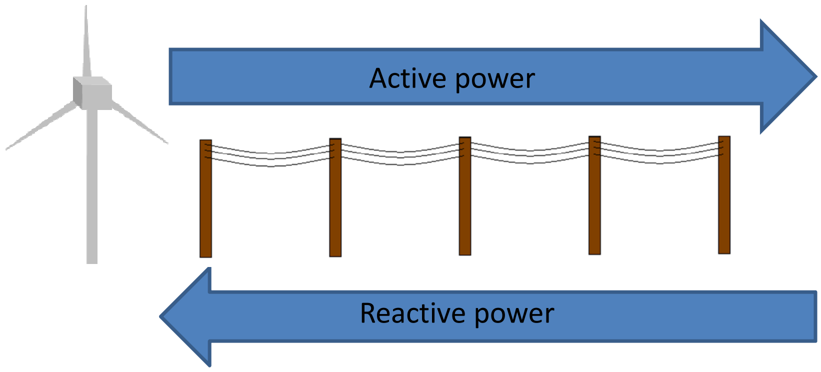

Figure 5.5. Need of reactive power to prevent the voltage rise in a weak grid.

Figure above shows a situation where reactive power is needed in a weak grid to lower the voltage rise caused by high active power transmission. Distribution of reactive power is not practical because it causes losses in the distribution grid. Example shows that even though the machinery offers needed capabilities, it will not guarantee successful operation of the system. Requirement of reactive power can be solved with capacitors that produce reactive power but it causes extra costs. Usually DER units are controlled so that the power factor stays close to one which keeps need for reactive power limited.

5.3.3 Demand side management

Demand side management is mentioned to be a part of microgrid power balance system for instance in Schawaegerl & al. (2009) and in Laaksonen (2011). In microgrids, the amount of controllable production is more limited than in traditional networks because of larger share of intermittent production. If the production cannot be controlled well enough, it is logical that also the demand side is controlled to secure power balance. All loads cannot be controlled and therefore they need to be categorized. Critical loads are not disconnected, however dispatchable loads can be disconnected when needed. Dispatchable loads can be shiftable or interruptible. Shiftable load means that the load can be shifted to some other time of the day. For instance, electric water heating device can be disconnected when needed, but the heating is completed when there is enough power. Interruptible load means unessential load that can be disconnected during emergency situations. Interruptible load can refer to day-time lighting, standby devices etc. However, this kind of load categorization and demand side management is not realistic yet. In future, high speed communication and smart household devices might enable demand side management that can be used also for rapid power balance activities. (Schawaegerl & al. 2009)

In this thesis, demand response and demand side management are differentiated with different control strategy. In demand response, the loads are controlled with signals that come from aggregator and are based on e.g. price. In demand side management, loads can be directly controlled by the system operator or local measurements. When the customer's smart household system receive demand response signal, it can reduce the consumption. Also, the term virtual power plant (VPP) is used for this kind of operation. Both demand side management and demand response include high potential if customers get interested. However, they are not yet available. Economical issues as well as lack of customer's interest are the main limitations of demand side management implementation. The fact that demand side management is not yet realistic to implement means that power balance need to be achieved with other options in the near future microgrid pilots. (Schawaegerl & al. 2009)

5.3.4 Transition between on-grid and off-grid modes

Transition between on-grid and off-grid modes is one of the most challenging features of microgrids. Risks of transients, oscillation, and disconnection of DER unit become higher during transition. Main problems of transition between microgrid and grid-connected operation are:

- Defining limits for power flow between microgrid and utility grid in islanding
- Management of re-synchronization
- Quarantine of safe operation during transition

The easiest way to start islanding is to set the power flow between microgrid and utility grid near to zero and then disconnect the microgrid from utility grid. However, to enable full potential and use of DG, power flow between microgrid and utility grid cannot always be near the zero. In fault situation, it is not possible to adjust the power levels before islanding and therefore some kinds of power changes need to be handled during islanding. Power difference that the microgrid can handle during islanding depends on the control capability of the grid and inertia of the grid. Rotating masses and rotating generators increase inertia and enables higher power differences. Fast controllability of production and/or loads helps the microgrid to survive from islanding. (Laaksonen 2011)

Synchronization is needed in the end of island operation to connect the operating microgrid back into utility grid. This means that measurements at both sides of the point of common coupling (PCC) are needed. Absolute values of voltage can vary a lot at the different sides of PCC when the grids are not synchronized. Also, the frequency can be different in microgrid mode. If microgrid is connected to the utility grid without synchronization, high transients, oscillation, or voltage variability might occur. Microgrid can be safely connected to utility grid with synchronization device. This device includes relaying that monitor differences in absolute voltage levels, frequencies, and load angles. (Laaksonen 2011)

Safe operation need to be guaranteed during the whole time but the protection settings cannot be too strict because it would lead to unnecessary disconnections. To avoid unnecessary disconnection, it is recommended in Laaksonen (2011) to set microgrid settings for protection devices after all transients that are related to islanding. In practice, this can be done with suitable time delay after islanding.

5.3.5 Blackstart

Blackstart is a part of microgrid management and protection strategy. Blackstart means capability to restore electricity distribution in the situation when the power is lost also from the microgrid. Microgrid might have blackout because of instability or fault during the island operation. Blackstart occurs rarely in a utility grid and with microgrid operation the need can be expected to reduce even more. Therefore, it can be put under question, whether the blackstart capability is really necessary or not. At least in wide scale outage, it is useful. Blackstart is challenging because most of the distributed generators are not planned to be connected to the grid without voltage reference from the utility grid. (Laaksonen 2011; Braun & Notholt-Vergara 2008)

Different blackstart strategies are introduced in different studies. Common for different strategies is that both communication and microgrid management system are needed to enable blackstart. In multi-microgrid scheme, the bigger microgrid is divided into smaller sections around distributed energy sources. Those sections are planned to start themselves after a blackout and then synchronize with each other. This kind of strategy needs lots of communication between sections and many synchronizing devices. One blackstart strategy is presented in Figure 5.6. (Braun & Notholt-Vergara 2008; Laaksonen 2011; Zheng & Li 2010)

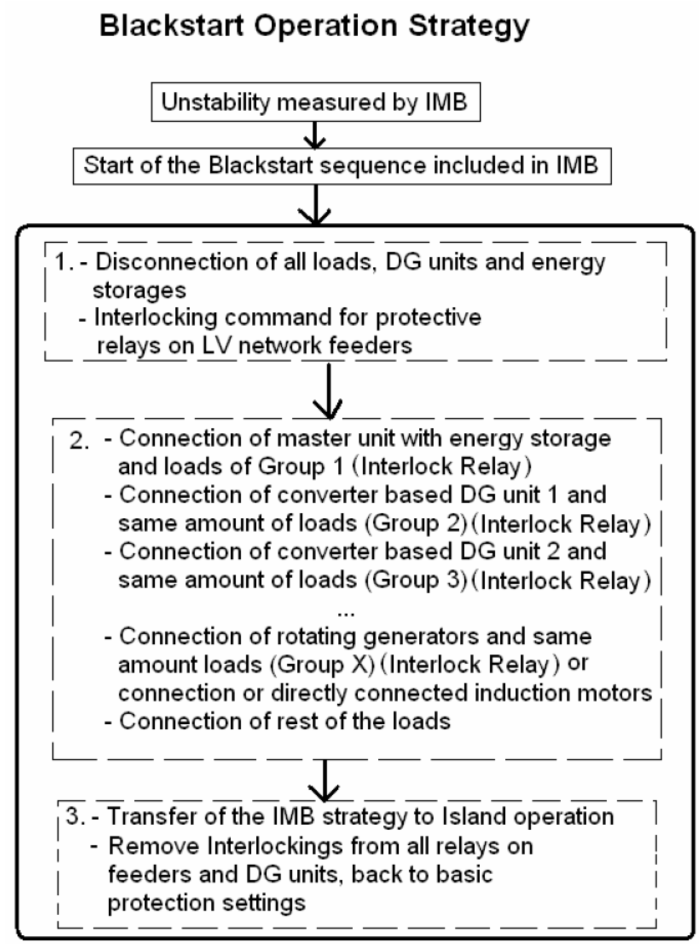

Figure 5.6. Example of blackstart strategy (Laaksonen 2011).

The blackstart strategy showed in figure above relies on energy storage that can provide suitable voltage reference for DG. This unit can also be a diesel generator. Other important components are MMS and communication between master unit, DGs, and loads. It is also suggested that the separated microgrid intelligence could be replaced with intelligent microgrid breaker (IMB). It is also good to notice that converter based

DG is connected first and rotating generators and motors are connected last. This is done because DG with power electronics is easier to connect and also the grid and inertia gets higher before rotating masses are connected. This way rotating mass does not cause that much disturbance from power quality point of view. (Laaksonen 2011)

Lots of communication and control is needed to enable blackstart. Use of load control and sectional connection are essential in many blackstart strategies. High level communication and control systems might be avoided with one main unit working as a system brain. The main unit can be large energy storage or large distributed generator, such as CHP plant or diesel generator. Suitable loading for blackstart does not include lots of rotating motors or other devices that take high starting current. Use of one main unit for blackstart might in practice mean oversized DG which might not be the most economical option.

5.4 Additional challenges

Study points out that there are still many challenges related to microgrid operation. However, most of the technical challenges can be overcome and it is already possible to test microgrid operation in some pilots. Although microgrid operation is possible, it is still far from economically reasonable operation. As presented, many microgrid solutions need high-speed communication which causes extra costs. It can be concluded that the biggest technical challenge of microgrids is to develop new technologies and strategies that work without heavy ICT infrastructure. Other possibility is to wait and see if the ICT infrastructure is implemented along with other smart grid features. This would also help implementation of smart grids because microgrid operation can be counted to share the costs of communication. Plug-and-play capability is one issue that needs development but is difficult to achieve. Overall system or concept development is needed to achieve plug-and-play capability that works without high level communication or over sizing of components. In future, techno-economical calculations are needed to show whether there will be a real potential for microgrids or not. Today, microgrids do not yet have enough economical potential with existing solutions. Therefore, other smart grid features that are going to be installed should be flexible so that they can be used as a part of microgrid operation. In countries, where the average interruption time is less than couple of hours, the interruption costs cannot be the only driver for microgrid operation. Customers' demand and interest might become a driver due to the widespread of DG. However, customers' interests are not deeply speculated in this thesis. Cost-efficiency and conceptual thinking will probably be the factors that separate the best solutions from large variety of different schemes.

5.5 Business opportunities and barriers

Microgrids can offer new kind of business opportunities by enabling higher penetration of DG and customer involvement. Aggregators are market players that buy electricity from small units, join the small power amounts and sell them as a larger package to the wholesale market. One business potential of microgrids is that they can create a local retail market where aggregator is suggested to be the controller of retail markets. The principle of local markets is against existing regulation, where energy from any generator should be available to any customer. Law needs to be changed to allow commercial microgrid operation. Technical operation of microgrids is not dependent on existence of local markets but the business is complicated to handle without transparent market structure. The acceptance of local markets might be the main challenge because then, for instance the living area would have impact on the electricity price. Some of the barriers for microgrid implementation are (Schawaegerl & al. 2009):

- Low implementation of DER
- Low electricity prices
- Lack of local energy trading
- Negligence of environmental values
- Lack of workable business models

The fact that low electricity price is a barrier for microgrid operation is interesting because low price is one of the customers' main interest. One important point is also the fact that costs of electricity consumption differ a lot in different countries. For instance in Germany, electricity costs are higher than in Finland which means that some solutions might be economically suitable in other country but not in other. In addition, it is good to remember that the average disturbance duration is shorter in German cities than in Finland. Figure 5.7. shows the power of politics and how different political decisions have lead to different situation in the electricity business sector of Finland and Germany. (Schawaegerl & al. 2009: Fette 2011)

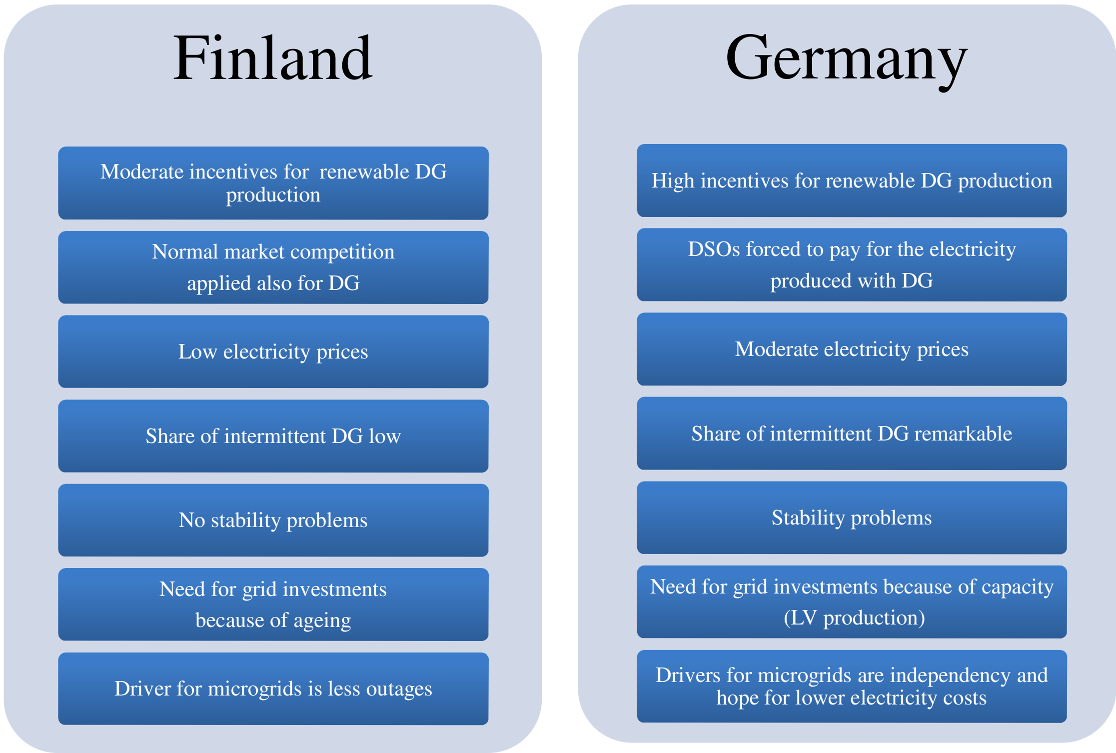

Figure 5.7. Comparison of Finland and Germany as a playground for microgrids.

As mentioned earlier, incentives for renewable DG have been and still are much higher in Germany than in Finland. Good incentives, favorable weather conditions, higher electricity prices, and positive attitudes have led to widespread of DG in Germany. However, relatively high share of intermittent production have led to transmission capacity problems as well as stability problems, such as the 50.2 Hz problem. In addition to German transmission grid, also distribution grids need high investments because large share of intermittent DG is connected to the LV grid. This might become a driver for microgrid operation because rebuild of the grids is expensive and it might be better for DSO to sell the grid. New owners could be local people or utilities that could operate the grid as independent microgrid, in the hope of lower electricity costs for customers. (Fette 2011)

5.5.1 Nordic energy sector and microgrids

Nordic energy markets have developed a lot during last decades. Some of this development is quite controversy to the development that is expected from microgrids (Schawaegerl & al. 2009). The main controversies are presented in Figure 5.8.

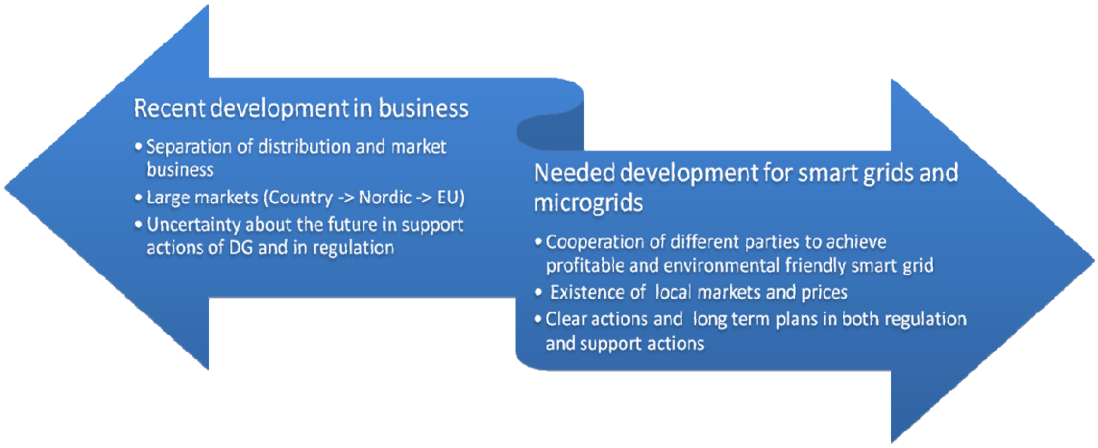

Figure 5.8. Development in Finnish electricity market and needed development for microgrids.

Nowadays in Finland, DG owners lose income during outages and DSOs are not obligated to pay compensation for DG owners. However in Germany, legislation obligates DSO to pay for the energy to the DG owner whether the paid electricity is distributed or not. Therefore, from DG owners point of view microgrids have opportunities and barriers. In Finland, DG owners can benefit from microgrid operation because they do not need to shut down the production as often as before. Other benefit, which might come with the energy storage capability or with better load control capability, is that producers do not need to limit the production during possible local overproduction because it can be stored and/or consumed locally. A drawback of microgrid operation for energy producers is the risk of lower energy prices in local markets. Lower prices would mean lower profits and longer payback times for DG investments. In recent market structure, electricity production is banned for DSOs. This is one reason why it is difficult for DSOs to get microgrid operation profitable. Therefore, cooperation between different market players is needed.

5.5.2 Aggregator in microgrids

Microgrid operation, demand response, and exploitation of electric vehicles as energy storages are issues that are often related to aggregator. In microgrid operation the aggregator might also act as a retailer. In this model, aggregator is a market player that buys energy from wholesale market and DER owners and sells it to customers. Differences of VPP and local retail market are presented in Figure 5.9. (Schawaegerl & al. 2009)

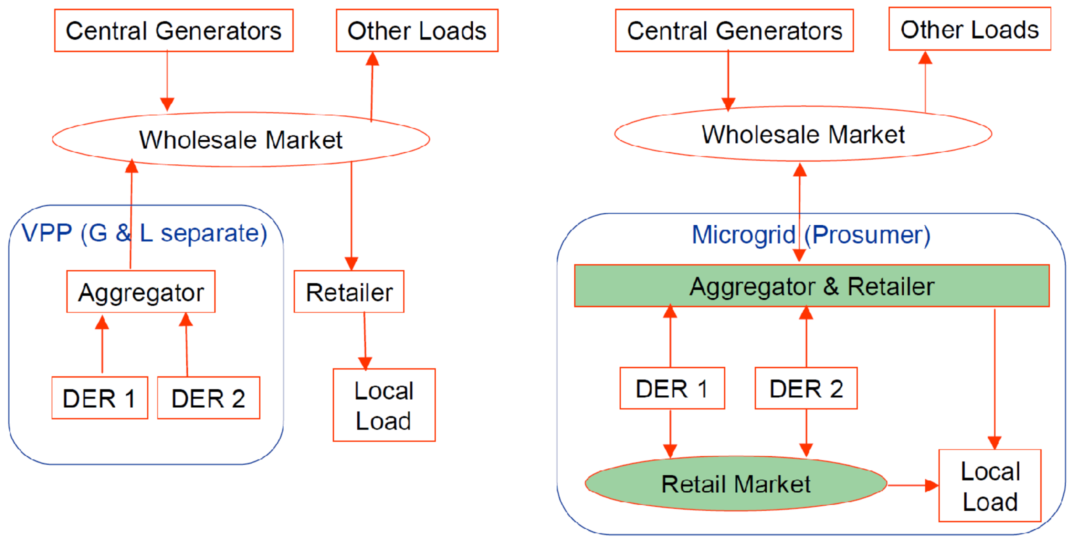

Figure 5.9. Differences of VPP and local retail market (Schawaegerl & al. 2009).

The main difference between microgrid market concept mentioned above and other aggregator models is that the local retail market is hosted directly between DER units and end consumers. Today's market models do not allow this kind of operation. One open question is whether the aggregator is going to be DSO, electricity producer, electricity retailer or someone else. Another question is how to get end customers interested about the aggregation so that the business can be created without significant raise of prices or at least high volatility of the prices. On the other hand, volatility might encourage people to save energy but on the other hand it gives opportunity for market play and "wind fall" profits. Gaming with the prices might lead to negative result from the customer point of view. (Schawaegerl & al. 2009)

Different aggregation models confront resistance in different business parties. DSOs and electricity retailers might be afraid of possible lower business share, electricity producers might be afraid of lower electricity prices and customers might be afraid of higher overall prices because of a new market player or higher volatility. Risks and opportunities of different market players in microgrid operation are described in Figure 5.10.

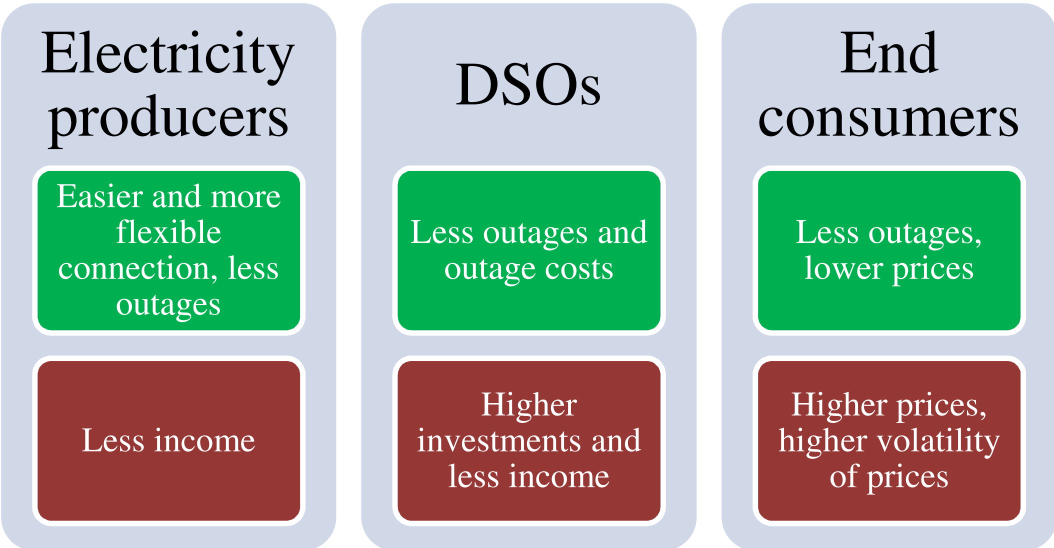

Figure 5.10. Opportunities and risks of different market players in microgrid operation.

In the terms of prices, costs, and profits, it is impossible that all of the market players can win in the final solution. Therefore, the acceptance of microgrid operation will be a challenge. Nowadays in Finland, energy production is forbidden for local grid owner, which is DSO. DSOs also have obligation to connect all paying customers into to the grid. This means that it might be difficult to form local subgrids that would be owned by local community, as discussed in Schawaegerl & al. (2009). In the presented scenario, energy production, electricity sales, and the grid would be owned by the same community. This is quite opposite to that what has happened in the business during last decades. (Schawaegerl & al. 2009)

5.5.3 Political guidelines

Because of monopoly business in distribution and dependency of supports in distributed production, the future guideline is going to be set by politicians and authorities. This might mean that the decision favor renewable energy producers but increase the costs of end customers and DSOs. Power of the political decision can be seen in the differences between Finland and Germany in Figure 5.7. For instance in Germany, support actions and political decision have increased the amount of installed DG capacity a lot but now DSOs and TSO are struggling with transmission capacity issues as well as frequency control problems (Fette 2011). Grid investments are finally paid by customers. Thus, customers pay the consequences of political decisions. Example shows that politicians need to be careful in their decisions and understand both direct and indirect consequences. In worst case, runaway implementation of DER units causes that the protection of the distribution grid is unsafe and might put human lives into danger. Because network investments are made for a long period of time, there is no easy and fast way out. Despite what the final political guideline is, the microgrid concept should be well planned and all viewpoints studied. Also, the effects of piecemeal changes need to be carefully considered. Transparent and long lasting guidelines are necessity to increase investments to the new technology. (Schawaegerl & al. 2009)

5.6 Summary

Microgrid operation is technically a complex task where many case specific features have impacts. In addition to technical challenges, market related challenges need to be solved and political decisions made. Microgrid concept need to fulfill both technical and economical criteria before implementation. Different visions of the industry development drive microgrid operation into different directions and changes in the law and regulation are needed to enable microgrid operation. Protection, stability, synchronization, and blackstart capability are the main technical challenges of microgrid operation. Protection is suggested to be solved with relay protection devices that have different settings in microgrid and utility mode. Need of LV relay protection in MV microgrid operation, needs to be considered case-by-case. High share of intermittent production is a risk for system stability. However, it can be reduced with the use of well controllable power sources, such as energy storages or diesel generators. Existing technology makes microgrid operation theoretically possible but it is not yet ready to compete economically with existing grid solutions.

6. INTEGRATION OF MICROGRIDS INTO DISTRIBUTION NETWORKS

Previous chapters show that many uncertainties and overlapping visions are related to microgrid operation. Many factors cause that there is not a one main microgrid solution that would fit for all implementations. Centralized energy production model and distributed model are examples of different microgrid models. Successful test of these models need to be carried out to get real integration of microgrids started. When the models are implemented into different microgrid concepts, such as LV microgrid or MV microgrid the combination leads to several different microgrid solutions. Because of the existing market model, grid ownership structure, and responsibilities, it would be good if the DSOs start the piloting. However, existing regulation do not give enough incentives for DSOs to integrate microgrids into distribution network. Also, involvement of electricity producers is needed because according to the Finnish laws production units cannot be owned by DSOs. When visionary microgrid concepts are implemented into existing distribution network, also some challenges are encountered. The piloting has to be done with available technology which might be a limitation for some of the scenarios. Challenges and some solutions for MV microgrid operation are discussed in the following sections.

6.1 Minimum requirements for microgrid operation

Visions in microgrid studies outline possibilities that microgrid operation could enable. Nevertheless, all of them will not come true and therefore it is good to define requirements of microgrid operation. Minimum requirements of microgrid operation are listed below:

- Islanding capability (normally connected to the utility grid)
- Safe and protected operation in MV and LV networks
- Control strategy that guarantee sufficient voltage quality

Islanding of the microgrid from the grid-connected operation happens according to islanding criteria. Islanding might be easiest to execute with communication between protection and control devices because then risk of accidental islanding can be avoided. In this communication based islanding protocol, the islanding criteria can be an act of feeding protection device (Laaksonen 2011). Another option is to rely on frequency and/or voltage measurements which can detect the instability. The challenge in measurement based method is the fault ride through capability. The islanding is not wanted to start after a voltage sag and therefore the islanding criteria need to be set carefully. Synchronization relaying is needed at the point of common coupling to enable resynchronization. To enable islanding, the power flow, from the microgrid towards utility grid or vice versa, need to be within predefined limits. These limits guarantee that the power control of the microgrid can handle the transients caused by islanding. Transients can be expected to be higher if the power difference is higher. In practice, the limits need to be defined based on the control capabilities of DGs. More information about control capabilities of different production units are described earlier in this thesis. Synchronization relaying measures voltages and frequencies in both microgrid and utility grid. When resynchronization from microgrid operation back to grid-connected operation is needed, the synchronization device communicates at least with the main DG. Then the main energy unit and synchronization device adjust the frequency and the voltage so that reconnection back to utility grid can be done without high transients.

Traditionally protection of distribution grid is based on over currents in MV and LV networks. In microgrid operation, fault currents are much smaller because many DG units are converter connected and therefore they are capable to provide short circuit current only 2-3 times their nominal current (Voima & al. 2011). Fault currents might be high enough for protection purposes if different settings in microgrid operation and grid connected operation are used. Existing feeder terminals have capability to adopt several setting groups that can be changed via communication link. Criteria for the change of protection settings could be the act of islanding switch at the point of common coupling. Traditional RF-communication link used for SCADA operation is fast enough because it is good to have some delay before introducing microgrid settings. Transients smoothen during the delay and tighter microgrid settings will not cause unwanted disconnection. Also, use of sensitive measurement devices can be recommended.

In addition to protection of medium voltage grid it can also be difficult to detect faults in low voltage grid. In MV microgrids, where DGs is connected to the MV grid, the direction of power flow in LV network remains same as before but fault currents might be lower. This might be a problem, especially in long outputs. Therefore, it is important to consider protection of LV grids when MV microgrid is created. Solutions for LV protection can be the use of more strictly dimensioned fuse protection, consolidation of the grid or bigger distribution transformer. Technically best solution would be LV relay protection because it can detect faults more sensitively. However, the costs of LV relays do not favor them. In addition, reliability of LV relaying is good to be tested before implementation because LV relays and switches might be planned for factory conditions. For instance, jamming problems in 1 kV distribution relaying have showed that outdoor conditions might have impact on the functionality of relaying.

Control strategy that guarantees sufficient voltage quality is probably the most undetermined of the main parts. Control of the microgrid is also the part that is totally different to what DER units are used to do. In this thesis, microgrid operation is not allowed to remarkably lower the existing conditions of the customers. This means that voltage quality issues need to be fulfilled according to the same standards as in utility grid, such as EN 50160. Advantages of centralized microgrid model realize also in control because the change of the main unit's control strategy might be enough to enable microgrid operation.

6.2 Existing technologies

Many of the technologies that are needed for microgrid operation exist but are not used because of high costs. Several microgrid visions are possible to be implemented but they are not often economically reasonable. First visible smart grid feature are the smart meters. Smart meters and communication infrastructure that comes with the meters is one enabler of demand response. For microgrid operation demand response is an additional good which can help the microgrid operation and maybe make it a bit more economically feasible. The cores of microgrids are DER units. In Germany, the amount of DER units is quite remarkable but in Finland the amount of units is so limited that it will not yet enable microgrid operation. Relay technology is also well developed, although some problems can be expected in the beginning. Many of the available LV relays are not yet used outdoors in a large scale which means that real long term operational data is not yet available. However, MV feeder terminal relaying is used at the primary substations and the experiences have been good. In LV grid, use of relaying is much more limited and for instance jamming problems in 1 kV relaying have stuck into people's mind. Synchronization relaying that is needed to resynchronize the microgrid back in to utility grid operation could be similar that is used to synchronize the DG into the grid.

As mentioned earlier in this thesis, the hardware technology is quite ready but there is still a lot of work to do in software technology. Management of microgrid is one of the most significant challenges and it is often planned to be software based (Laaksonen 2011). Working software often needs fast communication infrastructure that does not yet exist. Implementation of communication might be the greatest challenge in microgrid management. It might also be possible to handle microgrid management in a case of limited amount of DER units without building a heavy communication infrastructure. In this case, the control is based on operation limits of DER units. These limits are set so that the voltage quality fulfills the standards and unnecessary disconnections of DER units can be avoided. Nevertheless, modification of existing SCADA and DMS systems is needed so that the network operator is aware of the situation in the grid. It might be more difficult to achieve plug-in microgrid without communication because it is difficult to define universal operating limits that would quarantine successful microgrid operation in any conditions. Those limits would need to be general for all units, and in the most flexible scenarios, suit also for new production units. In addition, there is other technology in smart grid visions that might not be necessary for microgrid operation but would be helpful. For instance, use of on-line tap changers in MV microgrid could quarantine better voltage quality for LV customers. However, implementation of on-line tap changers is not reasonable only for island operation but if the benefits are good enough also in utility grid operation, the implementation can become reasonable.

One interesting factor in the existing networks is the dimensioning of the grid. Dimensioning is an important factor especially in Finnish rural networks but also in many suburban areas. These areas are also the most potential platforms for DER units and therefore for microgrids too. In distribution system, the resistance of the lines has remarkable role. For instance, simulations made in Laaksonen (2011) show that sensitivity for voltage fluctuations gets higher in weaker grids. Also, the control system needs to be more accurate and stabile. One of the challenges of the control in weak grids is the need of reactive power to control the voltage. If reactive power is transferred in the grid, it causes losses. In addition, capability to provide sufficient short circuit power for the household protection depends of the dimensioning. These are the reasons why sufficient dimensioning of the network is important. (Laaksonen 2011)

6.3 Required solutions and actions

Implementation of microgrids will not happen on its own along with other smart grid features. However, it might be beneficial for smart grid implementation to integrate microgrid features at the same time so that the costs are shared and best total benefits achieved. Lack of common plans and smart grid protocols that are compatible with microgrid operation can be seen as the biggest technological threats for microgrid implementation. Lack of working business models and also lack of business opportunities are also threats for implementation. Existing "fit and forget" mentality need to be forgotten if the goal is to achieve really flexible microgrids. Future grids need active management and more actions from the grid operator. Software development and field tests are needed to enable large scale implementation. Microgrid is a complex entity which means that it is difficult to build it right away with all comforts. That is why steps towards real microgrid operation needs be planned. Figure 6.1 shows one example of microgrid implementation that could be executed step by step.

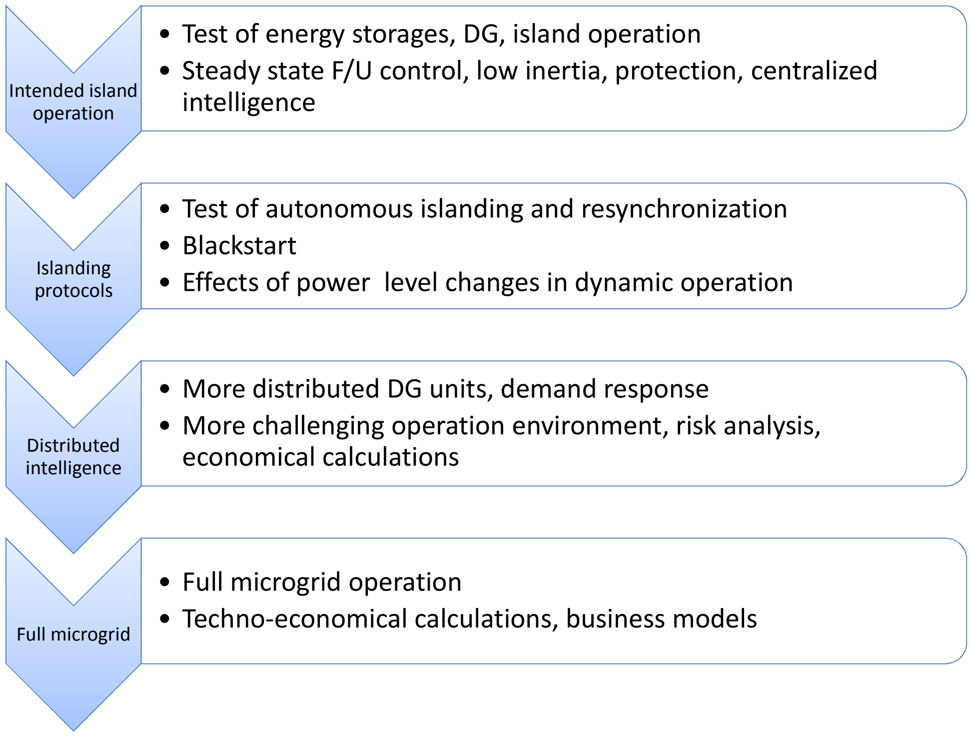

Figure 6.1. Example of required actions for microgrid implementation.

Figure above describes the tested functionalities and issues that should be considered in the tests. It can be expected that intermittent generation units are already installed into the grid but energy storages or other well controllable units are probably added in the microgrid implementation. However, if electric vehicles or solar panels with battery systems become general, also low capacity batteries might be available. Issues that are good to be tested in the first phase are the work of control strategies and how protection devices work in low inertia conditions. Tests are easier to start with centralized intelligence and small number of generators. It might also be reasonable to use only MV production units in the MV microgrid so that the multidirectional power flow in LV grid will not mess up the protection.

Second phase of suggested plan includes test of dynamic operations, such as autonomous islanding and resynchronization. Also, blackstart capability could be tested to enhance the usability of microgrids in long lasting fault situations. If the power levels in microgrid and utility grid operation differ a lot, it is difficult to achieve stability fast enough without disconnection of DER units. With the tests, it can be concluded what kind of power difference can be handled when moving from utility grid mode to microgrid mode and vice versa.

When the grid manages autonomous islanding and can stabilize small power differences, it is possible to add more complexity into the system. In other words, more distributed generators can be used. If demand response is not yet developed enough, as it is not today, it might also be possible to test the impacts of demand response. However, introduce of large scale demand response will need lots of customer interest. Issues that also need to be discussed are risk analysis and economical calculations. In some cases, it might be so that the distributed system, where DGs and intelligence are distributed, is economically more feasible choice. At this point of the microgrid implementation it is difficult to say which solution is the best in final smart grid environment. Today, the high costs of reliable and fast communication favor centralized solutions where need of communication is more limited.

Economical calculations are good to be done in parallel with technical examination. By this way the final solution is techno-economically feasible. When the full microgrid operation is technically proved to be possible and the costs of needed equipments are known, it is possible to discuss whether the microgrid operation is going to be economically reasonable or not. Business models that support microgrid operation need to be developed and implemented before large scale implementation of microgrids. Business models can be already preplanned in parallel with technical development.

6.4 Summary

Microgrid visions include ideas that are not yet applicable for existing distribution solutions. In future, when the distribution system changes, it might become possible to apply also some of those visions. However, in the beginning of microgrid implementation or at least during piloting, limitations of existing grids need to be taken into account. SWOT analysis is good way to review strengths, weaknesses, opportunities and threats of some project. SWOT analysis of microgrid implementation is presented in Figure 6.2.

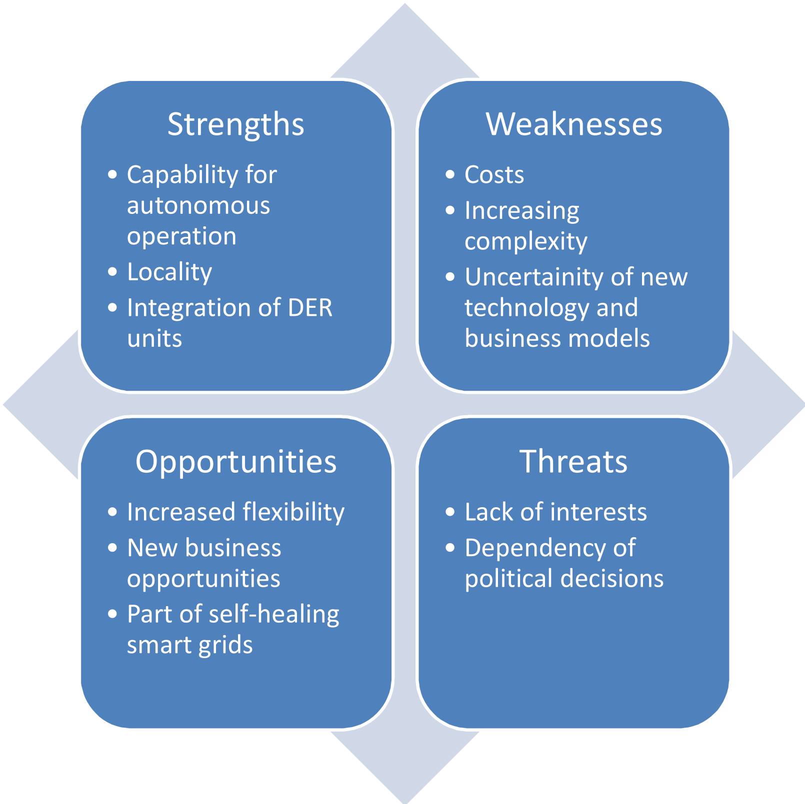

Figure 6.2. SWOT analysis of microgrid implementation.

Analysis reveals that the actions that enable microgrid operation are highly related to the balance between benefits and costs. This is usual in business life but this does not favor environmental acts. The fact that environmentally friendly production cannot yet compete with traditional solutions and also the existence of emission trading cause that political decisions have important role. At least in the short term, support actions decide whether penetration of distributed generation will increase or not. It is difficult to see development in the DG industry without support actions. Political decisions have also impact to the regulated distribution business and appreciation of outages in regulation will be significant factor in the microgrid profitability. However, political decisions cannot be made if the customers are not willing to pay enough for lower outage times. Nevertheless, the implementation of microgrids will not happen in a moment. Therefore, step by step forwarding implementation plans are needed.

7. FORTUM MICROGRID PILOT

Increase of distributed generation and development of smart grids have led to the point where piloting of microgrid operation has become not only interesting but also close to possible. Even though the amount of DGs has increased also in Finland, there is still limited amount of DGs for microgrid implementation. Nevertheless, medium voltage microgrids are interesting for DSOs because they can reduce the harms of outages for a large group of customers. After all, most of the outages that customers confront occur in MV grid. Finland's largest DSO, Fortum Sähkönsiirto Oy, plans to have a pilot microgrid as a part of its smart grid research. This chapter introduces the main ideas of Fortum microgrid pilot and discusses challenges related to that. The pilot case shows only one scenario of microgrid operation but it gives answers to many questions related to microgrid operation. So far, any real MV microgrid pilots are not introduced. Therefore, if the Fortum MV microgrid pilot is implemented within near future, it would be the first real MV microgrid.

7.1 Platform for piloting

Pilot planning starts with the search of suitable places for MV microgrid. This proves to be a challenge because the amount of distributed generation is still limited in Finland. Suitable pilot place has to be isolated which means that it cannot be in the middle of a MV output. From the available options, island of Högsåra seems to be the most suitable place for microgrid operation. Högsåra is an island in the southwest Finland. In the island, there is three pieces of 2 MVA wind turbines connected to the 20 kV distribution grid. Nominal power of 6 MVA is a significant amount in distribution grid. It causes that already in the normal operation the wind turbines feed power to primary substation. As mentioned earlier in this thesis, the type of production units have significant role for the control possibilities in microgrid operation. Following Table 7.1. gathers facts about the Högsåra wind turbines.

Table 7.1. Information about Högsåra wind turbines.

Nominal power	2 MW
Generator	Permanent magnet
Gearbox	No gearbox
Network connection	Full power converter
Hub height	65 m
Rotor diameter	72 m
Installation year	2007

WTs are connected to the 20 kV distribution grid with full power converters. This allows good control opportunities which are important in the microgrid piloting.

Because of the intermittent nature of wind production, also other DER units are needed. Energy storages are interesting from the grid operation's point of view because they can smooth the fluctuation caused by intermittent production and varying loads. However, costs of battery based energy storages that are suitable for medium voltage grid are still high even for piloting. Therefore, participation of other partners for the piloting is also important. In addition to microgrid operation, battery can be used also for other purposes in grid connected operation. Cooperation offers opportunity to achieve different research goals, set by different parties. In general, wind turbine owners can be interested about batteries because energy storages can offer more constant output power which might mean lower grid connection costs in a case of new DG implementation. Energy storage gives opportunity to get higher income because then the producers can control when they sell the energy. Also, forecast of the production is easier and more precise. For DSO, the main advantages are better control of the system and less outages. However, without outage reduction, economical benefits can be limited. In Finland, DSO is not allowed to own permanent electricity production or to sell energy. Therefore partners are needed for microgrid operation. For TSO, large energy storage can offer opportunity for fast frequency control, because in transmission system the system frequency depends mainly on the active power balance. As a summary, possible partners of microgrid project are DSO, producers, TSO, and in the beginning also device manufacturers who might be willing to test their devices in real life environment.

7.2 Preplanning

Microgrid piloting is taking its first steps which causes that the final solution will probably differ from the first vision. To understand the challenges related to microgrid piloting, the main questions are collected into following list:

- How DER units are controlled?
- How loads are controlled?
- How MV protection is executed?
- How LV protection is executed?
- How islanding and resynchronization is executed?
- What is the reasonable size for the battery system?

In Högsåra case, the microgrid is planned to consist of three wind turbines, energy storage, and loads. Figure 7.1. shows the existing feeding arrangement near Högsåra. Possible pilot microgrid area is showed in the figure with a circle.

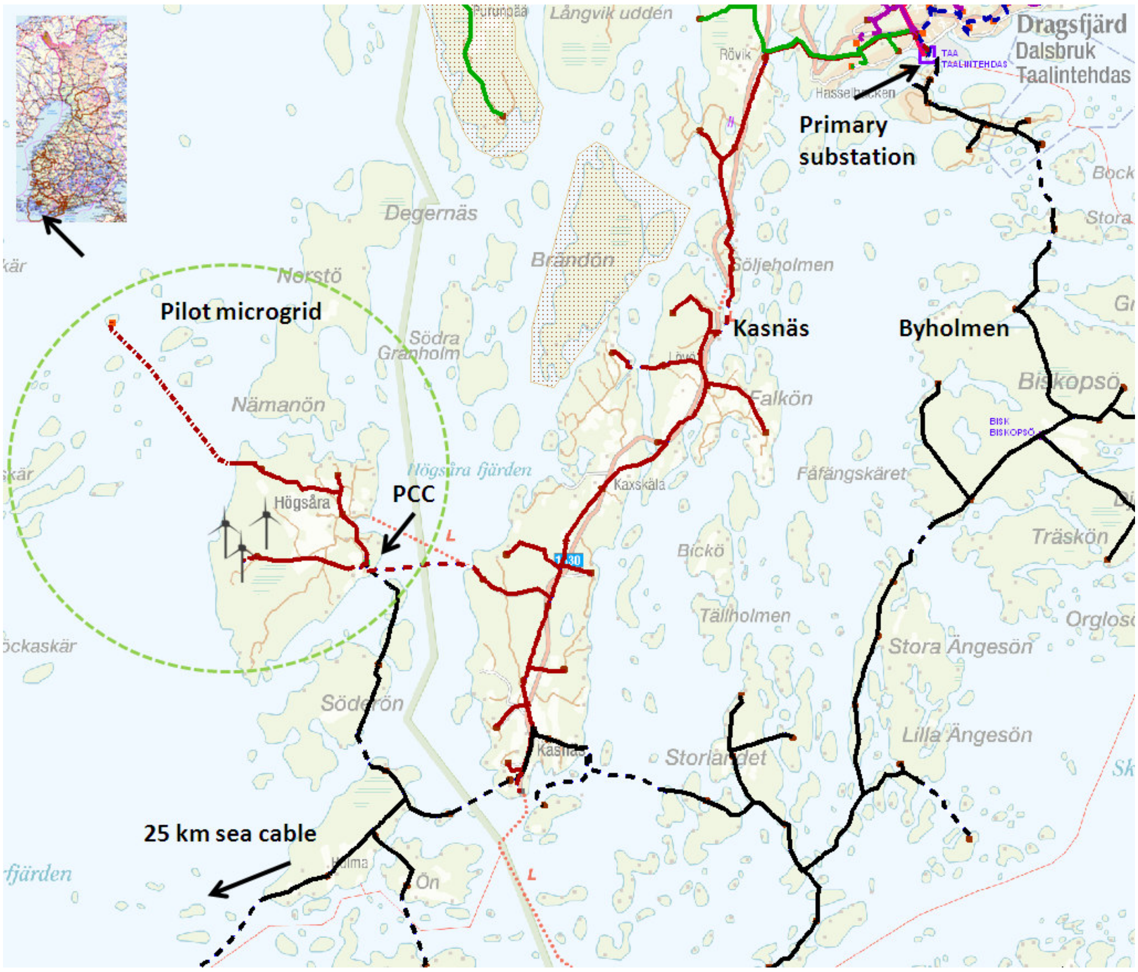

Figure 7.1. Feeding arrangement of Taalintehdas primary substation and Högsåra pilot microgrid area.

Primary substation output called "Kasnäs" (red one) feeds Högsåra and the wind turbines are also connected to the same output. The figure also shows the output "Byholmen" (black one) that is connected to the same primary substation called "Taalintehdas". Byholmen feeds also long sea cables which in addition to low dimensioning causes that wind turbines cannot be connected to the Byholmen output. Planned point of common coupling (PCC) that connects the microgrid to the utility grid is also presented in the figure above.

The first big problem in the Högsåra island operation is that the consumption is usually lower than the production. To avoid unnecessary reduction of wind production, battery storage can be used to store the excess energy during island operation. If this is required, it sets one boundary condition for battery dimensioning. In this thesis, it is suggested to use the battery system as the main unit of microgrid operation. The lack of existing fast and reliable communication infrastructure causes that the microgrid operation is reasonable to be planned on centralized protocol that does not need heavy communication infrastructure. Being the main unit means that the battery will be the V/f controlled unit that sets voltage and frequency for the microgrid. Full power converters can control the system stability well if the amount of reactive power is great enough.

In Högsåra case, the wind turbines are connected to the grid with full power converters which means that also WTs might be used for V/f control. In practice, this would require that WTs are driven with partial power so that they can increase and decrease their output power. However, the control capability of WTs might be limited even though the converters could be controlled well. Therefore, use of battery or diesel generator as the main control unit can be highly recommended. Because real microgrid test beds are rare, it could be reasonable to test also the V/f control with WTs at some point. Anyhow, this thesis focuses on the solution where energy storage is used as the main unit.

To get the maximum benefits of expensive storage system, the plan is to find a partner who is also interested about battery storage systems. Finnish TSO, Fingrid is found to be interested to use a battery for frequency control purposes. However, problems might occur, if the microgrid is operated in grid-connected mode and both WTs and the battery are wanted to provide full output power. Main reason for this is that Högsåra is quite far away from primary substation. After all, it can be concluded that the Högsåra is not an optimal place for microgrid piloting because of the weakness of the grid and remarkable unbalance between loads and production. In addition, low voltage grids are old and dimensioning has been made according to old standards. Therefore, challenges in low voltage protection can be expected.

7.3 Simulation

As discussed in chapter 5, adding large amount of electricity production into distribution might cause voltage raise problems. Simulation model is created to figure out whether the voltage rise is a problem or not in Högsåra. Simulation is done with the Power System Simulator for Engineering (PSS®E) by Siemens power technologies. In the simulation, all main parts of the grid are simulated but also some simplifications are done to ease the modeling. Figure 7.2. shows simulation of the existing network.

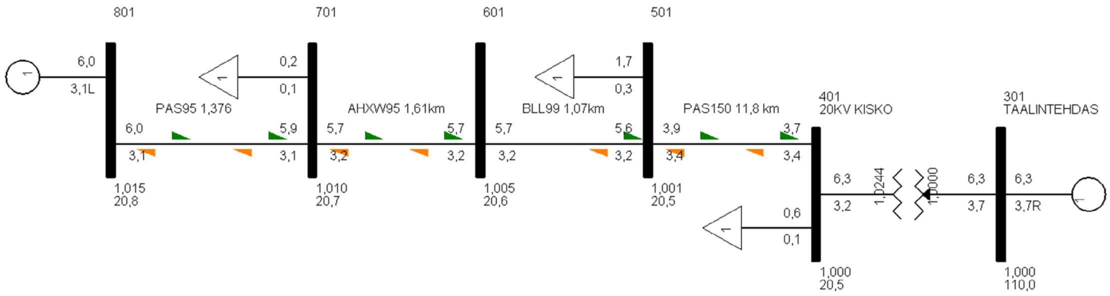

Figure 7.2. Simulation of the distribution grid that feeds Högsåra.

Voltage rise is limited to 21.0 kV in the network. Simulation shows that full 6 MW output power of the WTs rises the voltage to 20.8 kV in the connection point of Högsåra wind park. At the same time, wind turbines take 3.1 MVAr reactive power from the grid to compensate the voltage. Simulation does not take into account the WTs' capability to provide reactive power. However, the amount of distributed reactive power is so high that it is not reasonable to increase it during maximum output of WTs. Additional simulations show that voltage rise become a limit if battery system with high output power is connected to the end of the grid at the same time with WTs. Therefore, energy storage is recommended to be controlled so that it lowers the peak power by charging the battery during good wind conditions. This will also reduce distribution losses.

Simulation model of the microgrid operation is also carried out but because used installation of the simulation software does not include dynamic modeling, the results of load flow calculation are quite useless. In addition, real production components or their simulation models are not known and therefore the simulation uses ideal components. Ideal components can control the system well because full power converter connected battery and WTs can ideally control the frequency and voltage according to the needs. In future, dynamic modeling and also modeling of LV grid can be recommended.

7.4 Management solution

Because microgrids are new topic in the industry, management solutions are still under development. Management of this pilot microgrid relies on the idea that energy storage system includes intelligent and highly controllable management system. An advantage in this solution is that the energy storage system can be located where wanted, so it is not location dependent. This allows locating the energy storage system near of the point of common coupling. The fact that management system and the grid forming main unit are located near to PCC makes possible to avoid installation of heavy communication infrastructure. Communication, which is needed between the main unit and synchronization measurement devices, can be done in the same place with short communication connections.

Frequency and voltage control are expected to be done with the battery energy storage system (BESS). This system is full power converter connected and able to control the grid. However, because real life BESS do not yet exist, the real capabilities and limitations need to be confirmed when the BESS manufacturer is chosen. Because the technology is quite new and the control is based on software, the differences between manufacturers are good to be taken into count. With existing costs, the battery investment will not be an economical solution and therefore the size should be solved according to the research needs. If the battery is needed for frequency control, the energy capacity and especially dimensioning of the converters needs to be higher than only for the microgrid operation. If battery is wanted to store the excess energy of WTs' during microgrid mode, both storing capacity and converter dimensioning need to be high. For pure microgrid island operation, suitable battery size would be approximately 250 kW and 700 kWh because then the battery and WTs could secure the distribution. Calculation is based on the statistics of the last three years.

7.4.1 Protection

Protection of the pilot microgrid is planned to be executed with MV feeder terminals. The problem of low fault currents, presented earlier in this study, might be overcome because the nominal power of the used DER units is so high. The main limiting factor in the fault current feeding capability is the dimensioning of the converters. In this pilot scenario, the converters are dimensioned according to the grid-connected operation. In other words, the excess of production for the island operation purposes enables higher fault currents in microgrid operation. For the same reason it becomes obvious that separate protection settings are needed for MV protection.

As mentioned earlier in this study, also LV protection of the MV microgrid needs to be examined carefully. This pilot project is planned to be placed into typical Finnish rural area network where distances are long and dimensioning of the grid is weak. In addition, the grid is old which means that it is planned according to the old grid requirements. According to the new requirements, such as EN 50160 which is related to new grid installations, the fault currents in LV grid are low already in the grid connected mode. In other words, the recommendation for new grid installations is to have 250 A short circuit current at the customer connection point but it is not always fulfilled in the old grid. LV protection is definitely a subject that needs further study. If the LV protection becomes a challenge, one solution might be the use of fast fuses instead of slower ones. In fast fuses, the pre-arcing time is shorter which means that they work better with lower fault currents. Another, but much more expensive option is to use relay protection also in LV grid, as recommended for instance in Laaksonen (2011).

7.4.2 Transition between island and grid connected operation

Transition between island and grid connected operation is a challenge. In Högsåra case, especially the islanding situation is challenging because of the excess in production. Excess in production causes that most of the time microgrid feeds power to the utility grid. This causes that during sudden islanding, the microgrid needs to adjust its power level fast to stabilize the situation. In Högsåra case, the maximum output of wind turbines is 6 MW. Drop of 6 MW into couple of hundreds kilowatts is so enormous that it is difficult to manage. Dynamic modeling can be recommended to figure out the transients that this kind of unbalanced islanding causes. With the dynamic simulation, it can also be possible to define limits for power flow from the microgrid to the utility grid. These limits then guarantee that the islanding is still possible. In Hölgåra case, it is likely that the power flow from microgrid to the utility grid needs to be limited to enable autonomous islanding. Therefore, it might also be reasonable to allow higher transfer of energy from the microgrid to the utility grid and to disable autonomous islanding if the limits are exceeded.

Synchronization back to grid connected operation is easier to achieve than islanding because microgrid is balanced and connection does not cause sudden variation in power flow. The biggest challenge in resynchronization is to change the frequency of the microgrid so that it matches with the utility grid frequency. In practice, synchronization relaying needs to measure or otherwise get information from both utility grid and microgrid. If frequency, phase, or voltage differences exist, the relaying can give control signal to the main unit which adjusts the microgrid so that the conditions match.

7.5 Further study in the pilot project

This thesis works as pre study for Fortum microgrid piloting. To help the further pilot planning, it is good to highlight the subjects of further study. First thing that enables island operation is distributed generation. In Högsåra, the amount of DG is high but the suitability for microgrid operation is not the best. Therefore, use of battery system is recommended. A control capability of BESS is a subject of further study. Also the battery size needs to be decided according to the final research targets.

Network configuration of the Högsåra island enables use of a centralized microgrid model where battery is placed at the point of common coupling. Therefore, cooperation of battery system and synchronization devices can be executed without building a heavy communication infrastructure. Oversized production units for microgrid purposes enable quite high fault currents in MV grid. However, the fault currents in LV grid need to studied further. In some secondary substation LV grids, it might be possible to use fuse protection but the nature of the island with lots of distant summer houses causes that some secondary substations might need LV relays or grid investments.

7.6 Comparison of Fortum microgrid and other pilots

Fortum microgrid plan is the first real MV microgrid plan where real customer loads are used as the part of microgrid operation. The pilot environment is challenging although it reflects great the environment in which microgrid operation would be economically feasible. The plan of Fortum microgrid is ambitious and therefore the costs will be much higher than monetary benefits. If Fortum microgrid pilot is critically inspected, it can be noticed that the control and protection benefit from the oversized production units. On the other hand, excess in production causes additional challenges especially for islanding. Nevertheless, all options are good to be examined because practical limitations will also exist in the future and therefore it will never be possible to implement exactly optimal amount of DGs into the network. In addition, Fortum microgrid will give results from the use of battery energy storage in distribution network which is also very interesting.

8. CONCLUSION

Implementation of distributed generation, demands for better distribution reliability, and ageing of the grid set new challenges and opportunities for utilization of distribution system. Intermittent nature of the most popular distributed generators complicates stabilization of the grid and therefore increases the demand for other well controllable power sources. New solutions are needed to achieve implementation of higher share of renewable energy without high costs. Smarter grids can be a solution and the concept of microgrids is introduced to enable better distribution reliability and installation of DGs at the same time. The idea of microgrids is to enable island operation with local production. In a case of fault in the utility grid, the microgrid can isolate and sustain the electricity distribution. Aim of this thesis is to work as a preplan for microgrid piloting and discuss challenges and cornerstones of microgrid operation and implementation.

There are multiple different microgrid models that can be implemented into the distribution grid. Different microgrids are separated according to Laaksonen (2011) to four cases which are separated island microgrid, low voltage customer microgrid, low voltage microgrid, and medium voltage microgrid. Case specific features, such as amount of generators, type of the generators, or grid configuration, have impact to the final solution. Low voltage microgrids can be seen as customer solutions in which the distribution system operator is not involved. Medium voltage microgrids instead are much more interesting also for DSOs because they can serve larger group of customers and increase the quality of service. However in existing operating environment and with the existing valuation of interruptions, there is no business case for DSO to invest into microgrids. In addition, existing market legislation does not allow microgrid operation and therefore laws need to be changed before real microgrid implementations.

Smart grids utilize communication and new technology to increase the reliability and to offer new services. In practice this means that distribution grid might change also without microgrids. Only few smart grid features are profitable on their own but the combined benefits can be better than in a single solution. For instance, implementation of fast and reliable communication will not be profitable for one solution but when the costs are shared for many applications, implementation might become reasonable.

However, this needs cooperation of different business parties which might be a challenge in the existing competitive business environment. Estimations made in this thesis show that the smart grid features that are needed for microgrid operation will not be available within next ten years.

Microgrids arouse interest around the world and several test beds and pilots that are called microgrids are established. However, study reveals that many of them do not fulfill real microgrid requirements. In addition, most of the tests are focused on low voltage microgrids instead of medium voltage microgrids which are the main focus in this thesis. However, microgrid piloting will offer new information about microgrid operation and most of the principles are scalable despite the voltage level. It is good to notice the use of well adjustable diesel generators in many microgrid pilots. If less environmental friendly diesel generators are not used, they are replaced with energy storages. Therefore, it can be said that energy storages have significant role in future emission free microgrid installations. Energy storages can also be used in grid connected operation to smoothen the variation of intermittent renewable energy resources.

Thesis also considers implementation of medium voltage microgrids into Finnish distribution network in the near future. In this case the existing distribution system, configuration of the grid, as well as domination of wind turbines as main distributed energy resource have big role. Wind turbines need to be located near good wind conditions, in other words near waters or on high lands. In these places, the need for microgrid operation exists because windy areas are susceptible to fault and outages. However, the consumption in these areas is not usually high and therefore the dimensioning of the grid is usually quite narrow. This might be a challenge for protection because the lack of high fault currents is the main problem in microgrid protection. Multidirectional power flow is also challenging for protection.

Use of centralized microgrid model in which energy production is focused to near the substation or point of common coupling is recommended in this thesis. In centralized microgrid model the direction of current flow remains the same and therefore the protection settings are easier to handle. Use of energy storages is also recommended because they can be located where needed and they have necessary control features to achieve stability in islanded operation. However, the converters' limited capability to provide fault current needs to be taken into account. Thesis also highlights that technology is ready for microgrid implementations but software based control strategies are needed to achieve microgrid operation. Microgrid operation is not yet economically reasonable option and therefore development is needed.

Preplan of medium voltage microgrid pilot is also carried out in this thesis. The study reveals that existing potential of microgrids is limited due to lack of distributed generators. In addition, the outage times of existing grids are quite short and therefore the need for islanded operation is limited. For critical customer, even short outages can be crucial and therefore microgrid operation might become an option. Preplanned microgrid shows example of real life situation where the grid components are not ideal for microgrid purposes. In the pilot case, production is much higher than consumption which is good for protection purposes. However, the full potential of intermittent production cannot always be utilized without outsized battery system. Dimensioning of the grid is also a challenge because short circuit power drops in narrow low voltage lines and therefore the protection of low voltage grid is challenging.

Low voltage protection of medium voltage microgrids is an issue of further study because it is ignored in many studies. Use of low voltage relays can be recommended in difficult destinations, although it comes with high cost. Microgrids as well as smart grid are often told to include new kind of intelligence. This usually means that software executes preplanned functions. Experiences of the battery energy storage systems that include this kind of intelligence are limited and therefore they should be tested in real life microgrid environment. Dynamic modeling of medium voltage microgrid, in which also low voltage grid is modeled, was not carried out in this thesis but it is an issue that requires further study.

REFERENCES

(Antikainen & al. 2009)	Antikainen, J., Repo, S., Verho, P., Järventausta, P. (2009) "*Possibilities to improve reliability of distribution network by intended island operation*", 7 pages, Tampere, Finland
(Biomeri 2009)	Biomeri Oy, (2009) *"Sähköajoneuvot Suomessa - selvitys",* "Electric vehicles in Finland", 130 pages, in Finnish. Available at: http://www.tem.fi/files/24099/Sahkoajoneuvot_Suomessa-selvitys.pdf [Referred 25.10.2011]
(Braun & Notholt-Vergara 2008)	Braun, M., Notholt-Vergara, A. (2008) "*Inverter Performance with regard to Ancillary Services and Fault-Ride-Through Capabilities",* More MicroGrids EU-project, 148 pages, Kassel, Germany.
(Carillo 2011)	Carillo, S., Endesa distribución (2011) *"Málaga Smartcity Smart Grids: Vision, Strategy, Implementation",* 35 pages, PowerPoint presentation, London, UK.
(Commission 2010)	The European Commission (2010), *"Energy 2020 - A strategy for competitive, sustainable and secure energy"* 21 pages, Brussels, Belgium.
(Cleen 2010)	CLEEN Oy (2011), SGEM -webpage, Available at http://research.cleen.fi/research/index.php/SGEM [Referred 21.10.2011]
(Dobakhshari & al 2011)	Dobakhshari, A. S., Azizi, S., and Ranjbar, A.M. (2011) "*Control of Microgrids: Aspects and Prospects*", 6 pages, IEEE paper 978-1-4244-9573-3. Presented in Delft, Netherlands.
(Elias-Alcega & al. 2011)	Elias-Alcega, A., Roman-Barri, M., Ruiz-Alvarez, A., Cairo-Molins, I., Sumper, A., Gomis-Bellmunt, O. (2011) *"Implementation of a test microgrid in Barcelona"* 4 pages, CIRED paper 0342, Barcelona, Spain. 2032-9644
(EN 50160)	SFS-EN 50160 (2000) *"Yleisen jakeluverkon jakelujännitteen ominaisuudet*", EN 50160 standard translated in Finnish by

Suomen standardisoimisliitto SFS ry. 28 pages, Helsinki, Finland.

(ETP 2010) European Technology Platform (2010), "*Strategic Deployment Document for Europe's Electricity Networks of the Future*", 69 pages. Available at: http://www.smartgrids.eu/documents/SmartGrids_SDD_FINAL_APRIL2010.pdf [Referred 20.10.2011]

(First Solar 2011) Mulder, L. (2011) *"Thinfilm PV: Cost Reduction and Market Development",* First Solar, Inc. Presentation at Climate Parliament Forum 26.5.2011. Available at: http://climateparl.net/cpcontent/ppt/presen%25204%2520110524%2520Lettemieke%2520Mulder%2520Climate%2520Parliament%2520Forum.ppt [Referred 24.10.2011]

(IEA 2010) IEA (2010), *"Technology Roadmap - Solar photovoltaic energy",* 48 pages, Available at: http://www.iea.org/papers/2010/pv_roadmap.pdf [Referred 24.10.2011]

(Ihamäki 2011) Ihamäki, J. (2011) *"Feasibility study of the available relay protection solutions for microgrid",* 29 pages, LUT, Lappeenranta, Finland.

(INCA 2010) Järventausta, P., Partanen J., Koponen, P. & research group (2010), *"INCA - Interaktiivinen asiakasliityntä ja sen hyödyntäminen sähköjärjestelmän hallinnassa ja energiatehokkuuteen kannustavissa palveluissa"*, "INCA - Interactive customer gateway for electricity distribution management, electricity market, and services for energy efficiency" 53 pages, in Finnish, TUT, LUT & VTT, Finland

(Jimeo & al. 2009) Jimeo, J., Agnostos, D., Arnold, G., Berg, A., Mustermann, E., Agnotstos, T., Mustermann, H., Yarza, J.M., Oyarzabal, J. (2009) *"Report on applied data structures and mapping to communication means",* More MicroGrids EU-project, 89 pages, Germany.

(Johnson & Ducey 2011)	Johnson, M.D., Ducey, R.A. (2011) *"Overview of U.S. Army Microgrid Efforts at Fixed Installations",* 2 pages, USA. IEEE paper 978-1-4577-1002-5
(Jussila 2010)	Jussila, S. (2010) *"Use of Electricity Storages in Smart Grids*", Master's thesis, 64 pages, TUT, Tampere, Finland.
(Kaipia & al. 2009)	Kaipia, T., Peltoniemi, P., Lassila, J., Salonen, P., Partanen, J. (2009) *"Impact of low voltage DC system on reliability of electricity distribution",* 4 pages, LUT, Lappeenranta, Finland, CIRED Paper 0795.
(Keeyoung & al. 2009)	Keeyoung, N., Jongbo, A., Heungkwan, C., Seulki, K., Jongyul, K., Changhee, C., Jinhong, J. (2009) *"Establishment of a Pilot Plant for KERI Microgrid System based on Power IT Development Program in Korea",* 6 pages, KERI, Korea. IEEE T&D Asia
(Khattabi & al. 2009)	Khattabi, M., Drenkard, S., Dietsmann, H., Dimeas, A., Panayiotis, M. (2009) *"Advanced Architectures and Control Concepts for MORE MICROGRIDS",* More MicroGrids EU-project , Deliverable DF5, 36 pages, Germany.
(Laaksonen 2011)	Laaksonen, H. (2011) *"Technical solutions for low-voltage microgrid concept",* Doctoral thesis, 271 pages, Acta Wasaensia, Vaasa, Finland. ISBN 978–952–476–345–5
(Lakervi & Partanen 2008)	Lakervi, E., Partanen, J. (2008) *"Sähkönjakelutekniikka",* Book of electricity distribution, 294 pages, in Finnish, Otatieto. ISBN 978-951-672-359-7
(Lasseter & al. 2011)	Lasseter, R., Eto, J., Schenkman, B., Stevens, J., Volkommer, H., Klapp, D., Linton, E., Hurtado, H., Roy, J. (2011) "*CERTS Microgrid Laboratory Test Bed"*, 8 pages, IEEE Transactions on power delivery, vol. 26, no. 1, January 2011.
(Liang & Campbell 2008)	Liang, Y., Campbell, R. (2008) "*Understanding and Simulating the IEC 61850 Standard*" 12 pages, Illinois, USA.
(Löf 2009)	Löf, N. (2009) *" Pienjänniteverkon automaatioratkaisuiden kehitysnäkymät",* "Aspects on Development of Low Voltage Network Automation*",* Master of Science Thesis, 127 pages,

	in Finnish, TUT, Tampere, Finland.
(Minerals 2006)	U.S. Department of the Interior, Minerals Management Service (2006) "*Technology White Paper on Wave Energy Potential on the U.S. Outer Continental Shelf*". Available at: http://ocsenergy.anl.gov [Referred 25.10.2011]
(Parkkinen & al. 2011)	Parkkinen, J. & al. (2011) *"Smart Grids RoadMap",* Study based on questionnaire, TUT, Tampere, Finland.
(Pasonen 2010)	Pasonen, R. (2010) "*Community microgrid - A building Block of Finnish Smart Grid",* Master's thesis, 119 pages, TUT, Tampere, Finland
(Perälä 2011)	Perälä, S. (2011) "*New Network Tariffs: Economical Effects and Possibilities for Demand Response",* Master's thesis, 101 pages, TUT, Tampere, Finland.
(Repo & al. 2005)	Repo, S., Laaksonen, H., Mäki, K., Mäkinen, A., Järventausta, P. (2005) *"Hajautetun sähköntuotannon vaikutukset keskijänniteverkossa",* Effects of distributed generation in medium voltage network, Research report, 183 pages, TUT, Tampere, Finland. ISBN 952-15-1382-9
(Sahay & Dwivedi 2009)	Sahay, K., Dwivedi, B. (2009) *"Supercapacitors Energy Storage System for Power Quality Improvement: An Overview",* 8 pages, UPTU, Lucknow, India.
(Schawaegerl & al. 2009)	Schwaegerl, C., Tao, L., Pecas Lopes, J., Madureira, A., Mancarella, P., Anastasiadis, A., Hatziargyriou, N. & Krkoleva, A. (2009). "*Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation."* More MicroGrids EU-project. 145 pages. Erlangen, Germany. Available at: http://www.microgrids.eu/documents/668.pdf [Referred 1.11.2011]
(Sortomme & al 2010)	Sortomme, E., Venkata, S. S., Mitra, J. (2010) "*Microgrid Protection Using Communication-Assisted Digital Relays"*, 8 pages, IEEE Transactions on Power Delivery, Vol 25, No. 4.
(Voima & al. 2011)	Voima, S., Kauhaniemi, K., Laaksonen, H. (2011) "*Novel*

protection approach for MV microgrid" 4 pages, CIRED paper 0430, Vaasa, Finland.

(VTT 2006) Kumpulainen, L., Laaksonen, H., Komulainen, R., Martikainen, A., Lehtonen, M., Heine, P., Silvast, A., Imris, P., Partanen, J., Lassila, J., Kaipia, T., Viljanen, S., Verho, P., Järventausta, P., Kivikko, K., Kauhaniemi, K., Lågland, H. & Saaristo, H. (2006), *"Distribution Network 2030 - Vision of the Future Power System"*, VTT Research notes. 86p., Espoo, Finland. Available at http://www.vtt.fi/inf/pdf/tiedotteet/2006/T2361.pdf [Referred 21.10.2011]

(VTT 2009) Holttinen, H., Meibom, P., Orths, A., Hulle, F., Lange, B., O'Malley, M., Pierik, J., Ummels, B., Tande, J.O., Estanqueiro, A., Matos, M., Gomez, E., Söder, L., Strbac, G., Shakoor, A., Ricardo, J., Smith, J.C., Milligan, M., & Ela, E. (2009) *"Design and operation of power systems with large amounts of wind power",* VTT Research notes, 239 pages, Espoo, Finland. ISBN 978-951-38-7308-0

(VTT 2011) VTT (2011) "*Wind energy statistics in Finland",* web page. Available at: http://www.vtt.fi/proj/windenergystatistics/windenergystatistics_archive.jsp [Referred 24.10.2011]

Wang & Gooi (2011) Wang, M.Q. and Gooi, H.B. (2011) *"Spinning Reserve Estimation in Microgrids",* 11 pages, IEEE paper 10.1109/TPWRS.2010.2100414. Published in IEEE Transactions on power systems vol. 26, NO. 3, August 2011

(Werner 2011) Werner, J. (2011) *"Monitoring, Controlling and Automation of Secondary Substations",* Report, 34 pages, TU Dresden, Germany.

(Zheng & Li 2010) Zheng, G., Li, N. (2010) *"Multi-Agent Based Control System for Multi-Microgrids"*, 4 pages, IEEE paper, Baoding, China.

Amount of marks (x-xxx) = How well study discusses the subject

Study	Source	Smart grids					Low voltage microgrids					Medium voltage microgrds				
		SG visions	Distributed energy resources	SG components	SG communication	Business opportunities	Microgrid models	Protection	Control/ stability	Pilot	Business opportunities	Microgrid models	Protection	Control/ stability	Pilot	Business opportunities
Strategic Deployment Document for Europe's Electricity Networks of the Future	(ETP 2010)	XXX				XX										
Energy 2020 - A strategy for competitive, sustainable and secure energy	(Commission 2010)	XX	X	X												
Distribution Network 2030 - Vision of the Future Power System	(VTT 2006)	XXX					X									
Sähköajoneuvot Suomessa (Electric vehicles in Finland)	(Biomeri 2009)	X	XX			X										
Technology Roadmap - Solar photovoltaic energy	(IEA 2010)		XXX			XX										
INCA - Interaktiivinen asiakasliityntä ja sen hyödyntäminen sähköjärjestelmän hallinnass	(INCA 2010)	XXX		XX	XXX	XX			X							
Design and operation of power systems with large amounts of wind power	(VTT 2009)	X	XXX			X										
Supercapacitors Energy Storage System for Power Quality Improvement: An Overview	(Sahay & Dwivedi 2009)	XX	XX						X					X		
Pienjänniteverkon automaatioratkaisuiden kehitysnäkymät (Aspects on Development of L	(Löf 2009)	X	XX	XXX	X	X										
Community microgrid - A building Block of Finnish Smart Grid	(Pasonen 2010)	XXX	XX	X	X		X	X	XX	X	XX					
Technical solutions for low-voltage microgrid concept	(Laaksonen 2011)			X	X		XXX	XX	XXX		XX					
Implementation of a test microgrid in Barcelona	(Elias-Alcega & al. 2011)				XX		XX	X	XXX	XXX						
CERTS Microgrid Laboratory Test Bed	(Lasseter & al. 2011)				XX				XX	XXX						
Overview of U.S. Army Microgrid Efforts at Fixed Installations	(Johnson & Ducey 2011)									XXX						
Advanced Architectures and Control Concepts for MORE MICROGRIDS	(Khattabi & al. 2009)				XXX		XX	XX	XXX	XXX	XX					
Possibilities to improve reliability of distribution network by intended island operation	(Antikainen & al. 2011)	X	XXX	X		X							X	X		
Establishment of a Pilot Plant for KERI Microgrid System based on Power IT Developme	(Keeyoung & al. 2009)		XX	X	XX				XXX	XXX			X	X	XX	
Report on the technical, social, economic, and environmental benefits provided by Micro	(Schawaegerl & al. 2009)						XX		XXX		XXX	X		X		X
Microgrid Protection Using Communication-Assisted Digital Relays	(Sortomme & al 2010)						X	XXX	X			X	XXX	X		
Novel protection approach for MV microgrid	(Voima & al. 2011)											X	XXX	X		