TAMPERE UNIVERSITY OF TECHNOLOGY

RIKU PASONEN

COMMUNITY MICROGRID – A BUILDING BLOCK OF FINNISH SMART GRID

Master of Science Thesis

Examiner: Lecturer Risto Mikkonen
Examiner and topic approved in
Faculty of Computing and Electrical
Engineering Council meeting on 2
June 2010

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master's Degree Programme in Electrical Engineering
PASONEN, RIKU: Community Microgrid - A building Block of Finnish Smart Grid
Master of Science Thesis, 107 pages, 4 Appendix pages
December 2010
Major: Alternative electric energy technologies
Examiner: Lecturer Risto Mikkonen
Keywords: Microgrid, Smart Grid, distributed generation, demand side management, LV reliability

Microgrid is self-sufficient part of low voltage distribution grid, which can be operated separately from rest of the distribution system if needed. The idea of a microgrid has become more feasible when small scale distributed production has increased and Smart Grid technology is being implemented to electric grids today. Most microgrid concepts consist of environmentally friendly production types together with energy storages but also simple diesel powered backup systems can be counted as microgrids.

The main objects of this thesis are to find technical, economical, environmental and legal factors concerning microgrid implementation in Finland and simulate and optimise system with HOMER® program for an example location. A basic concept model for community microgrids in Finland is proposed in this thesis. The thesis includes also a translation of the survey, which was sent to distribution system operators. Heat systems of microgrid were left out of the thesis.

Thesis shows that there are many advantages in a microgrid concerning increased reliability, emission savings, new business opportunities and increased self-sufficiency of energy sector. However there is also much work to be done and issues to be solved for a large-scale microgrid implementation. Largest issues and unanswered questions concern protection, legal factors and economic support systems in respect to microgrids. Most of the issues result from lack of microgrid practical experiences, standards and legal rulings. Full year simulation results indicate that islanded operation of microgrid system is considerably more expensive compared to system connected mostly to main grid. Simulations also show that solar power can be competitive against wind power if both are assumed to have same financial support. An alternative microgrid solution is presented in this thesis, which is based on energy centre concept allowing the use of standard fuse protection in client connections. The survey sent to distribution system operators indicates that most of them are interested in microgrids and larger use of backup system in general but there are still problems with small-scale production, legislation, power quality of micro generators bought by common people and following of guidelines for proper notices about the systems.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Sähkötekniikan koulutusohjelma
PASONEN, RIKU: Yhdyskunnan mikroverkko – Suomalaisen Smart Grid järjestelmän rakennusosa
Diplomityö, 107 sivua, 4 liitesivua
Joulukuu 2010
Pääaine: Vaihtoehtoiset sähköenergiateknologiat
Tarkastaja: Lehtori Risto Mikkonen
Avainsanat: Mikroverkko, Smart Grid, hajautettu tuotanto, PJ-verkko, sähköverkon luotettavuus.

Mikroverkko on energiataloudellisesti omavarainen osa pienjänniteverkkoa, joka voi tarpeen tullen toimia irrallaan muusta jakeluverkosta. Mikroverkon edellytykset ovat parantuneet, kun pientuotanto ja älykkään sähköverkon komponentit ovat lisääntyneet sähköverkossa. Suurin osa mikroverkkokonsepteista rakentuu ympäristöystävällisen sähköntuotannon ja energiavarastojen ympärille, mutta myös yksinkertainen diesel-varavoimajärjestelmä voidaan ajatella mikroverkoksi.

Tämän opinnäytetyön tarkoitus on selvittää teknisiä, taloudellisia, ekologisia ja lainopillisia seikkoja liittyen mikroverkkojen rakentamiselle Suomeen ja optimoida mikroverkon kokoonpano ja ohjaus esimerkkikohteeseen vuoden ympäri. Työssä myös esitetään pääpiirteinen konseptimalli ensimmäisille suomalaisille mikroverkoille. Myös selvitys liittyen pientuotantoon, mahdollisiin paikkoihin mikroverkolle ja käytössä oleviin varavoimajärjestelmiin lähetettiin työn yhteydessä jakeluverkkoyhtiöille. Lämpöjärjestelmien tarkastelu on rajattu pois työstä.

Työ osoittaa, että mikroverkossa on useita etuja liittyen sähkön jakelun luotettavuuteen, päästöihin, uusiin liiketoimintamahdollisuuksiin ja energiasektorin kansalliseen omavaraisuuteen. Mikroverkkoihin liittyy myös paljon ongelmia ja avoimia kysymyksiä liittyen suojaukseen, lakiteknisiin seikkoihin ja mikroverkkojen roolista tiettyjen tuotantomuotojen tukijärjestelmiin. Suurin osa näistä ongelmista johtuu vähäisestä käytännön kokemuksesta, puutteellisista standardeista ja laista. Ympärivuotisen käytön simulointi osoittaa, että jatkuva saarekekäyttö on huomattavasti kalliimpaa kuin mikroverkon käyttäminen pääosin kiinni jakeluverkossa. Simulointi osoittaa myös että aurinkosähkö voi olla kilpailukykyinen tuulivoimaan verrattuna, mikäli taloudellinen tuki molemmille on sama. Työssä on esitetty myös vaihtoehto mikroverkkojärjestelmän rakentamiselle perustuen energiakeskuskonseptiin, joka mahdollistaa sulakesuojauksen käyttämisen asiakasliitännöissä. Selvitys jakeluverkkoyhtiöille osoitti, että suurin osa on kiinnostunut mikroverkoista ja yleisesti varavoiman lisäämisestä, mutta ongelmat pientuotannon, mikroverkkojen lainopillisten seikkojen, tuotantolaitteiden sähkön laadun ja tuottajien ilmoitusvelvoitteiden laiminlyöntien kanssa herättivät epäluuloa ja kiinnostuksen puutetta.

PREFACE

This thesis was done for VTT’s Energy systems team as a part of SGEM development project which develops solutions for a smart electric grid for the future. Partners with VTT in work package 2.3 Microgrids of SGEM project are University of Vaasa, Fortum Distribution, and Nokia Siemens Networks. The main financing of the SGEM project comes from Tekes, the Finnish Funding Agency for Technology and Innovation.

Instructor for the thesis was DrTech Raili Alanen from VTT, whom I want to thank for an interesting topic and guidance during the work. Supervisor for this thesis was lecturer Risto Mikkonen from the Department of Electronics in Tampere University of Technology. I want to thank Mr. Mikkonen for constructive comments about the thesis and excellent lecturing during the years. Thanks also go to Department of Electronics and Department of Electric Energy Engineering for giving me a good base knowledge for this thesis.

Espoo 2.11.2010

Riku Pasonen

Email: riku.pasonen@gmail.com

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ABBREVATIONS AND NOTATION

AFC	Alkaline fuel cell
AMI	Advanced metering infrastructure
AMR	Automatic meter reading
CAES	Compressed air mechanical energy storage
CFL	Compact fluoresce lamp
DER	Distributed energy resources
DG	Distributed generation
DSO	Distribution system operator
EV	Electric vehicle
HTS	High temperature superconductor
ICT	Information and communications technology
IEC	International electrotechnical commission
Island operation	Electric system operates separately from main electrical system.
L-filter	Filter with one series inductor
LCL-filter	Filter with two inductors and one capacitor in parallel between
LED	Light emitting diode
LN	Logical node
LTS	Low temperature superconductor
LV	Low voltage 50 – 1000V of AC and 75 – 1500 of DC
MCFC	Molten carbonate fuel cell
MG	Microgrid
MV	Medium voltage 1-35VAC
NiMh	Nickel metal hydride
PAFC	Phosphorus acid fuel cell
PEMFC	Polymer electrolyte membrane fuel cell
PV-cell	Photovoltaic cell
PVGIS	Photovoltaic Geographical Information System
PWM	Pulse width modulation
RFC	Regenerating fuel cell
ROCOF	Rate Of Change Of Frequency
SCADA	Supervisory Control and Data Acquisition system
SF	Switching frequency
SG	Smart Grid
SMES	Superconducting magnetic energy storage
SOFC	Solid oxide fuel cell
THD	Total harmonic distortion
TSO	Transmission system operator (Fingrid in Finland)
UPS	Uninterruptible power source
WLAN	Wireless Local Area Network

1. INTRODUCTION

Rapid increase in environmentally friendly power generation has had an effect of distributing small-scale production in low voltage (LV) distribution grids. Increase in distributed generation (DG) and in new type of production owners, common people, has created many challenges for our current grid and opened up also many new opportunities. To respond to this challenge and opportunities, a Smart Grid idea has born.

As production is now present in LV grids, self-sufficient parts of grid operating independently from main grid have also become possible with Smart Grid technology. These small autonomous parts of the LV grid are called microgrids. Peter Asmus, an industry analyst from Pike Research estimates that there will be over 3 GW of new microgrid capacity installed globally between 2010 and 2015. Study also estimates that community microgrids will be the fastest growing type in Europe and Asia. [1]

2. GENERAL DEFINITIONS

Following chapters describe briefly definitions of Smart Grid, microgrid and common factors in them. In short, microgrid is a way to integrate small-scale production as an advantage rather than burden to electric lines and Smart Grid technology provides the means for this.

2.1. Smart Grid

Smart Grids (SG) can be defined as electric grid solutions that can respond to new demands in electric networks and offer extra value to all parties involved. Exact definitions vary but the general idea is more or less the same. Most common defining factors of a Smart Grid are better communication between network participants, more efficient system operation, opening new possibilities in production, in consumer participation, in businesses, and generally making the grid more flexible to changes in operation. Smart Grid features are being put in use one by one on existing grids as Smart Grids are in active development currently. Some possible components and functions of a Smart Grid are displayed in figure 2.1. The figure represents some clients of distribution system such as production units, households, factories and how they can manage energy usage and production with integrated communication system. [1] [2] [3]

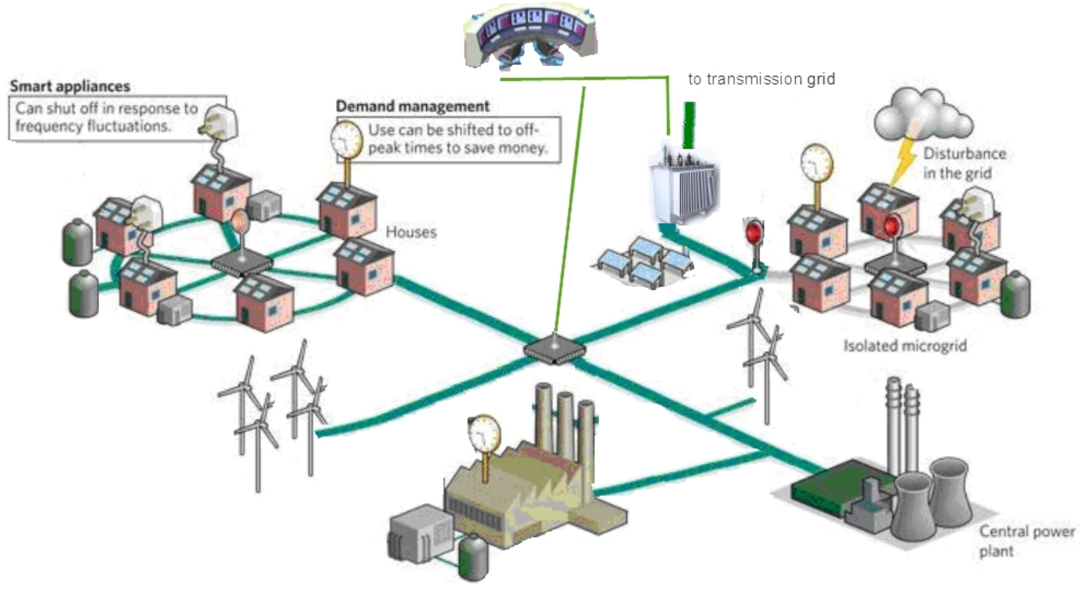


Figure 2.1. *Future Smart Grid. Based on figure in[4].*

Smart Grid includes the integration of distributed generation and storage, and advanced control, protection and communication systems providing new challenges and opportunities.

2.1.1. Production

Traditional energy sources nuclear power, hydro power and fossil fuels are still the base of electricity production to the foreseeable future and therefore have strong foothold in SG concepts. As the focus of the energy market today is to decrease CO_2 emissions, production types helping in these measures, are in growing role in SG concepts. More CO_2-friendly production types include e.g. PV-cells, wind power, bio fuel CHP-plants, fuel cells and hydropower from traditional sources. Every power plant type has its own characteristics that have to be taken into account in Smart Grid design.

2.1.2. Energy storage devices

As a result from using generation the power output of which fluctuates because of environment changes, more regulation capacity is needed to the top of demand side regulation capacity. This additional regulation capacity in most SG concepts consists of energy storage devices. Energy storage devices also provide additional possibilities in operation such as using them to provide backup power in black outs. Some storage types such as flywheels and supercapacitors serve better as power quality devices providing fast response to quick deviations in power balance and others such as batteries, compressed air systems and pumped storages are better suited handling larger amounts of energy in slower cycles.

2.1.3. Stability control

In every power system, there is a need for stability devices which maintain frequency, rotor angle and voltage stability. All those stabilities must be maintained in a smart way first to fulfil the electric quality standards but also to minimise the costs for operation. Stability can be characterised further as steady state, transient, and sub-transient stability. Steady state stability means stability in long-term operation, transient stability with operation changes like connections and sub-transient in between transient scale deviations. Stability management in Smart Grids is carried out with high automation and information exchange between stability equipment and loads. Stability control based on information exchange instead of action – reaction can be called active stability. [5]

Frequency stability means that line frequency will stabilise to 50Hz (EU) or 60Hz (US) after sudden changes in power production or consumption. When a big load or transmission line breaks off, electrical current will also decrease which affects electrical countertorque and rotating generators will tend to accelerate as moment balance is disturbed. Similarly frequency will tend to decrease when big loads are added to system or generator drops off the grid. Acceptable frequency limits are given in EN-SFS 50160 standard: Voltage characteristics of electricity supplied by public distribution systems. Thus there is a need for controllers to adjust power production as demand changes to stabilise frequency as quickly as possible. Controlled loads can also serve in frequency management. [5] Rotor angle stability means that after disturbance in electric grid, angle between two voltages in some points of the grid will return to stable state level. If system does not have enough damping, rotor angel could start to rise or decline so that voltages have to be cut. The maximum rotor angle that system can have before stability is lost will define time for interruptions to be cleared from the grid.[6]

Voltage stability means that voltage level is maintained in acceptable limits at all times and voltage fulfils the standard EN-SFS 50160 in other ways. Voltage level is strongly connected to reactive power generation in medium voltage and high voltage lines. In low voltage systems however active power is more related to voltage level and reactive power more to frequency. Reactive power is part of electrical energy transmitted in power grid that cannot be easily converted to mechanical energy. Reactive power is not desired in most cases but many devices connected to grid need it and produce it. Reactive power cannot be easily transmitted via power lines and it takes capacity away from normal active power. Therefore it is desirable to minimise reactive power transmission in power lines and pursue to produce required reactive power close to loads that need it. Devices designed to produce reactive power locally are called shunt compensators. Reactive power can be also produced with synchronous machines; synchronous generators and motors and with inverter units.

2.1.4. Protection devices

Protection is a crucial part of any electric grid. Relays are an important part of a modern protection system and they can de described as data collectors of grid that provide information on current, voltage, phase angle and power. The most critical type of relay is a protection relay main function of which is to provide commands to line breakers to act in a case of an emergency. Relays in Smart Grids can be nearly every type of relays used in grids today. Smart Grid relays have to provide information outputs for full integration to the system. Fault current management is needed in some cases. Devices used for this are called fault current limiters, fault current controllers, and fault current sources. The goal of fault current management is to limit fault current to safe levels but still high enough for protection relays to work.

2.1.5. Information and telecommunication technology in Smart Grids

Cross communication between equipment in Smart Grids is very important to achieve grid stability, and safe and optimal system operation. Requirements for information and communications technology (ICT) can be divided into high and low priority connections.

High priority low latency connections are needed in protection devices and devices controlling grid stability. High priority signals are usually transmitted in electric or optical cables solely designated for one use. Devices needing high priority connections include relays, breakers, automatic voltage regulation devices, power factor correctors and compensation devices. High priority information from grid is transmitted to Supervisory Control And Data Acquisition system (SCADA) or to Distribution management system DMS and between these systems. [7]

Low priority connections include connections used for information that is used to make decisions in bigger time frame to customers and other parties. Latency is not an issue in low priority connections and wide range of wireless connections can be used. [7]

2.1.6. Opportunities and challenges

Smart Grid offers all participants more active role in managing energy usage and opens opportunities for new businesses. Customers can for example see what the current market price is and what the estimated price is for certain other time period. With this information customers can lower their energy price if they allocate some of the electricity usage for cheaper time period. Also customers could e.g. get reduction for energy bills if they allow some of the loads to be taken offline during power shortages. New businesses could arise to provide management services for these kinds of tasks. Customers can also be characterised more accurately as automatic meter reading (AMR) devices provide online measurements from individual customers, instead of estimations. EU has set a goal that 80% of meters installed in the year 2020 will be AMRs[8]. [9]

Smart Grid’s vast automation and diverse infrastructure pose many challenges for grid design and operation. Transformation to Smart Grid practises, especially less stable pricing and load control might not be welcomed by all customers. Smart Grid environment will also change working practices in electric utility companies and could create social challenges. The average age of employees of utility companies in some countries is around 50 and major transformation from operation to active building could result in workforce shortages.[9] Some operators believe however that transformation will be a slow process and there won’t be quick changes in grid operation as standardization and concepts are in active development.

2.2. Microgrid

2.2.1. Structure

Microgrid can be defined as a low voltage (LV) electric network which consists of production and consumption, and can operate as an island if needed. Components of microgrids are mostly similar to Smart Grid concepts but centralised power generation is missing from most concepts. DC distribution is a viable option alongside with traditional alternating current distribution. Various grid shapes can be used in microgrids, but it is needed to ensure that there are enough alternative connections for flexible grid usage in alternating operating situations, fault situations and possible additions to grid afterwards. Figure 2.2 displays one possible grid configuration for a microgrid.

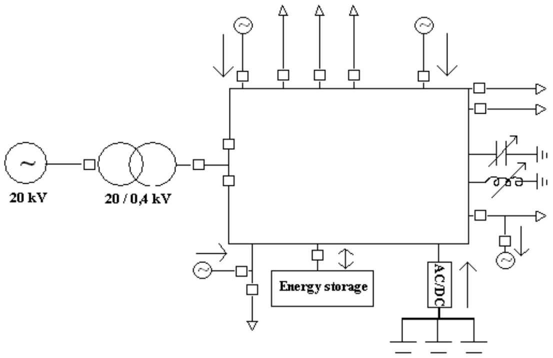


Figure 2.2. *One possible microgrid layout.*

There can be savings if the grid is not designed the worst case in mind. Full output power of generation is quite rare in situation when all energy storages are offline thus grid can be built weaker. [11]

2.2.2. Operation

As mentioned, microgrid can operate either connected to the rest of network through or separately as an island. Microgrid can have 3rd party operator to manage microgrid and represent microgrid owners as one to a local distribution system operator. Same thing that is possibly cheap for producers of microgrid can be expensive to a distribution system operator (DSO). This possible conflict of interests is also the main reason why in EU a DSO is not allowed to have power generation. Microgrid can also be owned by DSO excluding the power production and classified as a part of the public distribution grid.

When operating connected to main grid, there are a couple of topologies to control power transmission in and out of the microgrid. Constant power can be tried to be maintained between the grids, link to main grid can only be used as backup power and power transmission can be controlled in a way that minimises operation costs or some other higher goal like minimizing CO_2 emissions. Island operation requirement dictates that grid has to have enough production to serve loads in long run but in short time periods loads can be fed from energy storage devices or from other regulation capacity. Enough regulation capacity is also needed to ensure stable operation when electricity demand declines and production fluctuates.

2.2.3. Benefits and challenges

Shorter distances are a basic advantage of microgrids which comes solely from small-scale of most microgrids. This means short-range wireless connections like WLAN can be used in some cases. In protection shorter distances make differential relays a good choice as communication between relays is cheap to arrange. Distributed generation (DG) can reduce transmission losses as electricity is produced closer to demand. Microgrid can also provide cheaper option to improve power quality in distant locations which are fed from a long transmission line. Production of microgrids can support the main grid and even help in restoring the network after major failure. As microgrids are based mostly on same technology infrastructure as Smart Grids, advantages mentioned previously apply also microgrids. [12]

Protection is challenging in microgrids as short circuit currents fluctuate and often are quite small.[13] Overall challenge in microgrids is to ensure that customer gets good quality voltage even in small and weak grids operating as an island. Microgrid therefore has to have at least one generator that can be used to start up the grid if everything else is down. Microgrids are required to have more active stability control in respect to similar size disturbances in larger grids.[12] Also voltage level of cannot be controlled with reactive power injection as low voltage (LV) lines resistance is the major component of impedance compared to reactance.

2.3. Summary

Smart Grid technology can be defined as new electric grid solutions that improve grid performance and give value to different parties involved. The heart of Smart Grid system is improved communication which allows better allocation of resources and avoidance of problems. Microgrid is defined as a low voltage electric grid that takes advantage of Smart Grid technology and can operate separate from rest of distribution grid as an island. This means that microgrid has its own production and regulation capacity to satisfy electric quality standards also in island operation. Advantages of microgrids are better reliability of electricity supply due to backup power capacity. Also microgrid systems can support parts of distribution system in power outages if system is designed that way. The largest technological obstacle with microgrid systems is the problematic protection due to fluctuating short circuit currents and alternating power flow directions in most of the concepts.

3. FACTORS IN FUTURE COMMUNITY MICROGRID

Practical concepts for microgrids are currently forming thus there are still much open options for standardized systems. This chapter describes different factors involved in microgrid operation and goes in further on some technical concepts and requirements.

3.1. General structures

Grid structure describes basic physical, technical and operational properties of the grid. All grid types have technical and economical advantages and disadvantages in them that have to be considered when sorting out the most attractive grid type for a specific microgrid.

3.1.1. Basic layouts for microgrids

Radial grid

Most of the current grids are built to radial, meaning there is only one possible line with a specific consumption and generation connects to the grid. Due the popularity of radial grids today, they are an obvious choice for grid layout if existing infrastructure is wanted to be used as a base for microgrids. Figure 3.1 illustrates example layout of radial microgrid.

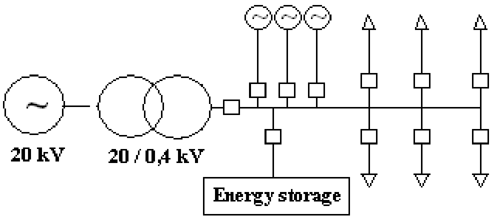


Figure 3.1. *Radial microgrid with one distribution line.*

Radial grid can have multiple distribution lines in parallel connected to the transformer. As radial type microgrids can use existing infrastructure, where design principle is that power flows from distribution transformer to consumption, production and storage units can be placed close to the transformer to utilize current infrastructure. As power flow and direction remain the same, no cables have to be changed because production in long distance would make lines undersized. Nothing of course will dictate that every house can’t have their own production units, if problems with protection and system control can be solved.

Ring grid

Ring or loop type grid is a grid with lines geometrically placed so that a ring shape can be formed. There are ring type grids currently in residential areas but they are operated always as if they were two parallel radial lines. Thus a one connector is always open in ring grids. Figure 3.2 represents ring shaped microgrid also operated as a ring.

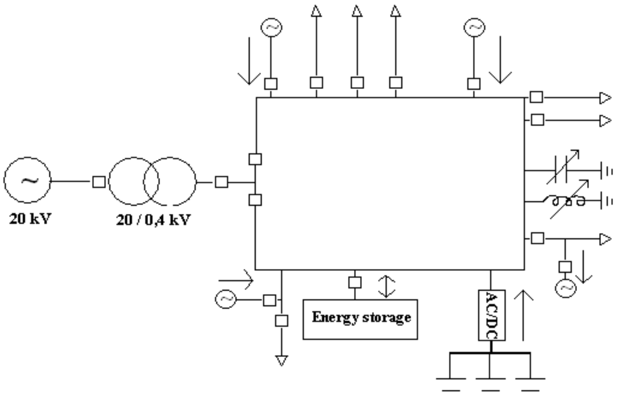


Figure 3.2. *Ring-shaped and ring-operated microgrid.*

Ring-shaped grid offers two alternative routes for power to flow to a customer. When a ring grid is also operated as a ring, advantages include also better voltage stability, smaller power losses and more even power distribution. Disadvantage is that short circuit currents are larger and protection is more complicated due to two power flow directions. [20]

Mesh grid

Mesh grid is an electrical network with multiple alternative connections between nodes. Figure 3.3 displays basic form of a mesh type microgrid.

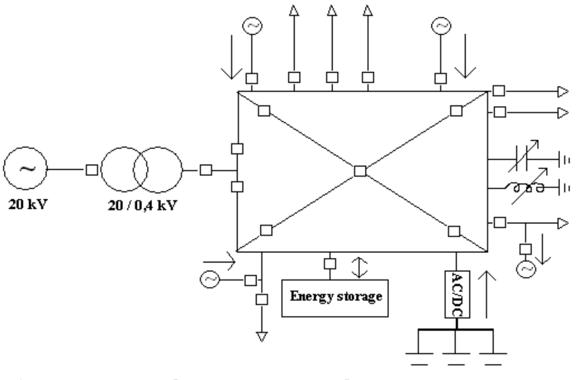


Figure 3.3. *Mesh type microgrid.*

Mesh grid does not necessarily have to be geometrically shaped like a ring grid with alternative connections. For operational and protection reasons, only some of the possible forms are used that mesh grid provides. Most obvious operational layouts are radial and ring types mentioned earlier. Table 3.1 presents a short summary of properties of different grid shape alternatives.

Table 3.1. *Summary comparison of different grid shapes.*

Grid shape	Simplicity	Present in current LV-system?	Natural short circuit current	Experience of usage	Flexibility for changes
Radial grid	good	yes	low	a lot of	bad
Ring grid	average	yes, but operated as radial	high	some	average
Mesh grid	bad	no	depends on operating shape	from transmission grid	good

Radial and ring grids can be implemented more easily on current infrastructure but mesh grid offers more possibilities because of many alternative connections helping grid to adjust to changes.

Lines and grounding in LV grids

Low voltage grids are the largest contributors to losses in electrical systems today. About 80% of losses in an electrical grid come from LV systems and transformers connected to them. [21] In a transmission system losses are about one percent of the power flow and with distribution grids around 3,5%.[22] Finnish LV systems use mostly TN-C configuration, which means that the neutral connector is combined to the ground cable. This combined lead is called PEN and all device grounds are connected to this wire. Standard SFS 6000 states that PEN-wire has to be connected to ground in a distribution transformer and also between 200m points in the grid. Also grounding should be done if there is an appropriate ground lead near the PEN-wire. Impedance in ground electrodes has to be less than 100 Ω. If ground does not lead current very well, grounding has to be done to every line connected to the grid separately. Figure 3.4 represents a TN-C system.

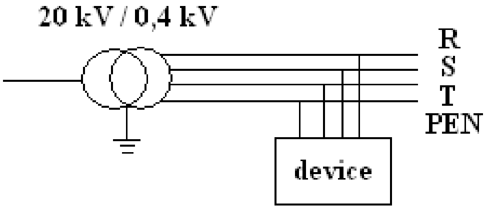
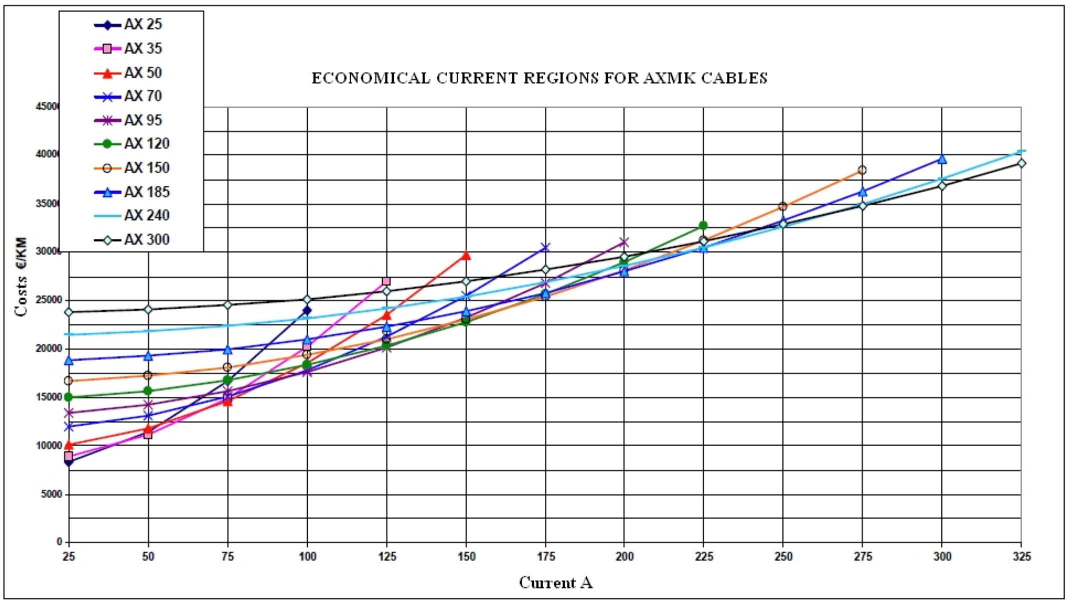


Figure 3.4. *TN-C system with 3-phase LV device connected.*

Underground cables are used instead of overhead lines in urban areas of Finland. Standard underground cables are named AXMK. Following figure 3.5 gives a general idea what would optimal cables be for different nominal currents. The figure is translated from an Insinööritoimisto Risto Anjala presentation slide.[23]



Total Energy / Nominal Power =2000 h Interest rate = 8 % Time period= 40 years

Figure 3.5. *Economical current regions for AXMK cables. Translated from [23].*

Variables in total cost equation are power loss costs, interruption costs, initial investment costs, maintenance costs, time period and financing costs(interest rate). Of course interruption valuation and financing costs can change so updating tables and curves is needed now and then.

3.2. Using current distribution grids

The Finnish electric distribution network has two structure types, radial network and ring network. However ring types of networks are operated as two radial lines, but this could change if requirements for protection and other important factors can be solved. Examples of current distribution network shapes are displayed in figure 3.1 and in figure 3.2. Ring shaped systems and underground cables are more popular in urban areas of Finland and overhead lines with radial shape is the common type in rural areas. Smart Grid technology is slowly increasing in these networks and some might be enabled to act as microgrids.

3.2.1. Advantages and problems associated with using old grids

The biggest advantages of using old grids as a base, is lower initial investment costs. Microgrids can also be built faster as there is no need waiting for new areas to attract housing. There can be some alterations needed to be made when updating current networks for microgrid usage. Usually lines are rated to lower currents the longer the distance is from the distribution transformer. This means that the lines have to be strengthened if production is wanted to be added to far side of the lines. Updating existing underground cables is more expensive in some areas as costs for digging of the ground vary. Also protection system has to be updated unless all storage and generation units are connect to the main bus.

3.3. Alternative technical grid configuration types

Technical configurations of microgrids and Smart Grids in general can be very diverse at component level. As mentioned in general definition, all microgrids need production, regulation capacity, protection and power quality equipment to function as an island. Two concepts described in this chapter are larger technological entities that can be implemented to any of the layouts described.

DC-microgrid

Most of microgrid concepts under development currently are based on an alternating current (AC) system. Direct current (DC) can also be implemented to microgrid usage. Rapid growth in digital electronics since the 80’s using DC voltage has made a huge demand for AC/DC inverters. Also now in DC lighting is increasing with light emitting diodes (LEDs) and compact fluorescent lamps (CFLs). One obvious advantage DC distribution would bring for using these devices is lack of need for an AC/DC inverter on every device, which could reduce the power losses of the system.[24]

In addition to possible loss reduction mentioned, DC system also has no problem with harmonic distortion, which is created by power electronic devices in AC grid. Also there are no base frequency related reactive power losses in a DC transmission system. Connecting devices with natural DC connection like batteries, PV-panels, fuel cells, and supercapacitors can be made easier with a DC grid. DC transmission is currently used in long distance high power links because reactive power losses would make system more expensive than high voltage direct current (HVDC) system.[24]

One large drawback in DC power transmission is that resistive losses are larger in DC power transmission than in AC transmission with the same voltage, active power demand and number of power cables (3). The reason for this is that in a 3-phase AC system there is no current going in the neutral cable as phase currents cancel each other out completely in an ideal situation. DC/DC converter is needed if use of the device is not possible with straight connection to DC grid due different voltage level. On top of the resistive losses and DC/DC converters, weak standardisation in maintenance practices, and higher costs in cables and power electronics make DC system more expensive than AC in most cases.[15] Currently in Finland DC microgrid systems are most popular in summer cottages. Figure 3.6 displays typical Finnish cottage with a DC system.

Figure 3.6. *Typical Finnish DC microgrid application [16].*

Electricity need is also low in most of these locations and connected devices can all be used without DC/DC converters. Typical DC systems in Finland are typically sold with lead acid batteries as energy storage, electricity is produced by a couple of solar panels and switches, sockets and cables are included in package. Easing factor is also that customers are allowed to install low voltage system by themselves and save money on installation fee. Connection to distribution grid in a location like islands would cost many thousands of euros and DC microgrid systems offer significant cost savings.[16]

Subgrid concept

Microgrid can consist of numerous possible combinations of clients and devices. One question is that how are client additions to microgrid handled and how can the design work be made simpler to manage all this. Splitting microgrid into smaller blocks, results in subgrids that are designed to work together and future street addition could be made easier using subgrid concept. Figure 3.7 displays the general idea behind the subgrid concept.

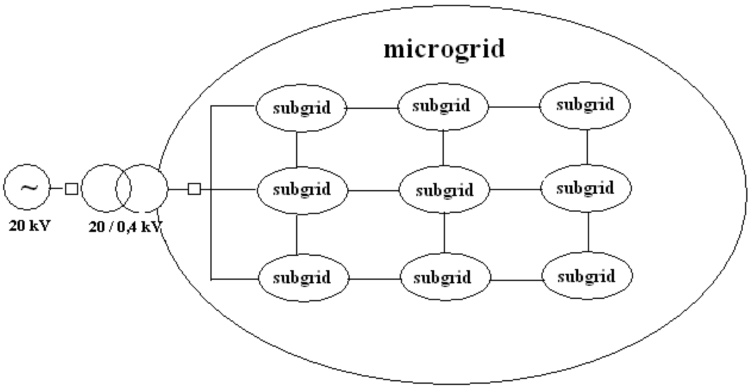


Figure 3.7. *General idea of subgrid as a part of a microgrid.*

Technical guidelines for subgrids could include:

- Should have at least one generator with blackstart capability and synchronising load to generator
- Subgrid islanding level does not have to be 100%, meaning all loads are not required to be able to be supplied by subgrid.

- Communication links to other subgrids for synchronising and building up the microgrid after failure
- Communication link to microgrid controller
- Input and output power capacity have requirements that power can flow between the subgrids without causing too much problems
- Power flow deviation limits would also help to reduce possible fluctuations in the whole microgrid

  -Local balancing of production and consumption to some level using controllable loads and energy storages

3.3.1. Component placing

Component placing plays a major role in general microgrid system design. Component placing includes physical locations of generation, loads, storage and power quality and ICT equipment. Component placing can be divided roughly into distributed placing or concentrated placing. Both have advantages and disadvantages.

Distributed placing

In distributed placing, all components are divided quite evenly to grid. Power transmission demand is lower when production is close to consumption. Grid stability and reliability increase when a single broken device is not connected to big sets of components. Disadvantage of distributed placing is higher component costs compared to concentrated placing and more complicated control and protection. Most of microgrid concepts are based on distribute placing and common term distributed generation (DG) is used. Because there are DG units in households, the scenery changes as roofs are covered with diverse variety production units. The most problematic situations might be with a wind power, if the light flicker from the blades hits a window (this is very annoying). Also noise level from the production units might become a problem if they are placed too close to homes.

Concentrated placing

In concentrated placing components are placed in predefined locations in sets. E.g. production and storages could be placed straight to transformer so that traditional power flow direction from transformer to customer is achieved. This means that distribution system can be used virtually with no changes. Old protection devices can also be used everywhere else but in storage and production areas, where of course new protection and control equipment is needed. Power electronic costs in a concentrated system can be lower. E.g. a shared DC/AC inverter can be used in a solar panel site. Also lots of DC systems like PV-panels can be linked so that their DC voltage is close to optimal for inverter efficiency. Single unit area means there is a notable new land mark from production and storage area if devices can not be “hidden” e.g. on large building close to distribution transformer. Good thing is that production is farther away from housing and units won’t disturb the households. Noise level, housing architectural planning and other possible things are unaffected in most cases with concentrated placing.

Cost savings example of concentrated placing

Let’s assume that microgrid has 40 clients, all of whom have components,

- 7.8kW of solar production
- 2kW of wind power with price of 6000€ [17](including the frequency converter)
- 2.3kWh of battery capacity
- 5kW inverter with price of 2000€[18]

If it is assumed that batteries and solar cells can share same converter, there are 40 AC/DC inverters and 40 frequency converters (wind power) in the distributed system. In concentrated placing all batteries and solar sells are lumped together, which means inverter size requirement is 200 kW. Price of 40 5 kW inverters is about 80 k€ and single 250 kW inverter costs about 60 k€. This means 20 k€ saving in initial costs for solar power and battery system.[18] Wind power system can be in theory also integrated with common DC-bus and inverter side of the frequency converter but implementation of this is trickier and every plant still needs its own rectifier. However the better option is just to use one larger turbine, a 80 kW turbine in this example. E.g. St1-wes 80 kW wind turbine costs 230 k€ [19] which would mean 10k€ savings compared to 40 2 kW units with price of 240 k€.

As conclusion of calculation, about 750 € per microgrid client can be saved on using concentrated placing instead of distributed placing. Also grid protection can be left as it is with standard grids as power flow direction is same. Savings are not huge and sometimes even smaller units can be cheaper than one larger unit as currently competition is much more vivid in sub 5 kW category.

3.4. Current requirements

There is currently no possibility to use a part of a public distribution network as an island due to safety reasons.[12] Private customer and industry networks are allowed to operate as an island.[12] It will be seen whether microgrids with multiple household are categorised as parts of public distribution network or not. But in any case, practices have to change to allow microgrids. Currently normal small-scale production installation and operation practises and legislation must be implemented on production in microgrids.

Legislation demands appropriate construction, land usage and environmental permits for new plants and networks. Communication to local distribution system operator (DSO) should start early in projects to avoid complications ahead. Following contracts and obligations are needed for any small-scale generation system operation: Connection contract with local distribution system operator (DSO), contract to sell the electricity including reactive power aspects, a tax must be paid on electricity produced and notice has to be left on local customs district. Also if production unit(s) is(are) larger than one megavolt amperes (MVA) a notice has to be also left to the Energy Market Authority (energiamarkkinavirasto in Finnish).[14] Network pricing recommendation by Finnish Energy Industries can be found in appendix 2.

3.5. Technical requirements

There are many technical requirements for microgrids and Smart Grids. Technical requirements include e.g. means for communication, connection of micro generators, metering and general requirements for all electric power system like electric quality and safety. Most of the requirements are defined in different standards.

3.5.1. Equipment standards for Smart Grids by IEC

International Electrotechnical Commission (IEC) has been working on standards for Smart Grid equipment and nearly all of them also apply to microgrids as they are a major part of the Smart Grid. There are still a lot of details to be agreed on and standards are also refined to new demands. [25] Standards define things like, terms, compatibility, safety and protection, communication and metering.

3.5.2. IEEE Smart Grid standards

There are a lot of standards already approved by Institute of Electrical and Electronics Engineers (IEEE) regarding Smart Grids. IEEE is also working on numerous other more specific standards and guides for Smart Grids and microgrids. The most relevant document for microgrids from IEEE is ongoing project IEEE P1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems. Also IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems, which is the base for similarly coded guide, is closely relevant to microgrids.

IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems

Standard sets limitations and regulations to DG, disconnection times, synchronisation rules, harmonics, DC injection, grounding other protection aspects. Standard is made 60Hz 120 V electrical systems in mind so it cannot be directly applied to Smart Grids in Europe. Also standard does not take into account intentional islanding, IEC and EN standards cover same matters, so value to microgrids in Finland is thin. IEEE P1547.4 guide in the other hand could be very useful as a base for building microgrid standards in Europe. Currently the guide is not available from IEEE as project is still running.

3.5.3. ICT in Smart Grids and Microgrids

As mentioned earlier information and communications technology (ICT) has a major role in Smart Grids. Production units, loads, meters, system operators, and power quality equipment need ways to communicate with each other. The base for European microgrid communication is IEC 61850 standard. Figure 3.8 displays interconnections of different logical nodes (LN) in a system based on IEC 61850. Seamless information model and seamless information exchange are defined in IEC 61850-7-4, IEC-61850-7-3 and IEC 61850-7-2 [28]

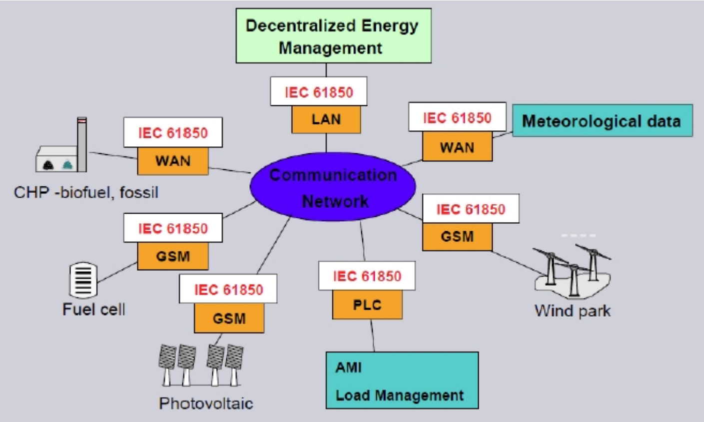


Figure 3.8. *Interconnection of communication means and protocols [26].*

Communication technology in IEC 61850

IEC 61850 uses Ethernet technology as it has matured in many applications over the years. In Ethernet systems, low priority and high priority information can be transmitted in same cables if wanted. It was determined in More Microgrids EU project that at least 100 Mb/s of capacity is needed to handle the entire load given by microgrid. A lot of planning should be put also in choosing proper physical layout for communication network. Latencies are dependant on distances and processing times of the equipment. [26]

Advanced metering infrastructure

Advanced metering infrastructure (AMI) consists of Smart Grid meters with multi function metering with communication possibilities. European smart metering alliance has set the following definition for smart metering [27]:

- Automatic processing, transfer, management and utilization of metering data
- Automatic management of meters
- 2-way data communication with meters
- Provides meaningful and timely consumption information to relevant actors and their systems, including consumer
- Supports services that improve energy efficiency of the energy consumption and the energy system (generation transmission, distribution and especially end-use)

The main applications of smart meters are:

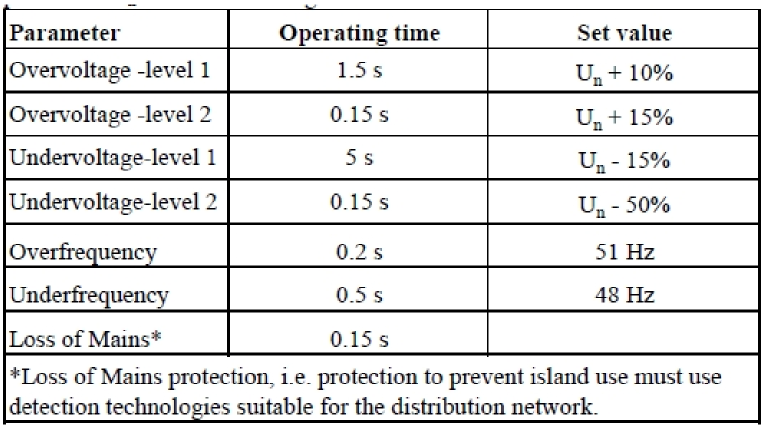
- More accurate settlement so that no estimation bills have to be sent by DSO.
- Faster and cheaper switching between electricity retailers
- Power flow and voltage measurements
- Possibly in future devices relaying data from other meters (wind speed, irradiation, etc.)
- Possibly in future devices relaying commands to load- and micro source controllers

Open source meters are essential for cross compatible systems to be built on a smart meter being the heart of Smart Grid communication. Also for the future, meters should have extra connection capacity to integrate system upgrades swiftly to an existing information system. Current Smart Grid meters are not necessarily developed with microgrid requirements in mind and main function is still just to measure power flows and voltage information.

3.5.4. Electric quality requirements and standards

Technical requirements for small-scale production are mostly same as with regular production. Standard EN 50438, Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks, gives disconnection rules and times for micro-generators. Standard gives specific values for each European country but also some common parameters are presented. Standard is meant for production units up to 3-phase 11 kVA and 3.7 kVA in single phase. [29] Table 3.2 displays 2-stage disconnection times from standard EN 50438 for Finland, and voltage and frequency deviation limits, which should trip the protection.

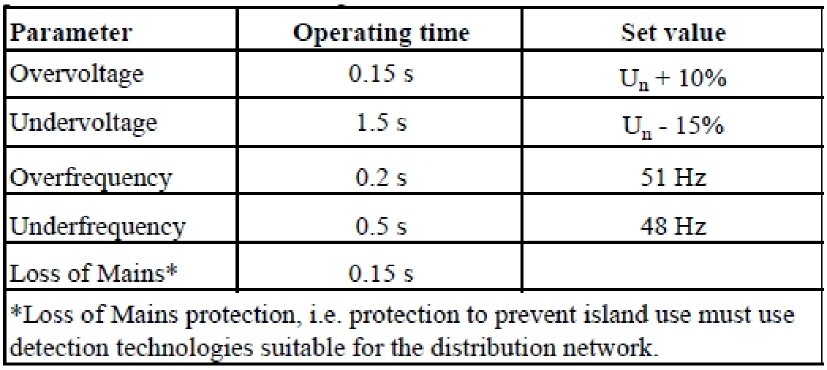
Table 3.2. *2-stage disconnection times and triggering limits for micro-generators [30].*



Parameter	Operating time	Set value
Overvoltage -level 1	1.5 s	U_n + 10%
Overvoltage -level 2	0.15 s	U_n + 15%
Undervoltage-level 1	5 s	U_n - 15%
Undervoltage-level 2	0.15 s	U_n - 50%
Overfrequency	0.2 s	51 Hz
Underfrequency	0.5 s	48 Hz
Loss of Mains*	0.15 s	
*Loss of Mains protection, i.e. protection to prevent island use must use detection technologies suitable for the distribution network.		

Standard also gives similar times for single stage disconnection parameters, which are listed in table 3.3.

Table 3.3. *Single stage disconnection times and triggers for micro-generators [30].*



Parameter	Operating time	Set value
Overvoltage	0.15 s	U_n + 10%
Undervoltage	1.5 s	U_n - 15%
Overfrequency	0.2 s	51 Hz
Underfrequency	0.5 s	48 Hz
Loss of Mains*	0.15 s	

*Loss of Mains protection, i.e. protection to prevent island use must use detection technologies suitable for the distribution network.

Action to be taken is in most cases disconnecting the microgrid if the problem is in MV grid. If fault is in microgrid, selective fault isolation can be used, but it can be tricky. Therefore engaging island operation first is safer in most cases. Before electric quality is at point, which would demand disconnection, many actions are taken to stabilize the system.

Recommendations for connection of micro-generation to the electricity distribution network are given by Finnish Energy Industries (Energiateollisuus ry in Finnish) in network recommendation YA9:09[30]. In addition to EN 50438 standard, YA9:09 gives recommendation for short circuit apparent power in generation point. Reason for this is that connecting generation should not result in voltage deviation larger than 4%. This recommendation is based on passive connection to grid. An active control system of microgrid can compensate most of the voltage drops resulted by alternations in grid. The recommendation for short circuit apparent power can be calculated by equation 1.[30]

$$S_k \geq 25 \cdot i_{ratio} \cdot S_N \tag{1}$$

S_k = short circuit apparent power

i_{ratio} = ratio of maximum current respect to nominal current

S_N =nominal apparent power of the generator

For detecting a loss of mains situation, a Rate of Change of Frequency (ROCOF) relay is recommended by YA9:09 with a trip time of 0.15s. Generator synchronisation should be fully automatic according to YA9:09.

SFS-EN 50160 quality standard for electricity must be fulfilled on all parts of the network unless agreed other ways. To achieve EN-SFS 50160, all equipment connected to the grid must fulfil EMC and compatibility standards. Low voltage directive 2006/95/EC also applies to microgrid devices.[37] [38] Details on SFS-EN 50160 are presented in appendix 1.

3.5.5. Protection

Reason for protection in any electric systems is to ensure safety for users and equipment involved in system operation. Equipment and power quality standards have a major role in ensuring safe operation of the grid. Protection also should be done in a smart way so that faults and other problems in grid only affect a minimal part of the grid. Following chapters describe common relay types, how different devices act in faults and two protection concepts: adaptive and fault current level protection concept.

Selectivity and protection zones

Protection zones are areas within microgrid that have specific protection devices handling the protection of this part of the grid. Protection zones can and are recommended to overlap each other so that other relay will act if first relay fails. Selectivity means smart way of disconnecting only minimal parts of the grid isolating the fault to certain section. There are problems for ensuring best possible selectivity in microgrids while aiming at minimal overloading of the lines and equipment in faults. Blinding is a term used for situations where protection does not see the fault as fault current maybe fed from mostly different line or from multiple sources. Blinding is also related to selectivity, as presented in the following example in figure 3.9.

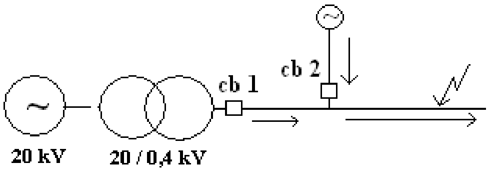


Figure 3.9. *Blinding example with arrow vectors representing fault currents.*

Fault is at the end of the line and the fault is fed from generator along the grid and from the MV transformer. In the example fault current of the cb 1(circuit breaker 1) 1 is not large enough for tripping the breaker. Fault current of cb 2 could be large enough to trip the cb 2. After cb 2 has acted, fault still exists and now cb 1 will trip as all the fault current is fed via cb 1. Even if protection works, there is now a double latency for fault clearing, which could be too much for some parts of the grid in terms of over current durability.

Overcoming unintentional circuit breaker operation; isolating right areas in faults, is also a challenge in microgrids. An example of the problem is displayed in figure 3.10.

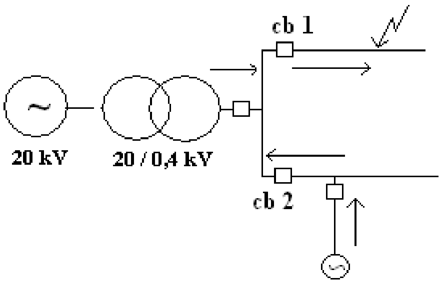


Figure 3.10. *Selectivity problem of wrong separation.*

Circuit breaker cb2 could be tripped first instead of cb 1 if fault is in cb 1 line. Solution for this problem could be setting the tripping time of cb 2 higher. This is problematic as there is a limit how long the time can be without risking safety. Use of directional relays could solve the problem as they would only trip if current is going to the line from the bus. [32] Alternatively the whole system could be designed in a way that most of the fault current would flow from transformer or energy storage connected to the bus. This could work if sources on cb2 are not capable of providing high peak short circuit power.

Relay types

Relays provide information about the grid to different systems. The most important relays are protection relays, which give break commands to circuit breakers when certain part of the grid must be cut off because electric quality is not adequate or there is fault in the protection zone of the relay.

Distance relay measures line impedance and sends signal to circuit breaker when line impedance drops under certain threshold. Most distance relays also have direction capability so that angle of the measured impedance also has to be out of preset range for relay to give break command. These two rules of distance relay can be presented with RX-diagrams, which display the area of when break triggering signal is sent and normal area of operation. An example of RX-diagram is displayed in figure 3.11.[31]

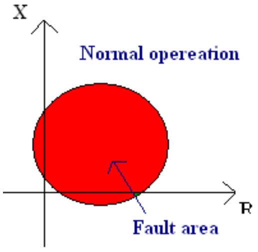


Figure 3.11. *RX-diagram example.*

Distance relay needs voltage and current information to calculate impedance. Also measurement transformers could be needed to make voltage and current information suitable for the relay. Advantages of distance relays are that fault power does not affect relay operation and communication to neighbour relays is not necessary.[31]

Differential relay takes measurements from multiple points of the grid and compares currents. Basic principle is that measurements of current are taken in both ends of protection zone and currents are compared whether fault is in protection zone or not. Relays monitoring symmetry phase currents and voltages work on same principle of calculating differences. It is crucial that measuring transformers are identical and have same saturation properties to avoid accidental triggering.[31]

Over-current relays will act when current is over certain threshold for certain time. Over current relay can have static delayed tripping time, instant triggering (as fast as possible), and inverse time tripping; time shortens when current increases or some more advanced tripping curves. Typical more advanced time tripping curve for over current relay is displayed in figure 3.12 [33].

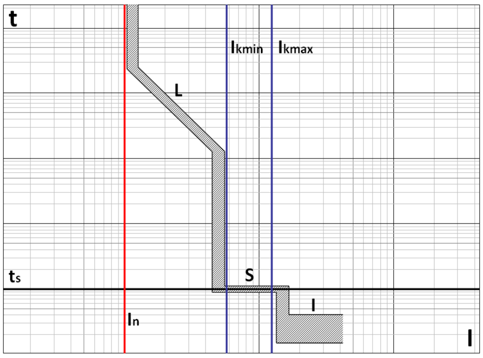


Figure 3.12. *Typical trip curve for LV circuit breaker [33].*

I-section in the figure is instant breaking section, S is preset time delay section and L is inverse time section.

Other relays include voltage relays which monitor voltage levels and angles, frequency relays that monitor base frequency (50 Hz) of the voltage, symmetry relays for phase voltage and current monitoring, power relays and supporting relays that support other relay operation like locking relays that prevent relay operation in some situations like in power fluctuations. Also a Rate of Change of Frequency (ROCOF) relay is recommended in network recommendation YA9:09 for loss of mains protection.

Relay operating latencies vary from relay type fastest being less than 10 ms. Actual relay operating time depends on its delay settings. Faster relays allow more flexibility to protection and also give time for selectivity. It should be remembered also that circuit breaker latency has to be also added to the top of relay operating time. Typical circuit breaker has at least 50 ms of latency.[31]

Components of the grid in fault situation and fault current level

Components react differently to faults. Inverters can be sensitive e.g. for voltage drops and cannot output high fault current. On the other hand synchronous machines can output very high fault currents and they might even become a problem in LV grid.

Fault-current is needed for over current based protection to notice the fault but fault current level should not be too high for breakers to be able to cut the fault or other equipment be damaged.[35]

Asynchronous generator cannot output high fault current as 3-phase faults prevent reactive current for magnetising the generator. This means asynchronous machines cannot be used for reliable triggering of circuit breakers in faults. In asymmetric faults, asynchronous generator can also maintain outputting fault current. Fault current level outputted by asynchronous generator is similar to starting the generator, 3…8 times the nominal current. When fault is cleared, there can be 10 times nominal transient current spike injected by asynchronous generator. [32] Typical RMS-current behaviour of asynchronous generator in 3-phase fault is presented in figure 3.13. The figure is based on [32]. A typical disruption in currents fed by an asynchronous machine lasts about couple of seconds but current during fault fades under a second.

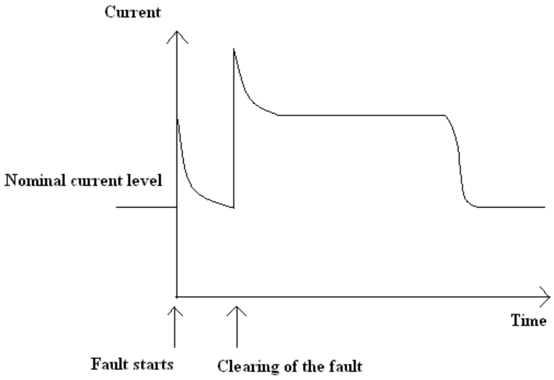


Figure 3.13. *Asynchronous generator in 3-phase fault [32].*

Synchronous generator can output fault current and can be used for maintaining voltage level in the grid. Synchronous generator fault current in 3-phase is typically 5.5…7.3 times nominal current. Also when generator is disconnected in a fault, there is usually a current spike of 10 times nominal current. In MV and HV grids, synchronous machines are in a major role for outputting fault current for the protection to work. Typical RMS-current of synchronous generator in fault is displayed in figure 3.14.

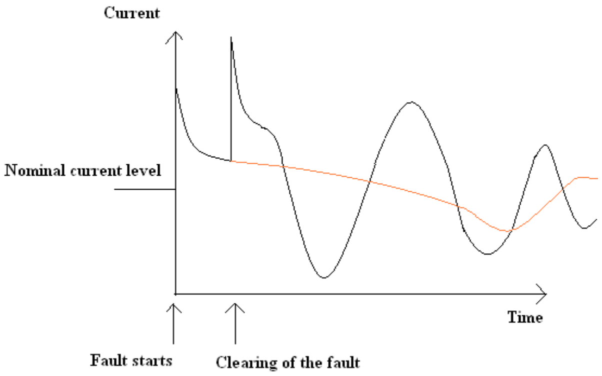


Figure 3.14. *Synchronous generator in 3-phase fault [32].*

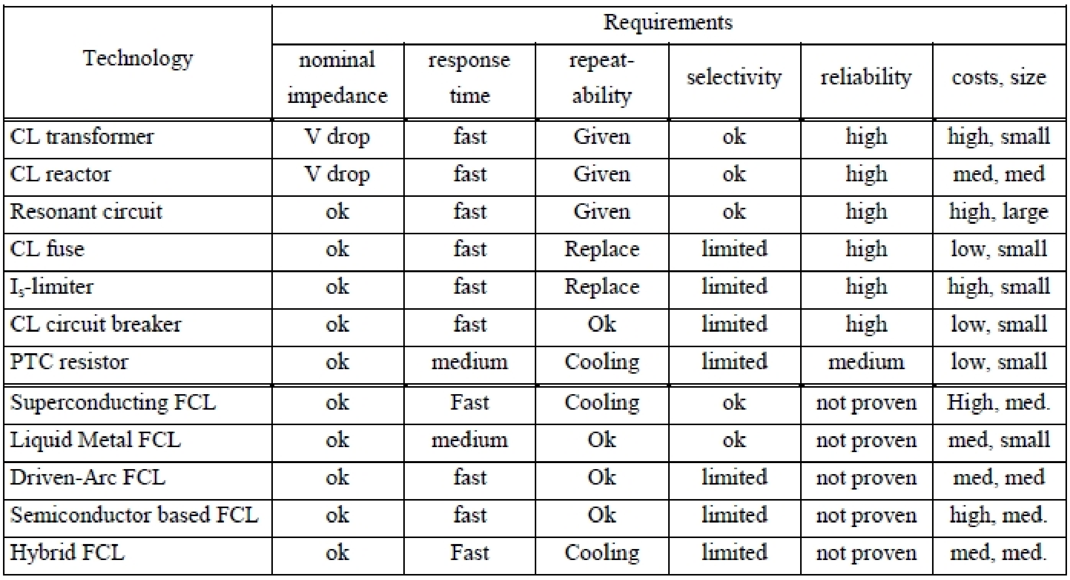
Brown curve represents the situation where fault is not cleared and generator is outputting continuous current. The time axis relation of brown curve to fault clearing situation is not necessarily the one given in the figure. [32]

Inverters cannot usually supply high short circuit current as the switching electronics are usually sized for nominal currents for cost savings. Also solar panel power output cannot suddenly increase so that system could output continuous fault current above normal operation levels. Fault current levels for PV inverter systems are usually presented to be around 1.5 times nominal.[32]

Fault current limiters

Fault current limiters can be used to control fault currents in electric grid. Fault current limiting options are passive and active fault current limitation. In passive limiters, impedance of a current path is increased which creates losses also in normal operation. Active methods increase impedance only when fault current level or slope is high enough. Table 3.4 displays comparison of different fault current limitation technologies.

Table 3.4. *Comparison of fault current limiting technologies [33].*



Technology	Requirements					
	nominal impedance	response time	repeat-ability	selectivity	reliability	costs, size
CL transformer	V drop	fast	Given	ok	high	high, small
CL reactor	V drop	fast	Given	ok	high	med, med
Resonant circuit	ok	fast	Given	ok	high	high, large
CL fuse	ok	fast	Replace	limited	high	low, small
I_s-limiter	ok	fast	Replace	limited	high	high, small
CL circuit breaker	ok	fast	Ok	limited	high	low, small
PTC resistor	ok	medium	Cooling	limited	medium	low, small
Superconducting FCL	ok	Fast	Cooling	ok	not proven	High, med.
Liquid Metal FCL	ok	medium	Ok	ok	not proven	med, small
Driven-Arc FCL	ok	fast	Ok	limited	not proven	med, med
Semiconductor based FCL	ok	fast	Ok	limited	not proven	high, med.
Hybrid FCL	ok	Fast	Cooling	limited	not proven	med, med.

Superconductive fault current limiters (SCFCLs) are maybe the most interesting options from the previous table but recovery times and AC-losses have to be made lower for SCFCLs to be competitive with other methods [34].

Protection concepts

The most popular concepts for microgrid protection are adaptive methods and fault current ensuring method. Adaptive protection of microgrid uses calculated values to set up grid protection settings and tripping so that it suits current grid operation. Calculation can be done online or offline using precalculated tables in operation. The form of table outputs to circuit breakers is presented in table 3.5 [13].

Table 3.5. *Form of precalculated event tables for adaptive protection of microgrid[13].*

	CB1	CB2	CB3	CB4	CB5	…	CBx
Base case	1	1		0	1		1/0
case 1	1	0	1	1	1		1
.							
.							
.							
case n	0	1	1	1	0		1

Circuit breaker has two modes, on and off. Every case of grid operation has a table row that gives information whether a specific circuit breaker should be open (0) or closed (1). Also similar type of tables can be used for other control purposes like whether microgrid is wanted to be in island mode or connected to MV grid in terms of energy market situation or other management decisions.

As mentioned, adaptive protection can also be based on online calculation of suitable circuit breaker modes. This means that a computer model of the grid has to be running constantly. Adequate grid simulators can be very expensive large machines. ABB has experimented on both of the adaptive protection methods.[13]

Ensuring adequate fault current from fault current source (FCS) is the other popular choice for microgrid protection concept. The function of FCS is to provide fault current so those currents are large enough for relays to work properly. FCS is especially needed when microgrid consists of generators like PV-panels or other inverter connected sources that are not capable of providing fault current.[13] As energy storages are needed for other reasons also in most microgrid concepts, they are the obvious choice also to provide fault current. This means that energy storage(s) has to have good peak power capacity. Energy storage systems are examined in chapter 4.2.

3.6. Control of grid balance

As mentioned previously, the reactance of a low voltage grid is small compared to the resistance. This results in a bit different relations between voltages, frequency, reactive and active power. This chapter describes these relations with vectors and their simplistic forms in high and low voltage networks and the most commonly used control methods in microgrids and UPS-systems.

3.6.1. Control fundamentals in microgrids

Voltage, current, reactive and active power can be expressed using complex vector representation. These relations are important so that control mechanisms can be understood. Length of the vector represents RMS-value of the quantity and angle of the vector represents how RMS value is divided into real and imaginary part. Figure 3.15 represents a model of short electric line in vector form.

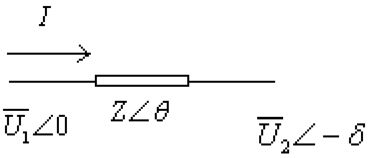


Figure 3.15. *Model of a short electrical line.*

$\overline{U}_1 = U_1\angle 0$ = Potential in transmitting end
$\overline{U}_2 = U_2\angle -\delta$ = Voltage vector in receiving end
$\bar{I}$ = Electric current in line
$\overline{Z} = Z\angle\theta$ =Impedance vector of the line (R+iX)

Current can be calculated with voltages and impedance.

$$\bar{I} = \frac{U_1\angle 0 - U_2\angle -\delta}{Z\angle\theta} \tag{2}$$

Apparent power in transmitting end S_1 can be calculated with potential $\overline{U}_1$ and complex conjugant of the current vector $\bar{I}^*$.

$$\overline{S}_1 = \overline{U_1}\cdot\bar{I}^* \tag{3}$$

$$\bar{I}^* = \frac{U_1}{Z}\angle\theta - \frac{U_2}{Z}\angle\delta + \theta \tag{4}$$

$$\overline{S}_1 = \frac{U_1^{\,2}}{Z}\angle\theta - \frac{U_2U_1}{Z}\angle\delta + \theta \tag{5}$$

Apparent power can separated to reactive Q_S and active power P_S components

$$P_S = \frac{U_1^{\,2}}{Z}\cos(\theta) - \frac{U_1U_2}{Z}\cos(\delta+\theta) \tag{6}$$

$$Q_S = \left(\frac{U_1^{\,2}}{Z}\sin(\theta) - \frac{U_1U_2}{Z}\sin(\delta+\theta)\right) \tag{7}$$

Power equation can be formulated with Z=R+iX

$$P_s = \frac{U_1}{R^2 + X^2}\left[R(U_1 - U_2\cos(\delta) + XU_2\sin(\delta)\right] \tag{8}$$

$$Q_s = \frac{U_1}{R^2 + X^2}\left[-R(U_2\sin(\delta) + X(U_1 - U_2\cos(\delta)\right] \tag{9}$$

If approximating that R=0 and δ small like in high voltage lines, power equations 8 and 9 can be expressed as equations 10 and 11 a. In other words $\sin(\delta) \sim \delta$ (radians), $\cos(\delta) \sim 1$, $\cos(\theta) = 0$ and $\sin(\theta) = 1$

$$P_s = \frac{U_1 U_2}{X}\delta \tag{10}$$

$$Q_s = \frac{U_1^{\ 2}}{X} - \frac{U_1 U_2}{X} \tag{11}$$

Active power and frequency are related and reactive power and voltage are related. Using these relations to control frequency and voltage is called conventional droop control. In low voltage grids situation is however a bit different.

As reactance is quite small in most LV lines, angle of the impedance θ can be approximated to be zero (Z=R). Also angle between voltages is usually small, so equations 8 and 9 can be approximated with simple versions of 12 and 13 in this case,

$$P_S = \frac{U_1^{\ 2}}{R} - \frac{U_1 U_2}{R} \tag{12}$$

$$Q_S = -\frac{U_1 U_2}{R}\sin(\delta),\ \sin(\delta) \approx \delta \ -> Q_S = -\frac{U_1 U_2}{R}\delta \tag{13}$$

It can be seen from the simpler versions of the equations, that active power and voltage are closely related in LV lines and reactive power and frequency are closely related.

3.6.2. Review of control methods for parallel operation of inverters

Centralised control

In centralised control, current reference to each inverter is done using load controller, which measures total load current and divides it into equal sized reference for every inverter. Figure 3.16 displays layout of a centralised control system.

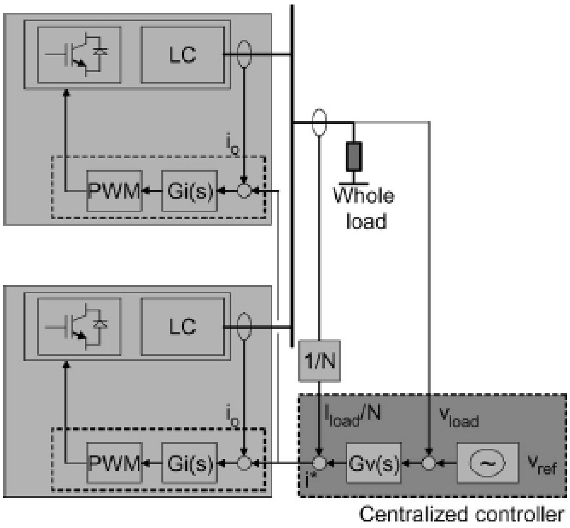


Figure 3.16. *Centralised controller control scheme[101].*

In outer control loop, there is a voltage controller. Current is usually controlled using two component representation of 3-phase values with DQ-components. Reason for this is that in a symmetric situation, inverter can be controlled with only 2 components. Transformation between coordinates can be found e.g. in [99]. As there is a need for total current measurement, system cannot be very large. Also there is a need for a central controller and communication is needed in this system between devices.[101]

Master and slave

In master and slave control systems master inverter acts in voltage source inverter VSI-mode giving reference voltage and others only as current sources (PQ-mode). Figure 3.17 represents master and slave control system.

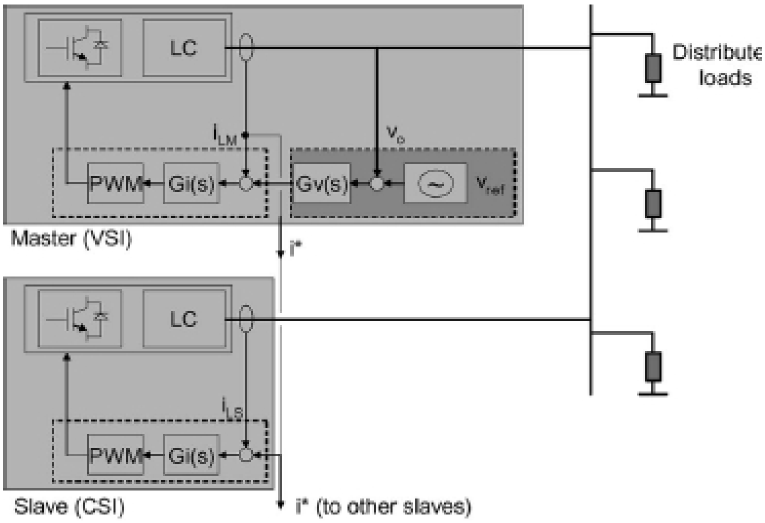


Figure 3.17. *Master and slave control scheme[101].*

Master inverter can be usually replaced by slave if master does not function properly. Master inverter should be the inverter with widest current band so that it can be more effective against larger deviations. Master inverter controls other adjustable slave sources to give wanted power.[101] Inverters can also be single 1-phase units as in sunny island product by SMA technologies AG in which a-phase gives angle and frequency reference to b and c. Also sunny island differs from the traditional master and slave as slaves also control voltage level [100].

Active load sharing

In active load sharing current of each inverter is measured and summed together. This sum current is then divided to inverters evenly. Figure 3.18 displays active load sharing method control of two inverters. [101]

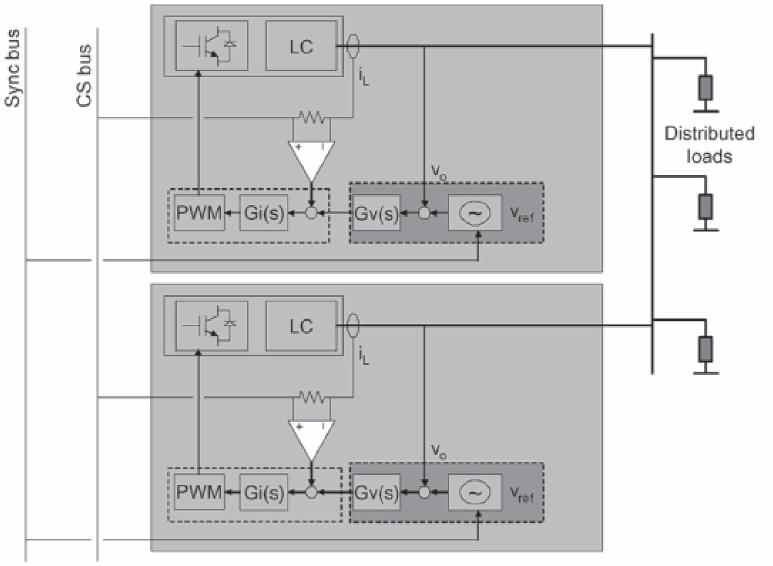


Figure 3.18. *Active load sharing using connected current measurements [101].*

Current sharing can be made using resistor system expressed in the figure. In this way average current is set to every controller as measurements are electrically connected. Same procedure can be also made using power measurements and then set power references instead of current references. It should be noted that if power is measured only in base frequency component, harmonics would not be shared in this way. This can lead to larger circulating harmonic currents in the system.

3C

This control method makes a control ring where each inverter takes reference from the last inverter in ring. This operation mode suits to ring operated grids. Figure 3.19 represents this system.

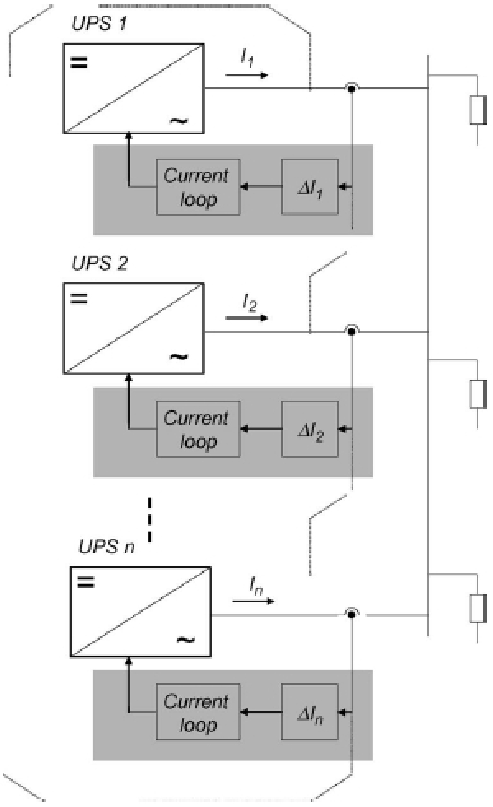


Figure 3.19. *3C type control ring of three inverters [101].*

Current reference that goes to current controller is difference between measured current of inverter that has controller and previous inverter in ring. This control system therefore minimises current difference between inverters and load is shared equally.[101]

Droop control

The most common way of control is conventional droop control, which means controlling grid frequency with active power and voltage level with reactive power. This control method is suited best for low R/X ratio power lines. Droop slope means the rate that power component is adjusted to control frequency or voltage level. Using different slopes of W/Hz and Var/V to each inverter makes sure that two inverter won’t start competing with each other and system to continue to oscillate after disruption. Also as mentioned in chapter 3.6.1, the connection between power components to frequency and voltage depends on the power lines. This connection of opposite component can be removed when current and voltage are divided into DQ-axis system. Imaginary part of current with coupling inductance makes real part component to voltage and this affects the system to be able to control frequency just with active power. In a similar way active component in system affects voltage. Decoupling of these components is therefore needed. Using coupling inductance and using it to act as filter in connection and to calculate decoupling of component in PQ-control, is called virtual impedance method in [101]. Also opposite droops can be used in systems with high R/X ratio. Figure 3.20 displays control droop slopes for both types of systems.

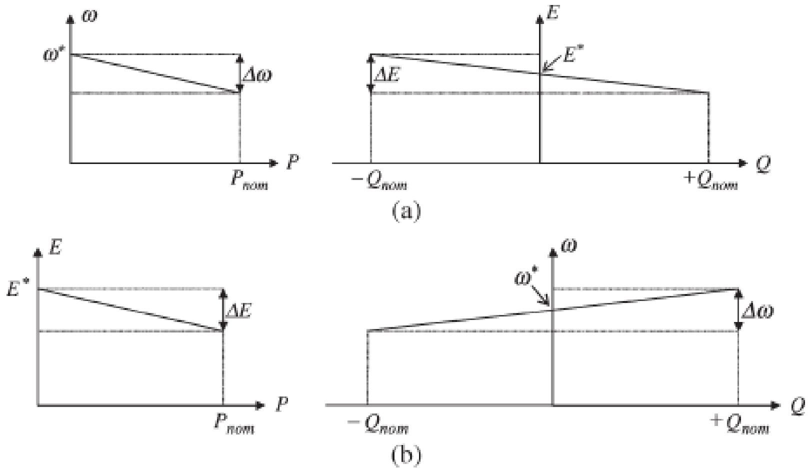


Figure 3.20. *Control droop slopes for inductive power systems (a) and for resistive power systems (b) [101].*

Droop control system does not need communication after every inverter has a proper slope setup. So if plug & play connectivity is wanted from droop-controlled inverters, a communication line is needed for them to know which inverters are connected and how slopes are divided.

Example micro source classification [74]:

- Grid forming units: Grid forming unit defines the voltage and frequency with fast response to load and production changes in the grid. This device is also called as master in master and slave control. As mentioned previously energy storages are good choice to master units.
- Grid supporting units: Grid supporting units have some possibilities for flexibility of the production. P and Q are determined by the voltage and frequency characteristics of the grid. Microturbines, fuel cells, hydro generators can be counted as grid supporting units.
- Grid parallel units: Grid parallel units have the least amount of flexibility and their production depends on external factors or it is just wanted that these units inject as much power as possible to the grid. PV-systems and wind turbines are examples of grid parallel units.

Master energy storage control should be made in a way that energy storage (ES) would only try to fix transient frequency deviations and not continue to supply power if frequency is constantly under the nominal. ES has limited capacity and socalled secondary control of the frequency should be done with production units. Secondary control can also be done with load shedding if needed. Power/voltage droop characteristics of inverters in multimaster systems should be adjusted so that reactive power won’t flow between VSI units. [73] Operational mode of the grid is of course not only technical issue but also management issue.

3.6.3. Disconnection detection and rules

One question for microgrid operation is that how and on what condition islanded mode operation is started; for microgrid to be disconnected from the rest of distribution network. How means mostly that how microgrid is driven down and restarted or can the system “jump” to islanded mode so that customers won’t even notice. When question means that how is problem in distribution system detected. Also if there is no communication possibilities to inverters, how inverters know that now system is separated from distribution system. Reason for this is that inverter control especially the master inverter differs greatly between modes in most concepts.

Loss of mains protection using ROCOF method

Rate of change of frequency protection relays are recommended by the network recommendation for interconnection of micro generators by Finnish energy industries to fulfil the disconnection rules in tables table 3.2 and table 3.3 [30]. For this reason microgrid generator should all have some type of loss of mains (LOM) protection and microgrid in theory would get disconnected as every generator should disconnect when distribution system is down. Active methods by sending pulses of current to grid and measuring it’s response have caused problems in some cases and do not fill the required disconnection times[102]. For this reason ROCOF method is the most widely used and recommended.

Loss of mains protection of microgrid concept using signal voltages

To be able to disconnect microgrid before LOM protection of different devices kicks in is needed so that microgrid could switch more flawlessly to islanded mode and still devices and system would fulfil the disconnection recommendation. One concept proposal for LOM protection of the microgrid and to control point of common coupling disconnector, is to use signal voltage on every phase of distribution system voltage. Signal voltages are high frequency voltage signals summed to main transmission signal which acts as a carrier wave. So if this signal is in each phase, meter voltage connected to frequency pass filter is at acceptable level and relay knows that there is power on every phase of distribution system.

Signal voltage method has been inspected previously e.g. in [103] with recommended signal frequency of 72 kHz and in [104] for frequency below 500 Hz. Later in [105] lower frequencies have been noticed to be better option as low frequency signal passes distribution transformer and “there is a lot of experience on the propagation of low frequency signals in traditional ripple control systems”.

3.6.4. Neutral point in an inverter dominated microgrid

Neutral point in normal LV system is drawn from distribution transformer, which has real neutral point of sum voltage of all line voltages. In islanded mode there is no obvious neutral point if circuit breaker is cut at LV side of distribution transformer. Neutral point problem can be solved by:

- Splitting DC-voltage of inverter in half with two capacitors and connecting neutral wire to the middle
- Using transformer at master inverter connection and utilize it’s neutral point
- Using 4-leg inverter with neutral point control to fix asymmetry (possible problem with grounding rules)
- Using 1-phase inverters to build 3-phase system and connect neutral wires together. Example of one inverter in this option presented in figure 3.21.[100]

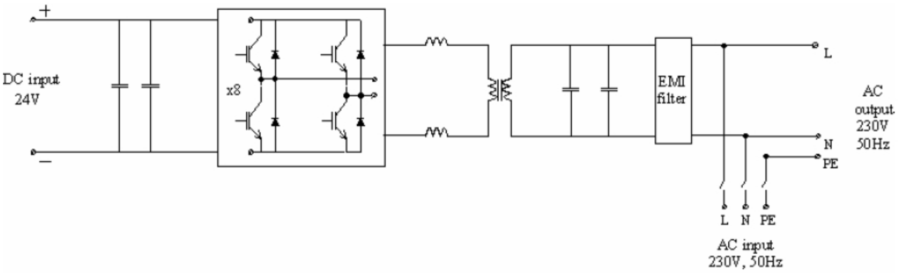


Figure 3.21. *Sunny island inverter model [100].*

3.6.5. Summary

There are plenty of options presented in literature for microgrid or UPS system balance control. Most concepts use droop control as base and vary slopes and controller setting depending between grid and islanded mode. Master and slave control system is combined in many cases together with droop control to categorise micro sources. Also symmetrical control between phases is used in some real VSI inverters as like with sunny island.[100] Some control systems need more communication and others need none after initial setup.

3.7. Grid supporting possibilities and blackstart of a microgrid

Traditionally LV-grids are the last ones to be energized after blackout. Functionality of microgrid allows it to support MV side in short periods (or longer if production of the MG is oversized) and this can be exploited for electric quality purposes. Figure 3.22 displays example of situation when fault exists in the grid and microgrid can support the MV grid.

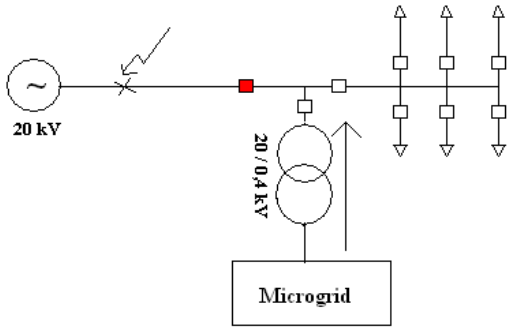


Figure 3.22. *MG supporting MV side.*

When blackout occurs microgrid should be able to go islanded mode. Islanded microgrid could be used to energize some part of the MV grid. Load shedding on the same time will reduce the stress on the generation units and especially the energy storage devices.

Sometime total blackout could also bring down the microgrid. Stages to build up the microgrid are [73]:

1. Selecting specific loads for each source so that they form own smaller islands inside the microgrid. These first generators are the grid forming type by the previous classification.
2. Main energy storage is used to energise the most of the LV grid and rest of the open breakers closed.
3. Synchronizing the small islands (subgrids) inside the microgrid to each other. Phase voltages should be at same level on amplitude, frequency and angle.
4. Connecting controllable loads to microgrid step by step to avoid large deviations.
5. Connecting uncontrollable loads and generators operating in PQ-mode.
6. Increasing load. Large motor loads must be connected at same time with large micro sources to avoid problems in voltage
7. Some of the VSI units can be switched to current source mode when system is stable.
8. Connection back to the MV grid can be done when the voltage there becomes available or by trying to start section MV grid with multiple microgrids.

It is clear that supporting features of microgrids increase the reliability of the distribution network and this will yield interruption savings for DSO. Legal and agreement matters will determine how the financial savings are divided between different parities.

3.8. Summary

Microgrid has many options in grid configuration, control of grid balance, protection and communication. All these are constrained by electric quality and safety regulations, standards and recommendations. Some options work well in some types of grids and some with others. The bottom line still is that there is no silver bullet to resolve all the problems in every case but regulation, standards and recommendations help in this process. And of course as the whole concept of microgrid is relatively new thus the there is still much to do in standardisation and recommendations.

4. POWER PRODUCTION AND STORAGE

Energy sources in this thesis are described with small-scale application in mind. Although in standard EN 50438 units only up to 11 kVA 3-phase and 3.7 kVA single phase are characterised as micro generators, it is clear that also larger units will be installed to microgrids. Renewable energy sources are most likely to propel microgrid installations so they get the main focus in this thesis.

4.1. Power generation

Power generation in microgrid concepts mostly consists of wind power, solar panels, fuel cells, microturbines and small hydropower plants. Common factor between all types is that usability and price of all them depend heavily on surrounding conditions. With wind power it is wind speed, with solar energy it is solar radiation and shading and with microturbines it is availability of gas.

4.1.1. Wind power

Wind power generator converts kinetic energy from wind to electricity. Wind speed probability is a critical parameter for wind power production estimation. Wind speed probability can be estimated by collecting measurement data and constructing curve, which represents probabilities of wind speeds during year. Wind speed in most locations can be approximated very well with Weibull curves. Example curve of Weibull distribution of wind speeds and energy at different wind speeds is displayed in figure 4.1.

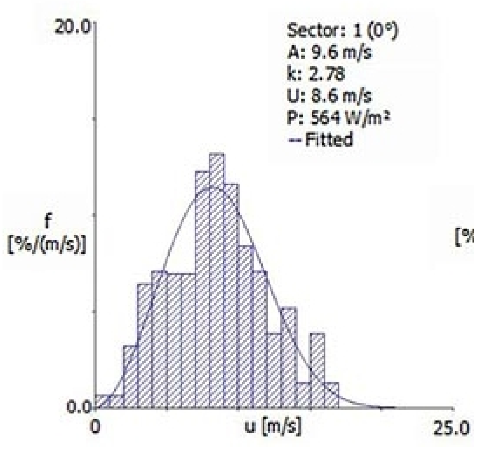


***Figure 4.1.** Example of wind distribution [39].*

Higher wind speeds have more power but if they are too rare there is not much sense to optimise blade for those speeds. Power delivered by turbine to generator axle has to be multiplied with power coefficient, C_P. Power coefficient for modern blades varies from 0.3 to 0.47 [40]

Power to rotor axle $P_a(v)$ is,

$$P_a(v) = \frac{1}{2} C_P \rho A v^3 \tag{14}$$

Finally approximation for yearly energy can be calculated with formula (5.1.1b).

$$E_g = \int_0^\infty \eta_e P_a W(v) dv \cdot 8760h \cdot C_f \tag{15}$$

η_e = combined electrical efficiency of generator and power electronics

P_a = power delivered to generator axle

$W(v)$ = wind speed probability distribution

C_f = reliability factor of system (between 0…1, fraction of time turbine is not broken in inspected time period)

$8760h$ = hours in a year

v = wind speed m/s

Note that reliability fraction C_f can also be used as variable if probabilities for that can be expressed e.g. as function of age. Time for that turbine would need to run on nominal power to produce the yearly energy production in Finland is typically around 2200h. From about 2000 W of nominal power, there are turbines suitable from connecting to the AC grid. These systems can have AC generators but are always equipped with frequency converter as electric quality standard is very hard to fulfil with connecting generator straight to grid. Larger wind power plants can have very wide range of control and connection options.[32]

There are four ways for connecting an AC wind generator to grid

- Induction generator with static speed
- Slip-ring generator with limited adjustability
- Double fed slip-ring generator with more adjustability (DFIG)
- Using frequency converter

Frequency converter is the best option for better grid stability as it allows more flexibility for control and includes also lots of protection functions without extra devices, which are needed in other solutions.

Controlling turbine speed is important that tip speed ratio is suitable and also for protecting the system in case of an extremely strong wind. With electric control, there is also mechanical control of the turbine.[40] Following protection systems are most commonly used in small wind turbines.

- Stall control: Turbine blades are forced to lose lift by regulating rotor speed. Blade angle is fixed.
- Active stall control by using flexible blades that change form in different wind speeds.
- Turning turbine away from the strong wind

As wind power production depends on wind speed, there is a large variation in output power. For this reason power cables have to be sized for the maximum output power, if energy storage or other suitable loads are not connected to the same bus with wind power plant.

If wind turbine selection and installation location is wanted to be made very carefully, a model of structures and landscape can help to identify the spots of high local wind. To help in this calculation and in selecting parameters for Weibull curve can be done with Wind Atlas, a map and database of wind speeds in Finland. By selecting similarly shaped landscape near the desired location from Wind Atlas, the suitable Weibull curve can be drawn. Lowest point Wind Atlas gives data is from 50m from ground level. Small-scale wind turbines are usually lower, so Weibull diagram has to be modified so that it fits the application. To approximate wind conditions sub 50m, we can use equation 16 calculate this [41].

$$v = v_{ref}\left(\frac{h}{h_{ref}}\right)^{\alpha} \tag{16}$$

v = wind speed at desired altitude [m/s]

v_{ref} = known wind speed at some altitude; reference [m/s]

h_{ref} = reference altitude [m]

h= desired altitude [m]

α = Hellman exponent

Hellman exponent depends on landscape condition, trees, buildings, water, and other factors that affect wind conditions. Following table can be used for reference values.

Table 4.1. *Hellman exponent in different conditions [41].*

Unstable air above open water surface:	0.06
Neutral air above open water surface:	0.1
Neutral air above flat open coast:	0.16
Unstable air above flat open coast:	0.11
Stable air above open water surface:	0.27
Unstable air above human inhabited areas:	0.27
Neutral air above human inhabited areas:	0.34
Stable air above flat open coast:	0.4
Stable air above human inhabited areas:	0.6

Figure 4.2 represents Weibull distribution scaled from 50m wind data to 20m by using equations in [41] to scale the A_w parameter.

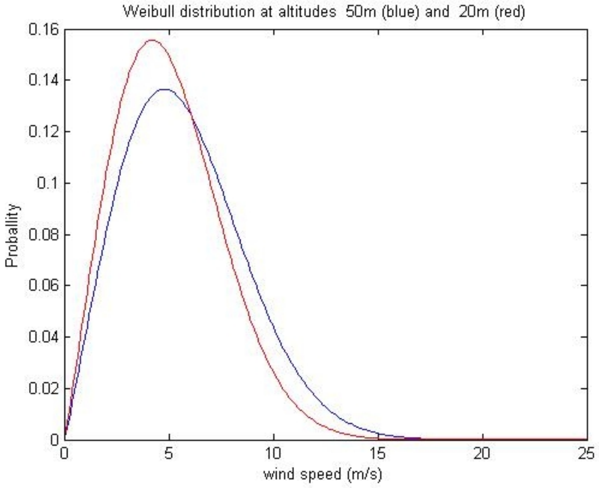


Figure 4.2. *Weibull distribution scaled from 50m to 20m.*

Parameters used for 50m Weibull data are:
A_w=6.51, k_w=2.107, Hellman exponent used for scaling: α =0.143;

As altitude is lower, lower wind speed become more probable. Also average wind speed is lower.

4.1.2. Solar power

Solar energy is basically the base primary energy that all other energy sources come from more or less. Producing electricity from sun radiation can be do with photo voltaic (PV) cells or by collecting energy from sun as heat and then producing electricity using the steam turbines. PV cells are currently more popular but heat based systems are gaining popularity in large-scale installations.

Photo voltaic phenomenon relates to energy levels in atom and how photons interact when hitting surface of PV-cell. Electrons have only some allowable energy levels. For material to be able to conduct electricity there has to be electrons in conduction band.

Electrons need energy to rise to conduction band and this energy can be from sun radiation or heat. For solar cell to be able to produce external electric current, semiconductor has to be mixed with other material to create positive and negative type conductors. PN-connection is connection between these different semiconductors.[42] Figure 4.3 portrays a solar panel structure and electron flows with external connector to a light bulb load.[42]

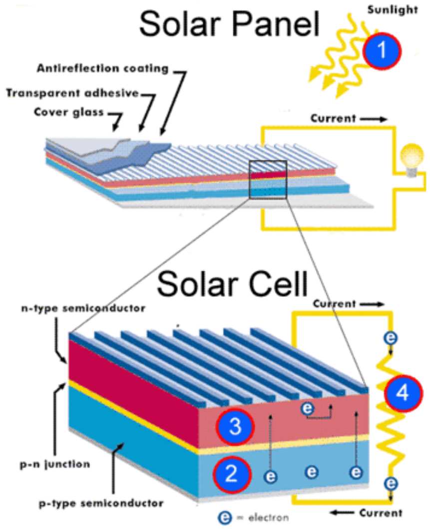


Figure 4.3. *Solar panel structure and electron flows [43].*

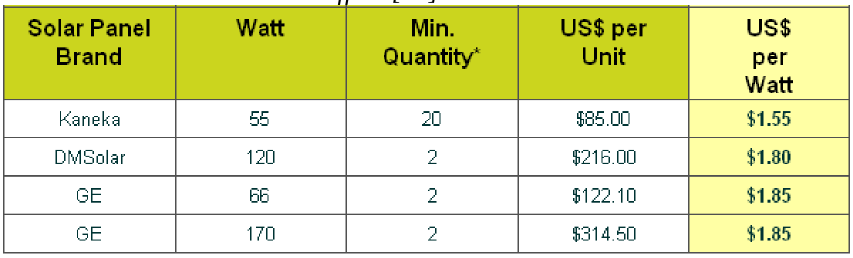
Materials on top of the cell are glass to protect the cell and anti reflection coating for reducing reflection related losses. Note that in Finland we define direction of electric current as opposite from real electron flow direction. (In the figure it is in the direction of real electron flow)

The maximum power point of the solar system depends on the conditions and challenge is to track this point for optimal inverter operation. As radiation intensity increases, current will increase but voltage increases only a little. Temperature rise results in power loss because open cell voltage lowers. It should be noted that standard conditions for panel performance differ from actual day to day operating conditions and actual performance is lower. Efficiencies of polycrystalline cells are typically around 11-15% and with monocrystalline cell efficiencies are about five percentage units higher. Efficiencies do not matter much in residential applications as performance per money spent is much more important factor.

Other types of cells

Other types of cells include different thin film cells like amorphous silicon cells and dye-sensitized solar cells (DSSC). Efficiencies of these types of cells are lower than traditional silicon cells but price per peak power can be lower. Amorphous silicon cells have commercialised fairly well but the availability of them is poor in Finnish markets. DSSCs in their current form are fairly new type and availability is very low all around world. Problem with low efficiency panels is that their use in some cases limited by amount of needed area for specific power level. Table 4.2 lists some discount prices for solar panels.

Table 4.2. *Solar cell discount offers [44].*



Solar Panel Brand	Watt	Min. Quantity*	US$ per Unit	US$ per Watt
Kaneka	55	20	$85.00	**$1.55**
DMSolar	120	2	$216.00	**$1.80**
GE	66	2	$122.10	**$1.85**
GE	170	2	$314.50	**$1.85**

Usually these cheaper panels are lower efficiency panels thus space requirement should be verified.

Optimal panel direction

Photovoltaic Geographical Information System PVGIS can be used for optimal direction for solar panels in different location around the globe.[45] E.g. for Uusimaa region of Finland, the optimum inclination angle for panels is 41°. Horizontal direction of panels should be close to south. It should be noted that these optimal angles are meant for full year production. If system is installed on summer cottage, which is visited only in the summer months, panel production should be optimised for those months. Figure 4.4 displays how these angles are measured on an installed panel.

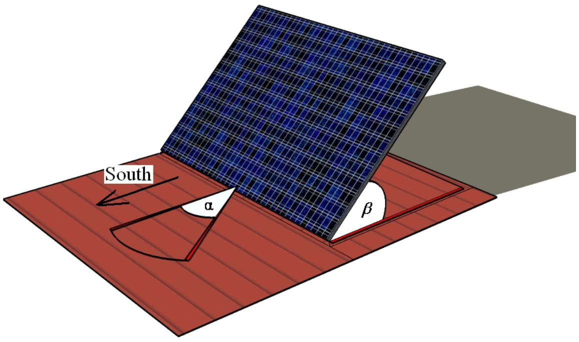


Figure 4.4. *Solar panel installation angles.*

β in the figure is the inclination angle and α is directional angle. Production estimation for 220 W solar panel in Helsinki for yearly usage is 193 kWh (losses subtracted). Monthly production of panel is presented in figure 4.5.

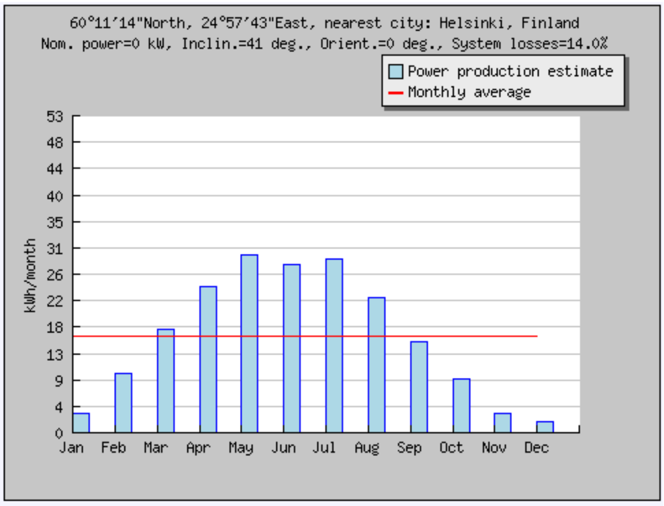
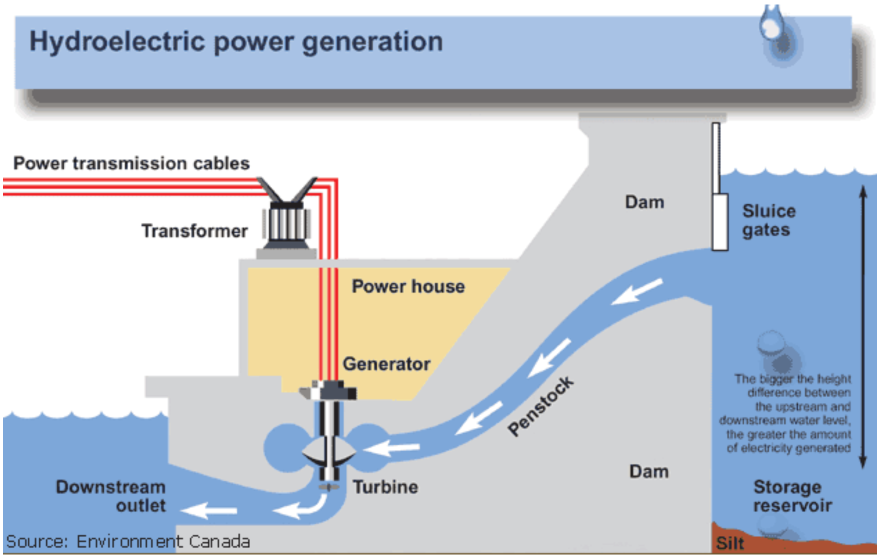


Figure 4.5. *220 W solar panel production estimation with 14% power losses due to cabling and power electronics.*

If panel had optimum angle tracking, power output would increase 42% according to calculations done by PVGIS system. In this case panel would follow sun position by adjusting α and β angles with servomotors. Sun tracking it self can be made with calendar timing or with light direction measurement sensors.

4.1.3. Hydro power

Vertical waterfall energy in dams can be converted to electricity by directing waterfall through a water turbine driving a generator. Water energy from river currents and waves can also be utilised for electricity production. Figure 4.6 represents basic layout of a hydroelectric plant. When gates are open, water starts to flow from upper reservoir to lower one and rotating turbine converts flow energy to rotating energy of the generator, which produces electricity.



Source: Environment Canada

Figure 4.6. *Layout of hydroelectric power generation [46].*

Total efficiencies of over 90% can be achieved in some cases. Small-scale hydro power plants usually use asynchronous generator, which have lower efficiency but are cheaper than synchronous generators (same as with small-scale wind power). Asynchronous generators always need reactive power, which should be produced as close as possible with compensation devices.[47]

Possibilities for hydroelectric power are limited due to the basic reason that elevation changes are quite minimal in Finland. Also legislation for environmental matters is tough for most cases of new plants, as dams have large impact for fish living conditions. Easiest way is to rebuild old mills, which already have permits for electricity production. Mean values of Mini-hydropower potential predictions for Finland are presented in table 4.3 .[48]

Table 4.3. *Increase in mini-hydropower potentials, largest evaluations of different studies [48].*

Hydropower potential Mini-hydro, less 1MW	Non-protected	Environmentally protected	Together
POWER (MW)	144	148	292
ENERGY (GWh/a)	1021	916	1937

Wave energy can be also harnessed to produce electricity. Development for wave power plants is currently very active and multiple concepts have been proposed.

4.1.4. Micro turbines and diesel generators

Micro turbines are small gas turbines that operate with the same basic principle as jet engines in planes, with the difference that they do not generate trust but only rotating force. Basic system layout is presented in figure 4.7.

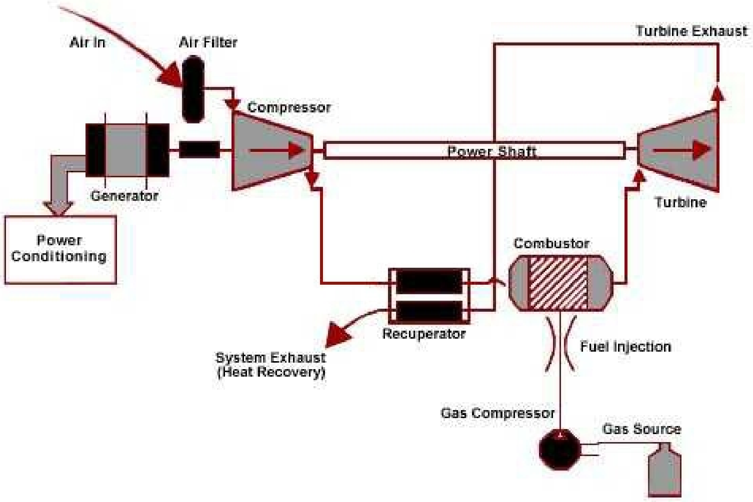


Figure 4.7. *Layout of micro turbine system [49].*

Micro turbine produces also heat with electricity therefore combined heat and power (CHP) systems are possible and are recommendable to be implemented if heating is needed. Air is first compressed, then preheated and injected with fuel to combustion chamber. Rapidly expanding exhaust gases drive the turbine blades and rotate the axel. Rotating axle turns the generator and also drives the air compressor. Electrical efficiencies of micro turbines are around 20 to 30%, but with CHP system combined heat and electric efficiency can be over 80%. Natural gas and bio fuels can be used in most of the micro turbines. A gas turbine has good pickup for backup power purposes as systems can go to full output from start in 10 s. [49] [50]

Diesel generators are the most common backup generator type currently in use. Diesel generators have similar electrical efficiency as micro turbines. Diesel generator systems are cheaper than gas turbine system in entry levels but commonly CHP operation is not considered as they are optimised for electricity production in short periods. Using bio fuels is possible with some generators, but many manufacturers have had problems with bio fuels and warranties can be voided if bio fuels are used.[51]

4.1.5. Fuel cells

Hydrogen is of the cleanest fuels. Fuel cell operating with pure hydrogen and oxygen produces only water and heat as reaction product. Hydrogen can be manufactured with electrolysis with minimal emissions from water (if electricity is produced in an environmentally friendly way). So basically fuel source for hydrogen based fuel cells is unlimited. Energy density of hydrogen related to weight in burn process, is about 3 times larger than with gasoline. [52]. Because of all this hydrogen is very lucrative alternative for climate change control. However emissions of fuel cell depend on type of cell and fuel used. Total reaction of molten carbonate fuel cell is expressed in formula 17 [53].

$$H_2 + \frac{1}{2}O_2(cathode) -> H_2O + CO_2(anode) \tag{17}$$

Fuel cell systems are based on converting chemical energy from hydrogen or other fuels to electricity and heat. Basic components of fuel cell are anode, cathode and electrolyte. When anode is fed with hydrogen and cathode with oxygen, electrochemical reactions start in anode and cathode. Ions start to flow trough the electrolyte and external current flows through the load. The reaction products are water, electricity and heat. Some low temperature fuel cells need also a catalyst to speed up the reactions. One principle difference between batteries and fuel cells is that power and energy do not depend on the same component. Power is determined by the fuel cell and energy by the fuel storage capacity.

Fuel cell types can be divided into groups by the electrolyte they use: Polymer electrolyte membrane fuel cell PEMFC, Alkaline fuel cells AFC, phosphor acid fuel cells PAFC, molten carbonate fuel cells MCFC and solid oxide fuel cells SOFC. Regenerating fuel cells are called commonly by acronym RFC, which are fuel cell that can be recharged with electricity. [53]

Disadvantages of fuel cells are, high price starting prices around 4000$/kW, low lifespan, operation in difficult conditions like in winter (catalyst freezing etc). Table 4.4 gives typical operational parameters of different fuel cells [56]. Fuel cells should be run at fairly steady power output level and not take too much part to handle current spikes for longer life time of the expensive cells.

Table 4.4. *Typical fuel cell operating parameters.*

	PAFC	MCFC	SOFC	AFC	PEMFC
Operating temperature in °C	175 - 200	600 - 1000	600 - 1000	65-220	60-100
Catalyst	platinum	nickel (not mandatory)	nickel (not mandatory)	platinum	platinum
Power	Up to 200 kW	Up to 2 MW	300- 220 kW	300 W - 5 kW	100 W - 10 MW
Electric efficiency	40 - 50%	50 - 60%	45 - 55%	~50%	40-50%

When a high temperature fuel cell is connected with a steam process, electrical efficiency of the system increases. Figure 4.8 displays the maximum efficiencies of combined system and comparison to standalone unit.[53]

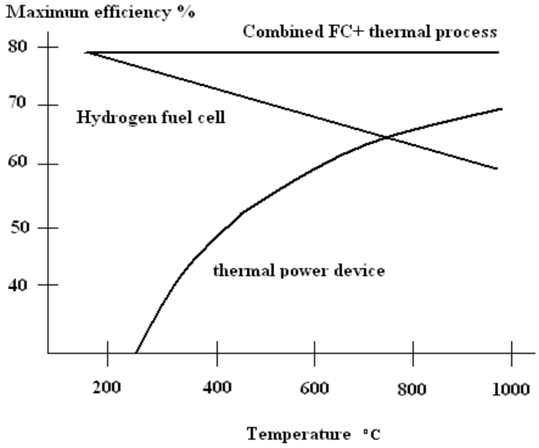


Figure 4.8. *Maximum efficiencies of combined and standalone systems [53].*

4.2. Energy storages

Energy storages store energy to other form for later use. Energy storages in microgrid can be used to serve as power quality devices to respond to quick deviations in voltage level and frequency or as reserve power capacity when own production can not supply all the electricity that loads in microgrid need. Basically some energy storages are good for supplying high power at quick time cycles (power quality purposes) and other are more suited for supplying energy at lower power levels but for longer cycles. Optimum system has usually couple types of energy storages so that requirements for high power and long lasting energy supply can be achieved at a reasonable price.

4.2.1. Electro-chemical energy storages

Electrical energy storages include batteries, supercapacitors, and superconducting magnetic energy storages. A comparison of properties of different energy storages is presented in table 4.5.

Batteries

Batteries are rechargeable electrochemical energy storages, called also secondary cells. Primary cells are non-rechargeable batteries and therefore not classified as energy storages. Functionality of batteries is based on reversible reduction-oxidation reaction.
Usually batteries are named by the materials they use.

Lead-acid battery is the most commonly used battery type due to its applications in motor vehicles. Lead-acid batteries are heavy but reasonably priced with respect to energy. Lead-acid batteries have a quite high self-discharging rate, cold temperatures are problematic for most lead-acid batteries and voltage drops while discharging the battery. Short life-span in recharge-discharge cycles also reduces possibilities for long term high energy usage. Lead-acid batteries are however very popular in UPS-systems and backup secondary power reserve usages are suitable applications also in microgrids. Most lead batteries are sealed so that there is no need to add electrolyte. Typical electrolyte is sulphuric acid. Electrolyte in these batteries is in a gel-form or absorbed into fibres. For ease of use, these closed lead batteries are the better choice especially if batteries are placed on hard to get places. Efficiency of lead-acid battery is around 75-85%.[56] [54] [55]

Nickel-cadmium battery is one of the first battery types to be used commonly in portable applications due its better performance compared to lead acid batteries of the time. Its life span, voltage stability and self-discharging rates are better than with traditional lead-acid batteries. NiCd-battery has a memory affect, which means battery capacity will decrease over time and especially if kept long time charged without fully discharging it time to time. Use of poisonous cadmium in these cells was stopped and replacement was metal hydrides.[55]

Nickel metal hydride cells (NiMh) are the latest version of commonly used batteries mostly in portable devices developed to replace NiCd cells. NiMh-cell advantages are a good number of recharge-discharge cycles, fast recharging and it does not contain any poisonous materials. Disadvantages are lower voltage, memory effect and low current density.[57]

Lithium has a high electrical normal potential and low weight which makes in good choice for batteries. Advantages are lack of memory effect, high cell voltage, low self-discharge and very high efficiency. Disadvantages are need for protection against overcharging and low and high voltages, resistance against moisture and possibility for explosion if protection equipment fails. The most advance lithium based cell is lithium polymer cell (Li-Po), which has liquid electrolyte replaced by polymers. Although these cells have a higher internal resistance compared to Lithium-ion batteries and therefore lower current density, high number of recharge-discharge cycles makes them better choice for most applications. Also much better safety and very high power density are among the advantages. High price with respect to energy is still main dragging factor for use of these cells in large systems. Li-Po is currently the main choice for electric cars and likely price will come down just like with lead-acid batteries when car manufacturers start using them. [58][59][57]

Natrium sulphur (NaS) batteries are high temperature batteries compared to most other types. NaS-batteries have good efficiency, long life span, reasonable price in respect to capacity and good number of recharge-discharge cycles. Disadvantages are declining efficiency if used to supply pulse currents. NaS batteries are used e.g. in Japan in peak saving where system power is megawatts and energy capacities of tens of megawatt hours.[60]

Flow batteries are different from most of the other type of batteries. Flow batteries have two circulating liquid electrolytes, both in separate containers. Operation of flow batteries is similar to fuel cells as power of cell depends on the cell and energy capacity depends on the size of electrolyte containers. Commonly these types of batteries are called redox batteries. Vanadium redox battery is the most common type of flow battery. Advantages of vanadium redox batteries are long lifespan (due to changeable electrolytes), good efficiency (~90%) and quick power response. Also battery can be recharged by electricity or by replacing the electrolytes. Disadvantages are complex structure (pumps, containers, sensors, etc) and high price in small-scale systems due to auxiliary equipment. Common applications are backup power reserve and peak saving. Other commercialized flow batteries are polysulfide-bromide and zinc-bromide batteries. Performance is similar to vanadium batteries but efficiency is a bit lower.[61][56]

Capacitors

Capacitors store electricity in an electric field between two plates. Electric charge condenses on electric plate when DC voltage is applied between the plates. One plate gets charge of Q and other –Q. Capacitor is discharged when electric contact is connected between the plates of the charged capacitor. Equation 18 represents how capacitance of capacitor can be calculated.

$$C = \frac{\varepsilon}{4\pi\delta}\int dA \tag{18}$$

A = area of plates (not combined)

δ = distance between electrode and ion

ε = dielectric constant of electrode material

The most suitable capacitor type for energy storage systems is a supercapacitor, which uses two-layer structure with electrolyte and carbon particles. Carbon particles are there to create large surface for high capacitance (see previous equation 18) and electrolyte to make these particles conduct electricity. There is insulator in the middle to prevent electrolytes connecting. Capacitances can be over 10000 times higher than with similar sized normal capacitors. Supercapacitor advantages include up to 10^6 charge-discharge cycles, good power to weight ratio, cheap price with respect to number of cycles, high power density and low internal resistance, which leads to high currents. Disadvantages are that voltage is dependant on the state of the charge, which means that a switch mode converter is needed to be used for stable voltage. Also energy capacity is low but structure can be optimised more towards peak power or energy density but supercapacitors are never good choice for high energy applications.[62] [56]

Supercapacitors are suitable for supplying high power for a short time. Supercapacitor could therefore be used in power quality application in microgrids. Also supercapacitors can be used to take away current spikes drawn from other power sources and in this way to enhance the durability of the system. E.g. fuel cells and batteries are examples of sources that can benefit from supercapacitor usage.[62] [56]

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) stores electricity into a magnetic field of a current flowing in lossless coil. Superconducting material experiences two effects when temperature of the material drops below critical temperature. Internal resistance of the material disappears and external magnetic field cannot penetrate the material.

Superconducting material has three critical quantities that define whether conductor is in superconductive state. Temperature, magnetic field, and current have to be below critical values for superconductivity. These quantities are functions of each other, meaning that if one is raised, others are needed to be lowered. Superconductors can be characterised as low (LTS) and high temperature superconductors (HTS). [63]

In case of disturbance in some of the three critical quantities, coil can drift into normal conduction mode, quench. In this case energy is wanted to be converted into heat outside the superconductor so that expensive coil is unharmed. Multiple protective measures can be taken to assure safe quench. [63]

Power electronics are needed for control and regulation of SMES and also protective and cooling equipment is needed. Advantages of SMES systems are high efficiency (90–95%), fast response (30–50ms), long lifespan and lack of hazardous materials. Disadvantages are high price, and need for cooling and auxiliary equipment. Also the magnetic field created by the storage makes some limitations on the location of the device.[56][63]

4.2.2. Mechanical energy storages

Flywheels

Flywheels are one popular type of kinetic energy storage. Flywheel is a rotating mass the momentum of which can be used to power a generator. Efficiency of flywheels depends mostly on the bearing systems they use. The most efficient bearing systems are based on using magnets and especially superconducting magnets are estimated to increase in the future devices. As rotating speed of flywheel drops while storage is discharged, at least a frequency converter is needed for the grid connection.[65] Advantages of flywheels are fairly fast response, low maintenance costs, number of charge-discharge cycles (100k), life span (20a) and wide operating temperature range. The major possible problem of flywheels is failure of bearing system. If the bearing fails, all the energy is also released as mechanical energy to structures. Self-discharging is also a disadvantage so flywheel are not suited for long time storage. Flywheels suit best to electric quality applications in microgrids.[64] [56]

Other types of mechanical energy storages

The most common potential energy storage is pumped hydropower. Pumped hydropower system can pump water to a higher altitude to a reservoir and water is released down through a turbine when energy is wanted to be released. Usually these systems are very large (thousands of MVAs) and their implementation possibilities to an urban area microgrid are very minimal. Underground caves and old mines are potential places to implement this type of storage in Finland as natural altitude differences are small.

Compressed air energy storage (CAES) is another large energy storage system that can not be easily implemented to small systems. System has a compressor, a turbine and a pressurised air storage. Higher pressure increases system efficiency. Total efficiency is dependant on compressor, turbine and air storage efficiency. Newer systems are planned especially to connect to off-shore wind parks where ocean could provide an inexpensive way for compressed air storage [66]

4.2.3. Comparison of energy storages

List of some energy storage devices is displayed in table 4.5. The table is constructed mainly on basis of International Energy Agency’s report IEA-PVPS T3-18:2004. Deviations from this are marked on the table with citation marks.

Table 4.5. Comparison of energy storage devices.

	Price(€/KWh)	Storage losses	Cycle efficiency (%)	Typical Capacity	Energy density (Wh/kg)	Typical power	Power density (W/Kg)	Charge-discharge cycles, life span
Flywheels	700 - 1000	72% / month	90 – 96	< 25 kWh [43]	5 - 100	1 – 100 kW	1600	100 k, 20 a
Pumped hydropower	~700 [68]	none	50 - 85	x*1000 MWh [65],[67]	irrelevant	x100 MW	irrelevant	75 a
CAES	300 - 800	25% / month	40 - 73	Usually x*100 MWh	irrelevant	1 – 1000 MW	irrelevant	20k - 100k, 20v
Lead-acid battery	50 - 150	1 – 4% / month	81 - 94	5 - 6000 Ah	35 - 40	0 – 10 MW	400	100-1500, 3 – 15 a
Lithium based batteries	300 - 1500	0 – 6% / month	93 - >	x*mAh - 100 Ah	30 - 200	x*100 kW	6 - 2000	200 - 3000, 6 – 20 a
Nickel batteries	220 - 3200	5 – 40% / month	60 - 83	<350 Ah	10 - 60	1-100 kW	40 - 1300	500-3000
NaS batteries	500 - 2500	none	75 - 86	Largest system. 48 MWh . [58] [56]	53 - 116	x*1 MW	9 - 15	>2500,-
Redox-batteries	100 - 200	<10% / day	60 - 75	Depends on container	10 - 70	10 – 1000 kW	10 - 25	>2000, 5 -15 a
Super capacitors	50000 - 150000	50% / month	85 ->	x*10Wh	0,1 - 5	X*MW (optimised for power)	100 - 10k	~500 k, 10 a
Fuel cell systems	4000 - 14500	Depends on fuel container	30 - 60	Depends on container	Up to 800[69]	x*100 kW	165 [72]	1kh – 50 kh
SMES	800 - 1800	none	>95% [70]	Typically 20 kWh [71]	4 - 75	1kW – 5000 MW	10 k – 100 k	100 k, 20 a

4.3. Demand side management

Basic parts of power infrastructure are demand and supply side. Demand side (loads) has a need for electricity which supply side (generation) provides. Demand side is a very important part of energy network and managing it wisely can avoid problems and create savings in money, energy and emissions. Traditionally demand side has been seen as a passive uncontrollable entity, but Smart Grid infrastructure adds much more flexibility to it. This chapter describes important load types in Finnish LV networks for MG design, loads that can give harmonic distortion to MG and control and management options that support smart use of resources in microgrid.

4.3.1. Important load types in Finnish urban areas

This chapter describes the load types that have to be taken into account for in microgrid design in Finland. The load types are:

- Asynchronous motor loads including heat pumps
- High harmonic loads
- Electric car loading

Some loads give more trouble than others but as microgrid is much weaker environment for disturbances, every possibly problematic load has to be taken into account. Nowadays people also have more high power tools, like drills, and wood cutting machines that give stress to electric quality. Figure 4.9 describes the power quality complaints in one DSO's grid in years 2003-2005[75].

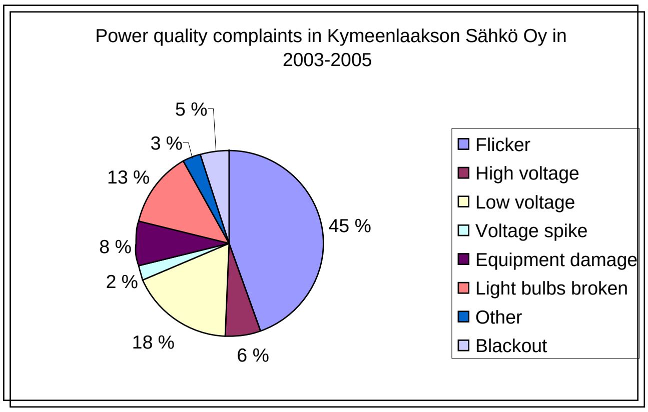


Figure 4.9. *Power quality complaints in Kymeenlaakso Sähkö Oy in 2003 – 2005 [75].*

Heat pumps and other pump systems

Heat pump systems have increased rapidly in Finland during last eight years. Figure 4.10 illustrates this fast growth of installed heat pumps.[76]

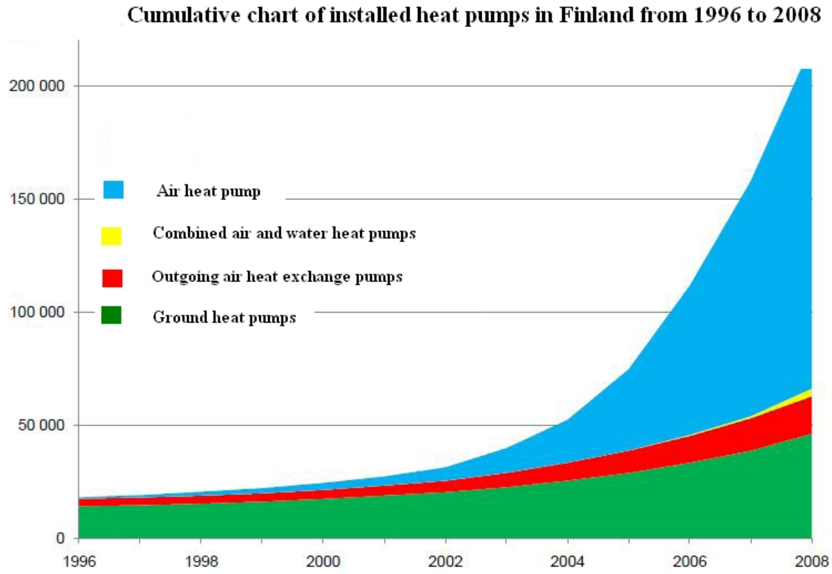


Figure 4.10. *Heat pump growth in Finland [76].*

Heat pumps often have an asynchronous motor to drive the compressor and fans and start-up current can create problems even in normal distribution network if number of pumps is large.

Heat pumps save energy by taking energy from air, water or ground. Figure 4.11 displays the basic layout of heat pump system. One popular operating fluid is R410-A, which contains difluoromethane and pentafluoroethane. R410-A was invented by Honeywell in 1991 to create a gas that does not contribute to ozone layer depletion.[77]

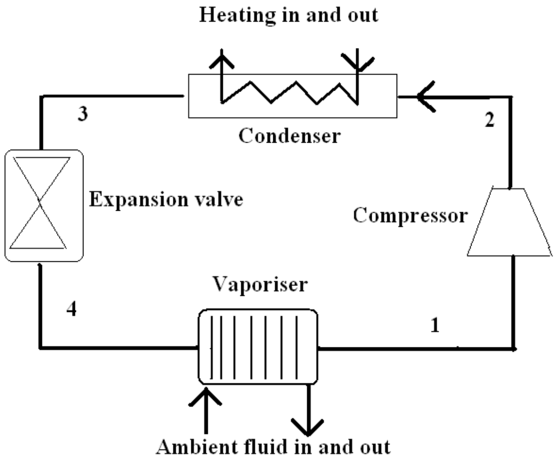


Figure 4.11. *Heat pump system layout.*

Some pumps have random latency in starting to reduce possible flicker in areas with multiple pumps starting at the same time. Manufactures do not publicly share the technological facts about starting systems other than maximum start up current. Microgrid operator should have some control over heat pumps if they do not have some kind of awareness of grid conditions or significantly lower start up currents than with normal asynchronous motors.

Asynchronous motor types and their characteristics

Asynchronous motors can be single or three-phase units. Single phase units can be categorised with auxiliary winding and capacitors they use. High start-up current is the main problem for grid that asynchronous motors have. Different motor types have different current characteristics but another key thing is how the motor is connected to grid and how the motor is driven. [78][79]

Main functional difference between three and single phase units is that single phase units do not have initial start-up torque. For this reason single phase asynchronous motors have to have auxiliary winding and usually capacitor connected in series to auxiliary winding. The auxiliary winding can be permanently connected or just used in start-up. Dual capacitor motor has one permanent and start up capacitor. Figure 4.12 displays the different characteristics of asynchronous motors.[79]

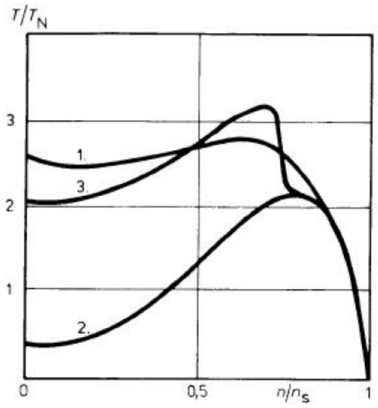


Figure 4.12. *Asynchronous motor torque characteristics. 1) 3-phase motor, 2)Permanent split capacitor motor 3)Dual capacitor motor [79].*

Current and torque have a strong relation and higher start-up torque means also high start-up current. Following connection types can be applied to motor to reduce start-up current:

- Use of frequency converter to control voltage amplitude and frequency
- Use of slip ring motor and start-up resistance
- Controlling rotor currents with power electronic switches
- Using star-delta connection at start.

How the device uses motor is also a key thing. E.g. constant on- off use of an asynchronous motor can cause problems. If motor is constantly running and mechanical load is connected with a clutch when needed, there is a significant reduction in the current spike.[78]

Electric vehicles

Electric vehicles and plug-in hybrids are gaining popularity and more and more manufacturers are starting production of electric vehicles (EV). Electric vehicles and plug-in hybrids have a battery system that can be charged from the grid and usually partly by collecting the energy while breaking. Current cars that are called hybrids have an internal combustion engine and electric motor(s). Usually these cars do not have a possibility to charge the battery externally but direction is clear for the future of plug-in hybrids and full electric vehicles.

Management of electric vehicle loading is important as load created from vehicles when everybody is returning from work or similar situations can create problems for the grid. Smart management of EV loads in microgrids is more important for the grid balance and resource allocation due to the way microgrid has to be managed. Communication in EV loading management is displayed in figure 4.13.

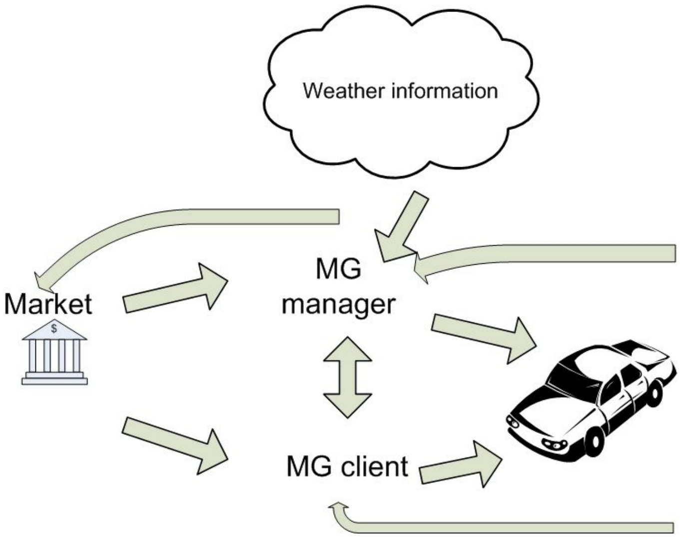


Figure 4.13. *Communication between parties in EV management.*

Microgrid client usually requires vehicle to be charged in certain times. This information has to be sent to MG manager to control the loading of multiple vehicles so that they all are charged and load to the grid is not too large especially in islanded mode operation. MG client and operator can use market and weather information to judge the best actions. The status of battery charge is also good information when allocation energy sources to feed it.

Quick charging

Current battery technology of lithium based cells allows very fast charging. This fast charging is not possible in any LV grid without designated energy storage device. The basic idea is to build up the energy slowly and grid friendly way and then dump the energy to vehicle when quick charge is needed. Quick charging also requires very high power output from the storage device and wide cables to avoid power losses.

Other high current loads

At present time people have also other type high current machines than motors. One example is MIG/MAG welding equipment that draws high currents to melt the welding metal. It is reasonable for MG operator to ban use of this kind of extremely high current device at least while operating in islanded mode. Of course dedicated energy storage could be used to compensate the current spike just like with electric car rapid charge systems.

4.3.2. Harmonic sources

Some mostly converter based devices emit harmonic components to electric lines which reduce the power quality. Limits for harmonics are presented in appendix 1. Even though all the devices are within standards, sum of the converters in microgrid can create resonances, which make electric quality deviations larger. When there is a connection to MV side, microgrid will handle harmonics much better as the grid has now much more passive stability and resonances go away better. It should be noted that every grid is different in handling of harmonics so there is no common laws how the devices will work in different microgrids.

Hannu Laaksonen and Kimmo Kauhaniemi from University of Vaasa have run simulations on how different harmonic sources affect the total harmonic distortion (THD) of the microgrid.

The article recommends following decisions based on the simulations [80]:

- Use LCL filters instead of L-type to avoid resonances
- Use adaptive switching frequency (SF) on converters
  -Change SF if resonances start to occur
- Thyristor based load should be limited to maximum of 15-20% of the total load in MG
- Space vector modulation should be used instead of PWM in microgrid due to lower THD.
- Use of negative sequence filtering to reduce THD in unbalanced load (between phases) and in unsymmetrical faults

Real systems test are still needed to verify how different device work in microgrids. One very common high THD device is a compact fluorescence lamp (CFL). Technology inside lamps is diverse and testing is needed to find out how CFLs influence the microgrid. Also poorly designed PC power sources are other possible problematic load type for microgrid.

4.3.3. Demand response

Demand response means that demand side power consumption is adjusted or adjusts to different load levels on the grid. Basically when load and electricity price are high, some controllable loads can be taken offline or their power consumption adjusted lower. This yields savings to client in energy bill and to MG manager as there is more flexibility in the grid for balance management. Demand response can be divided into market based and grid load based adjustment although they have positive correlation between them. Demand side control capacity from direct heating systems in Finnish households is estimated to be 1-2 kW and 600-1200 MW in total [81].

Grid load based demand response

Load based adjustment means that the control input for load is a technical factor related to grid load level. A usual way is to add frequency relation to load so that it reduces power consumption when frequency declines and increases power when frequency increases. This can be done with dynamic demand control in witch load controller measures frequency or voltage and acts alone to connect of disconnected load [82]. E.g. droop control methods mentioned in chapter 3.6.2 can be used also for active load management.

Market based demand response

In market based adjustment method, control input is usually electricity price. Client or microgrid operator can set price properties that have to be fulfilled for load to connect and disconnect from the grid. These price inputs can be:

- Setting disconnect and connect price levels using spot price
- Rate of price movement (if internal retail market has real time electricity price)
- Using Nord Pool futures, call-put ratios or other advanced market analysis
- Other market price than electricity (emission price, fuel price, etc)

Setting good triggering levels is the task that has to be done to make market based demand response to be profitable or to achieve the other desired result. Loads can be fed from MV side, from own generation or from energy storages in microgrid. Demand response system can provide answers how controllable loads are operated and which units are used to supply them.

4.3.4. Smart start-up synchronisation system concept

Equipment start-up procedure can create problems and even with good voltage and frequency control there are some deviations to electric quality. Microgrid communication possibilities can help in this using load – generation synchronisation; starting or increasing generation at the exactly same time as load is connected. Of course there are always some frequency deviations but this could ease up the step a bit. An example process layout is presented in figure 4.14.

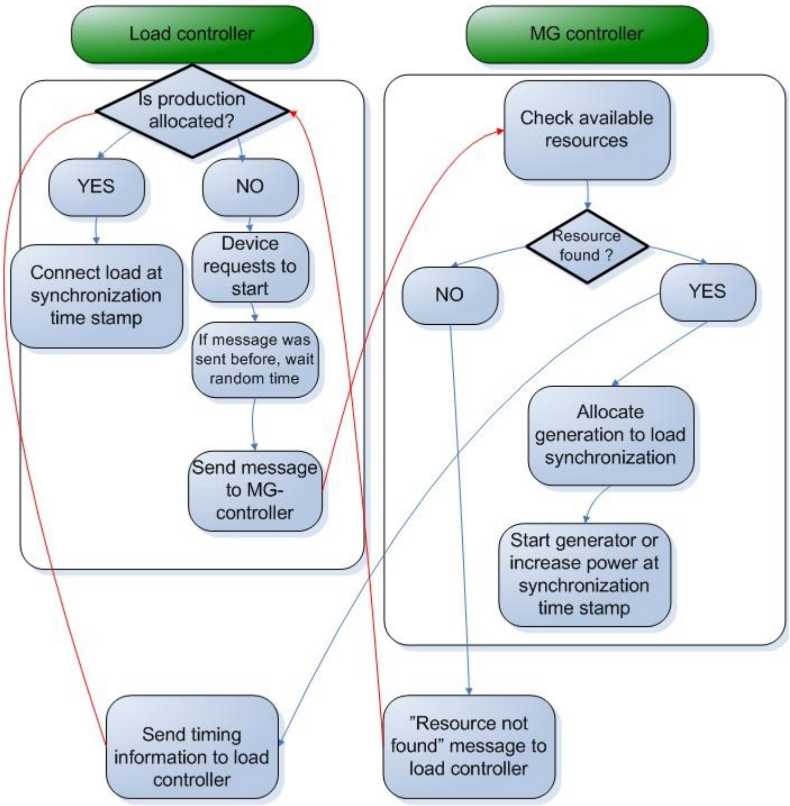


Figure 4.14. *Example load – generation synchronisation process.*

This system can be used to decrease possible problems of multiple heat pumps connecting at the same time to microgrid, and current variations on energy supplying units can be maintained more stable. Figure 4.15 illustrates the principle shape of currents drawn by three asynchronous motor driven heat pumps and energy supply unit feeding all pumps, when smart load – generation synchronisation is used.

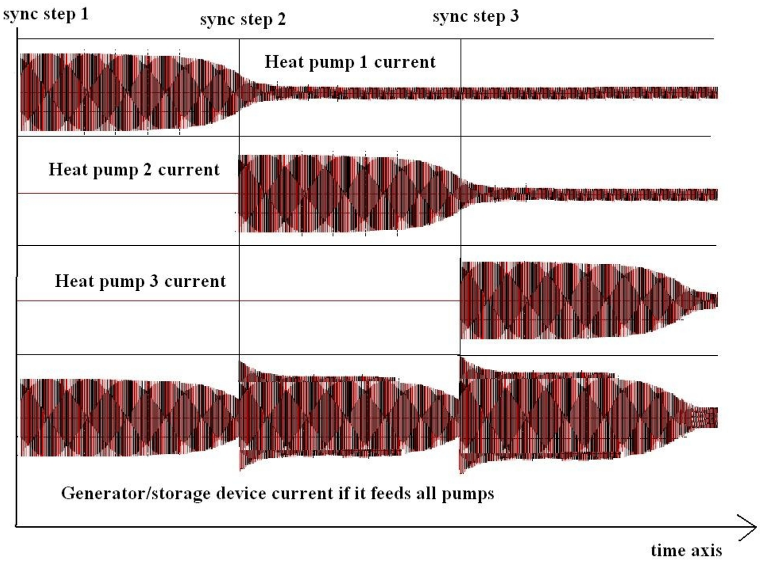


Figure 4.15. *Principle shapes of currents of three heat pumps and supply unit in smart load-generation synchronisation.*

Generator current shape would be a similar but three times larger if the all pumps were started at same time instead of the proposed concept. This kind of synchronisation can also be used when units are switched off.

4.3.5. Customer as a part of a microgrid

Client types

Client types that have to be taken into account are combinations that rise from the possibilities of loads, production and storage units that clients may have. Table 4.6 illustrates possible different combinations of device types client may have.

Table 4.6. *Possible client type combinations.*

	Client 1	Client 2	Client 3	Client 4	Client 5	…	client 128
1:Uncontrollable loads ,L1	1	1	1	1	1	1	1
2:Controllable loads; L2	0	1	0	1	0	..	1
3:Loads in peak shaving with no ICT link L3	0	0	0	0	1	..	1
4:Grid forming generation units, G1	0	0	0	0	1	..	1
5:Grid supporting generation units, G2	0	0	0	0	0	..	1
6:Grid parallel generation units, G3	0	0	1	1	0	..	1
7:Energy storage for household use only, ES1	0	0	0	1	1	..	1
8:Energy storages for grid support, ES2	0	0	0	0	1	..	1

As the number of possible client combinations is so huge even with quite simple classification, it is more reasonable to inspect how different unit types affect generally microgrid planning and land use etc. Assumption in the table is that every client has passive loads (takes away one variable) so the maximum combination number goes to 128 (2^7), when there are seven possibilities in units that each client can have.

Affect of different client devices for land usage and grid design

Loads affect how much power is needed for everyday operation of a household. Controllable loads L2 need ICT links to microgrid manager and take out line capacity need when used in peak shaping. ICT links in controllable loads have to have low latency if they are wanted to be used in primary frequency stability control. Uncontrollable loads L1 increase the line capacity demand as often loads do not have strict relation to grid conditions. L3 loads are allocated to peak shaving with frequency sensor or other device to tell when to connect to the microgrid. L3 loads increase the flexibility of the grid and reduce stress on lines. Loads affect together with production types how much energy storage capacity is needed in island operation. Example case of client type situation is described at the end of this chapter.

Generation type G1 is a grid forming unit and it needs a high priority ICT channel to communicate with other devices that are involved with grid balance regulation. G1 type increases required connection size of a household as balancing power is some cases needed outside of the internal household grid. Grid supporting units G2 can also have high priority connections but they will manage also with higher latency connections as they do take part in primary voltage balance control. Also G3 type production should have ICT even if disconnection from the grid is done via circuit breaker outside the communication possibilities of the micro source controller. The reason for this is that ICT functionality can be integrated in an inexpensive way as every household has some kind of need for an ICT channel and G3 can be transmitted with low priority flag among other information. ICT is needed for forecasting inputs of the production from e.g. weather conditions.

Energy storages have to be seen as loads but also as generation points. Affect of client based energy storage depends on how they are controlled and by whom. Energy storages can be used for client’s own purposes or they can take part in microgrid stability regulation. Also energy storage might have only functionality to be in secondary voltage control meaning that quick changes in power output are not possible or desirable. Energy storage systems should always have ICT link to devices the power of which they store and loads they serve. E.g. if a client has an electrical car, this can be seen as load from ES perspective. ES has to know when the storage is needed to be ready for discharge to an electric car. Also communication between production and storage is wise as production forecast changes, storages might be cheaper to be recharged in different times at the day.

It should be noted that structure of the ICT network in microgrids is done mostly in a centralised way. This means that devices will transmit all the necessary information to microgrid management system and all the devices can retrieve necessary information from there. This requires that the ICT system is always online. In a situation where ICT is down, devices should be automatically switched to local communication. The better solution would be to always run local communication in parallel with central ICT system so that there is always a backup and the data can be compared. Figure 4.16 represents one case what microgrid could look like in with a couple of client types.

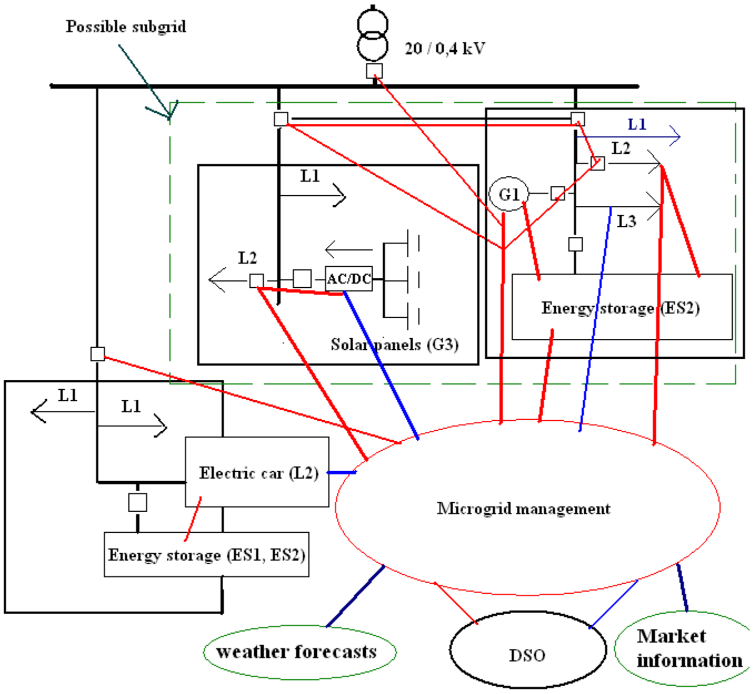


Figure 4.16. *Case with no centralised energy storage and with one subgrid.*

Information channels are drawn to picture with red representing a high priority connection with blue for a low priority connection. Clients in this example have enough regulation capacity from controllable loads and energy storages so that centralised energy storage in main bus is not needed. There is also a backup connection between two clients in this example that they can build up a subgrid when there is trouble in main bus and restore microgrid after blackout. Subgrid has to have at least one grid forming generation point, G1. G1 and controllable loads build up the subgrid after network failure. Subgrid area is highlighted as a green rectangle in the figure.

Need for an alternative connection to MV side

An alternative connection to MV side is needed in situations when important loads are wanted to be supplied in this way in situation when primary connection is down and own production and storage units are not adequate for technical, reliability, or management reasons. Example of an alternative connection arrangement is displayed in figure 4.17.

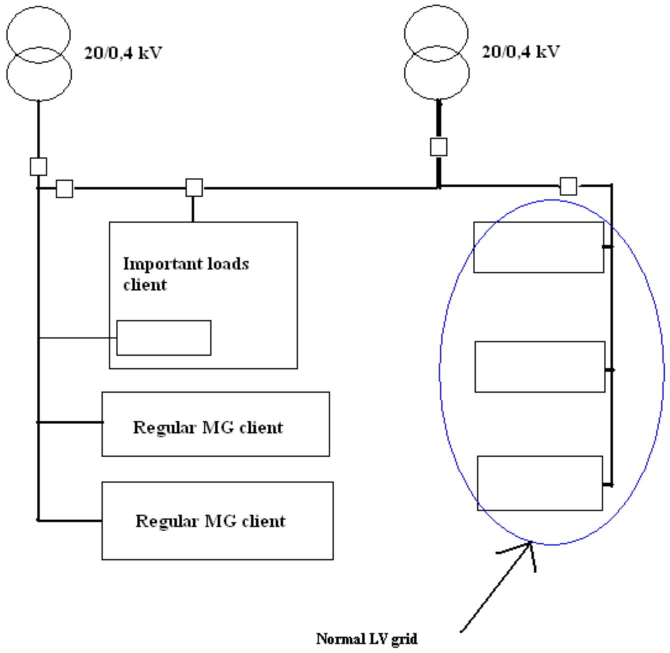


Figure 4.17. *Backup connection to MV-side due important loads.*

It is wise to build alternative connections if distance to closest transformer is short and ground is easy to dig. Of course backup connection can be always built if the client is prepared to pay and the costs can be divided between the clients needing the connection. It should be noted that important loads should always have their own backup power as the alternative connection won’t do much good if the whole MV side is down.

Need for a centralised energy storage or production

Centralised energy storage and production are needed if clients do not have enough own storage or production capacity. Also this can be a design choice for scenery or disturbance reasons. If microgrid is divided into subgrids, so that they have their own island generating features, there is no need for concentrated systems. Microgrid operator can demand that clients form subgrids as DSO can demand from MG operator that MG has to have its own regulation capacity in the contracts. Whatever the way is chosen, it is clear that careful planning is needed and customers cannot act as they like with no talks with MG-operator and DSO.

Circuit breakers or disconnectors

Circuit breakers are demanded by the micro generation standard EN 50438 in production and storage systems. Smart loads can be connected with disconnectors if currents are low enough or there is some other more advanced way to control load’s power. Disconnectors can be used with backup connections, but then part of the grid has to be sometimes cut off when original connections are restored. This is because disconnectors cannot open when there is too much current in the line.

External information needs

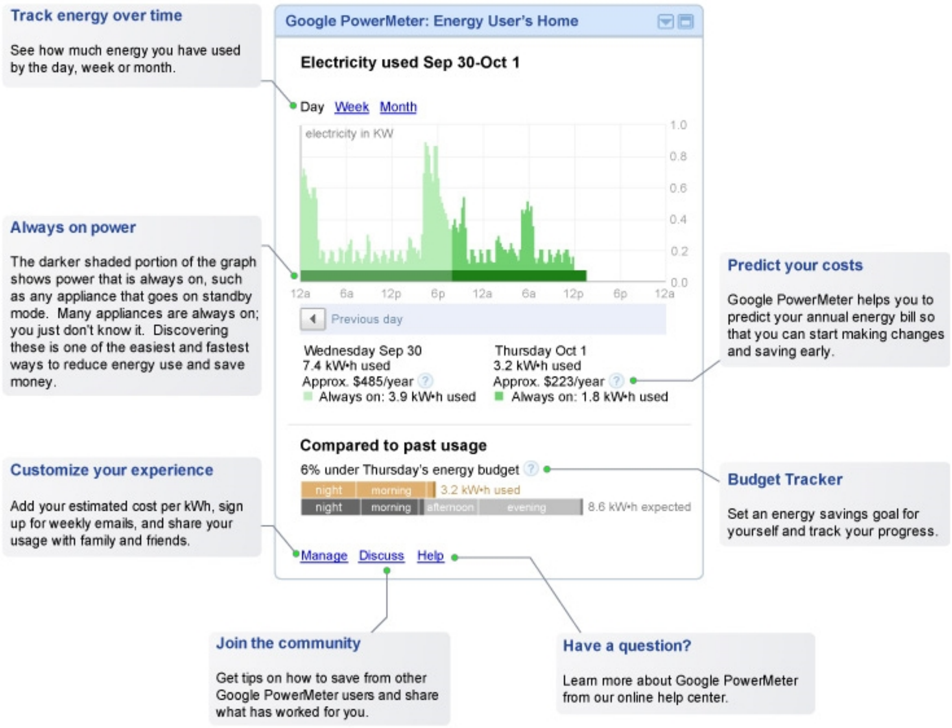
External information means data that is gathered from various outside sources to optimize technical or economical performance of the microgrid. This information can be,

- Weather forecasts about clouds, winds, temperatures and storms.
- Electricity market price forecasts
- MV Grid condition information and support requests from DSO
- Information from the clients outside the grid to make preparations etc.

Microgrid operator uses this data to organize the system to respond to the new situation that seems most likely from the information feeds. Microgrid operator can give clients couple of choices for how they wish the different situations to be handled. Some clients want more control and options than others so it should be also made possible within reasonable limits.

Customer interface and intelligent metering

Customer interface consist of a device or devices that the client uses to communicate with microgrid. Design must be simple and comprehensive for clients but also deliver all the functionality that is needed. Clear touch screen interface is a one option for comprehensive customer interface. Example how the data from smart meters can be used and processed in a comprehensive way is the Google PowerMeter software. Figure 4.18 displays the application functionality.



Track energy over time

See how much energy you have used by the day, week or month.

Always on power

The darker shaded portion of the graph shows power that is always on, such as any appliance that goes on standby mode. Many appliances are always on; you just don't know it. Discovering these is one of the easiest and fastest ways to reduce energy use and save money.

Customize your experience

Add your estimated cost per kWh, sign up for weekly emails, and share your usage with family and friends.

Google PowerMeter: Energy User's Home

Electricity used Sep 30-Oct 1

Wednesday Sep 30
7.4 kW•h used
Approx. $485/year
Always on: 3.9 kW•h used

Thursday Oct 1
3.2 kW•h used
Approx. $223/year
Always on: 1.8 kW•h used

Compared to past usage

6% under Thursday's energy budget

3.2 kW•h used

8.6 kW•h expected

Predict your costs

Google PowerMeter helps you to predict your annual energy bill so that you can start making changes and saving early.

Budget Tracker

Set an energy savings goal for yourself and track your progress.

Join the community

Get tips on how to save from other Google PowerMeter users and share what has worked for you.

Have a question?

Learn more about Google PowerMeter from our online help center.

Figure 4.18. *Google PowerMeter[83].*

4.3.6. Load priorities and islanding level

Different loads have different needs for power quality. Some loads could take part in active stability regulation disconnecting when load on the grid increases and connecting back when the load on the grid decreases. Some loads cannot be used in power quality regulation as device operation might be disturbed too much or they are just demanded to be connected as much of the time as possible. E.g. loads can be characterised with following table 4.7.

Table 4.7. *Load priority table.*

Question	Heating	Lighting	General appliances	Life support
Can take part in primary power quality regulation?	1	0	0	0
Can take part in secondary power quality regulation in step 1?	1	0	1	0
Can take part in secondary power quality regulation in step 2?	0	0	1	0
Can take part in secondary power quality regulation in step 3?	0	1	1	0
Always online (highest priority)	0	0	0	1

Secondary power quality regulation in the table with three steps means the order of the load groups that are disconnected when other regulation is not enough. Step one loads are disconnected first and then step two and step three if needed.

Islanding level means the percentage of the LV grid that is capable to operate in island mode. Islanding level is one important parameter, which can be used to manage microgrid initial costs. To simplify, islanding level must be at 100% if continuous island operation is wanted to be maintained. If on the other hand island mode is only a backup solution in case of distribution system is down, lowering islanding level gives cost savings as production and regulation demand is lower.

4.3.7. Summary

Demand side management of a microgrid means that production resources are allocated smartly to loads and information is exchanged between loads, production and storages. Loads can be classified by importance and controllability to help microgrid controller to maintain power quality and to aim for cheaper operation. Customer is one key factor in demand side management and giving simple alternatives for load and resource management is important for a consumer to be active in microgrid management.

5. OWNERSHIP AND OPERATION

Ownership and operating structures have many possibilities in microgrids. Some possibilities are not allowed by current legislation but many are possible even with current laws. One key issue in microgrids is identifying different financial benefits and costs and distributing them fairly to all stakeholders.

5.1. Ownership structures

Ownership can be divided into ownership of the microgrid lines and network equipment and ownership of the generation units and storages. In traditional systems DSO owns the LV grid and production is owned by another company in the MV or HV side. Same company owning production and distribution system is not possible with the current legislation in normal system operation.

5.1.1. DSO owns the MG units and network

Although DSO cannot own generation units in normal grid operation, DSO is allowed to take part in electricity market in following cases according to electricity market act [84]:

1) To cover network losses
2) To take care of system responsibility related tasks
3) To manage power transmission limits
4) To have portable backup power to support network construction and network repairs and to sell this electricity to the grid.
5) Acquire electricity for the own use of the company
6) Acquire electricity to clients when supply of electricity is interrupted due to reasons of the supplier.

The most important fact is number 4, to have portable backup power units. With this law, DSO could own MG units if they are only used when the MV side is down or needs support. However the problem is that MG units would have to be portable. Static installations of MG units are not allowed to be owned by DSO. The most of the urban LV-networks are currently owned by the DSO so no major changes are needed due this reason.

Disadvantage in this model is that microgrid would be only used as backup power source and no production would be allowed in normal grid conditions. Legislative enhancement that would be needed is to differentiate normal operation so that e.g. individuals could take the income from MG when MV side is fault free as compensation for that DSO gets savings in interruption costs. Of course financial matters have to be balanced out so that operation is fair for both sides.

Second thing that can be achieved with microgrids is to cover distribution losses (no. 1 in last list). As production is now closer to end consumer distribution losses are lower. This method needs calculation of all power flows so that loss reduction credits can be identified.[11]

5.1.2. DSO owns the network and 3rd party owns MG units

MG units can be owned by 3rd party operator like aggregator that owns and operates multiple microgrids. This model is legal in respect to electricity market act as the model does not differentiate on current production – distribution arrangements of the grid other than generation is now in LV-side.

5.1.3. DSO owns the network and units are owned by individuals

This case is similar to 3rd party owning the MG units. In this, individuals can form up a producer’s cooperative society that is the single entity between client and DSO. This model does not have any legal issues either. MG operating tasks are now the responsibility of the clients, but if wanted this service can be bought externally if needed. High automation level in Smart Grid systems makes grid management easier and external service could be used only in repair and maintenance related issues.

DSO could act as MG operator if enough regulation can be implemented to make sure that MG unit owners are still in command and DSO responsibility could only be grid stability and maintenance.

5.1.4. 3rd party owns the grid and individuals MG units

In this model DSO does not take part in microgrid operation and does not have responsibilities other than the distribution transformer they own. Grid is built and managed by 3rd party microgrid operator whose responsibility is to serve MG unit owners and consumer clients. Responsibilities of microgrid operators are described in chapter 5.2.1.

5.1.5. Individuals own the whole microgrid

This case is similar to previous but 3rd party grid owner is removed. So in addition to MG units, balancing equipment and lines are owned by end consumers. Operational and maintenance services have to be bought from somewhere else as individual clients won’t have the expertise or qualification in technical matters. Even in this case some management structure is needed for the communication to DSO and microgrid operator.

This model is possible with current legislation only if microgrid is categorised as private network and not open for everyone.

5.1.6. Summary of ownership structures

There are five ownership structure possibilities for microgrid. Some can be only accepted by law on special occasions and some need more initiative from individuals than others. Table 5.1 displays a summary of ownership structures and their legal possibilities.

Table 5.1. Summary of ownership structures.

	MG Units	**Grid**	**Legal combination?**
Case 5.1.1	DSO	DSO	only in disturbances
Case 5.1.2	Individuals	DSO	Yes
Case 5.1.3	3rd party	DSO	Yes
Case 5.1.4	Individuals	3rd party	Yes
Case 5.1.5	Individuals	Individuals	only if MG is counted as private network

5.2. Operation

Operation of microgrid consists of grid balance regulation and power flow management and taking MG units and client decisions into account. Some alternatives are good for some parties and some to others.

5.2.1. Responsibilities of the microgrid operator

Microgrid operator has a responsibility to control microgrid balance just like TSO manages the transmission system balance. MG operator also takes care of individual customer needs by implementing customer desires the best way possible to grid operation. MG operator also has to make sure that proper maintenance is done to equipment in the grid or at least supervise that MG unit owners do that. Tasks of microgrid operator can be:

- Grid stability management
- Grid maintenance
- Making sure that there is always a buyer for the electricity produced.
- Serving every MG client equally
- Managing all contracts
- Informing clients about price and other valuable information they need

Also providing microgrid with enough shared energy storage and other grid stability equipment should be the responsibility of the MG operator. Money for upgrades is collected from clients.

5.2.2. Responsibilities of the MG unit owners

MG unit owner has to give at least following information to grid operator according to recommendations for connection of micro-generation to the electricity distribution network by Finnish Energy Industries [30]:

- Information recorded in the nameplates of the production equipment, network connection device and any auxiliary equipment, and the maximum fault current fed by the equipment
- Testing record showing that the production installation meets the protection requirements (of the grid protection solution)
- Generation installation’s method of connection to the network (automatic/manual) and date of connection
- Information about the installation’s disconnection solution and disconnector data
- Testing records showing that the equipment meets the EMC requirements
- Phase which single phase unit is connected

Following additions are also important to microgrids:

- Finding out suitable classification and operation mode e.g. using the list mentioned in chapter 4.3.5 together with MG operator
- Notify MG operator immediately if there is a problem in the MG unit and it is not noticed by network sensors.

5.2.3. Operating models

Following operating models are some examples how microgrid models affect cash flow structures between different stakeholders.

DSO owned and operated backup microgrid

Operation mode where DSO owns the whole microgrid and microgrid is used only as backup power is represented in figure 5.1.[11] The figure describes how cash flows go in this situation. This model is not currently legal as back up power in the Electricity market act is required to be portable and local electricity market allowed.

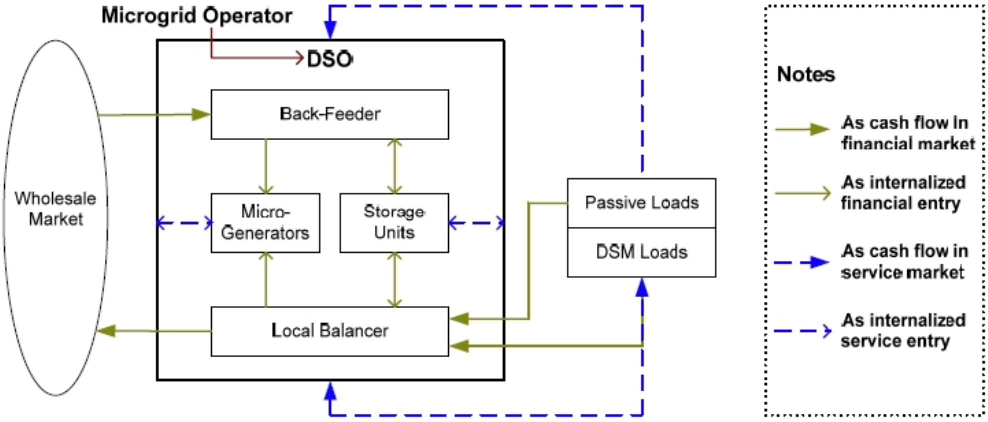


Figure 5.1. *DSO owned and operated microgrid [11].*

Wholesale market in this system is only local as microgrid operates only in cases of faults in MV side. DSO operated and owned grids typically consist of some large backup units that are connected straight to substation. Also as backup units are not needed to be really environmentally friendly as they are rarely used.[11]

The Prosumer Consortium Model

This model is based on maximising sales revenue from MG units or minimising electricity bill to consumers. High electricity price or significant financial support to renewable energy sources could lead to this model situation where MV link is only rarely used. If energy transmitted in MV-link is minimal, this could lead to higher power based pricing as the network upkeeping costs have to be directed somehow. Figure 5.2 illustrates the cash flows in prosumer consortium model.[11]

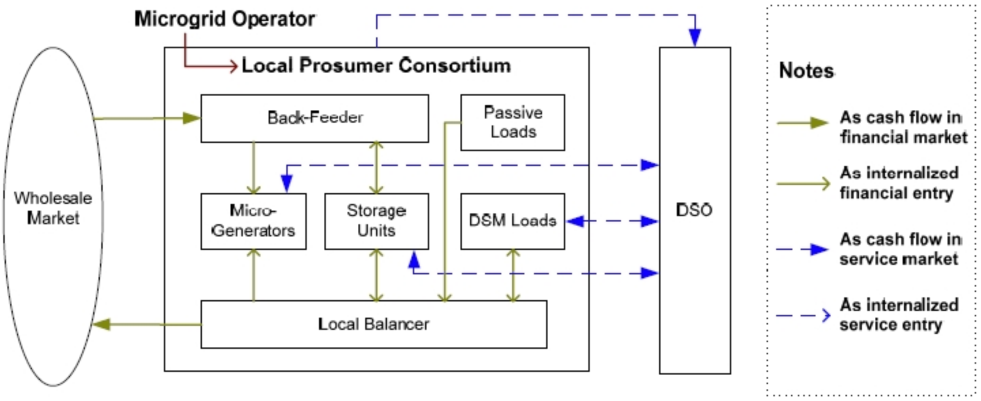


Figure 5.2. *Prosumer Consortium model [11].*

This model can use producer’s co-operative society as base entity. Producer’s co-operative society can avoid taxes if the operation is based on achieving zero result. Operation would be similar to Teollisuuden Voima (TVO), which produces electricity for its shareholders at cost price from nuclear power. Local retail market must be allowed for this model.

The Free market model

This model more or less describes all the rest model alternatives there are for microgrid. All clients in the grid can do own decisions and now no common line has to be drawn how grid is managed. One consumer can want to minimise green house gases and other might like to minimise energy bill. Microgrid controller acts as an interest arbitrator because individual goals usually contradict each other on some level. Potential benefits in this model are directed to proper recipients. Figure 5.3 displays the cash flows in free market model.[11]

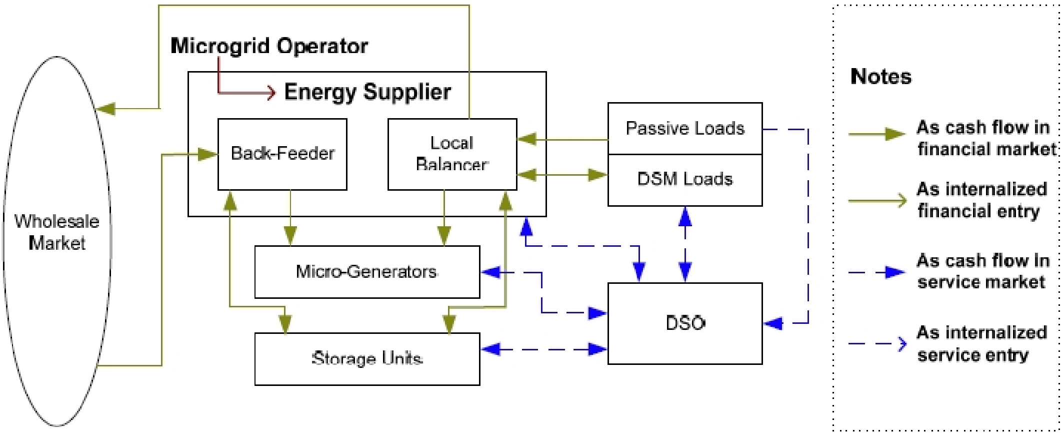


Figure 5.3. *Free market model cash flows [11].*

5.3. Acknowledgement of benefits and costs

Desirable goal is to make microgrid lucrative to all parties and take the most benefits out of microgrid avoiding hostile pricing and legislative environment which would hinder technological possibilities of microgrids. The basic financial, technological and environmental components that microgrid offers to stakeholders are displayed in figure 5.4.

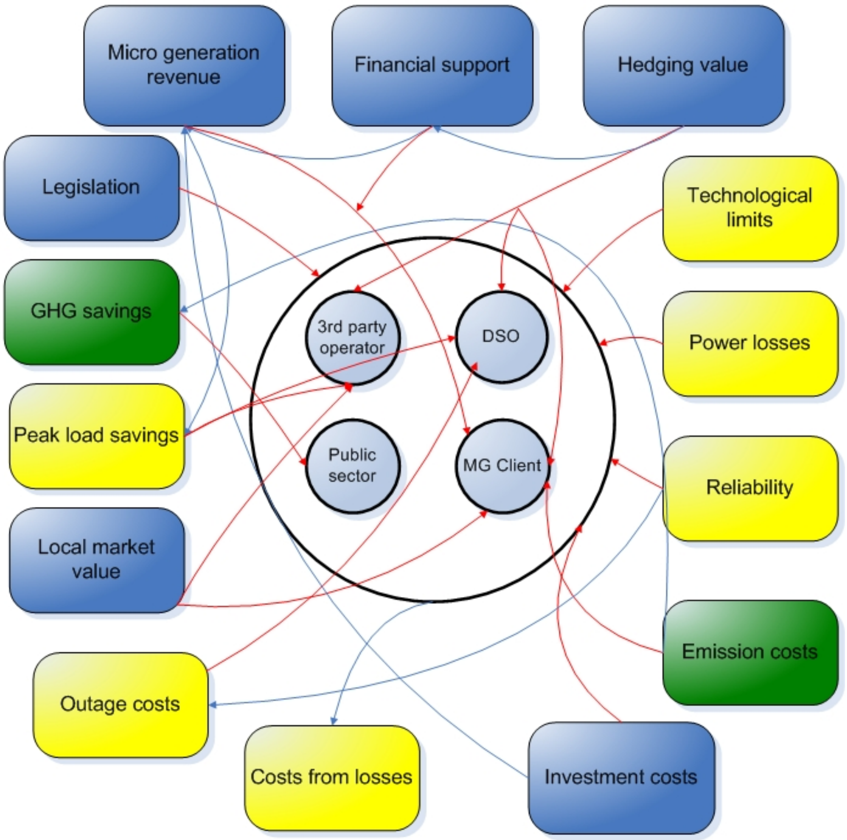


Figure 5.4. *Microgrid environmental, technological and financial components.*

Red pointers indicate which stakeholders are most related to specific type of factor. Blue pointers indicate which factors have close relations with each other. If some factor relates to all stakeholders, red arrow is connected to white circle around all stakeholders. Of course in the end, everything affects everything and relations can be drawn many ways.

5.3.1. Possible benefits from microgrid to different parties

DSO

Distribution system operator gets mostly benefits to grid stability, reliability and service related factors of microgrids. Stability improves as local power balancing and load shaping helps to reduce deviations caused by LV-grid. Also MGs can be used for MV side stability management if wanted. Reliability improvement results in lower outage costs both for MG and for MV side if MGs are used to support parts of MV system in power failures.

Automation in meter reading and in grid management reduces need for service related resources. Hourly meter reading gives more accurate information about the grid. Other possible benefits are good PR for being in renewable power generation integration business and experience to employees from project concerning new technology.

MG client

Microgrid client can get multiple benefits from microgrid and Smart Grid infrastructure. Improved power quality is a general benefit for microgrid users from better reliability and smart resource management. Microgrid technology enables new possibilities for users to acquire own production more economically and new possibilities like faster charging of electric cars and to be self-sufficient in energy. User interfaces that collect and process data can help clients to see more clearly how their decisions affect their energy use and energy price. MG can also provide inexpensive way to take part in electricity markets via aggregator.

3rd party MG operator

3rd party operator can take part in microgrids in few roles and key benefit for them is to create business from those roles. Main business role of 3rd party operator can be to provide microgrid management service to MG clients. Other roles can be to provide services like backup power and repair help to DSO. Also 3rd party operators can act as MG aggregators to collect small-scale production resources and manage smart loads demand side response.

Public sector

Public sector benefits from microgrids for use of renewable power resources and from advanced load management to reduce greenhouse gas emission and achieve national emission reduction goals. Microgrids also increase self-sufficiency of national energy sector.

5.3.2. Possible drawbacks from microgrid to different parties

Technological drawbacks

Technological drawbacks are mostly controllable with careful planning in design and operation. But as with all new technological systems, there will likely be some unwelcome surprises.

For DSOs and 3rd party operators, microgrid and other Smart Grid technologies create more investment pressures to grid. Also more equipment connected to the grid increases the risk for failures. Immature technology caused by lack of standards and power quality of equipment can also cause problems.

Technological drawbacks to microgrid clients can be related to too optimistic estimation of performance. This worse than estimated performance can be related to poor management of devices or basic quality of devices used. Power quality can also suffer from bad device choices. Use of some devices could also be banned in islanded operation mode.

Public sector technological drawbacks are few as is the case with technological connections of public sector to electric grids in usual. Fingrid is the only possibly fully government owned entity in the future that could possibly get technical problems from microgrids. This is however very unlikely as what microgrids are trying to achieve is self-sufficiency and to decrease the problems caused by renewable production. For that reason problems e.g. caused by increasing wind and solar production won't affect the transmission system as production and generation is balanced more locally.

Financial costs and possible drawback scenarios

Distribution system operator's income can decrease if power flow in MV connection lowers. This can mean pressures to increase power based pricing over energy based to compensate possible income loss. Generally transition from operation to active smart grid building increases investment costs initially. Competition from 3rd party system operators can also possibly decrease revenues to DSO. 3rd party operator on the other hand can estimate opportunity for business to be better than it is.

Own production costs also more money at least initially to microgrid clients. Of course microgrid can also be more expensive in operation than to use normal grid connection, but then there are other reasons more important for microgrid to be used. Previously mentioned possible increase in power base pricing from DSO will show on microgrid client's electricity bill. Also legislation changes can affect microgrid clients if e.g. microgrids are not allowed in financial support system or producer's co-operative societies are forbidden.

Public sector financial drawbacks can include loss of tax revenue due to producer's cooperative societies and of course financial support structures to environmentally friendly production cost a lot of money.

5.4. Financial support

Financial support structure for renewable power generation is currently under reform in Finland. Major components of financial support are energy investment support and planned feed-in tariff system of some production types.

Energy investment support

Energy investment support for investment cost can be granted to projects that involve use of renewable energy sources in Finland. Maximum support that plant can get is between 25%–40% depending on the type of benefit project gives. Investment support can be applied from Ministry of Employment and the Economy.[85]

Feed-in tariff

Feed-in tariff system currently proposed for the ministry of employment and the economy by Feed-in tariff working group suggests a tariff system for only wind power and bio based fuels. Tariff system's latest proposal gives a target price for wind and biogas power and support is the difference between target price and electricity price on Nord Pool.[88]

Starting target price for wind power is suggested to be 105.3 €/MWh and for biogas and wood 83.5 €/MWh. Later in 2015 wind power target price is suggested to be set on the same level as with biogas and wood. CHP-plants would get premium on top of tariff price of 20 €/MWh to biogas and 50 €/MWh to wood. Total energy produced in plant is agreed on feed-in contract and will be the limit for yearly support.[88][87]

Fixed support to replace tax support system

Proposed system would include following fixed support to plants that are not included in feed-in tariff system and produce more than 200 MWh of electricity a year. This 200 MWh means that average yearly power should be at 22.8 kW. This system is planned to replace existing tax support [88]:

- Wind power and woodchips: 6.9 €/MWh
- Biogas and small-scale hydroelectric power: 4.2€ / MWh
- Recyclable waste plants: 2.5 €/MWh

Proposed rates are same as with current tax support system.[86]

Comments on proposed support system

It should be noted that support levels are not based solely on green house gas emissions and wind power and bio based energy sources are wanted to be supported strongly over other types. E.g. solar energy is left with no support at this point. The reason for this is that long term climate and energy strategy by government states following (straight translation) “Large-scale use of solar electricity in Finland will be realized in latter decades and is dependant on research and development results” It is certainly true that there is a strong relation between R&D and implementation of technology but the relation is bidirectional.

So the question is, would it be wise for solar energy and other emission friendly energy sources to have all similar support structure even if it seems that large-scale use is forecasted to realize far in the future? In some cases even today some production types would have similar emission levels and better technological performance than highly supported generation types but would gather less investment due the tariff system for certain production.

Also the possible minimum unit size could mean that units inside microgrid cannot be accepted to feed-in tariff system. Microgrid as whole could be counted as a plant and be accepted to tariff system but how tariff would then be calculated would have to be figured out by legislation. One possibility would be to group similar production units as one larger unit and take part in tariff system. Investment support is however recommended for smaller units and also solar power plants could get support this way.[87]

5.5. Factors that have to be cleared by legislation

Some factors have to be cleared out for the use of microgrids. Allowing islanded mode operation in public microgrids or all microgrids have to be classified as private networks. Allowing local retail markets for electricity would help microgrid clients if system is not connected to distribution system. The largest single question with microgrid might be that can microgrids be accepted to feed-in tariff system and on what terms.

5.6. Summary

Ownership and operation alternatives for a microgrid are in basic form DSO owned system used only in power outages, DSO owned grid with 3rd party or consumer owned production, 3rd party owned grid and consumer owned production and totally consumer owned system. Whatever is the model chosen following things have to be cleared:

- What are specific responsibilities and how are they divided between stakeholders?
  -technical management
  -economical management
- How does legislation affect the operation and ownership structure selected?
- Who makes sure that every party is treated equally?
- How are disputes handled?

The key factors for financial management and analysis is to figure out the expenses, income and savings that microgrid can provide. Major role for identifying the financial benefits and costs is to have a legislation considering the possibility of microgrids and to clearly define how financial factors have to be calculated and to whom they belong. Likely the most important factor with legislation is to define what kinds of microgrids can be accepted to feed-in tariff system and what systems can get investment support. All this has to be made very clear and long term so that investment calculations can be made.

6. MICROGRID SYSTEM OPTIMIZATION WITH HOMER®

System design involves technical and economical performance analysis for a long time using a very small time step. This would require a lot of computing power because the number of differential equations is large in transient scale modelling of systems. For this reason long time analysis and transient optimisation of system usually is done by two different tools. Targets of full year simulations are:

- Figure out what is economically optimum production configuration for an average client in different cases and give reference for system configuration for possible transient simulations in future.
- How many microgrid clients would be economical to take part in Nord Pool.
- How optimal grid connected system and islanded system differ and how they compare economically.
- Figure out optimal backup system for microgrid client to cope with short interruptions if islanded mode is only used in distribution system interruptions.

To help in long-term system design, HOMER® program is used. HOMER® is hybrid power system optimisation program the development of which was started by US Department of Energy in 1992. Program version 2.68 was used in this thesis. The program bases comparisons mainly on economics but regulation can be given to emissions and renewable fraction. Program can be used to optimise system and operation hourly with given information and restrictions. Inspected location in base simulation is Tekniikantie 2, Espoo Finland. The reason for choosing this location is that this is one of VTT’s locations and data from possible future experiments can be compared to simulations. A guide for HOMER can be found at [89].

6.1. System inputs for HOMER®

HOMER® takes inputs like equipment options, weather data, electricity prices, load curves and does sensitivity analysis with multiple variables. HOMER® simulation is done with grid connection and islanded operation mode. Figure 6.1 represents two system layouts used in simulations.

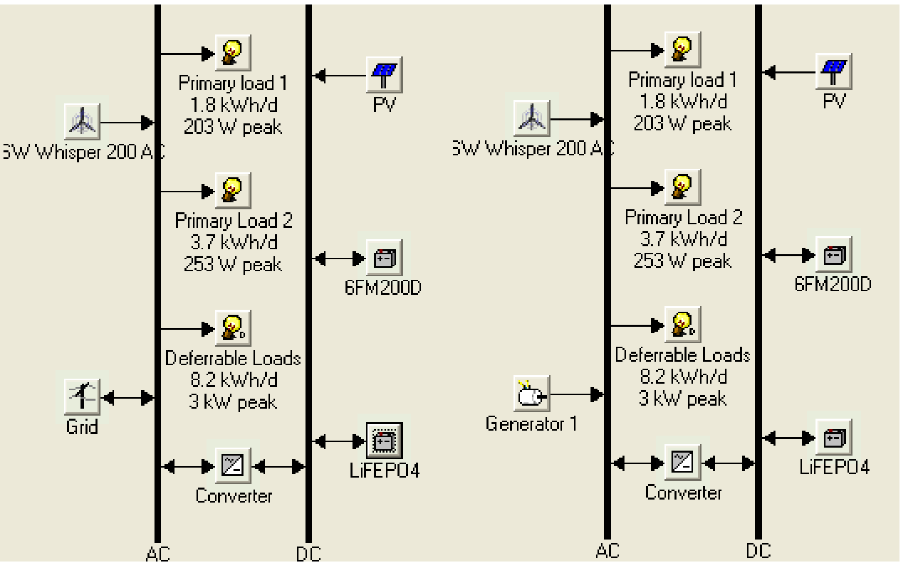


Figure 6.1. *Layout of inspected systems. Grid connected system is on the left and islanded system on the right.*

A diesel generator is only given as an option in islanded system because the program cannot differentiate sell-back price for each generation type and same financial support has to be assumed for all generators. Load inputs are presented in table 6.1, constraint inputs in table 6.2, device inputs in 6.3, economic inputs in table 6.4 and environmental inputs in table 6.5.

Data for HOMER® has to be in certain format when hourly data series over the year is wanted to be used. So input data had to be converted to format that is needed. Data conversions were done with applications written to Matlab®. Following tasks were done with Matlab®,

- Verification of altitude conversion in HOMER®
- Generation of file containing sell and buy price for electricity (see table 6.4 for details)
- Generation of file containing hourly load curves for three load types
- Conversion and approximation of hourly temperature data with sin fit using daily average, max, and min temperature (used for solar panel efficiency calculation)

Table 6.1. *Input data for loads to HOMER® simulations.*

Load inputs	Input method	Primary load 1	Primary load 2	Deferrable load
	As hourly averages	1.8 kWh/d 203 W peak	3.7 kWh/d 253 W peak	8.2kWh/d 3 kW peak

Table 6.2. *Constraint inputs for HOMER® simulations.*

Constraint inputs	
Set point of battery charge	80 and 95%
Operating capacity reserve for peaks	15% of hourly load
Grid connection capacity	17 kW
Minimum renewable fraction	0%, 90% and 99%
Forbid battery loading from grid	Yes

Table 6.3. *Input data for devices for HOMER® simulations.*

Device inputs	Investment cost	Replacement cost	O&M	Lifetime
Diesel generator				
0.65kW	180 $	180 $	0.015 $/h	15 kh
3kW	1000 $[95]	900 $	0.045 $/h	15 kh
6.4kW	3200 $[95]	3200 $	0.1 $/h	15 kh
--------------------------------- -	-----------------------------	-------------------	----------	-----------
Wind power	Investment cost	Replacement cost	O&M	Lifetime
Whisper 200 (1kW)	4000 $[92]	3500 $	20$/a	20a
Mast height	25m	||		
--------------------------------- -	-----------------------------	-------------------	----------	-----------
PV system	Investment cost	Replacement cost	O&M	Lifetime
Dupont DA100[96]	1.4 $/W	1 $/W	0	20a
--------------------------------- -	-----------------------------			
Losses from dirt	5 %(an educated guess)	||		
Slope	41 degrees	||		
Direction	south	||		
Ground reflectance	20%	||		
Temperature coefficient of power	-0.25% / Celsius	|| ||		
Nominal operating temp.	25 Celsius	||		
Efficiency at nominal conditions	6.50%	|| ||		
-------------------------	-----------------------------	-------------------	--------	------------
Energy storages	Investment cost	Replacement cost	O&M	Lifetime
Vision 6FM200D (200Ah)	750 $[94]	600 $	0	as function of usage
Generic LiFePO4 (20Ah)	400 $[93]	400 $	0	as function of usage
AC/DC Converter	300 $/kW	200 $/kW		
----------------------------	-----------------------------	-------------------	----------	------------
Inverter efficiency	90%	||		15a
Rectifier efficiency	85%	||		
Rectifier capacity in relation to inverter	100%	|| ||		

Table 6.4. *Economic data for HOMER® simulations.*

Economic inputs	
Buy price	Spot price of Finland in 2009[97] +40€ / MWh of transmission fees
Sell price	Spot price for Finland in 2009 if price is over 83.5€ /MWh If lower, price is 83.5€ / MWh
	+feed-in charge of 0.7€ / MWh
	+clearing fee of 0.13€ / MWh charged by Nord Pool
Min. market fee at Nord Pool	3000 €/a [97]
Project lifetime	30a
Interest rate	5 %
Investment support for islanded system	20, 30 or 40%
Capacity shortage penalty for islanded system	0.2$ and 5$ /kWh
Diesel price	1.59$/l and 2$/l

Table 6.5. *Environmental input data to HOMER® simulations.*

Environmental inputs	
Wind speed	A monthly averages from measurements in 2009 (wind atlas)
Data generation from hourly values using Weibull curve	
Weibull parameters	k=2.1, autocorrelation 0.8, pattern strength=0.2
hour of peak wind speed	15
Annual average	5.7 6.7 and 8 m/s
Hellman exponent for altitude correction	0.1
Temperature	as hourly values generated from daily averages, max and min value using sin fit from year 2009
Solar irradiance	NASA hourly measurements from year 1998
Scaled annual average sensitivity values	2.73 and 3.12 kWh/m^2/day

6.1.1. Details about data inputs

Temperature data

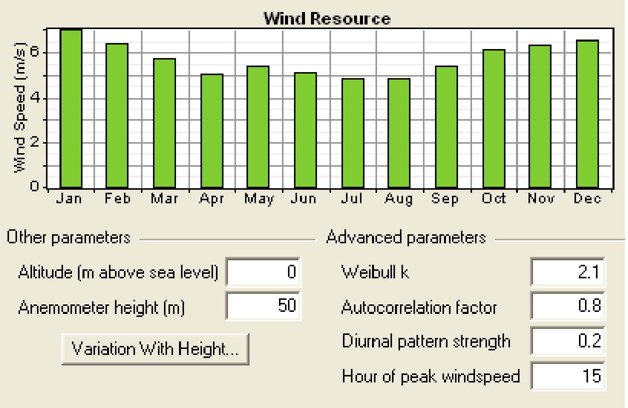
Daily temperature readings from Helsinki are imported to HOMER®. (source wunderground.com) Temperature data is used to calculate solar panel temperature and effect on panel performance. Data provided was as daily max., min. and average values so MATLAB® was used to do sine curve fit to create hourly curves for the whole year. Sine fit was chosen as max, min and average temperatures were easily formatted into daily function of time using sin fit. Hourly temperature curves are important because solar panel efficiency would be simulated too high if only daily average temperatures were used. Delay between solar radiation and air temperature was set to 2h.

Tariff-model

Tariff model used in simulations is based on feed-in tariff of 83.5€ / MWh for the whole system. This level is same as in the latest proposal for the government (chap.5.4). Tariff price is replaced by spot price if spot price is higher than tariff.

Solar and wind data

Two optional turbines were given for wind power system, Skystream 3.7 and Whisper 200. But as initial tests were run, Whisper 200 seems to be the better option every time so Skystream was deleted from the search space to reduce computation time. Whisper 200 specs were included in the HOMER® software version 2.67 but Skystream specifications were based on older 1.7kW model so they were updated to latest 2.4 kW specification. HOMER® tries number of wind turbines from zero to 20. Wind data was generated from monthly data collected from Wind Atlas (www.windatlas.fi) from Tekniikantie 2 location in Espoo and HOMER® did hourly curves based on the parameters presented in figure 6.2.



Other parameters

Altitude (m above sea level) 0

Anemometer height (m) 50

Advanced parameters

Weibull k 2.1

Autocorrelation factor 0.8

Diurnal pattern strength 0.2

Hour of peak windspeed 15

Figure 6.2. *Wind data for HOMER®.*

Solar radiation input was done with HOMER®'s integrated option to connect to NASA weather data base. Only coordinates of the location had to be given to application. Figure 6.3 represents monthly values of average irradiance values in Helsinki area.

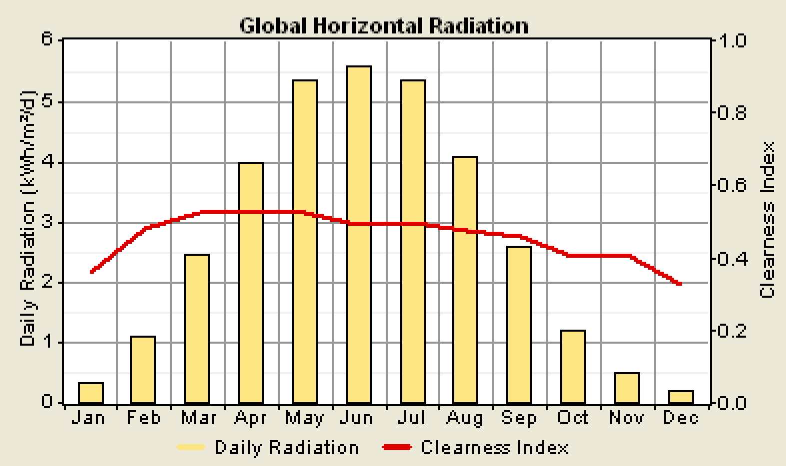


Figure 6.3. *Monthly plot of solar radiation in Helsinki area.*

The clearness index in figure represents the fraction of solar radiation that is transmitted through atmosphere to earth surface.

Load inputs

First a base curve was created how on average electricity is used by a house without electric heating. Base load curve is based on measurements in [90]. Red curve in figure 6.4 represents this base.

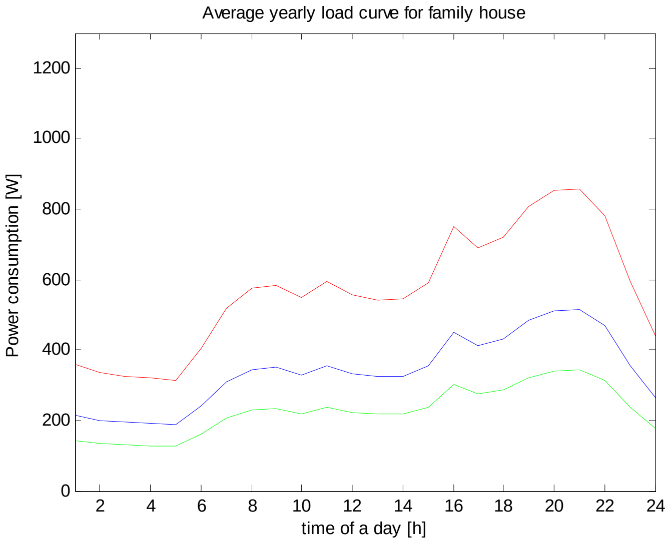


Figure 6.4. *Base curves for loads. Red is total curve, blue controllable loads, and green uncontrollable primary loads.*

Base curve is then divided into controllable and uncontrollable loads. Ratio for controllable load is set to 60%. These loads can be done in different times of the day to balance consumption peaks. As base curve is just an average, primary loads are divided into two groups by how high the randomised deviations are from base curve. 33% are set to have higher deviation and rest lower. Controllable loads have 5 kWh of storage capacity; 5kWh of energy demand can be supplied later. Figure 6.5 represents sample hourly load curve for the whole year.

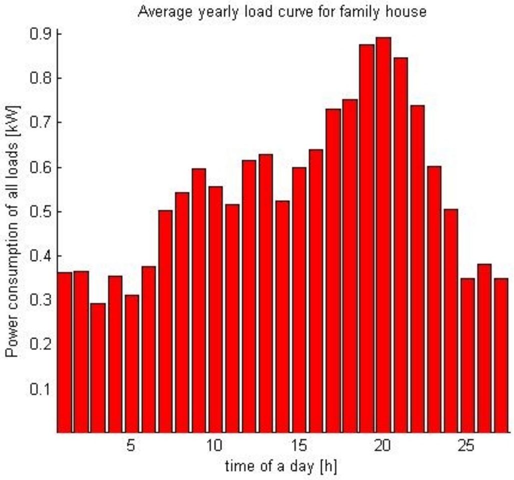
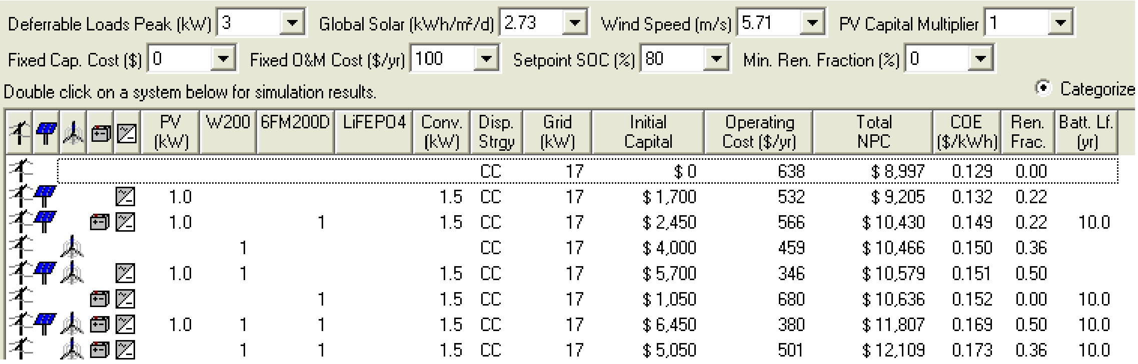


Figure 6.5. *Sample of randomised load curve.*

6.1.2. Grid-connected mode results

In grid-connected mode there is always distribution grid that can be used to buy and sell electricity at any time. Results of calculation depend on sensitivity values used in specific case but also some common facts can be drawn from them. Calculations of 2880 simulations with 2592 sensitivities lasted two days. Figure 6.6 represents one case in which there is no minimum for renewable factor and wind speed and solar radiation sensitivities are in their lowest. This case represents renewable energy resources in Tekniikantie 2 Espoo.



Deferrable Loads Peak (kW) 3
Global Solar (kWh/m²/d) 2.73
Wind Speed (m/s) 5.71
PV Capital Multiplier 1
Fixed Cap. Cost ($) 0
Fixed O&M Cost ($/yr) 100
Setpoint SOC (%) 80
Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

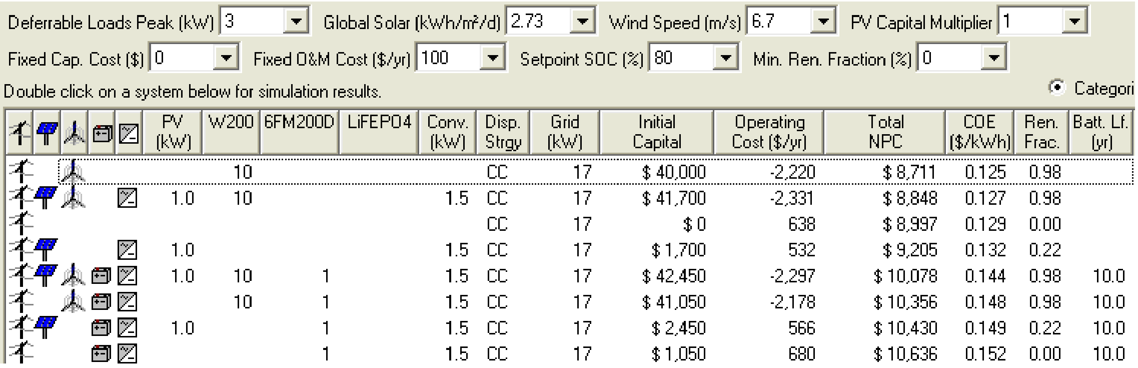
● Categorize

PV (kW)	W200	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
					CC	17	$ 0	638	$ 8,997	0.129	0.00	
1.0				1.5	CC	17	$ 1,700	532	$ 9,205	0.132	0.22	
1.0		1		1.5	CC	17	$ 2,450	566	$ 10,430	0.149	0.22	10.0
	1				CC	17	$ 4,000	459	$ 10,466	0.150	0.36	
1.0	1			1.5	CC	17	$ 5,700	346	$ 10,579	0.151	0.50	
		1		1.5	CC	17	$ 1,050	680	$ 10,636	0.152	0.00	10.0
1.0	1	1		1.5	CC	17	$ 6,450	380	$ 11,807	0.169	0.50	10.0
	1	1		1.5	CC	17	$ 5,050	501	$ 12,109	0.173	0.36	10.0

Figure 6.6. *Case with lowest renewable resources and no renewable fraction limitations.*

Cheapest option in case in figure 6.6 is normal grid without microgrid system. Sensitivity values controllable in drop down menus on grey background. Results of different cases are listed in lines under the sensitivity controls. On the left there is graphical representation of system configuration. Next to it on the right are numbers of storages and nominal power of other devices. Dispatch strategy CC mean cycle charging (production runs at full power when it runs). Moving to right side there are financial results of simulation. Total NPC means total net present cost of the system and

COE means cost of energy. Renewable fraction means the fraction of electricity produced with renewable sources. Estimated battery life is on the far right in the figure. Results for increasing wind speed annual average to 6-7 m/s, are represented in figure 6.7. Now the cheapest system is recommended to have 10 kW of wind power. Negative values in operating costs mean that operation creates income.

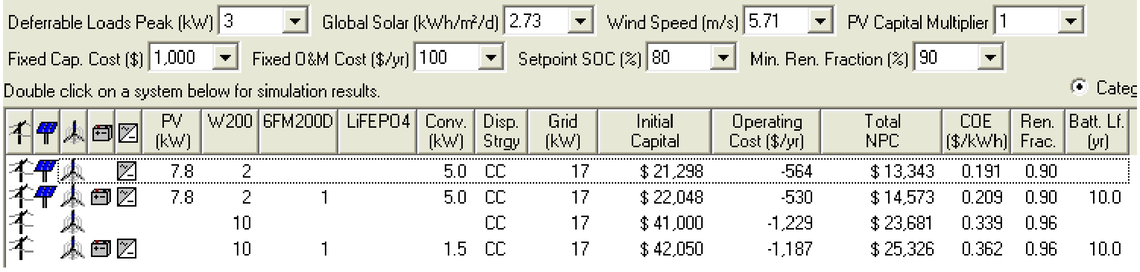


Deferrable Loads Peak (kW) 3 Global Solar (kWh/m²/d) 2.73 Wind Speed (m/s) 6.7 PV Capital Multiplier 1
Fixed Cap. Cost ($) 0 Fixed O&M Cost ($/yr) 100 Setpoint SOC (%) 80 Min. Ren. Fraction (%) 0
Double click on a system below for simulation results.

PV (kW)	W200	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
	10				CC	17	$ 40,000	-2,220	$ 8,711	0.125	0.98	
1.0	10			1.5	CC	17	$ 41,700	-2,331	$ 8,848	0.127	0.98	
					CC	17	$ 0	638	$ 8,997	0.129	0.00	
1.0				1.5	CC	17	$ 1,700	532	$ 9,205	0.132	0.22	
1.0	10	1		1.5	CC	17	$ 42,450	-2,297	$ 10,078	0.144	0.98	10.0
	10	1		1.5	CC	17	$ 41,050	-2,178	$ 10,356	0.148	0.98	10.0
1.0		1		1.5	CC	17	$ 2,450	566	$ 10,430	0.149	0.22	10.0
		1		1.5	CC	17	$ 1,050	680	$ 10,636	0.152	0.00	10.0

Figure 6.7. *Case with annual wind speed average of 6.7 m/s.*

Optimum system can also be found in graphic representation showing how different sensitivities affect the system configuration. If minimum renewable factor of 90% is added to case in figure 6.6, it can be seen more clearly that solar energy is the cheaper option compared to wind power in these conditions. This case is presented in figure 6.8.



Deferrable Loads Peak (kW) 3 Global Solar (kWh/m²/d) 2.73 Wind Speed (m/s) 5.71 PV Capital Multiplier 1
Fixed Cap. Cost ($) 1,000 Fixed O&M Cost ($/yr) 100 Setpoint SOC (%) 80 Min. Ren. Fraction (%) 90
Double click on a system below for simulation results.

PV (kW)	W200	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
7.8	2			5.0	CC	17	$ 21,298	-564	$ 13,343	0.191	0.90	
7.8	2	1		5.0	CC	17	$ 22,048	-530	$ 14,573	0.209	0.90	10.0
	10				CC	17	$ 41,000	-1,229	$ 23,681	0.339	0.96	
	10	1		1.5	CC	17	$ 42,050	-1,187	$ 25,326	0.362	0.96	10.0

Figure 6.8. *Case with lowest renewable resources and minimum renewable fraction limitation of 90%.*

Figure 6.9 displays distribution of electricity by source in cheapest system in figure 6.8.

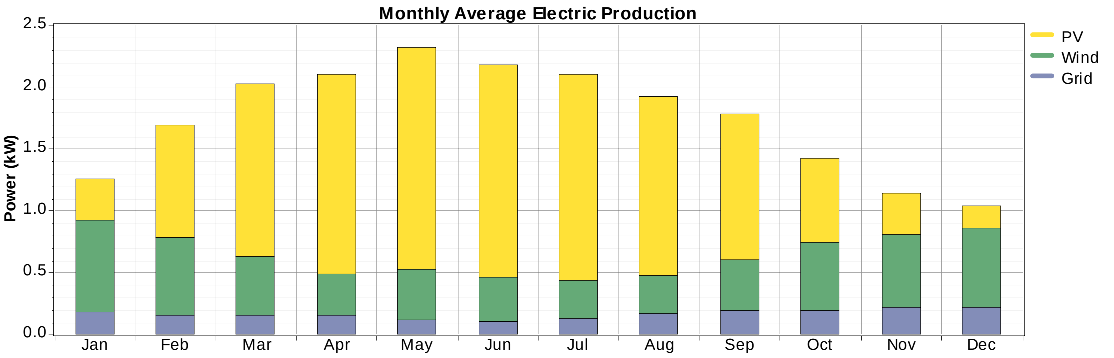


Figure 6.9. *Distribution of electricity produced by source in cheapest case of figure 6.8.*

As major portion of system production is solar based, production curve has similar shape as solar radiation. Figure 6.10 represents how wind speed and solar panel price affect on optimum system configuration. Fixed parameters in figure are the same as in figure 6.6 (only wind speed and PV-price varies). If there is not much wind and solar panel price is highest, cheapest option is to just buy everything from the grid but that is not of course microgrid anymore. Wind power becomes cheaper than solar power after average wind speed exceeds about 6.5 m/s.

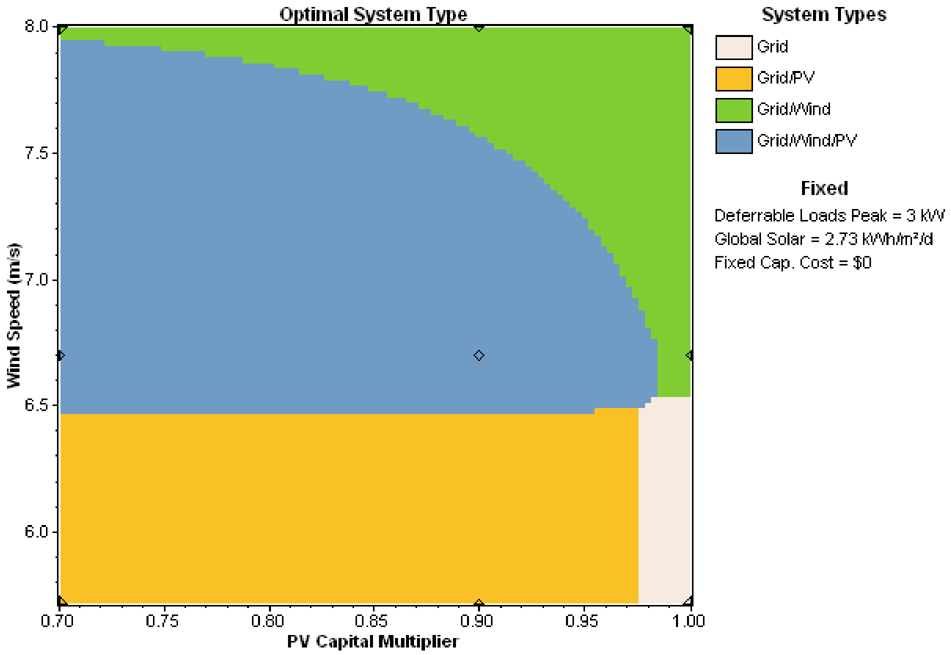


Figure 6.10. *Optimal system type with respect to wind speed and solar power price.*

Figure 6.11 is a snap shot from hourly microgrid operation.

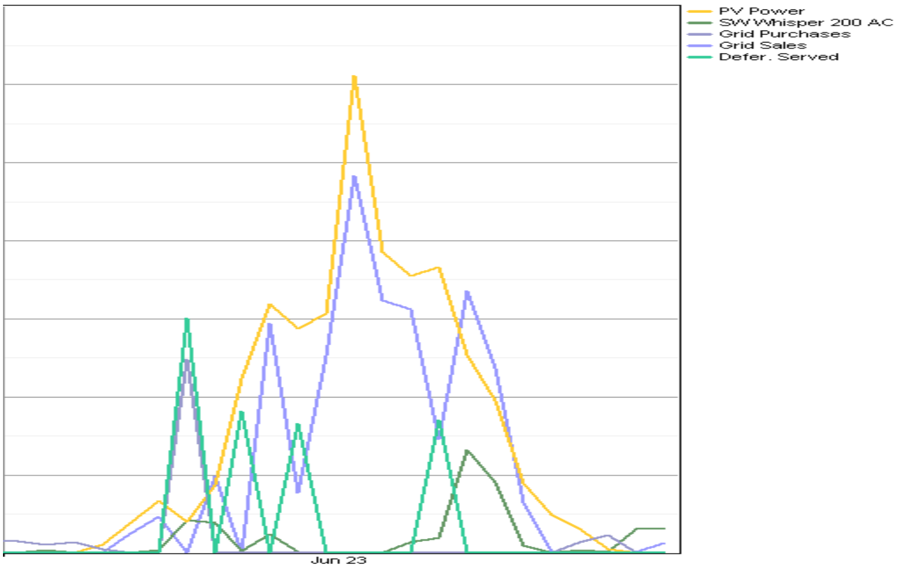
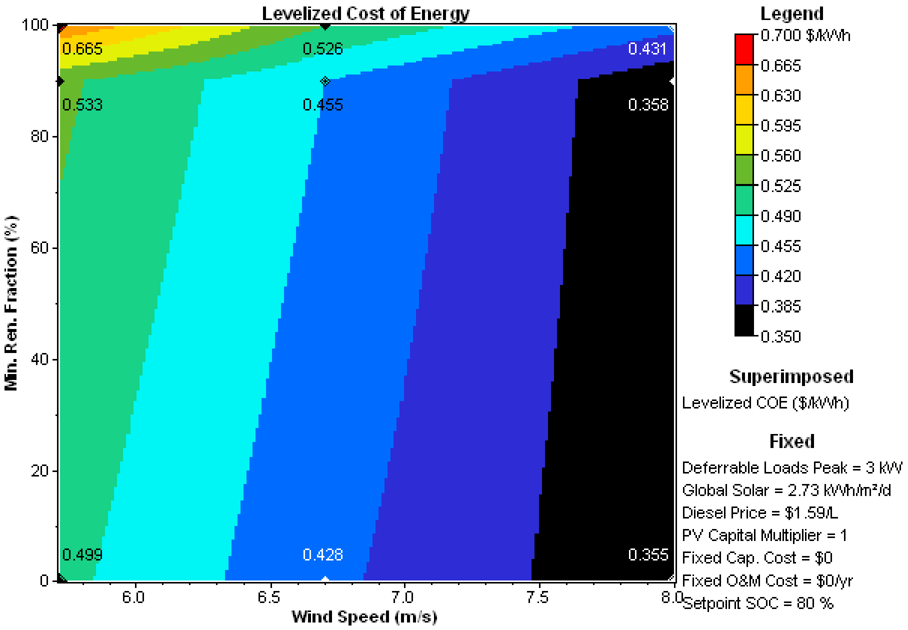


Figure 6.11. *Snap shot of hourly operation of the system.*

Grid is used in this day to supply power spikes and production is sold almost entirely to the grid as there are no storages.

6.1.3. Islanded system results

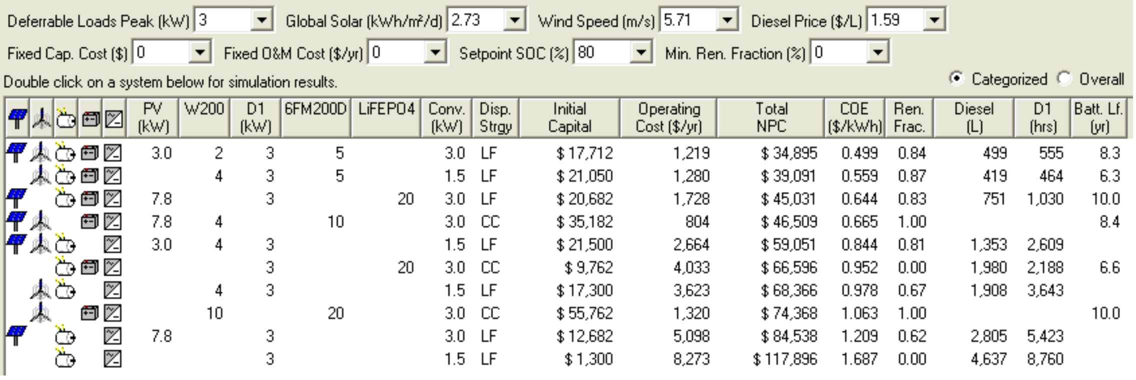
In islanded mode sensitivity values had smaller effect on system configuration. Also energy price is at significantly higher level from 0.35$/kWh to about 0.67$/kWh mostly depending on wind speed the location and renewable fraction desired as presented in figure 6.12



Deferrable Loads Peak = 3 kW
Global Solar = 2.73 kWh/m²/d
Diesel Price = $1.59/L
PV Capital Multiplier = 1
Fixed Cap. Cost = $0
Fixed O&M Cost = $0/yr
Setpoint SOC = 80 %

Figure 6.12. *Affect of wind speed and renewable fraction limitation to energy price in islanded system.*

Figure 6.13 displays results for renewable resources that correspond to Tekniikantie 2 location without renewable limitation and figure 6.15 with renewable fraction minimum at 90%.



Deferrable Loads Peak (kW) 3
Global Solar (kWh/m²/d) 2.73
Wind Speed (m/s) 5.71
Diesel Price ($/L) 1.59
Fixed Cap. Cost ($) 0
Fixed O&M Cost ($/yr) 0
Setpoint SOC (%) 80
Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

● Categorized ○ Overall

PV (kW)	W200	D1 (kW)	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D1 (hrs)	Batt. Lf. (yr)
3.0	2	3	5		3.0	LF	$ 17,712	1,219	$ 34,895	0.499	0.84	499	555	8.3
	4	3	5		1.5	LF	$ 21,050	1,280	$ 39,091	0.559	0.87	419	464	6.3
7.8		3		20	3.0	LF	$ 20,682	1,728	$ 45,031	0.644	0.83	751	1,030	10.0
7.8	4		10		3.0	CC	$ 35,182	804	$ 46,509	0.665	1.00			8.4
3.0	4	3			1.5	LF	$ 21,500	2,664	$ 59,051	0.844	0.81	1,353	2,609	
		3		20	3.0	CC	$ 9,762	4,033	$ 66,596	0.952	0.00	1,980	2,188	6.6
	4	3			1.5	LF	$ 17,300	3,623	$ 68,366	0.978	0.67	1,908	3,643	
	10		20		3.0	CC	$ 55,762	1,320	$ 74,368	1.063	1.00			10.0
7.8		3			3.0	LF	$ 12,682	5,098	$ 84,538	1.209	0.62	2,805	5,423	
		3			1.5	LF	$ 1,300	8,273	$ 117,896	1.687	0.00	4,637	8,760	

Figure 6.13. *Islanded mode results without minimum renewable fraction.*

Figure 6.14 displays the distribution of electricity sources in the cheapest system of previous figure.

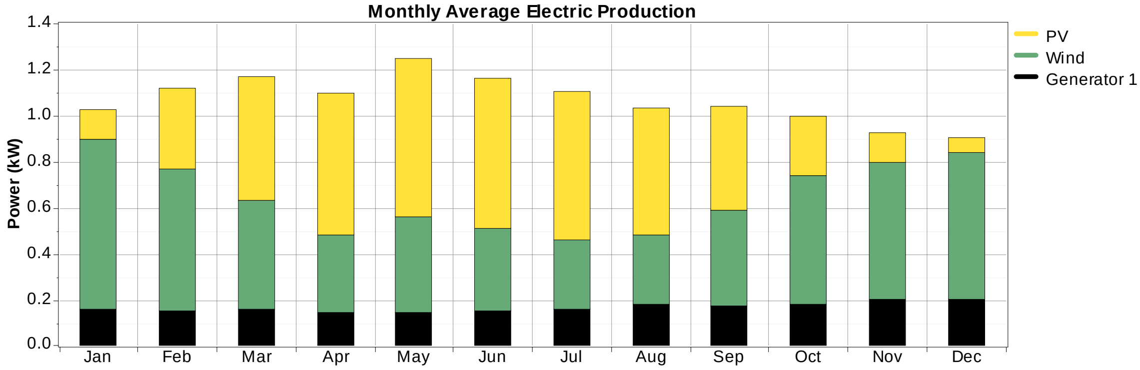
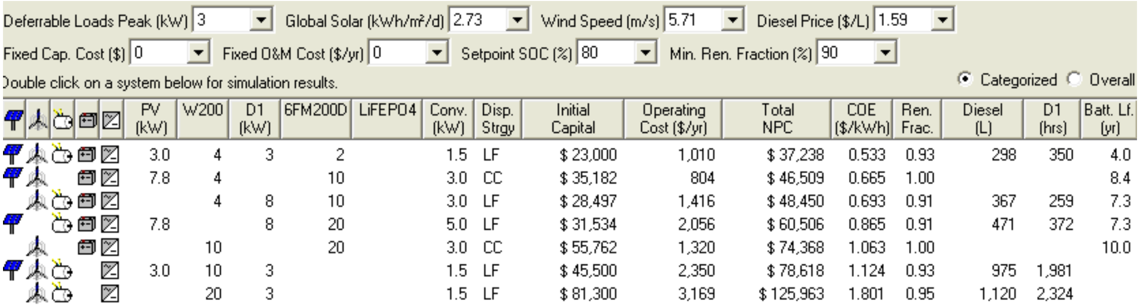


Figure 6.14. *Distribution of electricity sources in cheapest option without renewable fraction limitation*

Even as electric demand is roughly the same during the year, there is more production in summer as solar energy generation is higher.



Deferrable Loads Peak (kW) 3 · Global Solar (kWh/m²/d) 2.73 · Wind Speed (m/s) 5.71 · Diesel Price ($/L) 1.59
Fixed Cap. Cost ($) 0 · Fixed O&M Cost ($/yr) 0 · Setpoint SOC (%) 80 · Min. Ren. Fraction (%) 90
Double click on a system below for simulation results.
● Categorized ○ Overall

PV (kW)	W200	D1 (kW)	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D1 (hrs)	Batt. Lf. (yr)
3.0	4	3	2		1.5	LF	$ 23,000	1,010	$ 37,238	0.533	0.93	298	350	4.0
7.8	4		10		3.0	CC	$ 35,182	804	$ 46,509	0.665	1.00			8.4
	4	8	10		3.0	LF	$ 28,497	1,416	$ 48,450	0.693	0.91	367	259	7.3
7.8		8	20		5.0	LF	$ 31,534	2,056	$ 60,506	0.865	0.91	471	372	7.3
	10		20		3.0	CC	$ 55,762	1,320	$ 74,368	1.063	1.00			10.0
3.0	10	3			1.5	LF	$ 45,500	2,350	$ 78,618	1.124	0.93	975	1,981	
	20	3			1.5	LF	$ 81,300	3,169	$ 125,963	1.801	0.95	1,120	2,324	

Figure 6.15. *Islanded mode results with minimum renewable fraction (RF) of 90%.*

Cheapest system in both cases have load following control meaning diesel is run only at power required by the load and not at full power to the batteries. Cheapest system in figure 6.13 produces about 40% of excess energy and in figure 6.15 about 60%. So it is cheaper to have oversized system in terms of power capacity and consume extra energy in additional loads than use batteries to store energy. Figure 6.16 displays how investment support levels and wind speed affect renewable fraction the cheapest system in an isolated microgrid.

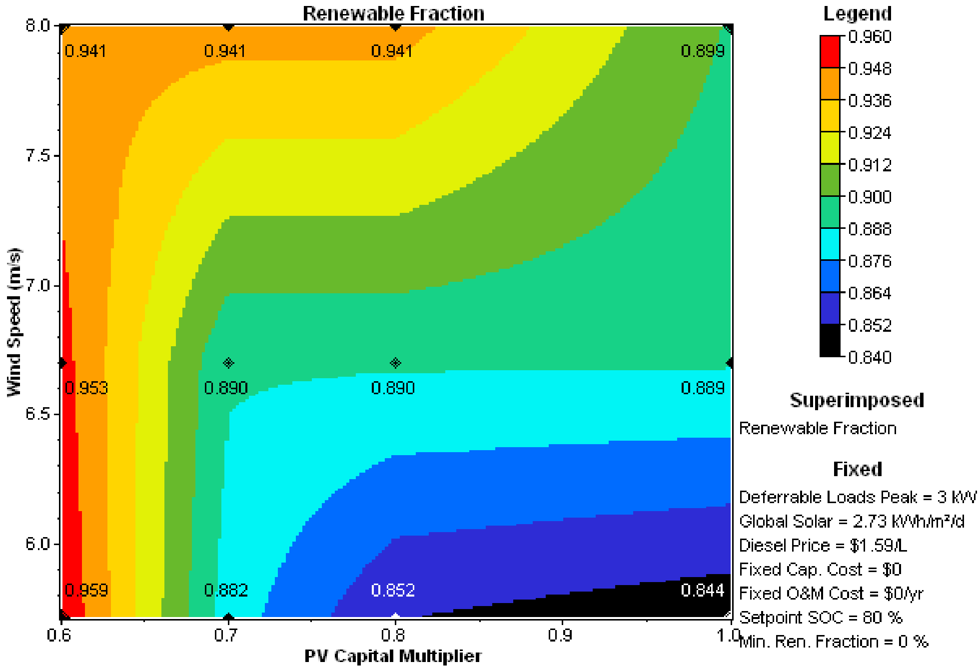
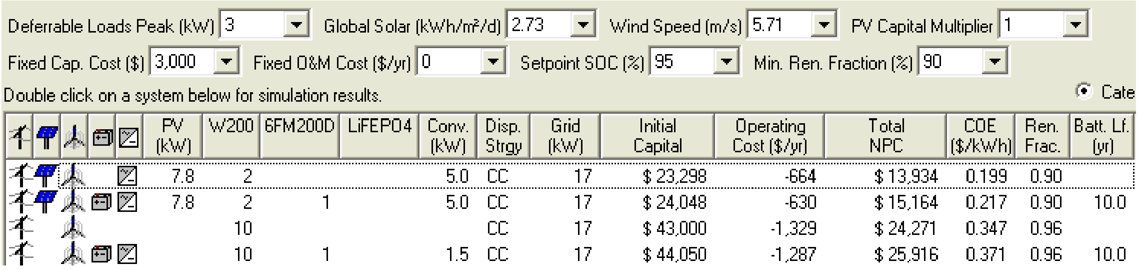


Figure 6.16. *Investment support and wind speed effect on renewable fraction.*

Coloured sections on the figure represent how much renewable energy production is in the cheapest system. Numerical values are also placed into key spots in the figure with black font. PV-capital multiplier represents the investment support level for the whole system (not only PV!) from left to right in cases of 40, 30, 20, 10 and 0% in the horizontal axis. Vertical axis represents average yearly wind speed. Investment support has better results on lower wind speed areas as higher wind speed drives towards clean wind power by it self over diesel generators. This can be seen in the figure as colour (renewable fraction) levels change more dense with respect to investment support in lower wind speeds. Of course supporting systems is questionable if energy production resources are not adequate.

6.1.4. Optimal backup system for maximum 1h interruptions in main distribution system

Both grid-connected and islanded mode results represent two specific situations and are not suited for system that operates in both modes time to time. If microgrid is mostly connected to grid and islanded mode is only started if MV side is down, grid connected mode gives quite accurate results if diesel generator price is added to initial capital costs and assume that use of diesel is so small that operative costs can be neglected. Figure 6.17 represents this situation.



Deferrable Loads Peak (kW) 3
Global Solar (kWh/m²/d) 2.73
Wind Speed (m/s) 5.71
PV Capital Multiplier 1
Fixed Cap. Cost ($) 3,000
Fixed O&M Cost ($/yr) 0
Setpoint SOC (%) 95
Min. Ren. Fraction (%) 90

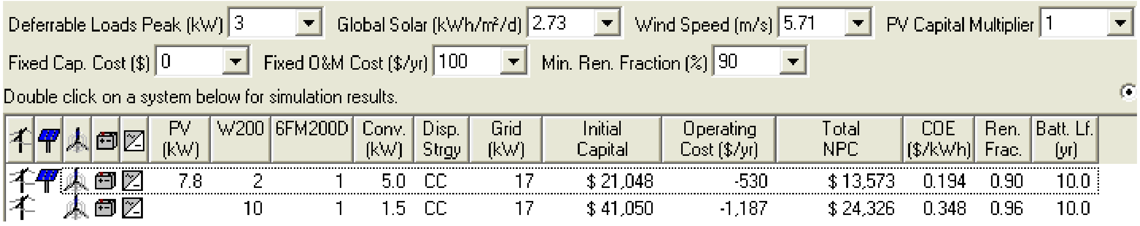
Double click on a system below for simulation results.

● Cate

PV (kW)	W200	6FM200D	LiFEPO4	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
7.8	2			5.0	CC	17	$ 23,298	-664	$ 13,934	0.199	0.90	
7.8	2	1		5.0	CC	17	$ 24,048	-630	$ 15,164	0.217	0.90	10.0
	10				CC	17	$ 43,000	-1,329	$ 24,271	0.347	0.96	
	10	1		1.5	CC	17	$ 44,050	-1,287	$ 25,916	0.371	0.96	10.0

Figure 6.17. *Optimal grid connected system with diesel capital costs added.*

Maximum interruption of 1 h can be assumed, as longer interruptions than that were very rare in 2009 especially in urban areas [98].Average yearly load is 570 W, but average hourly demand of 1 kW is assumed for the worst case in interruption. One MD200 battery has capacity of 2.3 kWh so that will be enough. Now the yearly simulation is run so that one MD200 battery has to be connected to system. Figure 6.18 displays the result of this simulation.



Deferrable Loads Peak (kW) 3
Global Solar (kWh/m²/d) 2.73
Wind Speed (m/s) 5.71
PV Capital Multiplier 1
Fixed Cap. Cost ($) 0
Fixed O&M Cost ($/yr) 100
Min. Ren. Fraction (%) 90

Double click on a system below for simulation results.

PV (kW)	W200	6FM200D	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf. (yr)
7.8	2	1	5.0	CC	17	$ 21,048	-530	$ 13,573	0.194	0.90	10.0
	10	1	1.5	CC	17	$ 41,050	-1,187	$ 24,326	0.348	0.96	10.0

Figure 6.18. *Optimal grid connected system with battery backup power for 2h and RF 90%.*

It can be seen that battery backup system for about one hour interruption costs about the same as to have a diesel generator as backup.

6.2. Summary and conclusions of HOMER® simulations

HOMER® software is a good tool for small-scale power system optimization. HOMER® software used in simulation was the free 2.68 beta version. Newest version has some minor things fixed but they did not affect the simulation of these two systems. Newest version supports flywheels as energy storage to supply peaks but other than that, all features are included in 2.68 version. HOMER® does not support multiple types of solar panels in same simulation and it would have been interesting to try also traditional higher efficiency silicon or other panels as the capacity of amorphous panels was limited by area to 7.8kW. Also HOMER® does not support the option to price the electricity differently for every generation type. So in grid connected mode it has to be assumed that every type is on the same level with sell back price. It should be noted that HOMER® does not allow very advanced load management so e.g. electric car load scheduling and comparisons to normal grid could not be done.

6.2.1. Technological results

Wind speed and solar radiation have strong affect on optimal power system configuration of microgrid with grid-connected systems. The affect is relatively smaller in islanded microgrids; systems without option for grid connection. Continuous islanded mode operation is considerably more expensive compared to grid connected. Reasons for this are that there is no revenue from excess electricity produced and energy storages or other regulation capacity is needed compared to grid connection where local balancing is optional.

6.2.2. Economic results

Planned tariff level of 83.5 €/MWh was inspected in simulations and it would seem to be enough for production in microgrids. If solar electricity is left without support, support of wind power will drive into more expensive systems as solar electricity is cheaper alternative in some cases. Wind based production starts to be cheaper alternative compared to solar power when yearly average wind speed exceeds about 6.5 m/s in the studied case. This is the limit in case where solar and wind power have same support level.

6.2.3. Backup power comparison results

Diesel and lead acid battery based backup power systems were compared in simulations. Maximum interruption time of one hour was taken into consideration. Battery backup system was a slightly cheaper alternative against generator in simulations. Of course the generator can supply as much energy as the fuel tank capacity allows, but noisy diesel generator is not very elegant choice compared to battery option.

7. PROCEEDING TOWARD MICROGRIDS

Microgrids have been researched for some time now but there are not very many systems implemented that can be called microgrids in community sector of Finland. A survey was sent to survey the current situation and future visions, opinions of backup power, microgrids and small-scale production as DSOs see it. Also concept proposition of microgrid is presented which tires to avoid some issues involved with microgrids that arose in survey and in this thesis.

7.1. Microgrid survey

A survey about production in LV grids and backup systems installed in Finnish electricity grid was sent to 89 distribution system operators which includes all except Helsinki-Vantaa airport. When the survey was sent, there had been a large wave of strong winds and storms in most parts of the country and electric grids were down in many places. This showed in survey two ways. As many distribution operators were busy to get grids back online, answer percentage was low, about 24%. But also DSOs replied that they would like to see more clients to have backup power in case of major failures in electric system. A translated copy the survey can found in appendix 3. (Original is in Finnish)

About 70% of distribution system operators that answered to the survey are interested in microgrids. Reasons for interest include:

- General knowledge about MGs as number of MGs is estimated to increase with energy price
- To improve reliability of the grid and reduce need to backup connections
- Business opportunities
- To help in major failures
- Customers can buy new technology just out of interest
- Electric quality affects
- Rules, legislation, protection
- Microgrids have to be taken into account in long term distribution system design

Reasons for not to be interested includes,

- Too much problems with control automation and reconnection after islanded mode

- Politics over estimate advantages in small-scale production
- Microgrid would have been implemented long time ago if there were major benefits
- Lack of legislation to allow DSO to take part actively in small-scale production systems
- Lack of interest for customers to buy equipment good enough to keep electric quality good.
- Problems with protection and safety
- Lack of clear legislation concerning distribution of benefits, costs and responsibilities.
- Installation of small-scale production has been wild and no proper reports have been left to DSO about production units.
- Problems with AMR devices

Clearly most DSOs are interested about microgrids and believe that they are a component that has to be taken into consideration in design of the future distribution grid. Bad experiences with small-scale production and islanded systems is the main reason for not to be interested according to survey. People have not always informed DSOs production about units installed to grid and things have been getting out of control so much in fact that couple of DSOs won’t allow any production at this point in LV grid. Also electric quality of some of the devices installed is not very good and gives problems to LV grid. Some DSOs did not want to comment on their views about microgrids as the role of DSO is seen neutral in these matters.

Survey also reveals that in major part of distribution grids, there are customers with backup units or backup service provided by the DSO. Most of these clients are farms, hospitals, communication links and large buildings like markets. Backup power in these systems ranges from couple of kilowatts to tens of megawatts. Also some areas within cities could be operated in islanded mode in theory but this has never been tested. Some DSOs also reported that lightning protection of some wind turbines has failed in recent thunder storms.

7.2. Energy centre microgrid concept and guidelines

As this thesis shows, microgrid involves many factors and there is no right system for every case. However general concepts for systems can be presented. This chapter describes one concept which tries to solve issues that arose in the thesis and survey. Fast integration to current urban distribution system, low price and using existing technology are given most of the weight in this concept.

7.3. Structure

This concept uses central power production model where energy production and storage devices are connected to main bus of the LV side of distribution transformer. Figure 7.1 represents structure of the system.

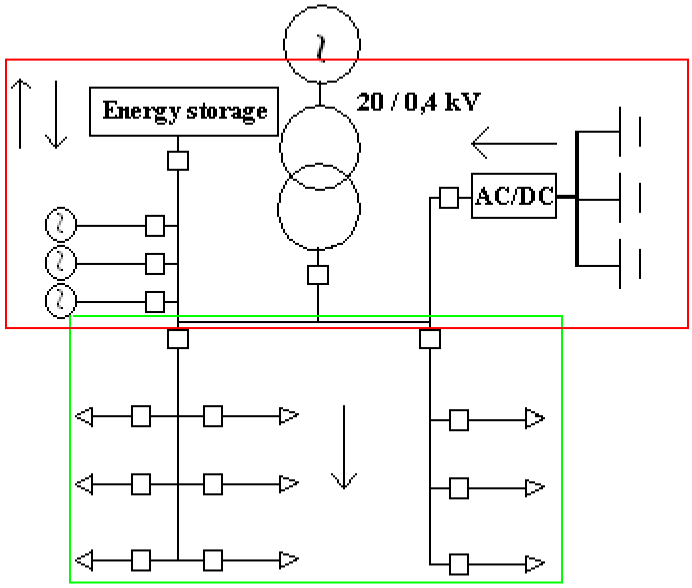


Figure 7.1. *Microgrid concept with centralised energy system.*

Green area highlights part of the grid that can be left as it is. The area highlighted in red, is part that can be called energy centre, which contains production units and storages. This centralised model can be used in different versions of island operation capability. Following list represents some options.

- Backup microgrid: Microgrid power production and operation is designed only for fault situations in mind.
  -Microgrid storages are recharged from the grid earlier to cope with short problems and e.g. diesel generators are started after battery system runs out. Battery capacity is selected to suit typical load level and to economically optimal time to switch to diesel.
  -Can be owned by DSO to provide only backup power if law is changed about requirement for backup power to be portable
- Production rich microgrid: Microgrid is used to supply power distribution system and has only short capability to operate as island.
- Microgrid with load controllers: Microgrid has production, storages and load control possibility to operate as island continuously if some loads are controlled e.g. like presented in chapter 4.3.6.

7.4. Protection equipment

Standard fuse protection will work in consumer side as power flow direction remains the same as it currently is. Protection devices of generation and storage units are same protectors that are currently demanded by the EN 50438 standard for micro generators. DC production units and storages can also share same DC-bus and inverter if possible.

To recognise fault in distribution system, signal voltage method described in chapter 3.6.3 can be used if this technology can be more reliable than ROCOF methods that are used in most devices designed for microgrid LOM-protection. System can be upgraded later to have load controller, which manages connection and disconnection of loads so that islanded operation can be maintained longer. Load priority tables presented in chapter 4.3.6, can be created to classify controllable loads.

7.5. Choosing production and storage devices

Careful planning is needed for finding the most suitable unit configuration, as it depends on many things like, availability of generation resources, governmental policies, demand for maximum island operation time and islanding level. Simulation applications like the one used in chapter 6 can help in this task. Also when more systems are installed, they can be used as references and to improve simulation accuracy and tailor system to better performance. As current plans are to give more support to bio energy and wind power, they are strong contenders to supply the power in microgrid the most economical way.

The need for storage devices and their type depends on whether electric quality and backup power can be maintained with production units and controllable loads selected. Some microturbines e.g. can be used for voltage control and also supply current peaks as their rotating mass acts like flywheel energy storage. Other example is production system consisting mostly of uncontrollable sources like wind power and solar energy, which means energy storage system is needed or advanced load control must be implemented.

7.6. Power quality control

Power quality and stability control schemes depend on devices selected. Most of the systems available on markets today are based on some kind of master and slave scheme. Interconnectability of the devices is very important in power quality control and also of course for general system operation. Currently manufacturers mostly have their own compatible list of devices to island operation. System manufacturers for microgrid type of systems include e.g. Schneider Electric, SMA Solar technology AG, Backup Power Source inc, Steca and Outback Power. Connection of devices from two manufacturers is not a plug & play job but hopefully it is in the future with standardisation.

Unbalanced load is problematic for microgrids. Some systems available have possibilities for load switching between phases. Some systems have independent inverters for each phase. Also research has been done with 4-leg inverters with controllable neutral point voltage and laboratory results for this kind of unbalance control have been promising. However neutral point voltage control could cause problems for grounding as current regulation states that LV grid has to be grounded at neutral point of distribution transformer and this would include energy storage in islanded mode. Neutral point grounding could interfere with 4th leg neutral point voltage control in unbalanced load situation. All devices in markets should have adequate filters but it has to be researched if some loads need filtering because otherwise they would interfere with microgrid too much.

This concept recommends using heat pumps for unbalance correction. Heat pumps have to be placed evenly on every phase (a, b, c) on the microgrid area. Heat pump is started on phase that has lowest load on the grid. When all pumps are required to be on for heating, they are run still on intervals with half pumps running and half resting for unbalance control possibilities on every phase to increase or decrease load. In summer pumps are used for cooling on similar topology. Communication to heat pumps can be done with AMR-meters or with pump’s own communication technology if possible. Additional controllable loads can be placed in first demos to main bus for balance control before heat pump system is operating adequately and also when additional capacity is needed. Other additional controllable load options can be roof heaters to manage snow problems, electrical heating and warm water systems.

7.7. Where this type of microgrid the most suitable to be used?

One would say that microgrids are not needed in urban areas as reliability of a distribution system is very high in these areas. However if location is planned to have own energy production or has a lot of critical loads, it is wise to be build a microgrid to ease the possible problems. This microgrid concept of centralised energy system is good alternative for places that have suitable location for energy centre. This energy centre containing production and possible storages can be placed on top of large buildings close to distribution transformer so that no extra land area is required. Roof space can be used to place wind turbines and solar panels and cellar for noisier production units like diesels and gas turbines. Also if area has very dense housing, centralised model is good option if production units are going to be placed close to each other anyway; there is no need to complicate things with multiple power flow directions.

7.8. Management and ownership

First big questions that have been raised for implementing microgrids in Finland are: Who is going to build them and how management and ownership issues are handled. Alternatives for these issues were presented in chapter 5. For the first implementations of microgrids, the initiative has to come from DSOs in Finland. DSOs have expertise in these matters and legal responsibility over managing LV grid safety currently. Units are not allowed to be owned by the DSO, so this concept recommends microgrid clients to form a producer's cooperative society to own the units and select one 3rd party expert to make sure that DSO manages the grid as it is agreed on. DSO will get income from grid maintenance and installation related tasks and of course lesser outage costs.

This thesis recommends that the law about requirement for backup power provided by DSO to be portable is changed to allow permanent backup installations. DSOs especially in rural areas can improve reliability of current grid by offering microgrid service with e.g. diesel installations to LV-transformers.

7.9. Advantages and disadvantages

Centralised energy system can result in financial savings if larger units are used instead of many small as presented in chapter 3.3.1. However for pilot projects, smaller units should be used for more flexible testing. The major advantage of this centralised concept is to get over the most of protection problems that are a result from distributed unit placement in LV grid. A lot of research has been done to solve protection issues but still today DSOs see protection as major problem in LV DG. Of course some day this could be solved but until that day, this protection issue will continue to postpone microgrid projects and other microgrid development. So advantage of energy centre model is that it allows quick integration to current energy system. Energy centre model also has safety advantage as all the production is in same place, electricians know where the production is and won't have to run through the entire area to use manual switches if needed.

Disadvantages for centralised system are decreased reliability due to the fact that all production is placed in one place. Also reliability of many multiple devices is lost if large units are used for cost savings. Architectural planning might create problems for energy centres if there is no building or other areas that can "mask" the units. Also a suitable system for loss of mains (LOM) protection has to be found if current devices available are not reliable.

7.10. Summary

A survey about microgrid, backup power and small-scale production was sent to DSOs. Clearly most DSOs are interested about microgrids and believe that they are a component that has to be taken into account in design of the future distribution grid. Bad experiences with small-scale production and islanded systems were two main reasons for not to be interested in microgrid according to survey. Also an issue with protection and safety of systems for distributed generation was also seen as big problem. Some DSOs did not want to comment on their views about microgrids and role of DSO is seen as neutral in these matters.

Concept idea for first microgrids presented to solve issues with protection and safety and to give recommendations on ownership and operative structures. This energy centre concept model offers cost friendly option for microgrids with fast integration possibility to current distribution system. This concept recommends DSOs to take initiative in first microgrid installations. System design is based on connecting all production and storage units to LV main bus of the distribution system. This allows use of standard fuse protection in feeders and households. Other advantages include possible equipment savings because larger units and better worker safety as production area is one identifiable location. Unbalance between phases is controlled using single phase heat pumps, warm water systems, snow melting systems and other suitable loads. The most significant disadvantage is reliability loss as equipment is placed close to each other and because possibly fewer units. Initial systems are better to be built with smaller units for more testing options.

8. CONCLUSIONS

The idea of microgrids, self-sufficient energy communities has become more feasible as energy production in low voltage grids has been increasing. Microgrid utilises smart communication and operating practises to save energy, money and emissions. Largest capacity of microgrids is estimated to be in housing sector in Finland [1]. Multiple of different configurations for microgrid can be used depending on the surrounding environment, willingness to use renewable energy sources and control and management possibilities desired. The technology for microgrids exists, however the implementation practices are not fully standardised yet and this creates problems and prejudice against microgrid concept.

A survey about small-scale electricity production and backup power was sent to distribution system operators in this thesis. The survey indicates that most of DSOs are interested in microgrids and will take possibility of them into account in grid design. Reasons for interest include e.g. reliability improvements, increase of MGs seems inevitable, electric quality affects, protection issues and clearing out rules in small-scale production legislation. Reasons that make microgrids uninteresting were seen to be e.g. bad experiences with backup automation, protection problems, poor micro generation equipment bought by clients, lack of clear legislation, unauthorized installation of micro generators (DSO is not aware) and problems with AMR devices.

Energy production, energy storages, demand side management, stability control and protection are the most important technical factors in microgrids. Microgrid offers possibilities to improve power quality in systems that have much hardly controllable energy production like wind power and solar power or demanding consumption like electric cars and heat pumps. Also active demand side management improves energy efficiency and save money to microgrid clients and DSO. Public sector can also get advantages in reduction of greenhouse gas emissions and improve self-sufficiency of the energy sector.

The major factors of any system are the financial and legislative side and their co-operation. Renewable production in Finland is planned to be given feed-in tariff system. Idea of this is to make wind power and other emission friendly production profitable business and in that way to reduce greenhouse gas emissions to achieve the targets set for Finland by European commission. The big question is how microgrids and other small-scale production are treated by this support system. Can microgrid be accepted for the tariff system and what kind of systems can get investment support? Legislation does not currently allow islanded operation of public grid, so use of microgrids has to be taken a look by legislation also in this point. Other financial question is how costs and income are distributed between parties. Legislation also has to define the responsibilities of different parties so that everything is safe and nobody gets “free lunch”. Following obstacles have to removed for utilisation of microgrids:

- Standardised solutions for protection and safety
- Clear distribution of responsibilities and financial factors
- Clear legislation with microgrids
- Practical experience is needed

Microgrid systems have many strengths (S) and opportunities (O) but also weaknesses (W) and threats (T) related to them. Table 11 displays a classic SWOT analysis of the most significant ones of these factors.

Table 11. *SWOT analysis of microgrid.*

Strengths:	**Weaknesses:**
-Provides means to ease DG burden on distribution system -Saves emissions for power production -Improves reliability of electric system -Can improve self-sufficiency of energy sector	-Immature technology and lack of standardisation -Lack of practical experiences -Implementation relies mostly on governments financial support for renewable energy sources
Opportunities: -New business possibilities for managers, aggregators, equipment manufacturers and DSOs.	**Threats:** -Utilisation of standards fails -Small-scale production is left outside financial support structure -Scepticism wins over curiosity

Year round system simulation and optimisation for microgrid was done with HOMER® software which optimised system configuration and control hourly. Results indicate that,

- Renewable resources have strong effect on optimal power system configuration in grid connected systems but relatively smaller in islanded systems.
- To use microgrid always in islanded mode is considerably more expensive to grid connected system as there is no revenue from excess energy.
- 70 € seems to be a reasonable yearly charge for taking part in electricity markets in inspected case. It would take about 40 clients so that current Nord Pool fee of 3000 € would split into 75 € portions.

- For the consumer who can have a solar and wind power based microgrid system, wind power starts to be more profitable alternative if average wind speed exceeds about 6.5m/s. When average wind speed is below 6.5 m/s, solar energy seems to be cheaper option compared to wind power. This statement is valid only if both sources get same financial support level
- For small interruptions in distribution system, a battery backup system is slightly cheaper alternative against generator in the inspected case.

One alternative concept for first microgrids in Finland was presented also in this thesis, an energy centre microgrid model. Energy centre model offers cost friendly option for microgrids with fast integration possibility to current distribution system. This concept recommends DSOs to take initiative in first microgrid installations. System design is based on connecting all production units and storages to LV main bus of the distribution system. This allows use of standard fuse protection in feeders and households. Other advantages include possible savings because larger units and better worker safety as production area is one identifiable location. Unbalance between phases is controlled using single-phase heat pumps, warm water systems, snow melting systems and other suitable loads. The most significant disadvantage is reliability loss as equipment is placed close to each other and because of possibly fewer units but initial systems should probably be built with smaller units for more testing options.

It has been estimated that renewable and small-scale production will continue to increase and many DSOs are current involved in utilising some Smart Grid technologies to their grids. Also construction of communities aiming for own energy production has been started in Finland. This makes fairly friendly ground for microgrids. Much still depends on practical experiences gain by DSOs, 3rd party operators and of course by microgrid clients from the installed microgrid systems and small-scale production.

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APPENDICIES

Appendix 1 :

SFS-EN 50160 gives limits for:

- Voltage frequency
- Voltage level
- Voltage deviations
- Quick voltage deviations: Magnitude, flicker index
- Voltage dips
- Short interruptions
- Long interruptions
- Temporary over voltages between conductor and ground at base frequency(50Hz)
- Transient over voltages between conductor and ground
- Voltage asymmetry
- Harmonic voltage amplitudes
- Unharmonic voltage amplitudes
- Grid signal voltages (if electric lines are used for data transmission)

Table A1 *Electric quality classifications [36] [37].*

Voltage property	High quality	Normal quality	SFS-EN 50160	Attention
Frequency	50Hz +/-0,5%	50 Hz +/-1%	99,5% of the time 50 Hz 1%, and always +4% /-6%	Measurement in 10s averages
Voltage deviation	100% of the time 220-240 V and as average 225 – 235 V	207-244 V	95% of the time between ±10% And always +10%/-15%	RMS value in 10min sessions during one week

Quick voltage deviations (flicker)*	$P_{st,3max} \leq 1$ $P_{lt,max} \leq 0{,}8$	$P_{lt,max} \leq 1{,}0$	95% of the time $P_{lt,max} \leq 1{,}0$	
Harmonics	THD ≤ 3%	Un ≤ values in table A2 and THD ≤ 6%	95% of the time, Un≤ values in table A2 and THD ≤ 8%	RMS value in 10min sessions during one week
Asymmetry	$u_{uSh} \leq 1\%$	$u_{uSh} \leq 1{,}5\%$	95% of the time $u_{uSh} \leq 2\%$	RMS value in 10min sessions during one week
Signal voltages	figure A1	figure A1	99% of the time under the values of figure A1	Measurement in 3s sessions during a day

*Flicker is calculated by formula expressed in standard IEC 61000-4- 15:2003

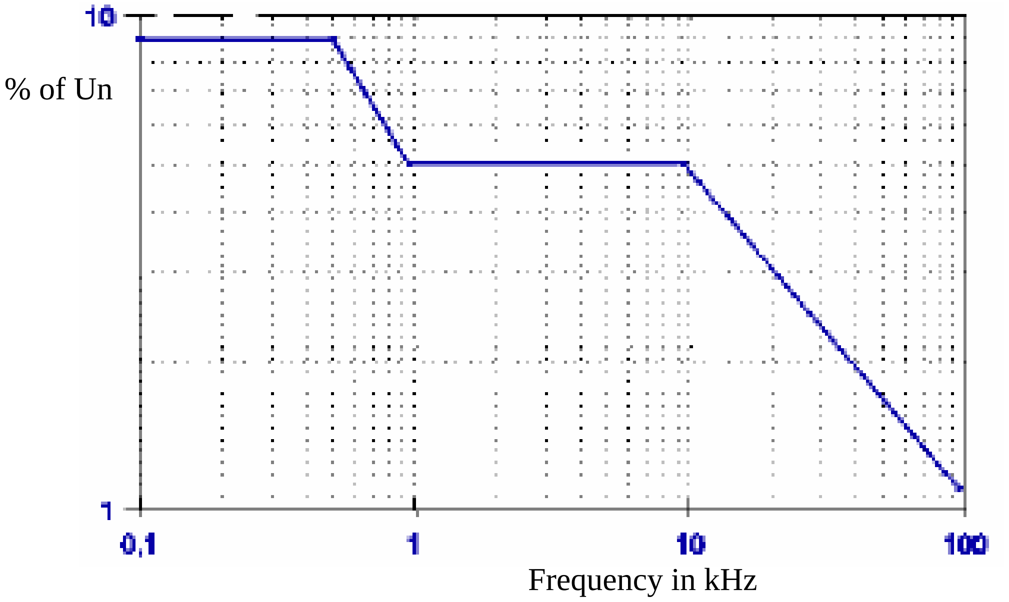

Figure A1 *Signal voltage levels [37].*

Table A2 *Maximum harmonic voltages to number 25 [37].*

Odd harmonics				Even harmonics	
Others		Multiples of three			
Number (n)	Percentage of Un	Number (n)	Percentage of Un	Number (n)	Percentage of Un
5	6%	3	5%	2	2%
7	5%	9	1,5%	4	1%
11	3,5%	15	0,5%	6 - 24	0,5%
13	3%	21	0,5%		
17	2%				
19	1,5%				
23	1,5%				
25	1,5%				

Appendix 2

Current network recommendation by Finnish Energy industries YA9:09 is based on DG units connection to DSO owned grid. The recommendation states [30]:

- Reasonable connection cost and no costs related to strengthening the grid if unit is smaller than 2 MVA. Protection costs can be directed straight to unit owner if protection system needs update with installation.
- If production is smaller than consumption in connection point, normal load point connection charges apply.

- If production is higher than consumption connection charge is sum of normal connection point charge and the production point charge related to amount of power fed to the grid.
- Maximum feed-in charge to grid is 0,7€ / MWh
- No cost related to own usage.
- Metering cost can be higher than normal load point charge as balance sheet task is double if there are measurements for load and production.

Appendix 3

Riku Pasonen Survey 2.8.2010
VTT Electricity and Heat systems
Tekniikantie 2 PL 1000 02044 VTT

Distribution system operators

Dear distribution system operator.
I am working on my Master of Science thesis about microgrids in VTT. The goal of this survey is to investigate how much there are areas that could have microgrid and possible future new areas as well. Microgrid in this survey is defined as LV-grid that has own production and regulation capacity so that it can operate as island, if needed. Results of the survey are presented as sum up in the thesis and answers of specific company are not revealed.

Current state

1) Are there parts in your LV-grid that have significant amount of small-scale production?

2) Are there clients with backup systems in your grid? (Can operate as island)

2b) If there are, what kind of clients? (Size, rural/urban/city, production)

Future

3a) Are you aware of any new suitable areas for microgrid? (E.g. new housing areas, house fair)

3b) If there are, what kind of?

4) Do microgrids interest you at all? Why and why not?

Yours sincerely
Riku Pasonen
VTT