Open your mind. LUT.
Lappeenranta University of Technology

FACULTY OF TECHNOLOGY
LUT ENERGY
ELECTRICAL ENGINEERING

MASTER'S THESIS

OPERATIONAL REQUIREMENTS AND CONTROL OF ISLAND LVDC MICROGRID

Examiners Prof. Jarmo Partanen
M.Sc. Tero Kaipia

Author Anton Shevchuk

Lappeenranta 24.05.2012

Abstract

Lappeenranta University of Technology

Faculty of Technology

Electrical Engineering

Anton Shevchuk

Operational Requirements and Control of LVDC Microgrid

Master's thesis

2012

60 pages, 30 pictures, 0 tables and 1 appendix

Examiners: Professor Jarmo Partanen and M.Sc. Tero Kaipia

Keywords: LVDC microgrids, distribution networks, island operation, low voltage, DC system, island PV generation.

The development of power electronic devices and technologies in renewable power production open possibilities for implementation the low voltage DC distribution systems in concern with renewable sources if energy, especially with photovoltaic generation. It can become one of the most beneficial solution in island operating conditions.

This master's thesis is focused on the solving actual problems related to the development of novel LVDC microgrid for islanding positioning, such as formulation of functional and operational requirements for the system, finding effective ways of control for proposed microgrid. In present work most attention is paid for application of PV generation in Island LVDC system, however it doesn't restrict the utilization of alternative renewable power sources.

Аннотация

Технологический Университет г. Лаппеенранты
Технологический Факультет
Кафедра Электротехники

Антон Шевчук

Функциональные Требования и Управление Низковольтными Сетями Постоянного Тока

Магистерская Работа

2012

60 страниц, 30 иллюстраций, 0 таблиц and 1 приложение

Научные руководители: Проф. Ярмо Партанен, Теро Каипиа.

Ключевые слова: низковольтные распределительные сети, сети постоянного тока, островное функционирование, фотоэлектрические системы.

Развитие силовой электроники и технологий, связанных с применением возобновляемых источников электроэнергии, открывает возможность использования низковольтных распределительных сетей постоянного тока.

Данная работа посвящена решению актуальных проблем, связанных с разработкой инновационной низковольтной распределительной сети постоянного тока в условиях островного функционирования. Основное внимание уделяется разработке системных и функциональных требований для данной системы и обоснованию наиболее рациональных методов управления. В работе сделан акцент на применение фотоэлектрических систем в качестве основного источника электроэнергии.

Table of contents

Appendices:

Abbreviations and symbols

AC	Alternative Current
DC	Direct Current
DG	Distributed Generation
EOL	End-of-Life Capacity
EV	Electric Vehicle
HVDC	High Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
IT	Isolation Terre
LV	Low Voltage
LVDC	Low Voltage Direct Current
MDOD	Maximum Depth of Discharge
MDDOD	Maximum Daily Depth of Discharge
MMS	Microgrid Management System
MV	Medium Voltage
PI	Proportional Integral
PV	Photovoltaic
RMS	Root-Mean-Square
SAIFI	System Average Interruption Frequency Index
SOC	State of Charge
STC	Standard Test Conditions
THD	Total Harmonic Distortion
TN	Terre Neutral

ε	annual payment
η	coefficient of power conversion
k	efficiency coefficient
μ	membership function
π	constant

ρ	air density
A	area
B	linguistic variable “Battery charge”
C	price
d	days
E	efficiency of wind utilization
K	correction coefficient
L	linguistic variable “Load forecast”
P	active power
R	radius
V	wind speed
W	linguistic variable “Weather forecast”

Subindexes

a	annual
bat	battery
e	electric
h	hour
h,pv	photovoltaic by hour
i	index
Jun	June
m	monthly
max	maximum
nom	nominal
pk	peak
pv	photovoltaic
rel	relevant
total	total value

Acknowledgments

The work was carried out at Lappeenranta University of Technology (LUT) during 2011/2012 studying period. I would like to express my sincere appreciation to the people who helped me with presented work.

At first, I would like to thank to Professor Jarmo Partanen for the possibility of work under your supervision and M.Sc. Tero Kaipia for the great help and support.

I want to tell thanks to staff of Department of Electrical Engineering of the Saint-Petersburg State Mining University and especially to my supervisor Prof. Boris Abramovich for that knowledge and experience which they gave me.

Special thanks to Vladimir Borzenkov who provided me the opportunity to study in Lappeenranta.

I wish to express my thanks to my parents for love and support me in difficult times and to my darling Mary for understanding and patience.

1 Introduction

Nowadays the LVDC distribution system is one of the new primary technological innovations in electricity distribution. The utilization of the LVDC systems opens a lot of possibilities in developing power supply systems and also has considerable impacts in such ways as enhance of the reliability, power quality and energy efficiency of the electricity distribution system. By using the allowed DC voltage range (determined by LVD 2006/95/EC), it is possible to improve mentioned network parameters, the benefits of which are directly visible to the customers.

Expansion of power electronics applications, upgrowth of renewable sources of energy, especially the increase in small-scale distributed generation, and development of LVDC microgrids makes possible to solve one of the most important issue for the isolated networks such as sustainable power supply with minimization of total costs and providing maximum of power efficiency. This challenge especially actual in case of island location and north regions where exist problems with delivering energy.

At the present stage of development of low voltage DC distribution networks the issues which are related to the voltage control and power balance control are particularly relevant and important, because of strict dependence between such challenges and quality of electric supply, especially in isolated operation.

Another important issue is to study problems related to the determination of the most effective system setup for the island LVDC network from technical and economical points of view simultaneously, and also find the answer for the demand response problem: which kind of control mechanism is more beneficial – priced-based or technical-based? This master's thesis focused on solving mentioned above problems and bases on comparison of different alternatives and computer modeling.

1.1 Main objective and research tasks of the thesis

The main objective of following work is to define operational requirements and develop structure for power balance control and voltage control in LVDC island network system which maintains maximum of power efficiency in the distribution area by the optimisation of use of demand control, battery charge control and generator control as well as maintains minimum of total costs of the system.

In carrying out theoretical research aimed at the study and development power balance control algorithm for low voltage DC distribution networks, following research tasks:

1. Literature survey of microgrids
   - Technical construction alternatives for AC and DC microgrids (pros and cons), control methods and automation systems;
   - Modelling of the behaviour of consumption, generation and state of battery charge in microgrids.
2. System structures and operational requirements
   - Determination of the operational requirements for LVDC microgrid and functional requirements of customer, generation and storage interfaces (converters);
   - Electric safety and fault protection schemes;
   - Definition of general level system concept and equipment layout – system setup that maximises the energy efficiency and minimises the total costs.
3. Control and automation system
   - Requirements and realisation for DC-network voltage control;
   - Definition of power balance control algorithm that optimises the use of demand control, battery charge control and generator control;
   - Analysis of the robustness of the control system;
   - Requirements for the communication between the active components in the system and needs for system supervision.

1.2 Research methods

Methods of electrical circuits theory, automatic control theory, numerical methods of solving equations were used in present study to decide problems related to the development of the novel LVDC microgrid.

Mathematical and computer modelling were used also to implement and study the model of low voltage DC distribution network equipped with photovoltaic power generation.

In present work the possibility of utilization of Fuzzy logic methods is described. Theory of fuzzy sets could be proposed for solving problem with price determination in LVDC microgrid.

2 DC microgrids as the alternative for AC distribution systems in Island conditions

Nowadays the low voltage distribution networks designed mainly as a three-phase alternative current (AC) systems with basic voltage level 0.4kV. However, the European Union low voltage directive (LVD 72/23/EEC), which defines the boundaries for the low voltage levels, determines voltage rating between 50-1000V for AC systems and 75-1500V for DC systems. In that case, the utilization of LVDC microgrids with 1500V as a nominal voltage level, has good perspectives and opens new possibilities for future network developing, such as utilization of a public low voltage DC distribution network instead of traditional AC distribution system (Fig.2.1), due to highly meaningful advantages which will be discussed below.

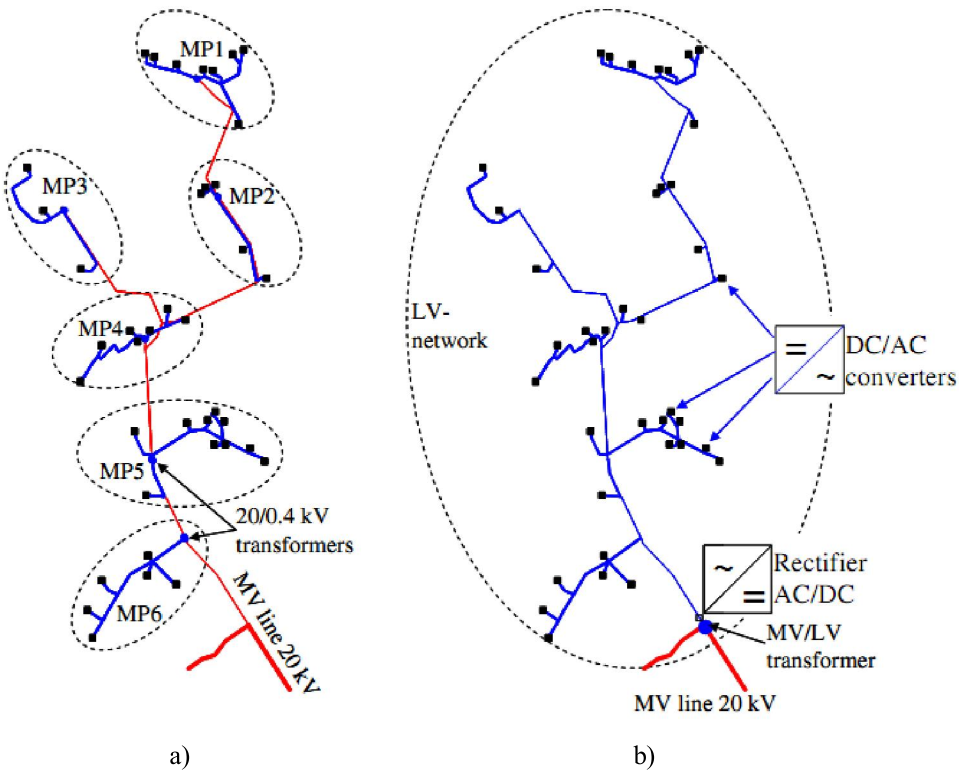

Fig. 2.1. Utilization of LVDC distribution network (b) instead of traditional AC distribution systems (a). [14]

The studies show [11], [12] that different power-electronics-based DC solutions have a significant application potential in rural areas and in the electricity distribution networks in centres of urban areas. As one of important moments it seems perspective to implement such technologies in isolated network systems, such as in island operating networks, especially in cases of application of renewable sources of energy, such as for example PV power systems, and accomplishment of distributed generation (Fig2.2.).

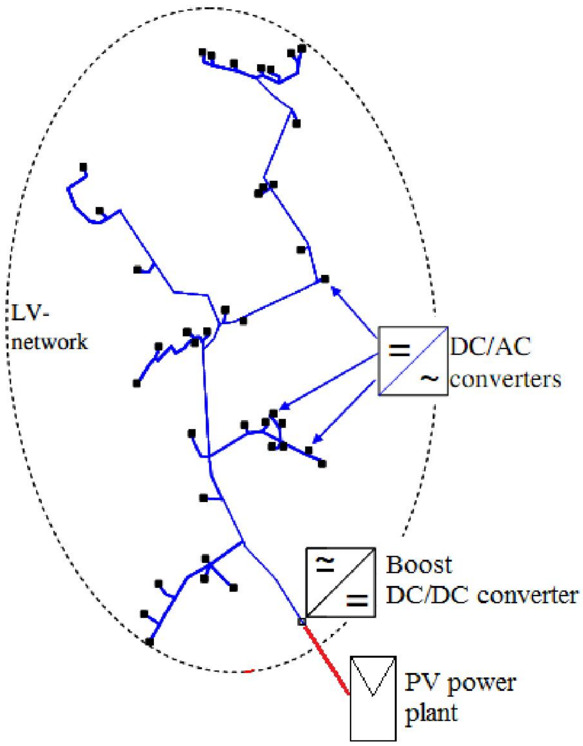

Fig. 2.2. Island LVDC distribution network.

The possible targets of a low voltage DC system are not limited only to public electricity distribution networks, but the such system can also be widely applied for instance in different industries areas and in internal networks in customers' premises [15].

2.1 Advantages and challenges of LVDC microgrids

According to the results of significant research work, utilization of low voltage DC distribution networks introduces benefits compared to AC systems. First of all the transmission capacity of LVDC systems is higher than traditional AC systems due to the voltage difference between the systems. Research results shows that the transmission capacity can be over 16 times at the voltage drop limit and over 4 times at thermal limit compared to the traditional 400VAC system. At the same time, the transmission capacity coefficient depends on the used DC voltage level and structure of the system [15].

In case of traditional distribution network, high transmission capacity of LVDC distribution system opens the possibility of replacement of a part of MV line, so that application of LVDC structure for distribution of electricity allows to reduces the investment costs of an electricity distribution network. In that case the smaller cable cross-sections can be used than in traditional 400V AC distribution system which reduces distribution system total costs. Replacing of medium-voltage distribution network also reduces interruption costs, as the total MV network length decreases. At the same time, in the instance of replacement of a part of MV structure, there is reduction in the number of LV transformers as DC distribution system includes only one LV transformer in the beginning of LVDC system [18].

Island operating systems have specific operational and functional requirements which are defined by unconventional operating conditions. Low voltage DC networks bring novel beneficial solutions in this engineering area. First of all, utilization of DC technologies allows to avoid the problem with synchronization of power sources in electric grid. It is one of the major benefit in case of hybrid-power systems and networks with distributed generation (DG). It is also no need to consider about reactive power.

However, there are additional costs caused by the DC and AC converters. The price development for power electronics devices, however, show a downward trend, and at the same time, the costs of traditional distribution network technologies are steadily increasing as shown on the Fig.2.1.1.

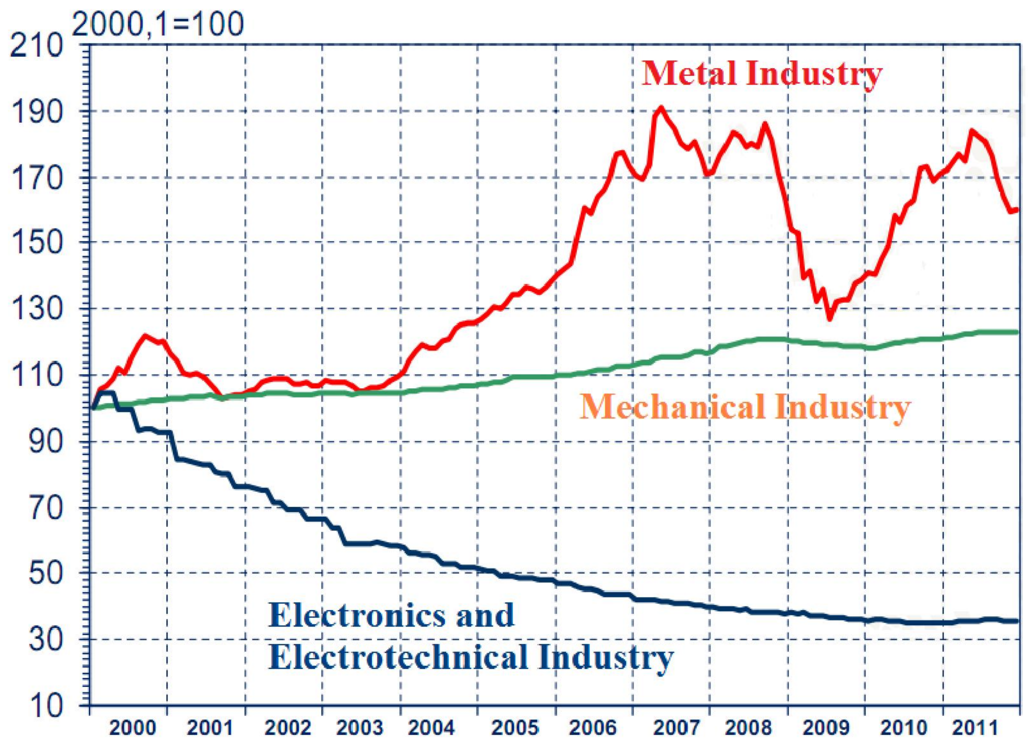

Fig. 2.1.1. Price development of technology industry between 1999 and 2011. [2]

In that case, permanent rise of the quality of power electronics components simultaneously with the price reduction makes it possible to apply power electronics devices in application of LVDC distribution networks.

Another important benefit is that the voltage quality improves due to active voltage control of an inverter's. As customer AC voltage is converted from much larger DC voltage the customer operating voltage can nearly be kept constant. For the same reason network voltage fluctuations and drops can be eliminated and they may not influence on the customer operating voltage [18].

From the protection point of view, the LVDC distribution system creates its own protection zone, so that the faults occurring in the DC line causes outage to the customers in the DC district only, thus systems reliability increases.

However, it should be mentioned another aspect of the problem that is mean that new distribution system introduces challenges as well. The DC power supply system is more complex than traditional 20/0.4 kV AC distribution system which makes system operation more difficult technically.

In addition the LVDC system also causes difficulties from the electrical safety point of view. In the LVDC system high DC voltage can be a reason of dangerous earth voltage levels in difficult grounding conditions which may require additional earthing equipment.

Another important moment is that the power electronic devices introduce new challenges to distribution system also. The power electronic converter usage can cause switch faults and complicate protection device operations, which simultaneously has sufficient fault current capability. Besides, lifetimes of power electronic device may be only a quarter than traditional ones which provides additional maintenance issues and costs of converters [18].

2.2 Possible structures of LVDC microgrids

Typically, an LVDC distribution system consists of power electronic converters and DC link between the converters. The topology of LVDC distribution system can have different kind of variations. Common to the traditional grid-connected distribution networks topologies is that AC/DC conversion is always located near MV line. The DC/AC conversion can instead be located at different locations [19].

In isolated network systems (stand-alone systems) the AC/DC conversion is located near generator of electric energy and usually equipped with battery bank. Depending on the location the LVDC system can be either a HVDC link type solution or a wide LVDC distribution district where the DC/AC conversion is made at the customer-ends.

The LVDC distribution system can be made with two basic implementations: unipolar and bipolar. The unipolar system has a one voltage level via energy is transmitted. All the customers are connected to this one voltage level [19]. Unipolar DC systems are shown in Fig. 2.2.1-2.2.2.

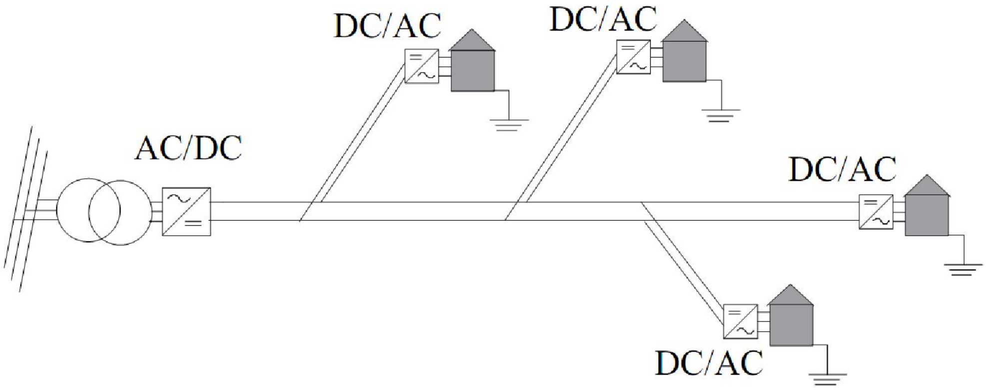

Fig. 2.2.1. A grid-connected unipolar LVDC distribution system.

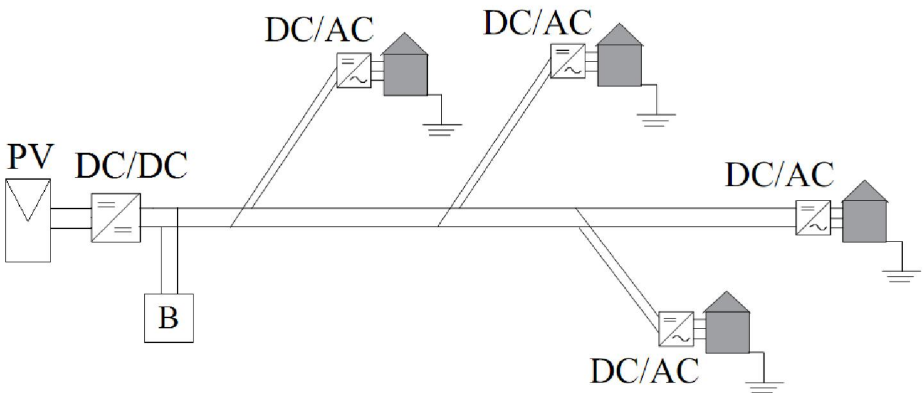

Fig. 2.2.2. A stand-alone unipolar LVDC distribution system with PV source of energy.

The bipolar system can be introduced as two unipolar systems which are connected in series. Thus, there are two voltage levels, which are equal but of opposite sign compared with their common neutral voltage level. A bipolar connection requires a three-wire transmission line, but customer connections are two-wire cables connected between positive or negative pole. Therefore customer supply voltage is either + 750 VDC or - 750 VDC. The converters of a bipolar connection consist of two similar structure converter units connected between the neutral and phase voltage levels. They can also be similar to the ones used in a unipolar connection [17]. Bipolar DC systems with connection alternatives are shown in Fig. 2.2.3-2.2.4.

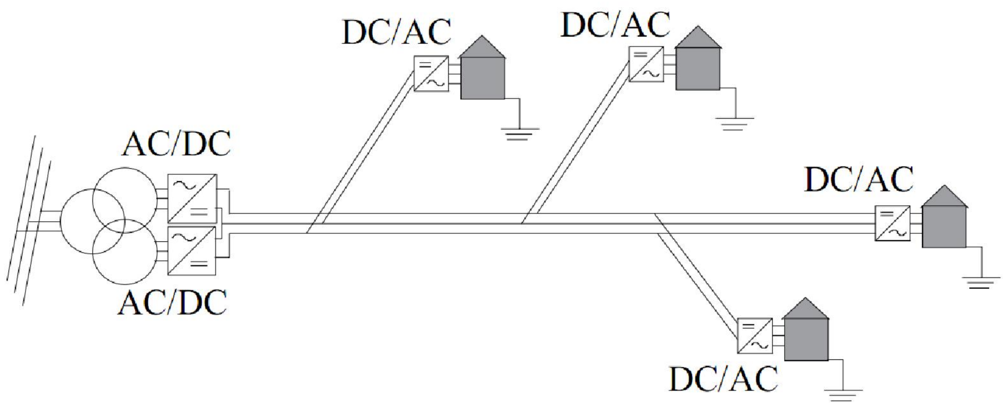

Fig. 2.2.3. A grid-connected bipolar DC system.

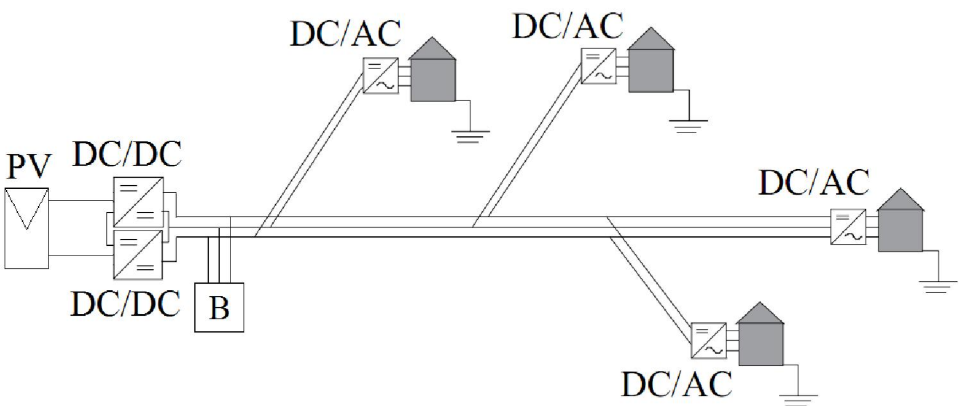

Fig. 2.2.4. A stand-alone bipolar DC system with PV source of energy.

Previous research results show that the bipolar ±750 VDC system is more beneficial for LVDC distribution networks for the following reasons. First of all, the bipolar system enables exploitation of the whole DC voltage range defined by the low-voltage directive without a need to exceed the standardized DC voltage limits of commercial low-voltage underground power cables (SFS 4879), (SFS 4880) [14]. Secondly, the bipolar system enables the use of 750 V voltage level of converters with appropriate customer connection (neutral-pole), which allows to reduces the price of converters. Also it is very important that it makes possible to keep the other half of the network in operation if the other half is faulted , hence it is the way of increasing the supply reliability.

However, from the drawbacks point of view, the bipolar system has disadvantages compared to the unipolar system. First, the load asymmetry of the system leads to voltage asymmetry because of the current superposition in the neutral of the system. This phenomenon causes extra losses in the system and can also cause overvoltages in a fault situation as the voltage of the healthy pole will rise [14]. Besides, bipolar structure has less transmission capacity then unipolar system cause of difference in voltage levels.

2.3 Application of Island LVDC microgrid with PV system in Finland

Using of solar power as a major source of energy is one of the most perspective solutions in island conditions and has a huge potential when considering technological innovations. Novel low voltage DC microgrid conception and development of photovoltaic technologies allow to create an independent system for power supply in cases when it’s impossible or non-efficient from economical point of view to create traditional power supply system. Besides, it is estimated that the price of solar electricity will fall dramatically over the next few years.

Despite the long and dark winters, potential for solar energy production in Finland could be high enough. Compared to Central Europe, the lack of dust and smog in Finland’s micro climate makes good conditions for domestic solar energy production. Solar radiation reaches its peak in Finland in May-July and achieve its minimum in January-February [16].

Along the coasts of the Gulf of Finland and Gulf of Bothnia there are thousands of islands, the main archipelagos are Åland archipelago and the archipelago of Turku. In the south-west the heavily dissected coast grew into the largest archipelago in Finland which is unique in the world due to great amount of islands.

Lake District is an inner plateau in the south of the country with thick forests and a large number of lakes, islands, swamps and marshes. Considering mentioned above, the development of independent island microgrids in Finland becomes very actual. In this chapter, there are three different island regions in different parts of Finland were chosen to estimate and compare possibilities of energy production from solar power and its utilization with LVDC microgrids.

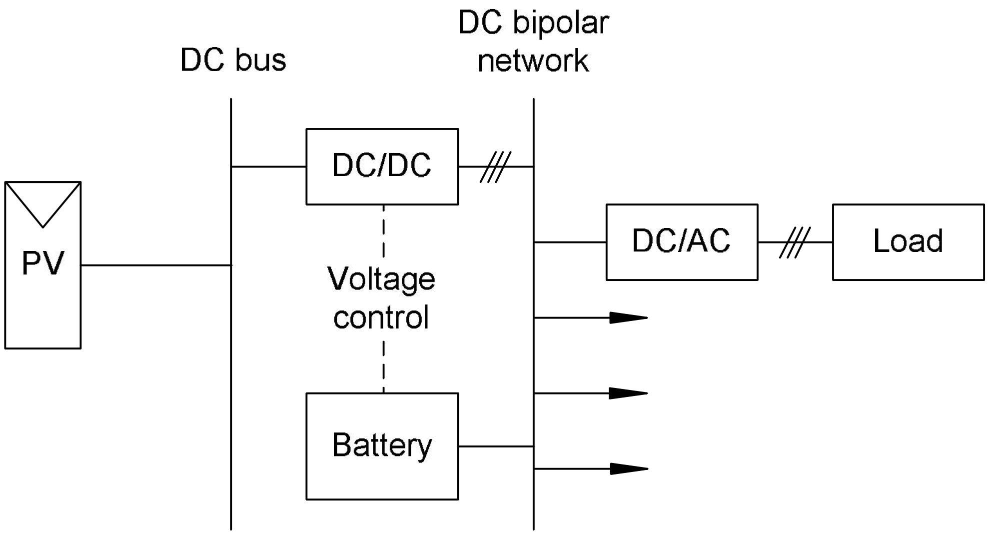

Fig. 2.3.1. Principle scheme of Island LVDC network with PV power source.

Power potential of photovoltaic system as source of energy in island conditions could be estimated on the example of Turku archipelago on the south-east part of Finland (60.449, 22.259), as it is very developed island part of Finland and seems perspective for island LVDC installations. Turku region has a humid continental climate with warm summers and no dry season. It is presented on the Fig.2.3.2.

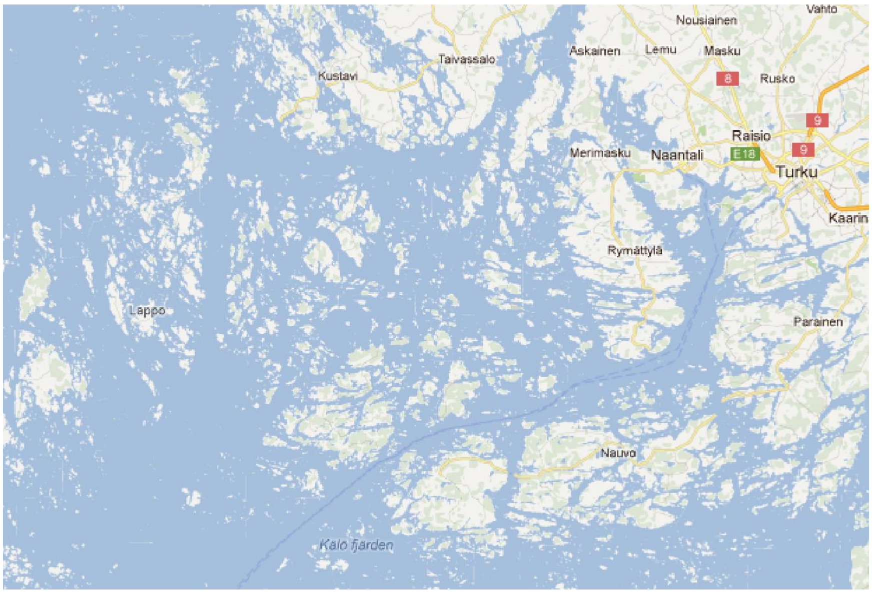

Fig.2.3.2 Island region near Turku

For estimation of energy production from solar power and also comparison with consumption were chosen January and June. January characterize as the month with worst weather conditions and highest consumption of electricity cause the solar activity and temperatures are minimal. June was chosen as the month with best weather conditions from the solar activity point of view, in which there is also a minimum of electricity consumption. The demand curve of electrical energy consumption in January is presented on the Fig.2.3.3.

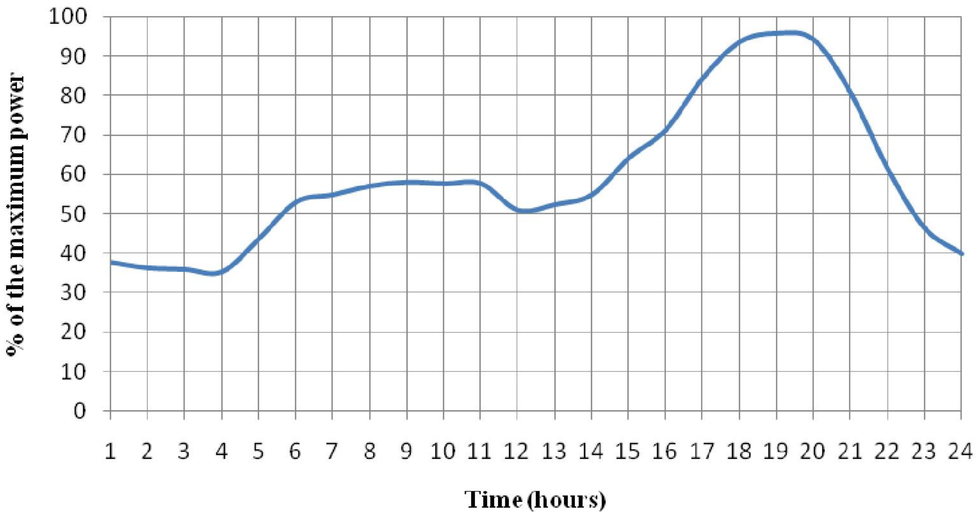

Fig.2.3.3. Average Hourly Demand Index (% of the maximum power) in January [1].

Information about solar power for Turku region in January is presented on Fig.2.3.4. Illustrated values describe daily solar irradiance in Watts for square meter with optimal inclination that region [16]. Real irradiance on a fixed plane (W/m^2) described by "global real-sky" curve, this values could be used for estimation of power production because it describes real sky-behavior with average cloud cover for that month. Global clear-sky irradiance on a fixed plane (W/m^2) described by "global clear-sky" curve, it is the ideal situation of possible irradiance when the sky is completely free of clouds. Diffuse irradiance on a fixed plane (W/m^2) described by "diffuse real-sky" curve.

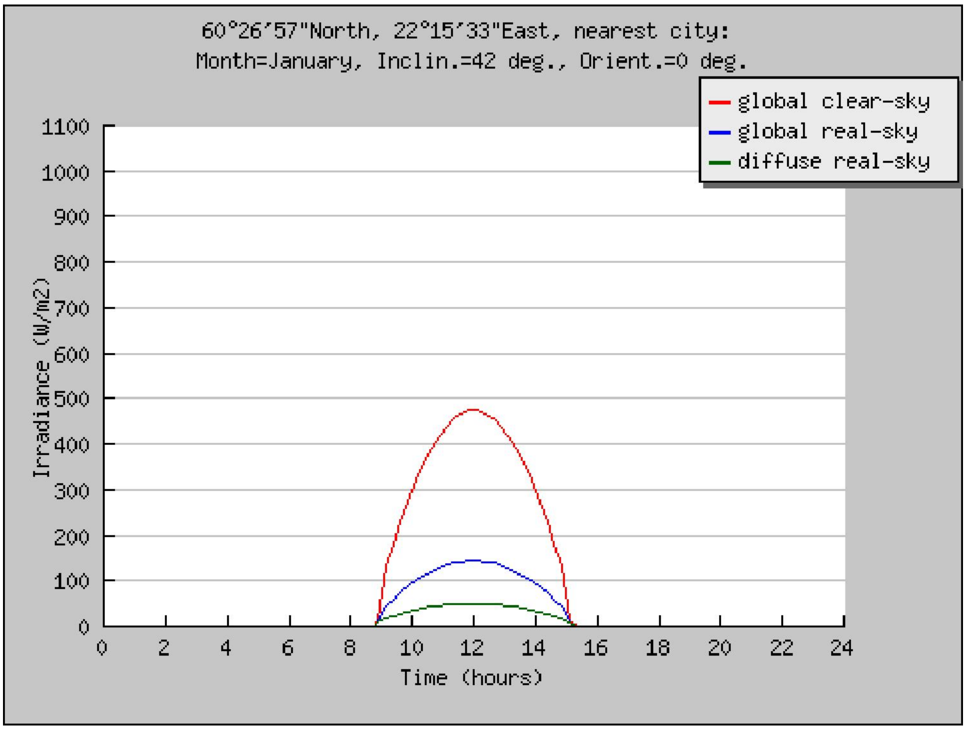

Fig.2.3.4. Solar irradiance in January for Turku region (optimal inclination 42°)

Using presented above data it is possible to preliminary estimate average energy production and consumption for January, also necessary area of solar panels:

If we assume that peak power P_{max}=100kW, then following Average Hourly Demand Index (Fig.4) we can assume that P_{max} = 100%, thus we can obtain daily consumption of power:

$P = \sum P_h = 1433.9$ kWh/day.

Using information about solar irradiance $P_{h,pv}$ (W/m^2) and the coefficient of photoelectric conversion it is possible to estimate how much electric power we can get from one square meter. Crystalline-silicon modules have efficiencies ranging from 10 to 15%, this values based on manufacturers' nameplate ratings (IEEE Std 1562™-2007). For Turku region in January electric power is:

$P_{pv} = \sum P_{h,pv} \cdot k/1000 = 648.1 \cdot 0.15/1000 = 0.097$ kWh/m^2/day.

Thus, to cover daily consumption P the needed area of solar panels is equal:

$A = P/P_{pv} = 1433.9/0.097 = 14782.47$ m^2. (It's a square 122x122m.)

As it could be seen the needed area of solar panels is quite big in case of power supply in worse conditions, which makes utilization of solar energy quite expensive and not-effective in winter time. Some problems could become with placement of such spread PV arrays, which in island conditions could be difficult.

There is an opposite situation in June. The demand curve of electrical energy consumption in June is presented on the Fig.2.3.5. Information about solar power for Turku region in June is presented on Fig.2.3.6. For calculations of solar power used "global real-sky" curve, which describes real irradiance on a fixed plane (W/m^2).

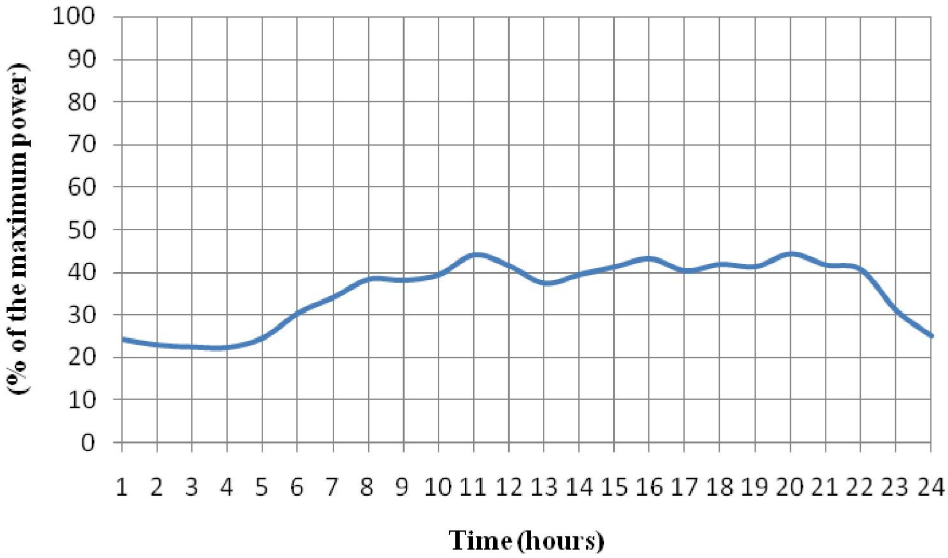

Fig.2.3.5. Average Hourly Demand Index (% of the maximum power) in June [1].

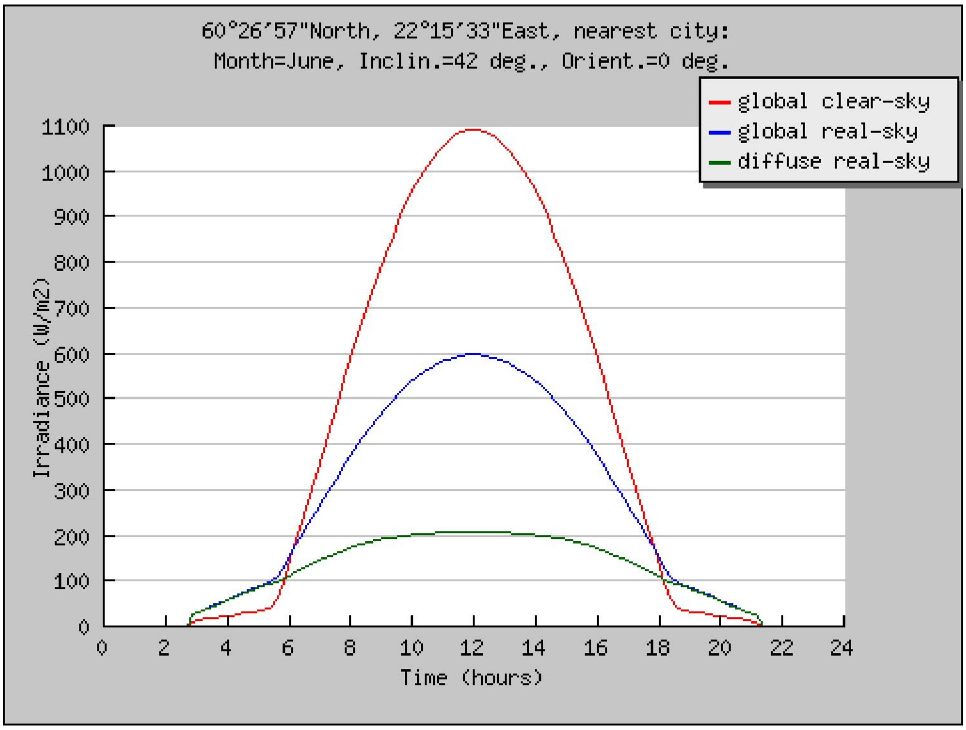

Fig.2.3.6. Solar irradiance in June for Turku region (optimal inclination 42°)

According to the information about energy consumption and also about solar irradiance it is clear that there are significant possibilities for utilization solar power plant as a source of electric energy in warm period of the year.

For comparison with previous results, calculations for June are presented below:

Peak power P_{max}=100kW;
Daily consumption $P=\sum P_h$=851.3 kWh/day.

$P_{pv}=\sum P_{h,pv}\cdot k/1000=22729\cdot 0.15/1000=3.41$ kWh/m^2/day.

Thus, to cover daily consumption P the needed area of solar panels is equal:

$A= P/ P_{pv}=851.3/3.41 =249.65$ m^2.

One of possible ways to decide problem with effective and beneficial power supply using renewable sources of energy in case of island operation is to apply hybrid PV-wind power plant. Wind energy could help to cover demand of electricity in winter time, especially in Finland.

Wind maps of Finland in winter and summer time from Finnish Metrological Institute are presented in Appendix 1. The following maps give the wind speed for each grid point representing a horizontal resolution of 2.5 x 2.5 km2. Each grid square thus has, or may have, areas with wind speed higher or lower than the average. According to that maps, it is clear that wind potential of island regions is quite high, especially in winter time.

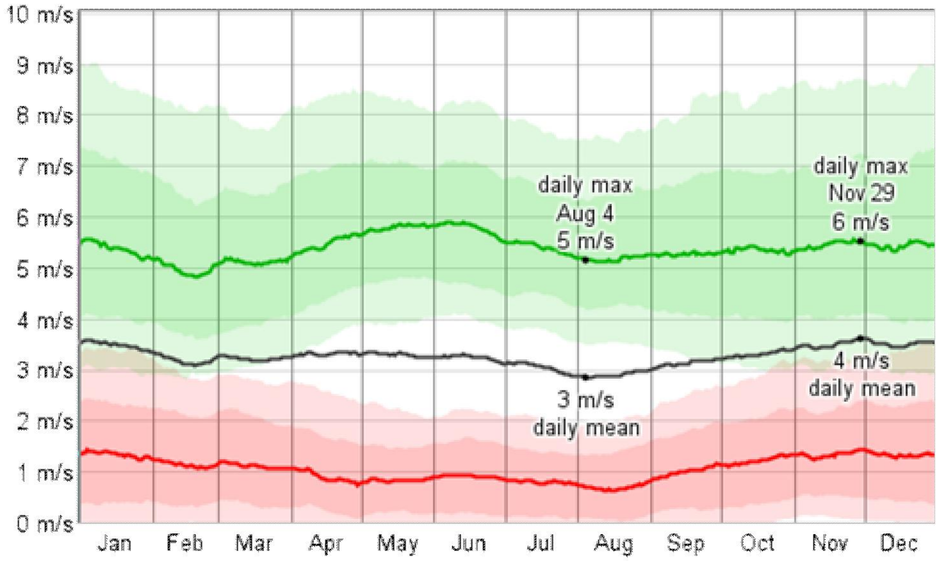

Fig.2.3.6. Average wind speed on the surface of the land in Turku region [26].

Even if we take for calculations wind conditions on the surface of the land (usually it is less wind speed on the surface of the land), it is possible to get satisfactory results (Fig.2.3.6).

For example, wind turbine with nominal power 100kW, radius of blade surface R=10m and wind speed V=11m/s (average speed in January for Turku region on the 50m height from the sea level (see Appendix 1), could produce electrical energy:

$$P_e=0.5E\rho\pi R^2V^3\eta=0.5\cdot0.45\cdot1.225\cdot3.14\cdot10^2\cdot11^3\cdot0.75=86.3\text{kW},$$

where E – efficiency of wind utilization, ρ – air density, η – coefficient of power conversion.

Thus, it is the task for determination an optimal relation between necessary PV and wind power capacity. As it could be seen, for example for Finland, in January there is a prefecit of wind power and defecit of solar power and opposite situation in June.

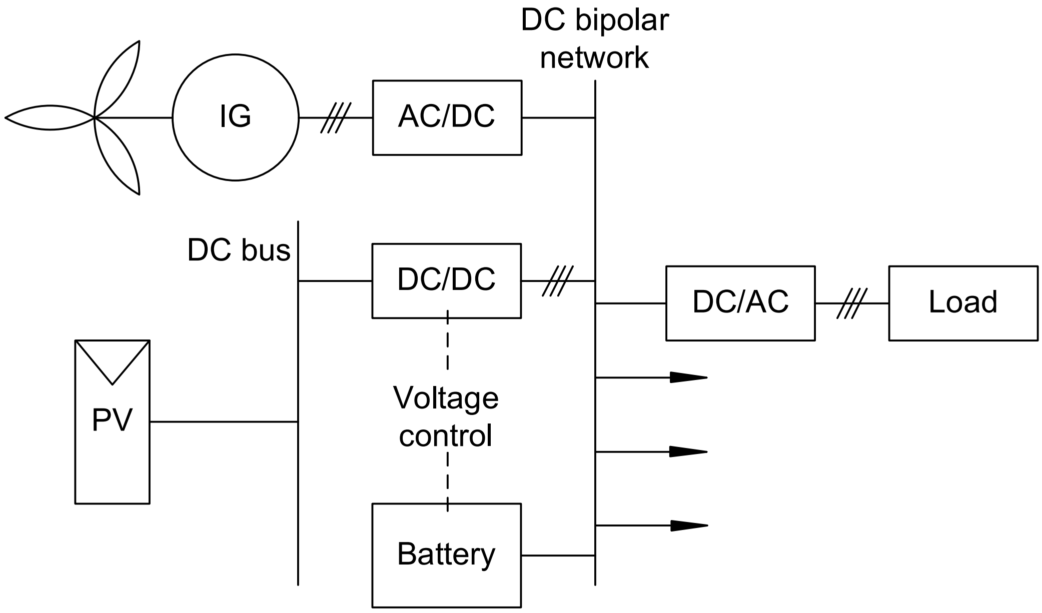

Fig.2.3.7. Principle scheme of Island LVDC network with hybrid PV-wind power system.

In general, the application of wind-solar hybrid energy systems (Fig.2.3.7) can reduce the storage capacity of batteries and the total cost of the system compared with stand alone PV or wind generation system. With the rapid development of renewable energy technique, PV-wind hybrid power system is more economical and reliable than a single PV or wind turbine for their complementary both in time and geography. The utilization of LVDC network system in hybrid power supply opens great benefit. There is no need of synchronization of power sources in the network cause of DC form of supply.

Besides, Finland can participate in global development by exporting novel technologies related to solar power to places where it can be more made use with higher efficiently than it is possible in Finland.

3 Requirements for Island LVDC system

This chapter is focused on the definition of necessary requirements for the novel low voltage DC system for conversion and distribution of electrical energy in island operating conditions. Innovation LVDC system is developed as independent uninterruptable power supply system which is also expected to be used mainly with renewable sources of energy, thus appropriate moments should be taken into account for determination of system, functional and operational requirements.

3.1 System requirements

Generating system and related storage equipment have to meet following requirements:

- they have to provide sustainable and uninterruptable power supply
- they have to meet the electrical safety requirements

LVDC distribution system and the related equipment have to meet at least the following systemic criteria:

- they have to answer to the purpose
- they have to meet the electrical safety regulations
- voltage quality has to meet the standards (minimum requirement)
- the efficiency of the system has to be high

Furthermore, there are some additional requirements, which are essential for the both applications:

- low acquisition costs
- low maintenance costs
- long lifetime, low life cycle costs
- easy maintenance, usability and replaceability
- opportunity to data transmission and measurement functions
- opportunity to active load control
- opportunity to connection of distributed generation

In design, manufacturing, installation, and use of equipment, standards concerning the system and its components have to be followed.

3.2 Functional requirements

The following requirements are developed with an emphases on photovoltaic power systems, as it is expected that it will the major source of energy in island operating conditions, however they are not exclude the possibility of utilization of other renewable sources of energy, such as wind, biomass or hybrid power systems.

The primary function of a LVDC electricity distribution system is power transmission between a source of energy and a customer, and voltage transformation for the customer needs. In low-voltage distribution, the system and its components have to meet at least the following functional criteria:

- Generating system supplying the DC system:
  - setup to low voltage required by rectification or DC/DC conversion

- Rectification to a LVDC distribution system and DC/DC conversion when observing from the renewable sources of energy:
  - low current distortion (THD to be less than 5 % [8], the power factor of the DC system, when loaded, should be > 0.9 unless otherwise agreed)
  - boost-control in cases of power drawdown
  - controlled start-up after a supply interruption
  - energy efficiency of the power electronic modules > 98 % (target)

- Energy storage system:
  - voltage level should correspond to the nominal supply voltage 1500 VDC to implement direct battery connection
  - have to be designed for autonomy system work (IEEE Std 1562™):

    - for non-critical loads and areas with high solar irradiance, 5 to 7 days of autonomy are acceptable.
    - for critical loads or areas with low solar irradiance, 7 to 14 days of autonomy or greater should be used.
  - battery-type should be chosen with maximum possible charge-current
  - batteries should be a deep-cycle type

- DC link:
  - nominal voltage 1500 VDC (+10, -25 %) neutral isolated, ripple <10%
    - momentary voltage being at minimum the minimum DC voltage required to generate the customer AC voltage
      - when applying full-bridge inversion, 325 VDC in one-phase inversion, 565 VDC in three-phase inversion
    - application of an earthing method that takes into account the touch voltage regulations
      - safety regulations concerning low-voltage distribution have to be met

- Voltage transformation according to the needs of the customer, maintenance of the appropriate voltage level (inversion):
  - sinusoidal voltage, 50 Hz constant frequency ±0.1 Hz
  - voltage level 1~230 V or 3~400 V, (<±10 %)
  - low voltage distortion < 5 % (0.05 x Un)
  - compatibility with the present electrical installations in premises
  - safety regulations concerning electrical installations in premises have to be met
    - compatibility with the protections of the present internal networks in premises
  - may not cause noise problems
  - controlled start-up after a supply interruption

- Operating conditions
  - applicable to outdoor installations, operating temperatures from -40 to +60 ºC
  - Voltage withstand capability in accordance with IEC 60664-1
  - target lifetime 15–20 a
  - easy maintenance/replaceability
  - readiness for disconnection of an individual device

3.3 Operational requirements

Following subchapter is related to definition of operational requirements for novel Island LVDC system. Operational requirements are developed to reach the aim of the maximum efficiency of the system simultaneously with the simplicity of realisation such system, and as a consequence minimization of investments costs.

Demand response control should be used as a major mechanism to link demand with supply. In particular, demand response can be used to reduce peak demand and therefore reduce the price volatility. This problem is more deeply introduced in Chapter 4.

Load control can be applied for cases of technical constrains and can be implemented by voltage-relays, which control voltage level on the DC side of customer converter and operate the switch-states of the loads. It means, that in the moments of maximum allowed discharge level of battery bank, some load will be disconnected automatically in order specified by customer. This problem is more deeply introduced in Chapter 4.

Information about system status, prices for customers, produced by and consumption power, time of possible autonomic work and another relevant information, should be provided for customers by special web-service. It will be the main customer' information instrument for demand regulating.

Bipolar structure of the distribution network with nominal voltage ±750 VDC have to be utilized to satisfy acting standards and not to exceed DC voltage limits for commercial low-voltage underground power cables. Also it makes possible to keep the other half of the network in operation if the other half is faulted.

Direct battery connection is more preferable for the novel LVDC system. Aspects, relating to this problem are described in Subchapter 3.3.1.

Control system for the line conversion and the state of charge of the battery bank should be implement by main DC/DC converter. It allows to decrease number of power electronic devices, hence reduce investment costs and increase the reliability. However, it is required to develop specific algorithm of control for such purposes.

Number of days with autonomy system works should be determined accordingly to weather conditions of a region, as the main source of energy in island conditions expected to be renewable, which is mainly weather-dependant. Battery bank size defines respectively to the number of autonomy days. More deeply it is described in Subchapter 3.3.2.

3.3.1 Battery connection

Following below variants of battery bank connections are described mostly for photovoltaic power systems, however those conceptions could implemented with any power sources.

First possible system setup is bipolar DC network with direct battery connection. In this variant DC voltage from the PV array converted to necessary system voltage with the help of two converters which have common neutral point. Battery is connected after filter part of the converter. Load is connected to the DC/AC converter, which is buck the voltage and transform in to the tree-phase alternative waveform. This system setup is presented on the Fig.3.3.1.1.

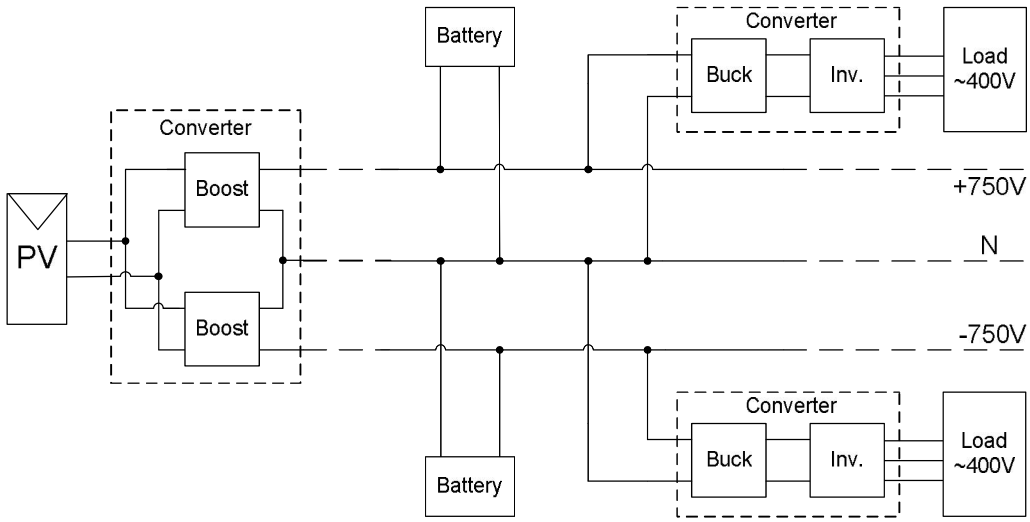

Fig.3.3.1.1. Bipolar island network with direct battery connection.

Such system seems the most beneficial for the Island LVDC system, because makes possible to reduce the number and power electronic devices. In that case DC/DC conversion and control of the state of battery charge lays on main line converter. Benefits are the reduction of investment costs and increasing reliability of the system.

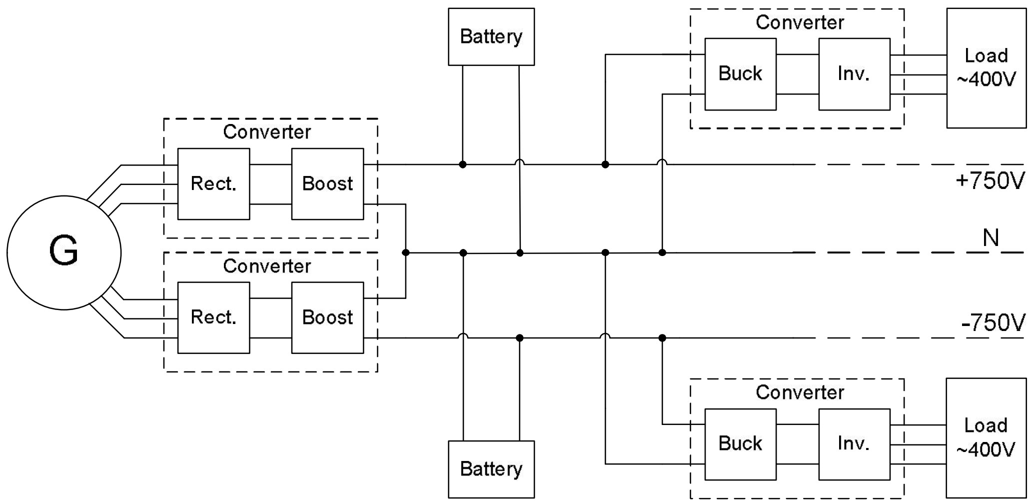

Fig.3.3.1.2. Bipolar island network with direct battery connection and AC generation.

It becomes especially beneficial in cases of utilization of AC generation (Fig.3.3.1.2) in conditions when customer' converters and the main converter are similar, but working in opposite setup regime, it means that main converter is in a boost-rectifier mode, customer' converters are in a buck-inverter mode. It could be implemented by using full-driven switches (IGBT for example) and control algorithm. Appropriate nominal voltage level of generator is needed for implementation of similar opposite working converters. It brings one more benefit related to improving power factor in case of utilization of full-driven switches and makes possible to catty out the high quality power supply.

However in the situation when system line converter and customer' inverter couldn't be similar, direct battery connection stays beneficial from the total investment costs point of view.

Alternative variant of the island LVDC network is bipolar system battery connection through the additional DC/DC converter. It is presented on the Fig.3.3.1.3.

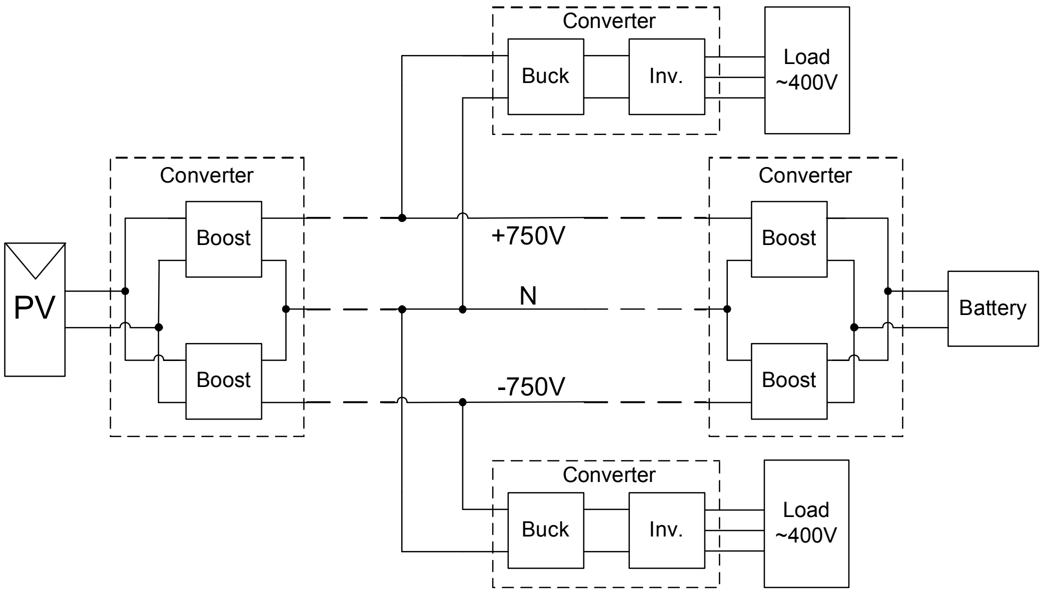

Fig.3.3.1.3. Bipolar island network with battery connection trough the DC/DC converter.

Battery DC/DC converter presents additional possibilities to the voltage control but it adds some extra investment and maintains costs. Variations of the converters in this system stay the same as in previous description and depend on system set up. Also it makes system more complex and reduces reliability of the system cause of implantation of extra complex power electronic devices.

3.3.2 Battery type selection

Batteries are designed to accumulate excess energy created by source of energy and store it to be used at night or when there is no other energy input. Batteries are rated according to their "cycles" and could have shallow cycles between 10% to 20% of the battery's total capacity, or deep cycles up to 50% to 80%.

According to the world practice in design of PV systems, there are two ways of a simple and effective determination of battery bank size. The first idea is that most batteries will last longer if they are shallow cycled–discharged only by about 20% of their capacity–rather than being deep-cycled daily. It means that a reasonable design will save the deep cycling for occasional duty, and the daily discharge should be about 20% of capacity [5].

Another statement is that deep cycle battery type is more beneficial for using in solar PV system. Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days.

Basing on the literature survey and different studies in this area, it is possible to make a conclusion that the most beneficial choice for Island LVDC microgrid, especially in Finnish conditions, is deep cycle battery type , because it allows to charge the bank very rapidly. It's very important in winter time, when solar energy is available only for few hours during daily time or in clearing time during cloudy weather. However, this battery bank has to be designed for working in shallow regime. This is done to increase the life time of batteries and simultaneously have the possibility for deep discharging during bad weather conditions and rapid charging in moments of suitable conditions.

3.3.3 Battery capacity

Application of photovoltaic power system island low voltage DC network may require some battery reserve, both for reliability of system and to provide time for intervention in the event of an unanticipated case such as unusually poor weather or failure of a system component. In general case, the number of days of battery reserve is commonly specified as a system design requirement, and is based on several considerations including the following [9]:

a) System application. Critical load applications generally require more days of battery reserve than noncritical applications.

b) System availability. System availability is the minimum percentage of the time that the PV system should be able to satisfy the system loads.

c) Solar irradiance variability. Daily and seasonal variations in solar irradiance affect the required number of days of battery reserve.

d) Predictability of load. The load may or may not be predictable; also, there may be the possibility of adjusting the loads, e.g., dropping non-essential loads.

e) Backup power provisions. If the PV system includes provisions for backup power, the desired frequency and duration of operation of the backup power source needs to be considered.

f) f) Accessibility of site. The worst-case time required for correction of any problem should be considered.

The number of days is defined by IEEE Standard 1562-2007 “IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic Systems”. For non-critical loads and areas with high solar irradiance, 5 to 7 days of autonomy are acceptable. For critical loads or areas with low solar irradiance, 7 to 14 days of autonomy or greater should be used [10].

The required battery capacity for a PV application is determined by the number of days of battery reserve and by the characteristics of the load, battery, and installation. A functional-hour rate for the application is determined by capacity and load calculations [9].

The unadjusted capacity, in ampere hours, is calculated by multiplying the days of battery reserve by the average daily load (in ampere hours/day). Then, the unadjusted capacity should be modified to assure satisfactory battery cycle life. Battery manufacturers rate cells for maximum depth of discharge (MDOD), maximum daily depth of discharge (MDDOD) and end-of-life (EOL) capacity. The battery capacity should be adjusted in the following ways [9]:

a) The capacity adjusted for MDOD is obtained by dividing the unadjusted capacity by MDOD (in percent).

b) The capacity adjusted for MDDOD is obtained by dividing the maximum daily ampere hours by MDDOD (in percent).

c) The capacity adjusted for life is obtained by dividing the unadjusted capacity by the end-of-life capacity expressed in percent of the rated capacity, commonly 80%.

The largest of these three capacities will satisfy the depth-of-discharge and end-of-life adjustments.

Besides, it is very important to take into account the temperature adjustment. The available capacity of a battery is affected by its operating temperature. Cell capacity ratings are generally standardized at 25°C. Capacity increases at temperatures above 25°C and decreases at temperatures below 25°C. Capacity is rarely adjusted for warm temperature operation, but adjustments are routinely made for cold weather applications. Refer to the battery manufacturer's literature for temperature correction factors. The adjusted capacity should be corrected by this factor to yield capacity adjusted for temperature [9].

In order to correctly determine size of the battery bank, the discharge rate and ampere hour capacity should be considered together. In continuous load applications, such as power supply in island operation conditions, the battery should have sufficient capacity to supply the constant discharge rate over the number of days of autonomy work. Using an average rate to size the battery could result in insufficient capacity to supply high currents above the minimum voltage late in the battery discharge. The functional-hour rate conservatively approximates a single discharge rate that is equivalent to the varying discharge rates of a particular duty cycle [9].

3.3.4 PV module selection

Before choosing the module for a PV system, the operation of the load and the site climate must be known. The power required by the loads and input voltage range are the major criterions for PV system definition. Of course the expected solar radiation and ambient temperature for the site have to be taken into account. If the solar radiation is typically low during the time of year the load demand is greatest, the array size will have to be increased. With this information, it necessary to calculate the maximum and minimum expected voltages from the array to verify the array will be able to power the load under all expected climate conditions. All voltage drops in the system wiring (round-trip), fuses, connectors, charge controllers, etc., must be taken into account to determine if the array output will still meet the needs of the load [10].

3.4 Electric safety and fault protection in LVDC microgrids

The electrical safety of the presented island distribution network cannot be neglected. Compared to the traditional distribution system the LVDC network has more different fault situations. One of the reasons of these challenges is application of power electronic devices. They could be the reason of switch faults and also need more complex protection device operation [20].

Possible fault situations in the DC network are

- short circuit in a positive pole
- short circuit in a negative pole
- short circuit between positive and negative pole
- without neutral connection
- short circuit between positive and negative pole
- with neutral connection
- earth fault in positive conductor
- earth fault in neutral conductor
- earth fault in negative conductor

Possible fault situations in the customer AC side are short circuit and earth fault. The customer network short circuits could be also the reason of short circuit situations in power electronic devices.

As it was mentioned above, power electronic devices can introduce switch faults which can create switches to be short circuits or open circuits. Also the modulation can stall introducing permanent connection from converter's input to its output [20].

3.4.1 System grounding

Used DC voltage levels in the LVDC system can be a reason of high earth voltages in difficult grounding conditions with incorrect grounding arrangement. In such conditions it is necessary to construct the DC system as an ungrounded IT system. Earth faults in a system with the IT grounding arrangement present only small earth voltages because of the lack of a fault current loop. In case of utilization of TN system, any earth-connected fault will cause immediate exceeding of the safe earth voltages in the typical Finnish grounding conditions [17]. High level of earth voltages can occur also in double earth fault situations of the IT systems, as it was mentioned. Therefore, standardization requires that at least alarming insulation monitoring is necessary to use in ungrounded systems to indicate the first fault [25]. In cases of the first fault it is also desirable to use tripping to reduce the possibility of double fault situations.

In a galvanic constant system with the IT grounding application, the average potential of customer networks depends of the earth potential and consequently floats continuously. Hence, it is important to keep the protective earth connections in good conditions. The potential difference of any energised part of the customer network is not allowed to exceed an RMS value of 500 V against the earth [22]. The pole voltages of the LVDC system have to be reduced to ±700 VDC to safely meet this standard requirement.

It is also possible to implement TN grounding system in the customers' networks, but it necessary to implement a galvanic isolation transformer between the DC and customer networks. In this case, floating potential difference between the earth and the customer's devices is eliminated. It allows to use full ±750 VDC voltage range in the public network. However, galvanic isolation arrangements makes the inverter structure more complex, and as a consequence there is a rise in investment cost and losses of the inverter.

3.4.2 Fault protection

The LVDC network faults can be eliminated with combination of different type of protections, such as over current and short circuit protection and earth fault protection. Molded case circuit breakers which includes circuit breaker and over current relay could be implemented in the LVDC system for the short circuit protection. It can be located either on AC or DC side of the converter. In case of the AC side the breaker can eliminate converter switch faults also. The poles of the LVDC bipolar system are needed to have its own protection devices. The molded case circuit breaker is illustrated with letter A in figure 3.4.2.1. The DC fuses also could be utilized in DC part of the system. The DC fuse is indicated with letter B in figure 3.4.2.1. [20] However, in modern conditions fuses could be replaced with DC circuit breakers, it improves reliability and decrease time of maintenance work.

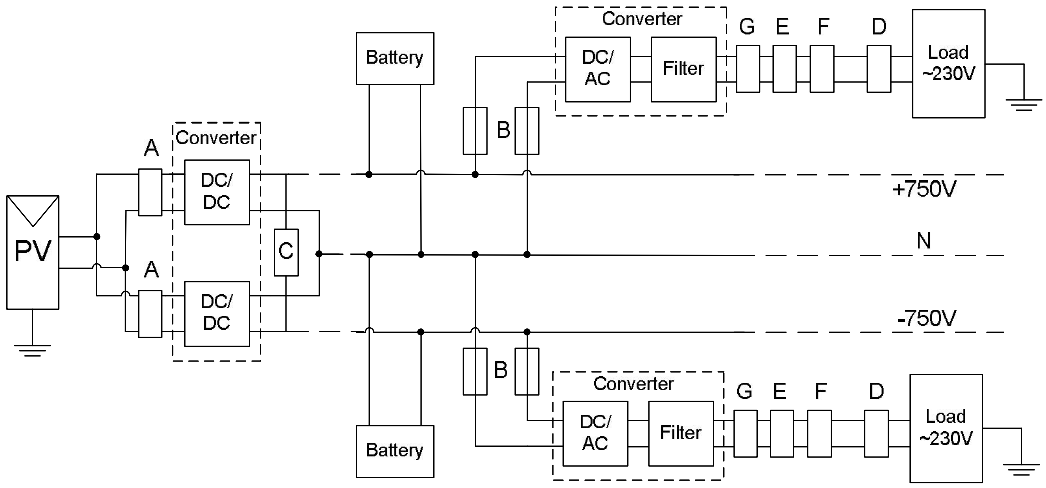

Fig. 3.4.2.1. A proposed protection scheme for bipolar LVDC microgrid with ungrounded IT system.

Utilization of ungrounded system requires individual protection device for the DC network earth faults. The insulation monitor can be applied to eliminate first fault. In that case the insulation monitor can be used for operation with circuit breaker which is used for short circuit protection also and no additional circuit breaker is needed. The insulation monitor is indicated with letter C in figure 3.4.2.1.

For short circuit protection in customer AC side can be applied circuit breakers and fuses. The circuit breakers and fuses is illustrated with letter D in figure 3.4.2.1.

Application of the insulation monitoring devices is necessary in customer AC side to cover earth faults and have selective directional earth fault protection. For this purposes also needs an additional device for directional operation. The customer insulation monitor is illustrated in the figure 3.4.2.1 with letter E.

The 30 mA residual current devices can be applied to improve human safety in double fault situations between DC and customer AC networks. In such situations residual current device separates customer network from DC side. The residual current device is indicated with letter F in figure 3.4.2.1.

3.4.3 Protection requirements

The protection requirements which are occur from LV standards and the system operation requirements of novel LVDC distribution system are determine the protection requirements. Power electronic device operation is also taken into account, because it is also needed that converters can withstand the fault situations without a breakdown [21].

The Finnish LV standardization [25] defines LVDC system to fulfill following requirements:

- maximum earth voltage 240 VDC
- maximum contact voltages 50 VAC and 120 VDC
- insulation monitoring needs to be used to at least give a alarm of insulation decrease in ungrounded system
- earth fault needs to be cleared within 2 h in ungrounded system
- DC network short circuit needs to be cleared within 5 s
- customer AC network short circuit needs to be cleared within 0.4 s in grounded system and within 0.8 s in ungrounded system

The requirements of desirable system operation are

- protection zone for LVDC system to reduce fault impact and decrease number of faults (SAIFI)

- selectivity in earth fault protection between customer network and DC network
- selectivity in short circuit protection between inverter current trip operation and customer network protection device operation
- to operate at first fault situations in DC network earth faults to decrease risk of double fault situations
- the healthy pole of bipolar system can be in operation while other pole is faulted

4 Control of the Island LVDC system

The Island LVDC microgrid is a complicated power system which requires efficient control algorithms and principles to provide reliable, sustainable and uninterruptable power supply for the customers. Simultaneously with that requirements is necessary to achieve maximum of economic benefit and reduce investment costs. Following chapter is related to the definition of main control concepts for low voltage DC network regulating, which allow to implement all mentioned above statements.

In general, control methods of the presented Island LVDC microgrid could be divided into two conditional parts. First is a price-based control, which allows to regulate customer' energy consumption using price for the electricity as the instrument of control. Proposed price mechanism can improve residential energy consumption patterns by using web services to provide information for customers and also aggregate consumer preferences, real-time metering and forecasting. It is expected that such type of control will be a major regularity tool for achieving the power balance in Island LVDC system.

Second mechanism is a technical regulation which includes technical constraints and control of system parameters. It combines customer voltage control, automatic load operation (connection/disconnection) and also protection arrangements. It can be presented as a the secondary level of control which starts to operate when first level cannot cope with the problem of power balance.

The arrangement of mentioned above regulating mechanisms have to provide flexible and effective control for the presented LVDC distribution system. These two principles are described more deeply in relevant subchapters below.

4.1 Price-based demand control

Demand side management becomes a key component of control for modern networks nowadays. It helps reduce peak load and adapt elastic demand to fluctuating generations. Besides, such responsive demand becomes increasingly important in electrical power systems with application of weather-dependent renewable generation, due to the difficulty and expense of storing electrical energy.

During study work one common approach for the presented problem was found. It lies in the fact that the each player develops an individual demand response program to deal with peak demand that suits their own objectives [13]. The Island LVDC system is not an exception, because weather-dependent generation and DC technologies are significantly affect on system behavior.

In this way, price-based demand response control is introduced as a mechanism to link demand with supply in Island LVDC power system. In particular, demand response can be applied to reduce peak demand and also to affect on consumption for effective battery management. As it was already mentioned, photovoltaic power production extremely depends of the weather conditions and it is needed to be taken into account. The main idea of demand response in Island LVDC system with PV generation is, at first, to reduce power consumption in time of solar activity and direct energy to charge battery bank as quickly as it possible, because next opportunity to make it may not be soon. Secondly, to transfer peak loads on the time with minimum consumption. It makes possible to reduce battery discharge state and prolong battery lifetime.

As the price is the instrument of regulating, it is necessary to affect on customers through it, it means that price should represent a signals for a particular user action. For example, it should be beneficial for customer to disable part of the load during the time of solar activity, because it is necessary for system to charge batteries quickly. It is also might be beneficial for customer to enable some load in night time, when consumption is minimal, for example washing machines and dishwashers, because it will allow to spread the loads evenly and as consequence to prolong battery discharge cycle.

Price formation, which reflects necessary actions for the system and allows to implement price-based demand response for LVDC microgrid is described in the subchapter following below.

4.1.1 Price determination

Novel Island LVDC microgrid requires an individual price formation principle because of specific power generations and operation conditions and also due to specific topology of the network and device installations.

Pricing should be carried out on a simple and efficient algorithm that takes into account the specifics of the application of weather-dependent renewable power source and low voltage DC distribution technologies, which are in significant investment costs, insufficient maintenance costs and high volatility of power supply.

Proposed mechanism for price determination is presented of the figure 4.4.1.1. Following presented scheme, structure of pricing could be conditionally divided into two ways which are costs for generation and costs for distribution. Considering annual generation and system profiles of load behavior and generation possibilities, it is possible to obtain these two components and by summing get actual price for the electricity for customer.

However, as it was described previously, it is necessary to affect on customer by price changing in required situations. The main idea of proposed below method is to include a so-called *Price Correction Coefficient*, which will readjust the price for required situations, for example make prices high in time necessary for battery charging and opposite make prices low in night time.

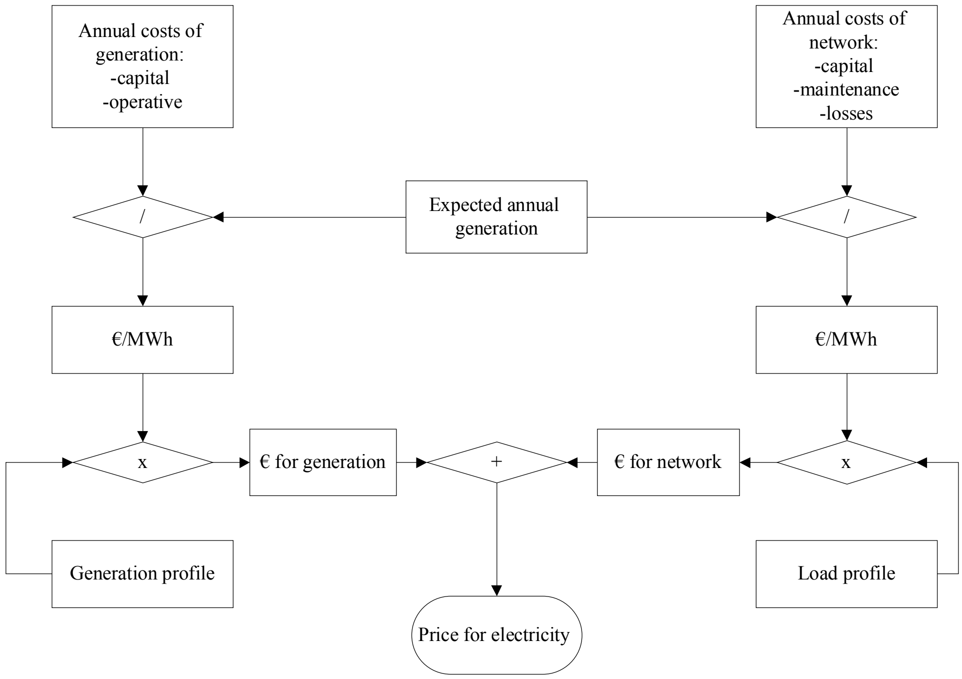

Fig. 4.4.1.1. A proposed price formation scheme.

As price have to reflect on external conditions, such as weather forecast and as a consequence possibilities for generation, load forecast and the most important state of battery charge, thus, this requirement could be implement with the correction price coefficient, which have to take into all mentioned information. Price determination, in this case, based on inaccurate information such as forecasted data. Therefore, for these purposes could be used fuzzy logic theory, suitable for work with inaccurate information even in linguistic form. This method based on expert assessments and allows to get quickly an accurate results in real time.

Expert methods define term-set of parameters that form the membership functions for all linguistic variables. The set of rules in fuzzy expert system generates a rule base. Generally, it is based on three stages, which are fuzzyfication, fuzzy logic output and defuzzyfication. Named stages are performed by following below functions:

- Fuzzyfication stage transforms input variables in categories of fuzzy logic, and any grade of membership (μ) is determined by obtained fuzzy set.

- Fuzzy logic output forms conclusions about the current fuzzy set based on information from the rule base.
- Defuzzyfication block transform fuzzy logic output to the concrete value. In presented problem it will be a value of correction price coefficient.

Rule base consists of terms which are describing correction price coefficient determination in such view (as possible example):

IF weather forecast (*W*) is in *good* **AND** load forecast (*L*) is *bad* **AND** battery charge (*B*) is *full* **THEN** correction price coefficient (*k*) is *low.*

Therefore, schematic illustration of fuzzy logic mechanism for determination of correction price coefficient *k* presented on the figure 4.4.1.2.

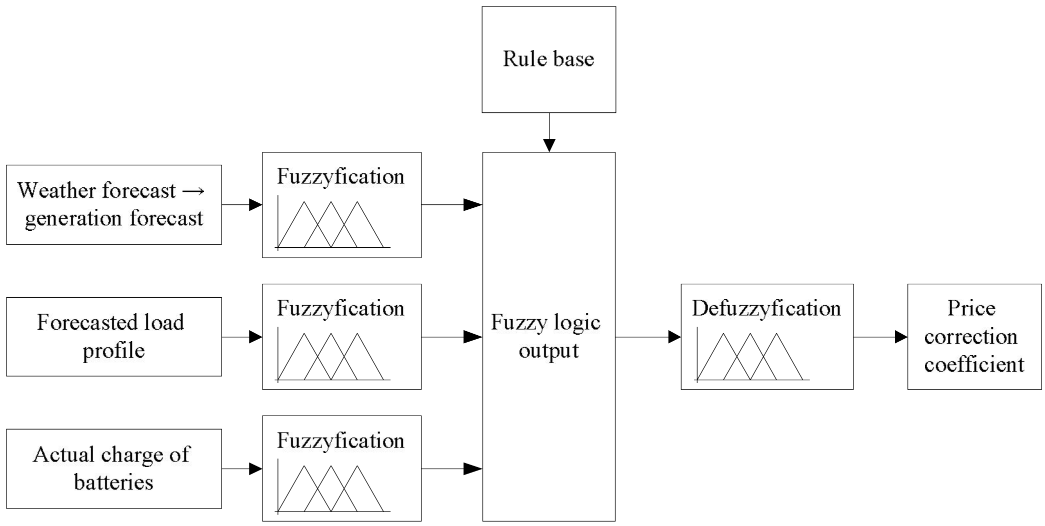

Fig. 4.4.1.2. Fuzzy-logic scheme of correction price coefficient.

Hence, customer price could be presented as equation (4.4.1.1):

$$C=C_e \cdot K, \tag{4.4.1.1}$$

where C_e is a price for electricity and k is a correction price coefficient, which is:

$$K = max\{\mu_i(W); \mu_i(L); \mu_i(B)\}, \tag{4.4.1.2}$$

where $\mu_i(W)$, $\mu_i(L)$, $\mu_i(B)$ are membership functions for Weather forecast, Load forecast and Battery charge. Using composition (*max*), all the fuzzy subsets assigned to each output variable are combined together and formed a single fuzzy subset for each value of the output variable.

4.1.2 Application of nodal pricing

In conditions of utilization of low voltage DC distribution system in Island operating situation it is possible to apply nodal price methods for determination of the price for the electricity. In that case, prices in each node of the distribution system will be calculated and bases on them, common price will be defined.

Nodal prices reflect the actual situation in the grid more transparently than uniform or zonal prices and represent adequate price allocation signals. Nodal prices may also save costly investments in transmission lines [27].

Nodal price shows the cost of energy purchased in single node. It includes generating costs, loss costs and costs of system's congestions. Nodal prices are usually different and it is necessary to determine them through the financial-technical models. In these models each generator costs, losses in network between supplier and buyer, physical and financial balances in nodes are considered. It is assumed also that nodal prices would send adequate signals in form of price increasing that show local demand for boosting of generation output or transmission capability of network. Equilibrium price in every node depends on demand and offer of electricity in that node, equilibrium prices in other node, and available transmission capacity of network and order of dispatching. Insufficient transmission capacity could lead to market's segmentation and increasing of participant's concentration.

The future research work should be forwarded to the deep study of possibility of application such methods for the novel LVDC system. In addition, on the next step a simultaneous optimization of the technical properties of the necessary scheme (power losses, and voltages in nodes) and electricity prices in nodes needs realization.

4.2 Technical control

Technical control from the LVDC microgrid point of view includes power balance control, voltage control and protection arrangement. As it was mentioned previously utilization of DC technologies provide great benefit as there is no need to care about reactive power component and synchronization of power sources in the network. Therefore, power balance regulation could be implemented with active power control, which means in island LVDC conditions that it is necessary to achieve equality between produced active power by photovoltaic power plant, active residential load, and stored active power in energy storage.

4.2.1 Power balance control

Main mechanism for achieving power balance in the system is to control the vital elements of the Island LVDC system, such as produced PV power, battery charge and customer loads, and to achieve power balance between it. It requires high speed communication system and intellectual microgrid management system (MMS), which will be responsible for the co-ordination of the power balance management.

In general, it is proposed that the microgrid power balance can be maintained by charging or discharging the energy storage as needed i.e. if control of the master unit cannot keep up the power balance.

Utilization of demand side management as part of LV microgrid power balance management requires full adoption of smart metering and smart control of loads within the microgrid. In addition, household MMSs should be able to directly control all dispatchable loads in the household. Fast load disconnection during island operation of LV microgrid requires utilization of high-speed communication, as it was mentioned above[6].

4.2.2 Voltage control

In general, power balance control is deeply interconnected with Voltage control, it could be said that it is main instrument of power balancing. Nowadays, there are two major different DC bus voltage control schemes investigated. One of the methods, known as the communication or master/slave method, which is strongly relies on fast communication between the source and load converters. The output power, with sign, is calculated for each of the converters. Information on total output power is fed forward to the converters. One of the converters, the master, is responsible for controlling the DC bus voltage. Feed forward of the total output power allows for high bandwidth DC bus voltage control. The DC bus voltage controller is, however, still required during transients and to compensate for losses in the DC power system. Due to the resistive voltage drop, a proportional-integral (PI) controller is adopted in order to avoid stationary DC bus voltage error.

The other method is referred to as voltage droop control. Droop control does not require any communication at all between the converters. Instead, the DC bus voltage is measured at the source converter terminals. All the source converters contribute to balance the total power consumed by the loads and the losses of the DC power system. In common voltage droop control, the DC bus voltage decreases linearly as the output power for the converter increases, in order to give stable operation. This, of course, yields a stationary error in the DC bus voltage. Therefore, a restoration process to reduce the stationary DC bus voltage error need to be taken into account.

4.2.3 Specific of voltage control

As it known, traditionally voltage regulation on passively managed low voltage distribution networks has been done with fixed off-load transformer tap changers at MV/LV distribution substations [6]. However island conditions, PV power generation and utilization of DC form of supply require more intelligent methods. In such system voltage control responsibility lays on main line converter control system and battery management system, and also as a secondary level on control of customer inverters. The control systems for converters, as also the load sharing mechanisms, is a separate and very important part of research work, because it is necessary to design a specific algorithms of control, suitable for the novel low-voltage DC distribution system.

In presented system, line converter takes the responsibility about boosted voltage control after conversion and also about control of the state of battery charge and. It allows to reduce amount of power electronic devices in the system, however it needs in intelligent and complicated control algorithm (Fig.4.2.3.1).

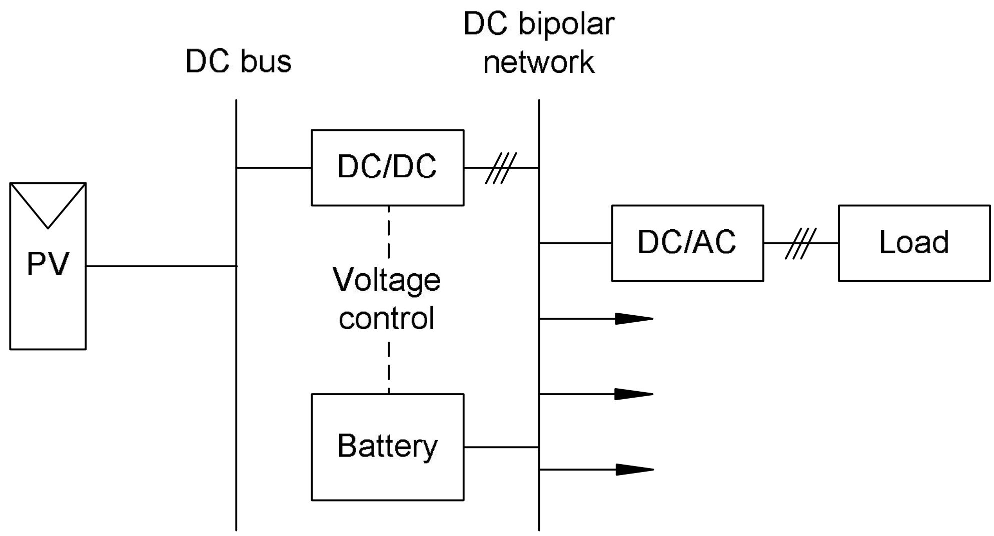

Fig. 4.2.3.1. Principle scheme of Island LVDC network with PV power source.

The application of bipolar structure in presented network system brings an important challenge in system operation. It is voltage unbalance between neutral point and poles. Therefore excessive voltage unbalance should be compensated mainly through the control of energy storage and controllable loads. In future scenario, single-phase DG units and charging of electrical vehicles have to be taken into account for decision of this problem.

In general, from the LV microgrid concept's point of view it is essential that the chosen method for the compensation of excessive voltage unbalance in island operated LV microgrid is compatible with other chosen technical solutions of LV microgrid concept. These are for instance protection principles and settings, voltage level and voltage THD management [6].

Controllable customer loads could be applied for power balance maintenance and prolong independent system operating in some way. It can be implemented by voltage-relays, which control voltage level on the DC side of customer converter and operate the switch-states of the loads. When the discharge level of energy storage achieve a certain value some loads disconnect automatically in order to reduce power consumption and keep system voltage at the appropriate level. The order of disconnection of load is determined by customer in advance. In worth case, when the energy storage devastated and power production eliminated cause of weather conditions there will be a total disconnection of a customer. For that reason customer' household have to be equipped with additional independent power source, for example diesel-generator or EV. Automatic recovery of power supply must be implemented.

4.2.4 Load sharing

There are also basically two different methods to achieve load sharing. One of the methods is referred to as the droop concept and the other as the master/slave concept.

For the droop concept, a finite loop gain for the DC voltage controller is adopted. A droop characteristic is obtained from the transfer function slope in the P-V plane at the desired DC bus voltage. Since this droop characteristic appears as a negative slope in the P-V plane, load sharing is obtained. The quality of load sharing is determined by the negative slope of the droop characteristic, i.e. for a steep slope, load sharing is good but voltage regulation is poor. On the other hand, for a shallow slope, load sharing is poor but voltage regulation is good. Therefore, a trade-off between voltage regulation and load sharing has to be made for the droop concept.

In the master/slave concept, only one of the source converters is controlling the DC bus voltage. The other source converters are current controlled. This results in a stiff DC bus voltage regulation and a fully controllable load sharing.

As research work sows [28], in a situation where several converters connected to the DC distribution bus that all control the voltage precisely to the reference at their respective connection point, load sharing among sources is not controlled. Instead, load sharing is entirely determined by the distribution bus impedance.

During design load sharing mechanism for the Island LVDC microgrid it is necessary to take into account specific of innovative system, and chose suitable method as the basis for future development.

5 Case calculations

In following chapter, case calculations are presented basis on the example of possible LVDC microgrid. The results helps to get preliminary answer the question: is it possible during summer time to have a microgrid system based on solar panels? Also the economical efficiency of represented system in summer time is estimated.

However, in spite of non-efficiency of application of PV panels in winter time, which was shown in Subchapter 2.3., such case was also emulated during modeling due to study the influence of consumption and production of energy in different conditions.

5.1 System definition

For presented case calculation following system example was accepted:

- Location on Turku archipelago - 60°26'57" North, 22°15'33" East, Elevation: 35 m a.s.l.;
- ±750V DC bipolar structure of system;
- Total power of the system – 100kW (peak value);
- Number customers – 15;
- Total length of LV network – 2700m;
- Load growth in the system – 1% for t = 40a;
- Depreciation time T = 15a;
- Lifetime for converters – 15a;
- Lifetime for PV panels – 20a;

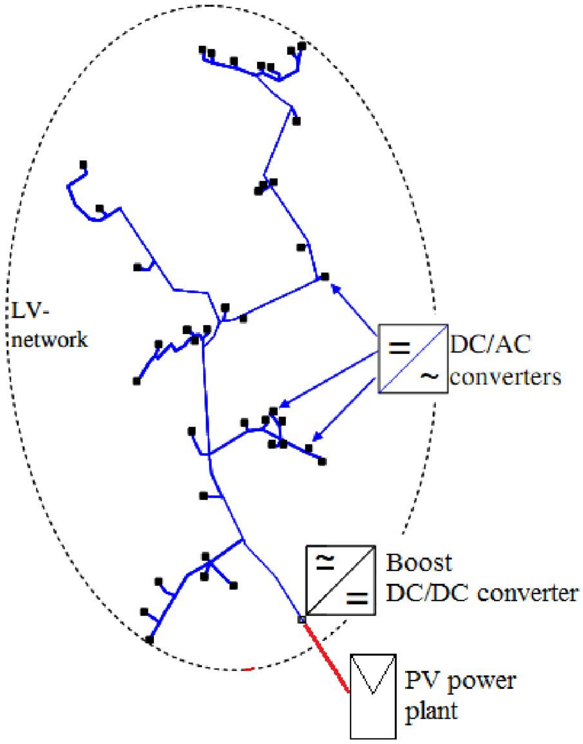

Fig. 5.1.1. Island LVDC distribution network.

5.2 Consumption calculations

For the purpose of defining of daily consumption were used graph 2.3.5. [1] presented in the Subchapter 2.3., which are describe customer' consumption behavior in June when there are the best conditions for power production from solar energy.

Peak power P_{max}=100kW;

Daily consumption in June $P_{Jun} = \int_{0}^{24} P_h dt = 851.3$ kWh/day.

Obtained result is used for determination of necessary energy storage capacity and required power of PV system.

5.3 Battery size calculation

As it was justified in previous chapters the deep-cycle type of batteries is more suitable for presented LVDC system. According to the standards related to the determination of battery capacity for stand-alone island systems with PV generation [9, 10] it is required that energy storage can maintain an uninterruptable power supply at least for 7 days in extra cases. So that, battery capacity could be obtained as:

$$P_{bat} = P_{Jun} \cdot d = 851.3 \cdot 7 = 5959.1\text{kWh} \approx 7945\text{Ah}.$$

For accurate determination of battery capacity the worst case of energy consumption have to be considered.

For following modeling batteries type was chosen Lead-Acid deep cycle type, nominal voltage 750V, maximum charged voltage 816.6V, nominal discharged current 30A. Characteristics of the battery bank were set up automatically from Matlab database according to the nominal voltage and rated capacity.

5.4 PV array size calculation

The *nominal peak power* is the power rating given by the manufacturer of the module or system. It is the power output of the module(s) measured at 1000W/m^2 solar irradiance (and a module temperature of 25°C and a solar spectrum corresponding to an air mass of 1.5). This means that if modules are 100% efficient, it is needed 1m^2 to get a system with a peak power of 1kW. These conditions are known as *Standard Test Conditions*(STC).[16]

In other words, if P_{pk} is the nominal peak power and A the area of the module(s), it is:

$$P_{pk} = A * eff_{nom} \quad (5.4.1.)$$

The actual power depends on the irradiance G and the real module efficiency eff which is a function of irradiance and module temperature T_m. So it is possible to obtain the actual power:

$$P = G/1000 * A*eff(G,T_m) = G/1000*A*eff_{nom} * eff_{rel}(G,T_m) \qquad (5.4.2.)$$

where we have written the actual efficiency as the product of the nominal efficiency eff_{nom} and the *relative efficiency* $eff_{rel}(G,T_m)$.

Combining Eq. 5.4.1 and 5.4.2 it is possible to get:

$$P = G/1000 * P_{pk} * eff_{rel}(G,T_m) \qquad (5.4.3.)$$

Therefore, if the relative efficiency and the peak power are know, there is no need to know the nominal efficiency or the area.

According to the introduced information and graph 2.3.6 represented in Subchapter 2.3., it possible to determine necessary area of PV panels if the efficiency and power consumption are known.

Daily irradiance in June: $G_{Jun} = \int_0^{24} G_h dt$ = 22729/1000 = 22.729kWh/day.

Power that could be obtained from 1m^2 in June: $P_{pv,Jun} = G_{Jun} \cdot k$ = 22.729·0.15 = 3.41 kWh/m^2/day, where k is efficiency [15].

Thus, to cover daily consumption P the needed area of solar panels is equal:

$A = P_{Jun}/ P_{pv,Jun}$ = 851.3/3.41 = 249.65 m^2. (It's a square 15x15m.)

For the most accurate calculations the worst case have to be take into account.

Thus, peak power that PV power plant can produce in STC:

$$P_{pk} = A \cdot k = 249.65 \cdot 0.15 = 37.45\text{kW}.$$

The value of peak power is necessary for following price calculations.

5.5 Price calculation

For decision problem with price determination it is necessary to define the situation with the ownership of the system. Will this system be provided for customers by some independent company and customers will need to pay to this company, or customers will own this system by themselves, which means that they will share the sufficient capital investment for constructing system.

In first case, company which provides power system is interested in a short depreciation period and needs to determine necessary monthly payments for customers. It is also requires a smart price-based demand control to prolong the lifetime of batteries and other equipment, reduce maintenance work, outages and costs.

In second case, customers, which own the power system and took money for construction for example in a bank, have to make monthly payments to the bank and save up money for future renovation and maintenance of the system. In that situation the price-based demand control could be represented as a virtual mechanism for effective system operation.

However, it is necessary to determine the capital investment in power system.

Distribution system:

- Line investment - 31400€;
- Converter investments - 72250€;

Capital investment in PV power plant:

- PV power plant investments – 74900€ ($C = P_{pk} \cdot c$ = 37.45kW · 2€/W);
- Energy storage - 1490000€ ($C = P_{bat} \cdot c$ = 5959.1kWh · 250€/ kWh);

Lifetime investment in the system:

- Line losses - 5000€;
- Converter losses - 9270€;
- Interruptions - 200€;
- Maintenance and fault repair - 2530€;

Total costs are C_{total} = 1685550€ ≈ 1.69 million euro.

For determination of a constant annual cost amount required for the repayment of the capital and interest charges during the lifetime it is necessary to make annuity calculation:

$$\varepsilon = \frac{p/100}{1-\frac{1}{(1+p/100)^t}} = \frac{5/100}{1-\frac{1}{(1+5/100)^{15}}} = 0.096;$$

where $p = 5\%$ is the interest rate and $t=15a$ is the investment lifetime in years.

Thus, the annuity payment is:

$$C_a = C_{total} \cdot \varepsilon = 1685550 \cdot 0.096 = 161812.8€.$$

So that it is possible to define monthly payment for customer:

$$C_m = C_a / (12 \cdot 15) = 684542.4 / (12 \cdot 15) = 898.96€.$$

Taking into account the obtained fixed price for electricity, then it is possible to change it with the help of correction coefficient, which is consider the external parameters, as it was described in Subchapter 4.1. Influence on the price with the help of correction coefficient could be illustrated on Fig.5.7.1 - 5.7.2. with the blue curve on the first graphs. Represented correction coefficient is automatically calculated according to the membership functions of "Weather", "Load", "Battery" and fuzzy logic algorithm, laid in Matlab Fuzzy Controller.

5.6 Modeling

For computer modeling was made the decision to simulate one half of the bipolar system, because it allows to get necessary results with more simple structure of model. Another pole of the system has the similar behavior, so that it is useful to implement this possibility. For simulating process was used the Matlab computer environment with SimPowerSystem toolbox.

5.6.1 Technical characteristics and constrains of the model

Technical characteristics and constrains of the model are presented in following list:

- Load: Resistive, peak power 100kW, consumption 880kWh/day in case of June (1450kWh/day in case of January);
- Batteries: Lead-Acid deep cycle type, nominal voltage 750V, maximum charged voltage 816.6V, nominal discharged current 30A, rated capacity 8kAh;
- PV power plant: Efficiency 15%, Area of panels 250m^2 in case of June (15000m^2 in case of January);
- Solar irradiance: presented in W/m^2 for Turku region;
- Network: no losses, one pole of bipolar structure;
- Simulating period: one day (1440 min.), scale is that 1 sec. of modeling is equal to 1 real min.

5.6.2 Subsystems

The model of LVDC system is presented on the Fig.5.6.2.1. and includes one pole of the bipolar network, PV power plant, presented as "PV generation", load, presented as the subsystem “Load”, energy storage, presented as “Battery” block and measurement equipment.

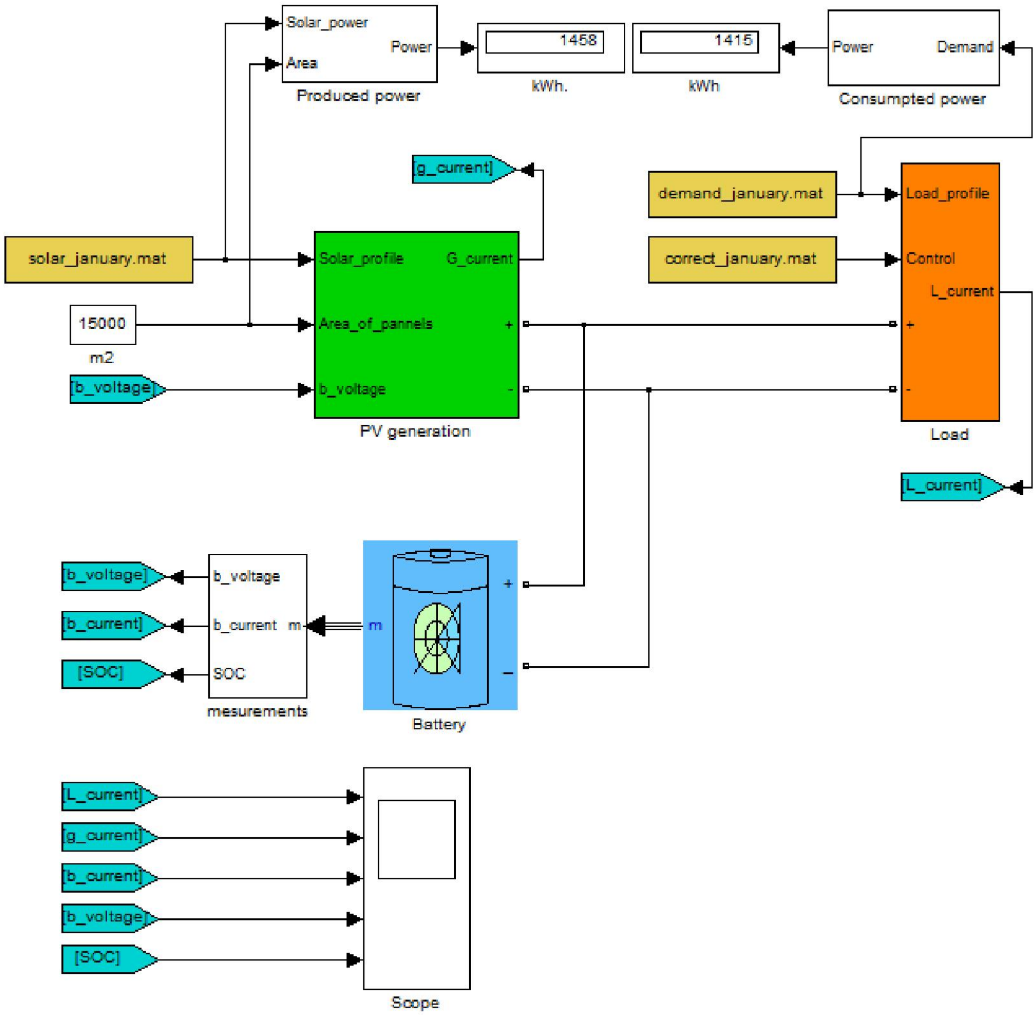

Fig.5.6.2.1. Model of the Island LVDC system.

Information about load behavior and solar irradiance for studied months was wrote in .mat-files in a table view. Those files were set up respectively to the necessary inputs of subsystems “Load” and “PV generation”.

Model is equipped with metering system to estimate the produced and consumed power which is present of Fig.5.6.2.2.-5.6.2.3. The calculation of the area under demand curve using integral gives the value about consumed power (Fig.5.6.2.2.). As it is need to get amount of kilowatts per hour, the period of 60 min is taken for calculations (1min – sample time of the model, so that integral use this period for calculations). This metering system is represented as the “Consumed power” subsystem in the model.

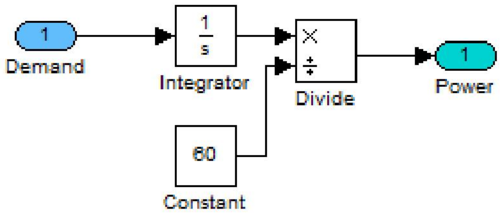

Fig. 5.6.2.2. Demand metering.

The calculation of the area under curve of solar irradiance using integral gives the value about produced power (Fig.5.6.2.3.). It is necessary to consider that irradiance is presented in Watts, therefore it have to be divided by 1000 to get kilowatts. The efficiency coefficient have to be also taken into account. It is 15% for Crystalline-silicon modules (IEEE Std 1562™-2007). This metering system is represented as the “Produced power” block in the model of LVDC system.

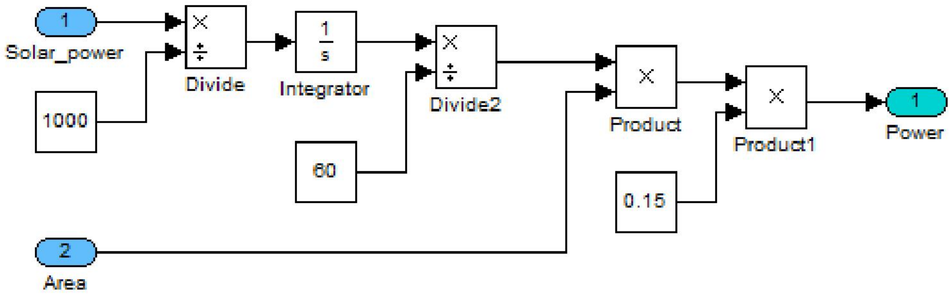

Fig. 5.6.2.3. Power production metering.

In studied Simulink model, PV power plant is presented as a controllable current source which included in the subsystem “PV generation” (Fig.5.6.2.4.). The control signal for current source is obtained from solar irradiance multiplied with area of PV panels and coefficient of efficiency and then divided on system voltage, which is a battery voltage in following case.

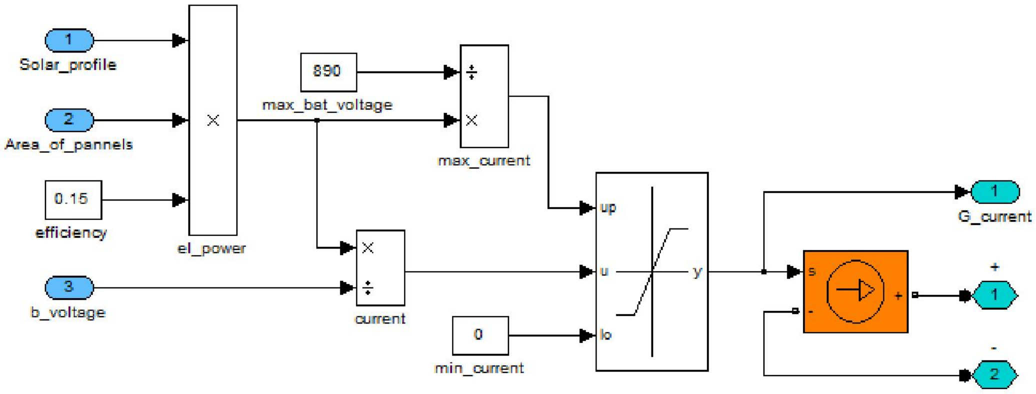

Fig. 5.6.2.4. PV generation subsystem.

Load is represented as controllable current source too, but with opposite connection (Fig.5.6.2.5.). The signal for current source can be obtained from Load profile and system voltage. Load profile provides the demand curve in kilowatts scale, therefore it is necessary to multiply it with 1000 to get power in Watts. The possibility of Load control is envisaged by summation the load curve with correction signal, it means that it is possible to influence on the load current through power consumption.

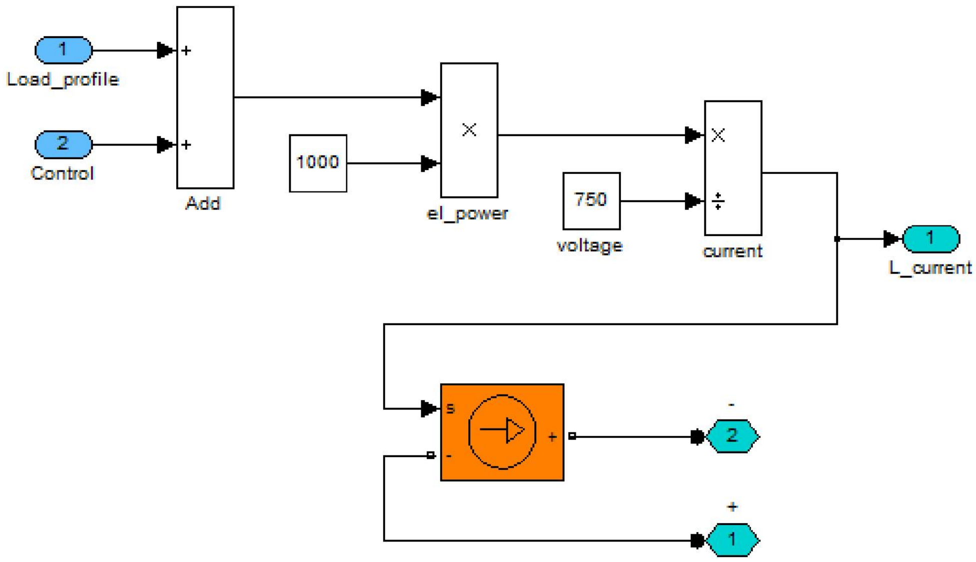

Fig. 5.6.2.5. Load subsystem.

The control signal for the "Load" subsystem is written in a table view like load curve and information about solar irradiance. It consists of time scale and set of correction coefficients (in presented model there are correction values), which could be obtained like was described in Subchapter 4.1. By summation with load curve it makes possible to affect on consumption. Hence, the demand control is implemented in a such view.

Energy storage has direct connection to the system and battery measurement block provide information about battery voltage, current and state of charge (SOC).

5.7 Results

During modeling process were obtained system characteristics for studied model. They are presented on Fig.5.7.1. – 5.7.2. Red curves are describe system behavior without demand control while blue curves describe it with implemented demand control. As it could be seen from graphs below, the main result is the reduction of battery discharge level on 1 – 2% in a day scale. It could seems insufficient, however in scale of whole time of autonomy work, for example 10 days, this value achieve 10 – 20%. Besides, consumption of electricity becomes more even, which reduce the range of power fluctuations in the system. The slight reduction by few percent in a charging time also observed, but not as significant as was expected.

Price calculations illustrates high investment costs mostly due to sufficient cost of PV power system and battery storage. It has strong impact on annual costs for customers, which are sufficient values too. In that case, application of hybrid system, e.g. diesel generator or small wind turbine with solar panels, seems more profitable, because it may allow to reduce investments and depreciation time of the system.

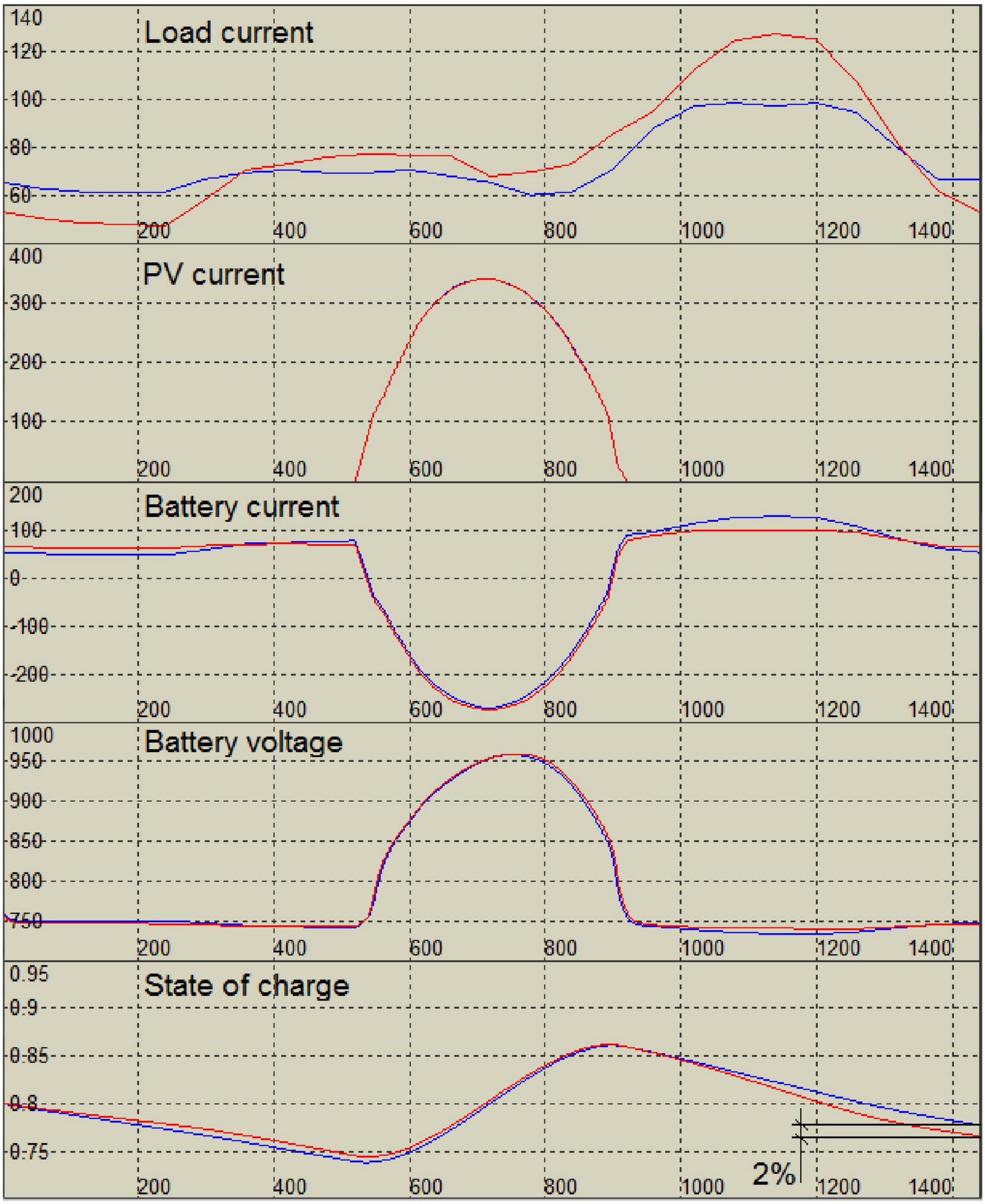

Fig. 5.7.1. System characteristics for January: red curves – without demand control; blue – with implemented demand control.

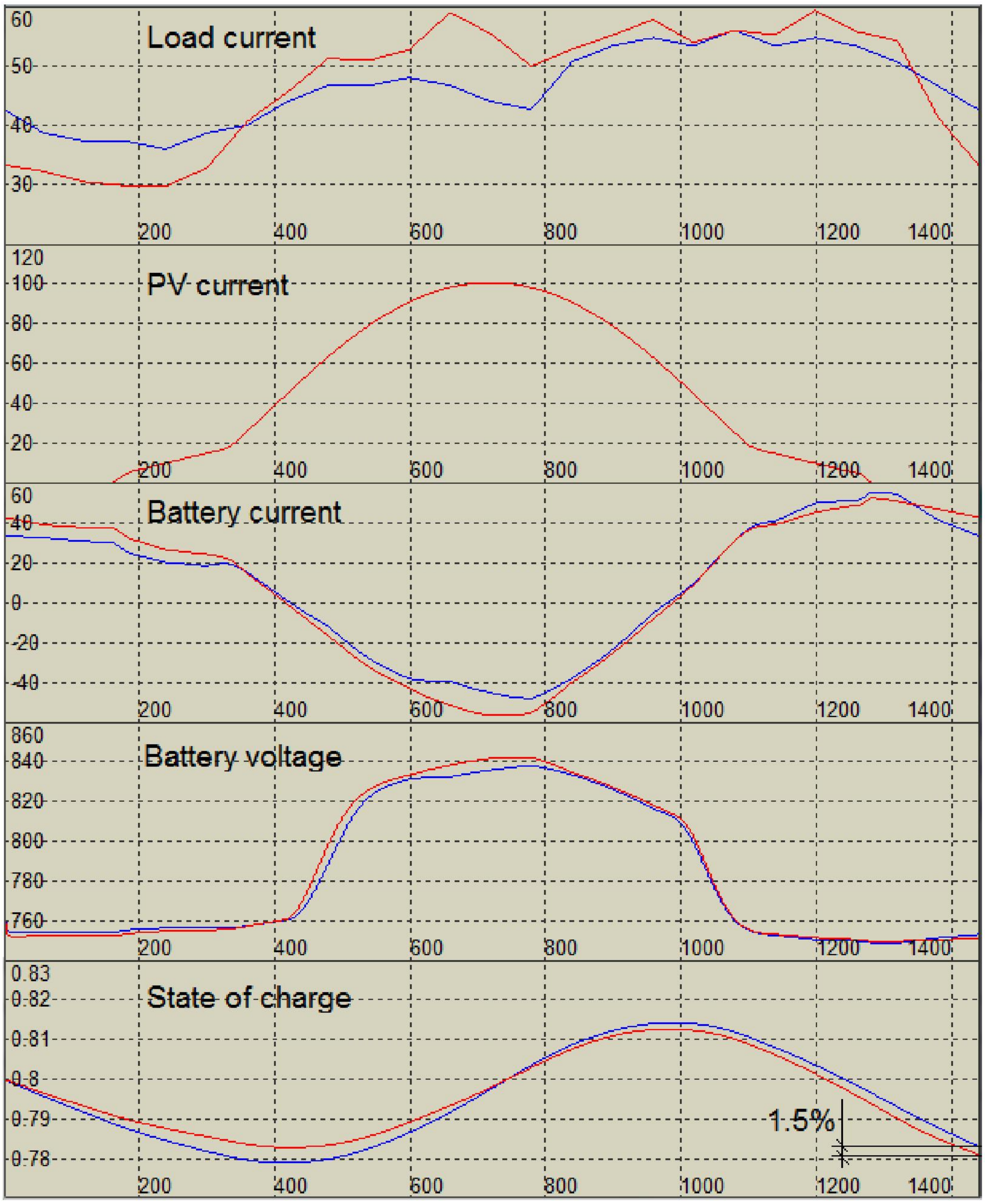

Fig.5.7.2. System characteristics for June: red curves – without demand control; blue – with implemented demand control.

6 Conclusion

During writing presented work there were studied different aspects related to creation of novel Island LVDC microgrid with utilization of photovoltaic power generation, however it should be emphasized that this system could be easily implemented with different renewable and traditional power sources. In that case utilization of LVDC system opens first significant benefit that there is no need of synchronization of power generators and no need to care about reactive power flows.

The possibilities of application of low voltage DC distribution systems in island operating conditions in Finland were studied. Weather conditions is the main constraining parameter for utilization of solar power as the main source of energy in presented system in Finland. Low solar activity, especially in winter time, affects on PV arrays sizing, which have to be significant to cover customer power demand in some applications. From that point of view, it could be beneficial to use hybrid systems for power supply, however it is require an independent research for determining an optimal ration between different type of power sources, for example wind and solar installations.

Proposed bipolar structure of the LVDC network is chosen due to actual cabling standards and provides benefits from reliability and transmission capacity point of view, cause it enables exploitation of the whole DC voltage range defined by the low-voltage directives.

Chosen voltage level, which is 750VDC, which allows not to exceed the standardized DC voltage limits of commercial low-voltage underground power cables, makes possible to increase the transmission capacity more than 3 times compared to the traditional 400VAC. Besides, such voltage level of converters with appropriate customer connection allows to reduces the price of converters.

Research results shows that direct battery connection, which is proposed, have advantages compared to the connection through an additional DC/DC converter, because allows to reduce the investment costs, however it is also required an intelligent control and management systems. In case of Finland it is beneficial to utilize deep-cycle type of batteries, cause of the possibility of deep discharge in situations with long cloudy periods.

Price based demand control is proposed to be the main instrument to influence on customer' power consumption. Present work offers to implement simple price determination, based mostly on investment and maintenance costs, with correction coefficient, which could be determined using fuzzy logic theory. It will allow to consider such inaccurate data as weather and consumption forecasts.

According to the specifics of novel LVDC system and based on international and national Finnish standards, basic system, functional, operational and protection requirements were defined in the present paper.

On the results of present work the main ways of realization Island low voltage DC microgrid were defined, however each problem requires a significant future independent research work to achieve effective and profitable solutions. It can be assumed that present paper has laid the foundations for future researches and identified the main problems with have to be solved.

References

[1] Average hourly demand hour indexes, Sähköenergialiitto ry Sener, Turku Energia, Turku, 2012.

[2] Development of producer prices in technology industries in Finland 1999-2011. Finnish technology industry (teknologiateollisuus ry), 2012.

[3] European commission. Low voltage directive LVD 73/23/EEC. European commission directive: Brussels,1973.

[4] European commission. Low voltage directive LVD 2006/95/EC. European commission directive: Brussels, 2006.

[5] Feasibility of Photovoltaic Systems, Broshure, Texas State Energy Conservation Office (SECO), http://InfinitePower.org, 2012.

[6] Hannu Laaksonent, Technical Solutions for Low-Voltage Microgrid Concept, University of Vaasa, Faculty of Technology, 2011.

[7] IEC 60664-1 International standart, Insulation coordination for equipment within low-voltage systems, International Electrotechnical Commission, 2002.

[8] IEEE Standard 519, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, The Institute of Electrical and Electronics Engineers, 1992.

[9] IEEE Standard 1013, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems, The Institute of Electrical and Electronics Engineers, 2000.

[10] IEEE Standard 1562, IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems, The Institute of Electrical and Electronics Engineers, 2007.

[11] Kaipia T., Salonen P., Lassila J., Partanen J. Application of Low Voltage DC-Distribution System – A Techno-Economical Study. CIRED 2007 conference, Vienna, 2007.

[12] Lassila J., Kaipia T., Voutilainen V., et al., Potential of power electronics in electricity distribution systems, CIRED Seminar 2008: SmartGrids for Distribution, Frankfurt, 2008.

[13] Nguyen D. T., Negnevitsky M., M. de Groot, Wang C., Demand Response in the Retail Market: Benefits and Challenges, Power Engineering Conference, AUPEC 2009, Australasian Universities, 2009.

[14] Partanen J., Pyrhönen J., Silventoinen P., et al., Tehoelektroniikka sähkönjakelussa – Pienjännitteinen tasasähkönjakelu, Lappeenrannan teknillinen yliopisto, Lappeenranta, 2010.

[15] Partanen J., Pyrhönen J., Silventoinen P., et al., Power Electronics in electricity distribution and DC distribution, Research Report, LUT, 2008.

[16] PVGIS © European Communities, 2001-2010, European Commission, Joint Research Centre Institute for Energy Renewable Energy Unit, 2012.

[17] Salonen P. Tasasähkön hyödyntämismahdollisuudet sähkönjakelussa. Diplomityö, Lappeenrannan teknillinen yliopisto, 2007.

[18] Salonen P., Kaipia T., Nuutinen P., Peltoniemi P., Partanen J. An LVDC Distribution System Concept. NORPIE 2008 conference, Espoo, 2008.

[19] Salonen P., Kaipia T., Nuutinen P., Peltoniemi P., Partanen J. A Study of LVDC Distribution System Grounding. NORDAC 2008 conference, Bergen, 2008.

[20] Salonen P., Nuutinen P., Peltoniemi P., Partanen J. Protection Scheme for an LVDC Distribution System. CIRED 2009 conference, Prague, 2009.

[21] Salonen P., Nuutinen P., Peltoniemi P., Partanen J. LVDC Distribution System Protection – Solutions, Implementation and Measurements. EPE 2009 conference, Barcelona, 2009.

[22] SFS 2091 SFS standardi. Asennuskaapelit. Muovivaippakaapeli MMJ. Suomen Standardisoimisliitto SFS ry, Helsinki, 1998.

[23] SFS 4879 0.6/1 kV power cables.XLPE-installed AL-cabels. Construction and testing. National cable standart. SESKO Standartization, Helsinki, 2008.

[24] SFS 4880 0.6/1 kV power cables.PVC-installed PVC-sheathed cabels. Construction and testing. National cable standart. SESKO Standartization, Helsinki, 2008.

[25] SFS 6000 – Low voltage Electrical Installations and Safety at Electrical Work. National Low Voltage Standard –series. SESKO standardization, Helsinki, 2007.

[26] WeatherSpark, Weather graphs and maps, http:// WeatherSpark.com, 2012

[27] Y. Fu, Z. Li, Different Models and Properties on LMP Calculations, The Institute of Electrical and Electronics Engineers, 2006

Z. Ye, K. Xing, S. Mazumder, D. Borojevic and F.C. Lee, ”Modeling and Control of Parallel Three-Phase PWM Boost Rectifiers in PEBB-Based DC Distributed Power Systems”, IEEE Applied Power Electronics Conference and Exposition, APEC ‘98 Conf. Rec., Anaheim, CA, USA, , 1998.

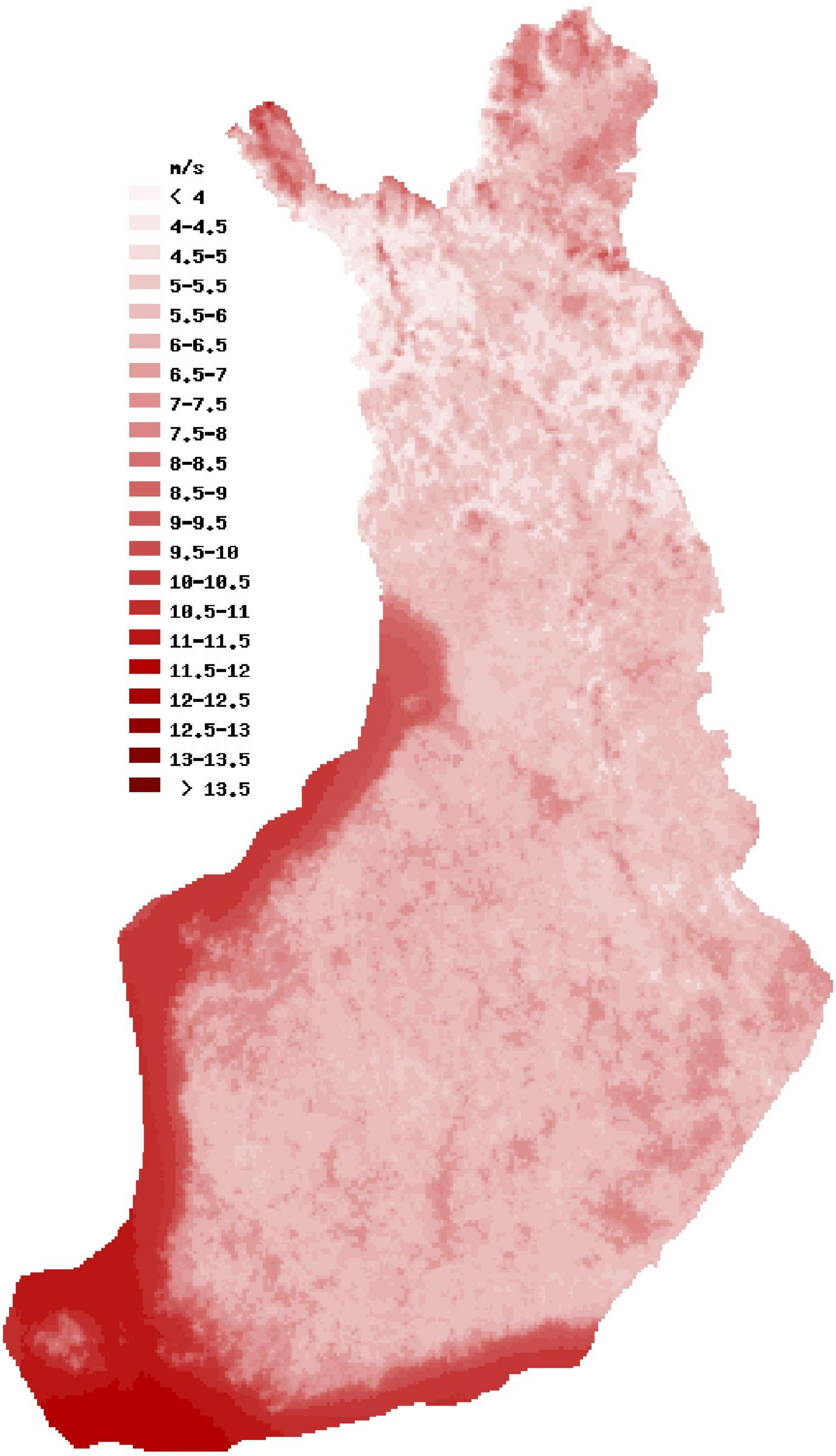

Fig.1. Wind map of Finland for January, 50m altitude.

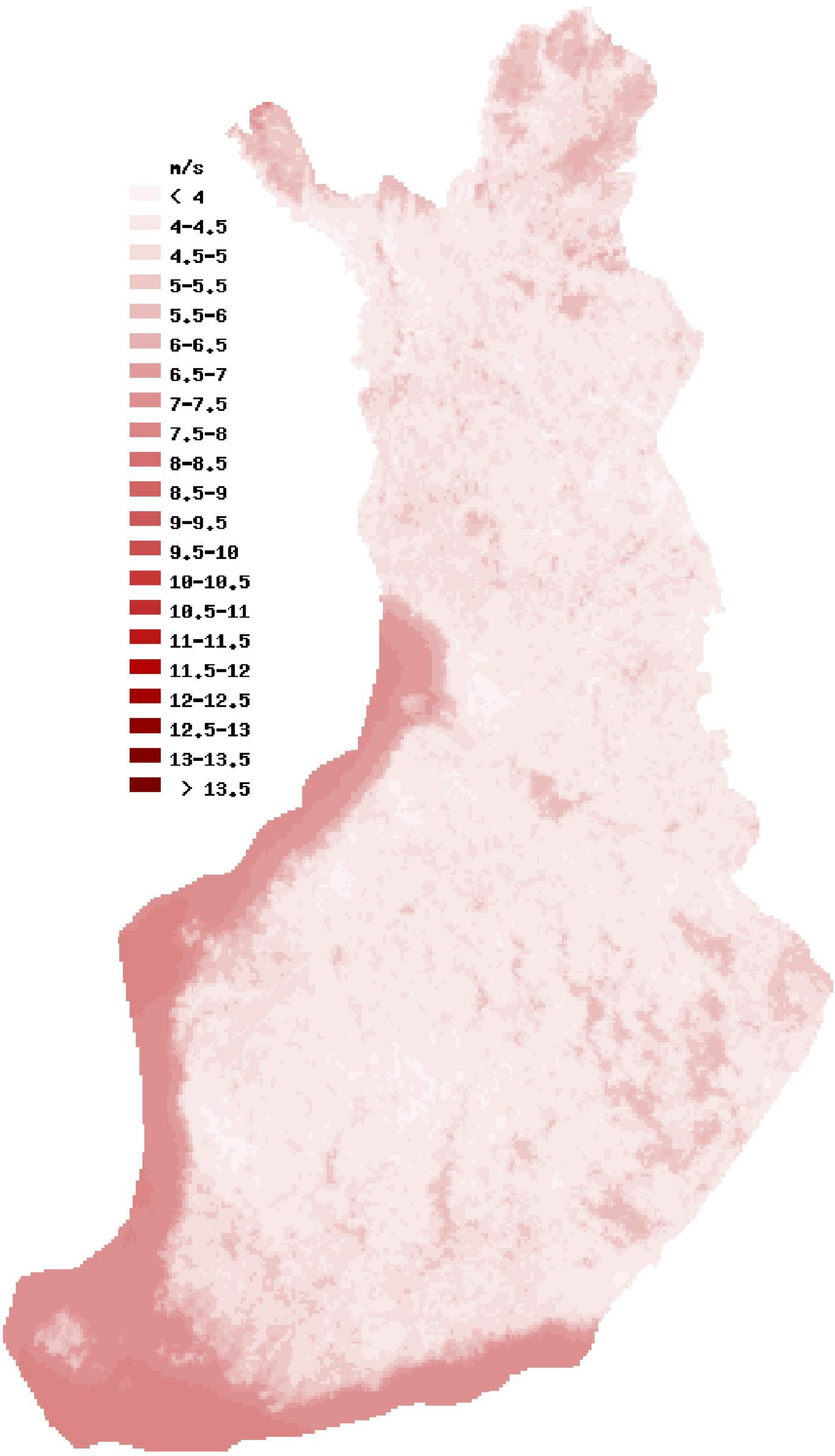

Fig.2. Wind map of Finland for June, 50m altitude.

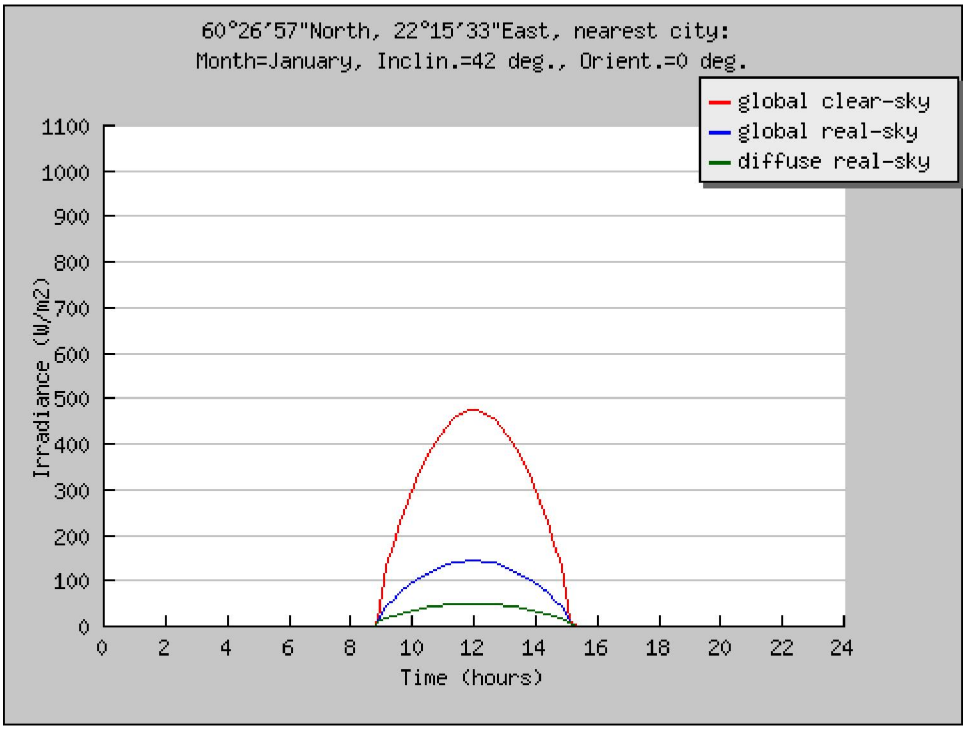

Fig.3. Solar irradiance in January for Turku region (optimal inclination 42°)

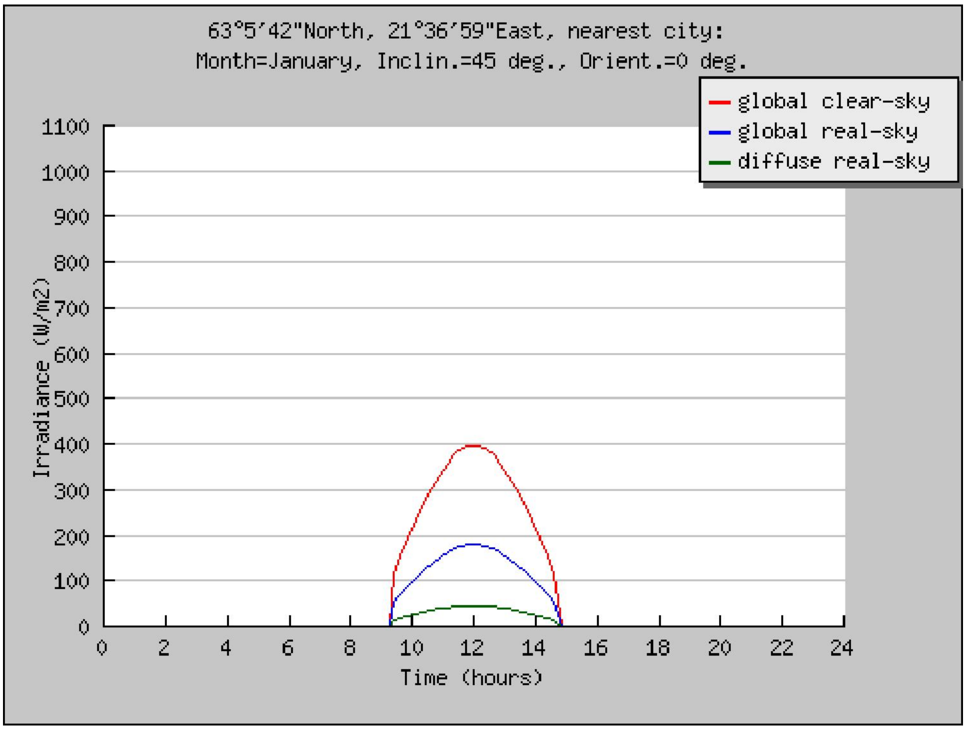

Fig.4. Solar irradiance in January for Vaasa region (optimal inclination 45°)

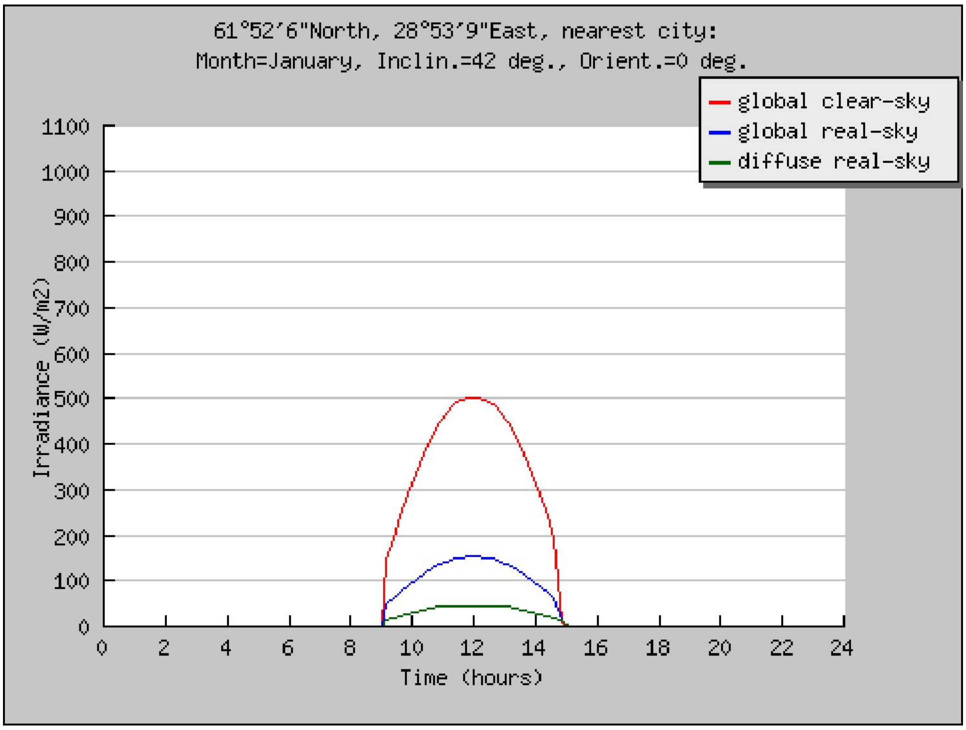

Fig.5. Solar irradiance in January for Savonlinna region (optimal inclination 42°)

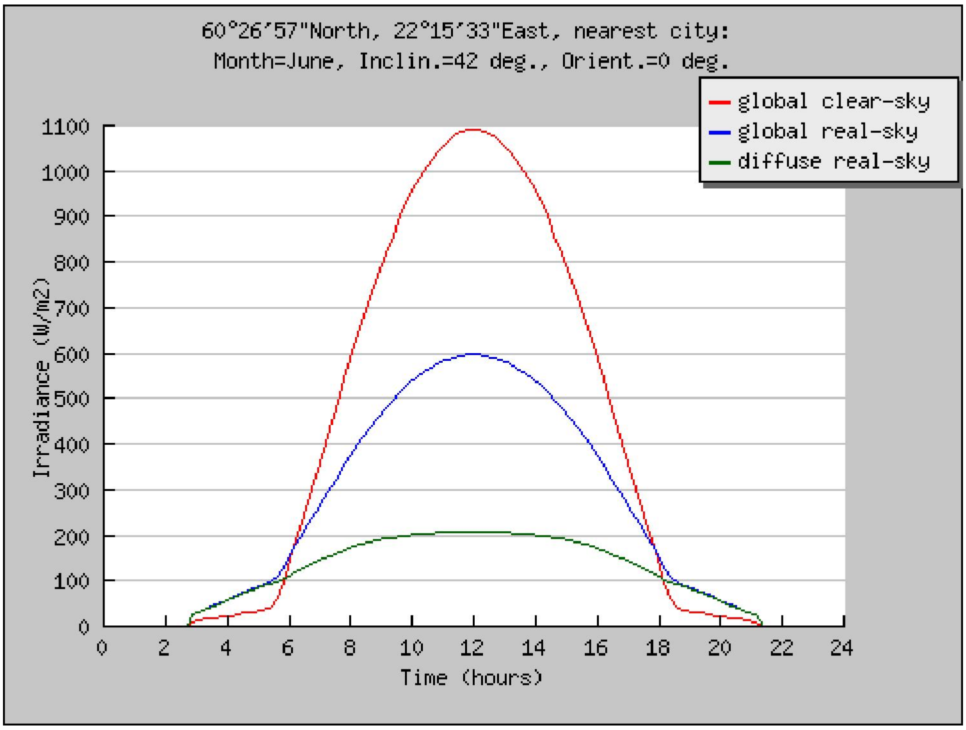

Fig.6. Solar irradiance in June for Turku region (optimal inclination 42°)

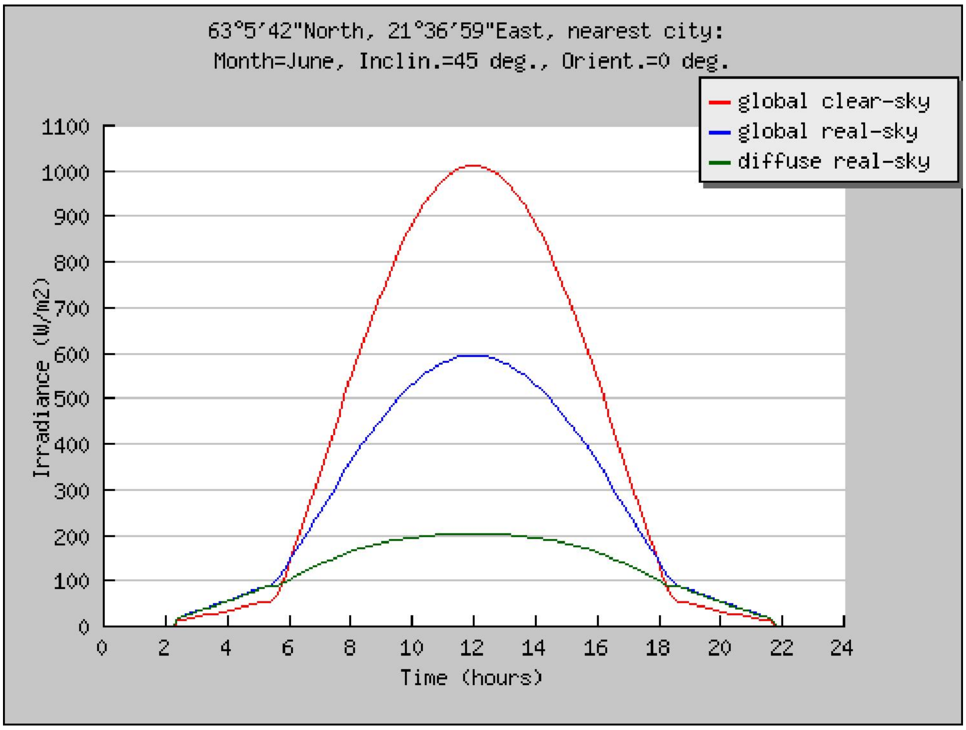

Fig.7. Solar irradiance in June for Vaasa region (optimal inclination 45°)

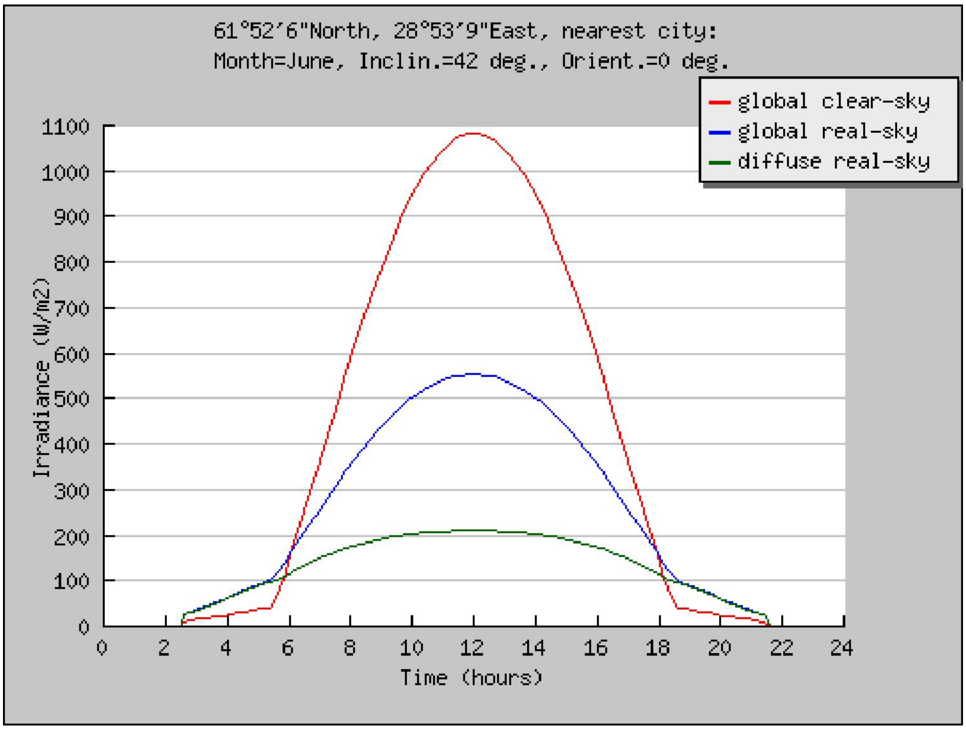

Fig.8. Solar irradiance in June for Savonlinna region (optimal inclination 42°)