Lappeenranta University of Technology
Faculty of Energy Technology
Master Degree Program in Electricity Markets and Power Systems

Master's Thesis

Arun Narayanan

ENERGY MANAGEMENT SYSTEM FOR LVDC ISLAND NETWORKS

Examiners: Prof. Jarmo Partanen
D.Sc. (Tech.) Pasi Peltoniemi

ABSTRACT

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Recent developments in power electronics technology have made it possible to develop competitive and reliable low-voltage DC (LVDC) distribution networks. Further, islanded microgrids—isolated small-scale localized distribution networks—have been proposed to reliably supply power using distributed generations. However, islanded operations face many issues such as power quality, voltage regulation, network stability, and protection. In this thesis, an energy management system (EMS) that ensures efficient energy and power balancing and voltage regulation has been proposed for an LVDC island network utilizing solar panels for electricity production *and lead-acid batteries for energy storage. The EMS uses the master/slave method with robust communication infrastructure to control the production, storage, and loads. The logical basis for the EMS operations has been established by proposing functionalities of the network components as well as by defining appropriate operation modes that encompass all situations. During loss-of-power-supply periods, load prioritizations and disconnections are employed to maintain the power supply to at least some loads. The proposed EMS ensures optimal energy balance in the network. A sizing method based on discrete-event simulations has also been proposed to obtain reliable capacities of the photovoltaic array and battery. In addition, an algorithm to determine the number of hours of electric power supply that can be guaranteed to the customers at any given location has been developed. The successful performances of all the proposed algorithms have been demonstrated by simulations.*

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This thesis was written at an important juncture in my life, and it has been an enriching and fulfilling experience; in particular, the actual research work, ideation, and software coding have been an adventurous and fun-filled journey. This journey could not have been successfully completed without the assistance, contributions, and encouragement of several people who supported me throughout the period of the research work. I am grateful to Ensto for giving me the opportunity and assistance to conduct research on this topic. In particular, the social relevance of this project—“replacing the candle” in small villages without electricity—made it a particularly special one; I had always wanted to participate in projects that attempt to make a *practical* difference to human lives, whether small or big, and I am truly thankful for this chance. Moreover, my work was made immensely easier by the invaluable feedback that I received during the several meetings with representatives from Ensto, Mr. Aki Lahdesmaki, Mr. Mika Luukkanen, Mr. Tommi Kasteenpohja, and Mr. Dai.

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Arun Narayanan

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List of Symbols and Abbreviations

Abbreviations

BEMS	Battery Energy Management Systems
CL	Critical Loads
CB	Critical-Battery
CEL	Critical-Essential Loads
DES	Discrete-Event Simulation
DG	Distributed Generation
DOD	Depth of Discharge
EMS	Energy Management System
HVDC	Low-Voltage Direct Current
ICT	Information and Communications Technology
LCEL	Limited Critical-Essential Loads
LCENL	Limited Critical-Essential-Normal Loads
LCL	Limited Critical Loads
LOPS	Loss of Power Supply
LOLP	Loss of Load Probability
LVAC	Low-Voltage Alternating Current
LVDC	Low-Voltage Direct Current
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NADs	Number of Autonomous Days
PSH	Peak Sun Hours
SOC	State of Charge
STC	Standard Test Conditions

Symbols

B_{Ch}	Battery Charge Rates
B_{Dch}	Battery Discharge Rates
E	Solar Irradiance
$E_{Batt.}$	Energy (Battery)
E_{Load}	Energy (Load)
E_{Losses}	Energy (Losses)
E_{PV}	Energy (PV)
H	Solar Irradiation
N	Number of Customers
L	Hourly Load Data for a Year for One Customer
$Loads_C$	Number of Critical Loads
$Loads_E$	Number of Essential Loads
$Loads_N$	Number of Normal Loads
$P_{Batt.}$	Power (Battery)
P_{Load}	Power (Load)
P_{Losses}	Power (Losses)
P_{PV}	Power (PV)
P_{PVmax}	Maximum Power (PV)
$Pr_{C1} - Pr_{CLoads_C}$	Priorities for each Critical Load
$Pr_{CE1} - Pr_{CLoads_{E1}}$	Priorities for each Essential Load
$Pr_{N1} - Pr_{NLoads_N}$	Priorities for each Normal Load
SOC_{min}	Minimum Battery SOC
SOC_{max}	Maximum Battery SOC
SOC_{least}	Lowest Possible Battery SOC

1 INTRODUCTION

1.1 Low-voltage DC distribution networks

Electricity is the most important power source produced worldwide and it is integral to modern society today; without electric power supply, modern civilization and technical progress are simply unimaginable. We have become increasingly reliant on electric power supply to sustain our economies, daily necessities, as well as comforts. The use of electricity is so ubiquitous that it is practically taken for granted, especially in countries with uninterrupted power supplies. However, the supply of uninterrupted electric power remains a challenging problem across the world, especially with increasing consumption and demand. Outages—short- or long-term loss of electric power supply to an area—often occur in many parts of the world, and they have severe effects on customers, thereby increasing the outage costs. The need for reduced outages has led to demands for more reliable network solutions than the traditional 3-phase AC distribution systems. The ageing of currently used AC distribution grids, as well as their sizes and complexity, have also increased concerns about the reliable transmission and supply of electric power, especially across long distances to remote places. In this scenario, DC distribution has been proposed as a viable alternative, especially at low voltages and in smaller areas such as remote villages or buildings.

DC systems were used for transmission in the early days of electricity production, but they were quickly replaced by AC systems for practical reasons such as, for example, AC voltages could be easily changed using transformers and power could be distributed more economically. Today, DC transmission technology is primarily focused on long-distance high-voltage DC (HVDC) transmission systems, industrial distribution, and electric drives. However, technical and economic developments during the last decade, especially in power electronics technology, have given the opportunity to develop competitive distribution systems based on low-voltage DC (LVDC) distributions (Salonen et al., 2008). The most important requirements of distribution networks are cost effectiveness and system reliability. At low voltages, the LVDC system is an economically feasible alternative that can enhance the reliability and energy efficiency of distribution systems as well as the power quality experienced by the customers. The transmission capacity of LVDC distributions is better than that of low-voltage AC (LVAC) distributions, leading to economic benefits. Further, small-scale power generation systems called distributed generations

(DGs) can be connected to the LVDC distribution network. (Kaipia et al., 2006) Today's power electronics technology and the possibility to use 1.5-kV DC voltage in the LV network make it possible to connect small-scale DGs and energy storages to LV networks. The customer's voltage quality can be improved by eliminating voltage dips, fluctuations, and short-term voltage drops using power electronics devices. The total costs of constructing and operating a distribution system can also be decreased. The LVDC distribution system is thus an economically and technically feasible alternative to conventional 3-phase AC distribution systems, and in fact, it is one of the primary new technological innovations in electricity distribution today. (Kaipia et al., 2008)

In an LVDC distribution system, the DC connection makes it possible to avoid the construction of medium voltage (MV) branch lines and traditional LVAC networks to supply a group of customers. In general, an LVDC distribution network comprises only a DC connection between the wide MV main line and the coupling points of the customers, where the DC voltage is inverted back to AC voltage. The DC distribution system can be constructed with unipolar or bipolar connections, with the primary difference between these two connections being the number of voltage levels (Kaipia et al., 2008).

1.2 Microgrids

A microgrid is defined as a small distribution system with distributed energy sources, storage devices, and controllable loads, which operates in two steady states: grid-connected and islanded. Microgrids are designed to be islanded and isolated from the main grid, if and when required; typically, there is a single point of common coupling with the macrogrid that can be disconnected. In other words, microgrids are a localized grouping of electricity production equipment, energy storage devices, and loads, with the ability to function autonomously and co-operatively. (Lasseter, 2002; Kaplan et al., 2009) In general, the generation resources in microgrids use small energy sources—microsources—placed at customer sites and interfaced with the help of power electronics devices. Power electronics technologies provide the control and flexibility required by the microgrids concept (Lasseter, 2002); of course, power electronics interfaces have the disadvantage that they may increase harmonic injections and they can be sensitive to system disturbances, but this is not problematic in DC grids (Barnes et al., 2007). DGs, which are often renewable sources such as solar or wind but can also be conventional, are typically used to supply the power in microgrids. Microgrids using DGs basically represent small electrical grids located closer to the demand location, thereby decreasing the power failures caused by long-distance transmission grids. Power is generated locally, and hence, the dependence on long-distance transmission lines is significantly reduced, which, in turn, decreases the transmission losses as well. Since multiple DGs can be used and the microgrid can be isolated from a larger network, the reliability of the electric power supply is increased considerably. Further, microgrids can be designed according to localized customer needs and any other special requirements as well. (Rizzo, 2012)

Island networks refer to networks that are completely isolated from the main grid and operate completely independently and co-operatively. Islanded operations lead to various economic and technical issues such as power quality, voltage regulation, network stability, harmonics, reliability, protection, and control; hence, the system network must be extremely well planned. Today, partially islanded operations of microgrids, which play a kind of temporary supporting role to the main grid operations, are more common than completely islanded networks and operations.

1.3 Renewable energy

Besides electrical transmission and distribution networks, the electric power production industry also faces several challenges today. The availability and prices of fossil fuels are unpredictable and highly volatile, leading to several economic challenges and geopolitical risks. Fossil-fuel supplies are not only limited but also expensive. Moreover, fossil fuel-based energy production leads to harmful environmental consequences since fossil fuels cause pollution and increase the dangers of adverse climate changes. Hydroelectric power is a clean and environment-friendly source of energy, but it can also alter or damage the surroundings, for example, by changing the water quality or by hampering aquatic life. Similarly, nuclear power plants also have potentially damaging environmental and human consequences. In general, the energy sector is one of the primary emitters of greenhouse gases. As a result, it has become imperative to utilize renewable energy sources that are continually replenished, such as sunlight, wind, rain, tides, waves, and geothermal heat, where possible. (Prof. Zervos et al., 2010; Turner, J., 1999) The deployment of renewable energy technologies is a promising approach that can be used to mitigate man-made climate changes, reduce hazardous pollution, and enhance local energy independence. Energy production from renewable sources such as wind and solar energy is an attractive alternative for solving energy crises. Renewable energy sources have already been deployed worldwide and many countries have begun to use them to generate electricity, especially wind and sunlight.

Since the energy production from renewable energy sources is variable, intermittent, and (usually) at comparatively low voltages, they are practical for applications to smaller grids with fewer loads, such as microgrids; this also helps in reducing their implementation costs. Hence, the use of renewable energy sources for microgrids has been considered from a very early stage. Many studies have proposed and analyzed the applicability of solar power, wind power, other renewable sources, or their combinations to microgrids, and various real-world installations (primarily on-grid) have been implemented across the world (Barnes et al., 2007). Most of these studies have focused on using microgrids as a backup to the main grid and completely islanded operations have rarely been considered due to the variability of the production. Moreover, completely islanded microgrids using renewable energy sources present numerous techno-economic challenges such as protection, communication, reliability, and power balance issues. Nevertheless, they are attractive because they can be employed to supply renewable-energy-based pollution-free electric power to isolated or remote locations comprising small loads, such as remote villages that have never received electric power supply. By using such completely islanded microgrids, such places can be supplied electricity in a cost-efficient and effective manner; this has important social benefits since the quality of human life will be improved.

Modern electric grids have begun to use information and communications technology (ICT) systems to collect power supply and load demand information, perform relevant operations, and send control signals automatically in order to improve the efficiency, reliability, economics, and sustainability of the network; such grids are commonly referred to as smart grids. Real-time load information is recorded by "smart" meters and communicated by ICT systems to a control center that also considers production statuses before taking the appropriate decisions; the decisions are then communicated to the appropriate network components in the form of control signals. Electric grids equipped with ICT systems are typically referred to as smart grids, and they are designed to respond automatically, quickly, and efficiently to power supply challenges. (Amin and Wollenberg, 2005)

In this thesis, an islanded and smart LVDC microgrid network that uses renewable energy sources for production and batteries for storage has been considered; as discussed previously, this offers the advantages of low losses, pollution, and costs, but the implementation is challenging because control, protection, communication, and other technical issues must be adequately resolved.

1.4 LVDC island networks

In an LVDC distribution system, the power production sources, storage devices, and loads are interconnected by DC buses at low voltages and interfaced by power electronic converters that also have DC links between them. Further, island networks do not have a connection to the main grid, and the entire grid is completely isolated and independent. The LVDC distribution network can be constructed with two implementations: unipolar or bipolar. The unipolar system has one voltage level and all the customers are connected to this voltage level. On the other hand, the bipolar system comprises two unipolar systems connected in series (Salonen et al., 2008). In the bipolar system, customers can be connected between voltage levels in many ways, for example, between a positive pole, between a negative pole, and between positive and negative poles. The two systems—unipolar and bipolar LVDC networks—are shown in Figs. 1 and 2, respectively. In this thesis, bipolar LVDC networks are primarily considered since they provide low transmission losses, high power transfer capability, high flexibility, and high availability (Lago, 2011); however, the network may also have unipolar branches.

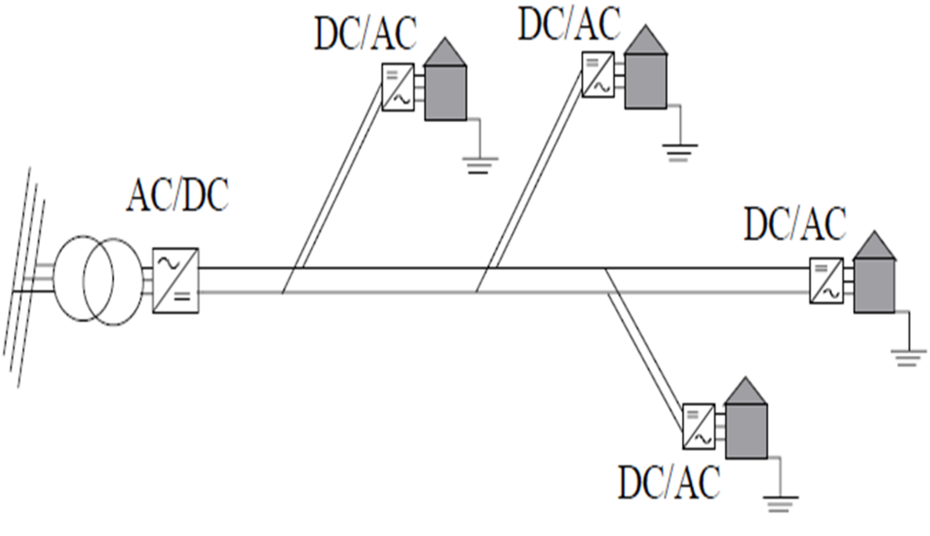


Figure 1: Example of a unipolar LVDC distribution system (Salonen et al., 2008).

The nominal voltage of the system must be selected such that the DC network transmission capacity is as high as possible, but simultaneously within the boundaries

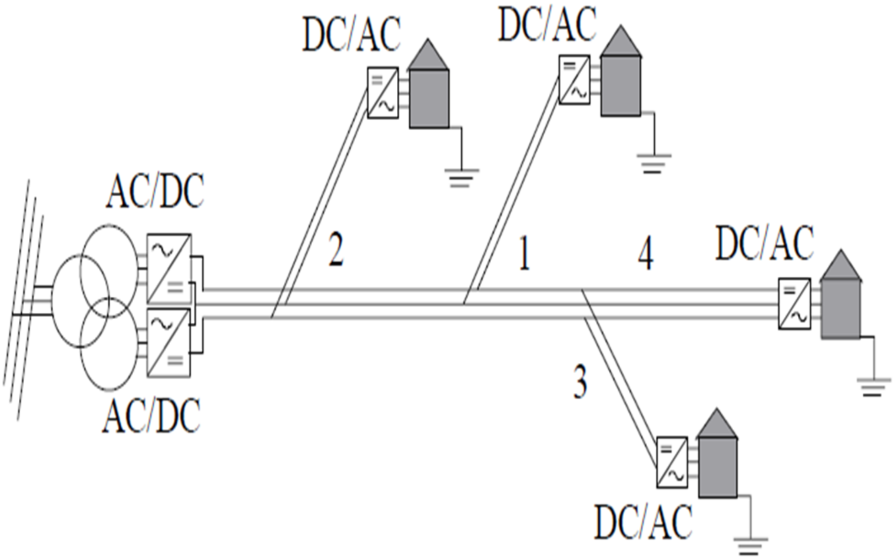


Figure 2: Example of a bipolar LVDC distribution system; different customer connection alternatives are also shown (Salonen et al., 2008).

of the standards set by LV directives and cable standardizations; the acquisition prices of converters are also a factor. The European Union directive 2006/95/EC defines the DC voltage to be in the range 75–1500 V DC (EU Low Voltage Directive, 2006). Further, the cable standardization allows LV cables to be used in DC voltage networks; the defined maximum voltage between conductors is 1500 V DC and between earth and conductor is 900 V DC (Salonen, 2008; SFS4879; SFS4880). Hence, the nominal voltage of the bipolar network in this thesis is ±750 V.

In this thesis, an islanded bipolar LVDC microgrid has been considered for a populated area having a diameter of approximately 6 km and 200 customers. The typical peak power of a single customer is specified to be 200 W with a projected increase up to 800 W; therefore, the power handling capability of the total network can be considered to be at least 160 kW for 200 customers. In practice, the populated areas consist of small villages that have spread randomly around the area of the island network and are located in the equatorial or tropical regions. In addition, single or three-phase DC/AC converters are used for the actual customer connections that have a voltage level of 230 V AC, and DC/DC converters are used to obtain DC voltages of 48 V that can then be used for lighting purposes.

It is not possible to predict the exact network topology since this significantly depends on the location where the project is implemented, leading to considerable variations. Typical topologies are linear, radial, looped, and other combinations whose complexity increases as the usage area increases. Figure 3 illustrates the LVDC network deployed with a simplified topology. Here, the power source is the PV array (the choice of solar power for power production is discussed in Chapter 2); a battery bank is used for backup; the loads are distributed randomly over the area; and converters are employed for all three components. In practice, the network would be somewhat more complicated with more uneven load distributions; however, complicated networks are beyond the scope of this thesis, and a linear network has been considered for simplicity in the proposed algorithms. At the same time, the adaptability of the proposed algorithms to larger and more complicated networks has been kept in mind while developing the EMS, and moreover, reasonable suggestions for network expansions have been proposed.

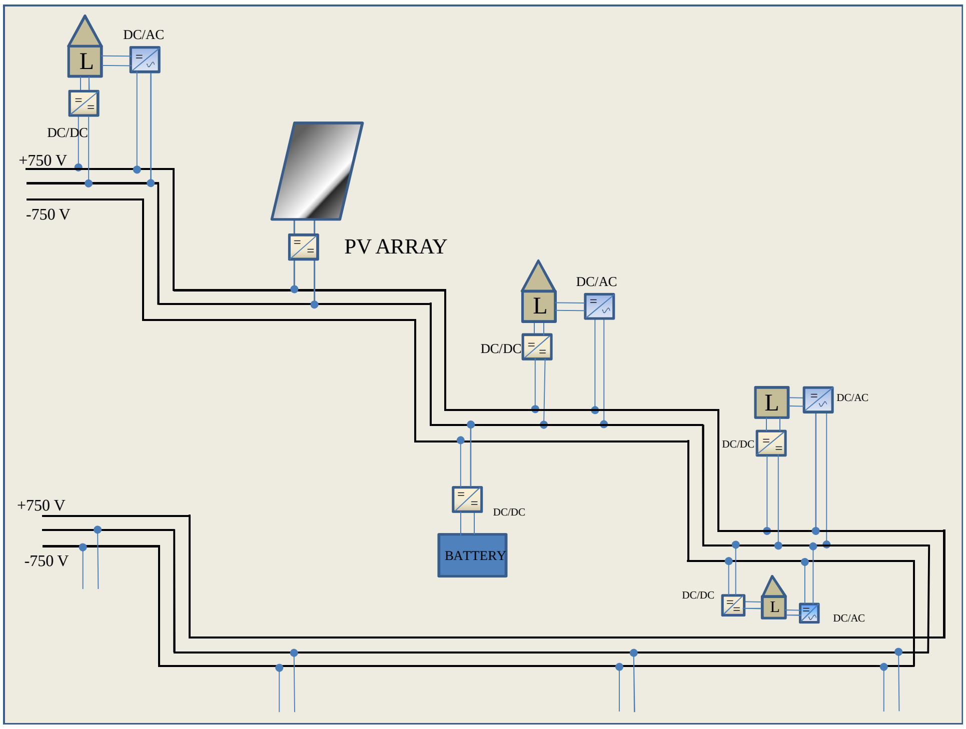


Figure 3: Example of an LVDC distribution network over an area (with simplified topology); a PV array supplies power to randomly distributed loads, while a battery bank is used as backup. In practice, the loads would be distributed more unevenly and the cables would be more circuitous.

1.5 Thesis purpose and challenges

As mentioned previously, the successful deployment of such islanded networks faces is not easy and there are several challenges such as the achievement of efficient power balance, protection, communication, and reliable operations. This thesis addresses the issue of network stability in terms of power balancing and voltage regulation. Real-time operations of any electric power system must ensure that the system remains stable and protected while meeting the customer's power requirements. Hence, a precise balance between power production and consumption is required at all times; if this balance is not maintained, the system can become unstable and the voltage may exceed the allowed limits, leading to damaged equipment as well as outages. The purpose of this thesis is to obtain methods to achieve efficient power balancing between the supply and demand in the network under all conditions, and further, to ensure that the voltage is regulated within the prescribed limits; in this manner, network stability is maintained under all circumstances and conditions. This thesis proposes an energy management system (EMS) that is basically a system of computer-aided tools and operations used to monitor, control, and optimize the production and/or transmission efficiencies and overall network performances (Lukszo, 2010); the EMS is facilitated by a robust communication infrastructure that regularly communicates the network system and component statuses, thereby enabling the software to perform the appropriate control operations.

The development of such an EMS for islanded LVDC networks is challenging for many reasons. Since the power production is based on renewable energy sources, it is unreliable and can even reduce to zero. The load demand must nevertheless be met. In order to enable this, energy storage devices such as batteries are used, but battery capacities decrease, and it is crucial to recharge the batteries at suitable time periods such as when the power production is more than the load requirements. Since the network is completely isolated, the load demand must be met solely by this combination of renewable energy-based power source and battery storage. The primary challenge faced by the EMS is to achieve this delicate balance between production, storage, and load during the entire operation period of the network by making the correct control decisions. The EMS has several tools at its disposal for achieving this balance, for example, load shedding, production and storage capacity planning, production control, battery state of charge (SOC) control, and the intelligent use of forecasted data of both production and load.

1.6 Energy management systems

The development of efficient and optimal EMSs for various kinds of networks has been discussed extensively in previous papers, and several approaches have been proposed. However, most of the published literature so far have focused on microgrids that are connected to AC grids; in such grid-connected microgrids, islanding operations have been typically considered as an alternative for deploying during emergencies or for any other specific requirements. Researchers have also considered many types of power production combinations such as PV–windpower AC microgrids, semi-autonomous microgrids, and hybrid AC–DC systems. The primary purpose of the proposed EMSs has been to ensure the stability of AC and DC bus voltages as well as to establish voltage and frequency controls during grid-connected operations, transitioning to islanded operations, and islanded operations. Some researches have also considered DC microgrids that are connected to the AC grid using bi-directional power converters, which typically operate either in the grid-connected mode or islanded mode, depending on the requirements.

Lopes et al. evaluated the feasibility of control strategies to be adopted for the operation of a microgrid when it becomes isolated. In particular, the need for storage devices and load shedding strategies has been included in this paper. Bo et al. introduced several strategies to maintain the power balance among renewable microsources, storage systems, loads, and the utility grid during grid-connected, islanded, and transition operations; their strategies involved the controlling of the different converters present in a microgrid comprising wind turbines, PV panels, and batteries. A three-phase inverter was used to maintain steady DC bus voltages during grid-connected operations, whereas microsources and storage systems were used in islanded operations; the magnitude and frequency of the AC bus were controlled by the droop character of parallel inverters. The droop control method has been the most frequently used technique in standalone AC microgrids for voltage and frequency control and has been analyzed many times (Barklund et al., 2008; Pogaku et al., 2007; Hu et al., 2011). Droop control essentially refers to active and reactive power regulation, and it is a decentralized control strategy wherein the active power output is adjusted according to the frequency deviation, and the reactive power output is adjusted based on the voltage deviation (Xiu et al., 2011). Brabandere et al. (2007) proposed strategies for the efficient and fault-tolerant control of microgrids with renewable energy sources, intelligent loads, and storage units; their strategies are based on droop control applied at the production unit, and they suggest that the control can be extended with appropriate communication infrastructure to other parts of the network.

Fuzzy control has also been proposed as a control method for DC microgrid systems. Chen at al. (2013) presented fuzzy control to optimize the energy distribution in a DC microgrid comprising solar and wind power production, lithium-ion battery, DC load, and AC/DC converters; fuzzy logic was used to establish the control rules and to vary the battery state of charge (SOC) parameters. In a similar fashion, Papadimitriou and Vovos (2010) proposed a fuzzy-based local controller for DGs that are either integrated into or isolated from the main network, depending on the requirements. Kakigano et al. (2011) adopted a gain-scheduling technique on the basis is that it is difficult to achieve good voltage regulation and good load sharing when the DC voltage is controlled by several converters. Their technique changes the DC gain according to the output power in order to obtain better voltage regulation and load sharing simultaneously. Zhang et al. (2011) proposed the power control of DC microgrids using DC bus signaling; the DC bus voltage level was employed as an information carrier to distinguish four different operation modes. The power was controlled by controlling the modular PV converters, battery converters, and grid-connected converters, and smooth switching was realized between constant voltage operations and maximum power point tracking (MPPT) operations. Even though their study basically involved grid-connected networks, the proposed control method maintained the power balance of the DC microgrid even when islanded.

In this thesis, the scope of the EMS is restricted to the effective and efficient management of the power balance and voltage regulation in the LVDC island network discussed previously (Fig. 3). Few researches have been conducted into the development of an EMS for such completely islanded LVDC microgrids whose power production is based on renewable (hence, variable) energy. Karlsson and Svensson (2003) suggested two methods for achieving power balance control in such networks: the *communication or master/slave method*, which relies on fast communication between the source and load converters, and *droop control* which does not require any communication at all. In Liao and Ruan (2009), a power management control strategy has been proposed for a stand-alone photovoltaic (PV) power system comprising PV array, battery, and DC–DC converters. Their power management control strategy was to control the converters to operate in suitable modes according to the PV power and battery statuses. However, their strategy is applicable only to small loads and does not cover all the possibilities that can occur when numerous customers have to be supplied power reliably. Moreover, they have not considered emergency situations wherein there is insufficient or no power production.

This thesis proposes a power management strategy in which the master/slave method is used with robust communication infrastructure and modern power electronics interfaces. Further, operation modes that encompass all conditions are derived, analyzed, and used as the basis for the EMS operations. The proposed EMS consists of a control algorithm that ensures optimal power balance in the network and elicits quick responses to emergencies. In addition, the concepts of load prioritization and disconnection are employed to ensure that some loads continue to receive power supply, even when there are power production issues. Load prioritization and disconnection are very widely known actions that are applied throughout the world, especially to AC grids (load shedding). However, in the case of AC grids, entire areas are disconnected from the power supply based on some criteria, whereas, in this thesis, only some loads are disconnected on the basis of prioritization. The EMS is thus designed to be able to not only ensure reliable power supply, good power balance, and fast voltage regulation during normal operations but also to ensure that suboptimal power production situations are handled capably. Moreover, this thesis also addresses the problem of determining the production and storage capacities that are required to supply power reliably at any location, since it is important for developing and testing the control algorithm. A sizing method based on discrete-event simulations (DESs) has been proposed to obtain reliable sizes of the PV array and battery. Finally, an additional question has been examined in this thesis: given the sizes of the network components, how many hours of electric power supply can be guaranteed to the customers at any given location? All the algorithms were implemented using MATLAB$^{©}$, and all the simulations were also performed using MATLAB$^{©}$.

1.7 Thesis organization

This thesis is organized in the following manner. After this initial introductory chapter, the basic concepts and choices for the power production system and storage devices are briefly discussed; further, typical consumption behaviors are described and illustrated. Subsequently, in the third chapter, first, the production capacity problem is examined and an algorithm to determine the optimum battery and PV sizes is presented; subsequently, a method to determine the impacts of different hours of sunlight on the number of service hours is presented. The two algorithms are implemented and simulated with real-time parameters, and the simulations results are presented to demonstrate their accuracy. Chapter 4 describes the basic principles of general EMSs as well as the EMSs applied to LVDC island networks; suboptimal situations that could occur along with methods to resolve them; the functionalities of the network components; and the structure of ICT systems and their requirements.

Chapter 5 discusses the operation modes in further detail and presents the developed EMS. The proposed EMS was implemented in a sample network, and simulations were conducted assuming various situations and parameters; the obtained responses were studied in detail. The simulation results are then presented, and they show the smooth operation and efficiency of the algorithm. The results clearly demonstrate that the LVDC network is adequately sized and well controlled using the given strategies. Power and energy balancing were achieved along with voltage regulation under all the considered circumstances. Nevertheless, several challenges still remain, and the algorithm and methodology can be improved in many ways. The limitations of the algorithm and future studies and pending researches are described in detail at the end of the chapter. In the final concluding chapter, the thesis problem, methods used, results obtained, and pending work are summarized.

2 ELECTRICITY PRODUCTION, STORAGE, AND CONSUMPTION

An island network is fundamentally a localized grouping of electricity production systems, energy storage devices, and loads, which function co-operatively and independently. In practice and in literature, microgrids in which islanded operations are employed as an option are more common than completely isolated islanded networks; nevertheless, islanded networks have several advantages, as mentioned in Chapter 1. In this thesis, an islanded LVDC network is considered.

During the planning, analysis, and implementation of an island network, it is important to choose the type of production systems and storage devices carefully (other components such as converters, cables, and protection and communication devices must also be carefully chosen but they are not considered in this thesis) since they directly affect the network performance and control. Several factors affect the choice of the appropriate systems and devices, including reliability, costs, and availability. The features and performance characteristics of the considered systems must be considered before making the appropriate choice; moreover, their impacts on the network performance must also be analyzed. Their applicability and suitability to the types of loads that can be anticipated must also be considered. The nature of loads and their consumption characteristics strongly influence the performance of the network. Load types and their demands may differ depending on the location, nature of load, and customer profiles, and it is difficult to accurately anticipate their behaviors. Nevertheless, a general overview of typical loads can be envisaged and their impacts can be considered. In particular, (typical) load types, load requirements, load profiles, and load usages can be examined.

This chapter briefly outlines and discusses the three crucial elements of the LVDC island network—power production, energy storage, and load consumption. This thesis is focused on the energy management (and partial system sizing) of the network, and discussions on production, storage, and consumption characteristics are restricted to their impacts on the relevant analyses of LVDC networks. The electricity production system used in this study—PV systems—and the applicability of their characteristics to this particular network are discussed first. Subsequently, the energy storage device selected for the investigated project—lead-acid battery—and their parameters of interest are described. The types of loads that can be expected during this project implementation are first discussed from a general viewpoint and general comments are made on the potential challenges and possible solutions; their characteristics that may influence the network performances are also discussed subsequently.

2.1 Electric power production

2.1.1 Introduction

Electric power is produced from sunlight by converting solar radiation into DC electricity using semiconductors exhibiting the PV effect; this method is commonly referred to as photovoltaics (PV) and is based on the effect that was discovered by Edmond Becquerel in 1839. Among the various renewable energy technologies available, solar power has been chosen in this thesis for several reasons. Solar PV is known to be both a feasible and sustainable energy source (Pearce, 2002). Further, PV systems are attractive for electricity production because they are noiseless, emission-free, flexible, and have reasonably simple operations and maintenance (Dinçer, 2011). Moreover, the cost of PV has declined at a steady rate in recent years (Swanson, 2009), and the increased demand for renewable energy sources has spurred the manufacture of solar cells and PV arrays. According to the Global Market Outlook for Photovoltaics 2013-2017 published by the European Photovoltaic Industry Association (Masson et al., 2013), solar energy is one of the fastest growing energy production sectors today, and it is expected to become a mainstream and mature source of electricity in the near future. The world's cumulative PV capacity has surpassed 100 GW, which is equivalent to as much annual electrical energy as that produced by 16 coal power plants or nuclear reactors of 1 GW each. Further, the LVDC island network is intended to be deployed in equatorial and tropical regions which receive fair amounts of sunlight. Hence, for all these reasons, solar power is a natural choice for the power source.

2.1.2 Solar power technology

PV panel design PV power production systems employ solar panels that comprise numerous solar cells consisting of one or two layers of a semiconducting material (Fraile et al., 2009). Light shining on a solar cell creates an electric field across the semiconducting layers, thereby causing electricity to flow; moreover, the electric current increases with the intensity of the light. The most commonly used PV material is silicon in various forms, such as monocrystalline silicon, polycrystalline silicon, and amorphous silicon; depending on the technology, cadmium telluride and copper indium gallium selenide/sulfide are also used (Jacobson, 2009).

Two broad categories of technologies have been employed for PV cells—crystalline silicon and thin film (Fraile et al., 2009). Crystalline silicon technology is the most popular technology in the market today (Fraile et al., 2009), but thin-film panels have shown tremendous potential, and considerable investments are being made into researches to improve them. A thin film is made by depositing extremely thin semiconductor material layers (hardly 0.3–2 μm thick) onto glass, plastic, or stainless steel substrates. Since the semiconductor layers are thin, the costs of raw material are considerably lower than the capital equipment and processing costs, thereby making this technology cost-effective. Further, its efficiency, which used to be lower than that of crystalline silicon PV modules, has increased in recent years (Doni et al., 2010). A comparison of crystalline silicon and thin film panel technologies for PV cells is given in Table 1. At an irradiation of 1000 W/m^2, a thin-film panel with 10% efficiency costs 0.5 €/W; in other words, 2 m^2 produces 200 W and costs 100 €. On the other hand, a crystalline silicon panel with 20% efficiency costs 0.7 €/W; that is, 1 m^2 produces 200 W and costs 140 €.

Table 1: Comparison between crystalline silicon and thin-film panel technologies for PV cells.

Crystalline Silicon Panels	**Thin Film Panels**	
Monocrystalline and multicrystalline	*Amorphous silicon (superstrate); Cadmium telluride (CdTe)*	*Amorphous silicon (substrate); Copper indium (gallium) selenide (CIS/CIGS)*
✓ Proven and reliable technology	✓ Low price	✓ Low price
✓ High efficiency	✓ Can be flexible installation	✓ Does not necessarily need a transformer
✓ Electrically the easiest	X Still unreliable	X Not as reliable as crystalline panel
✓ Numerous manufacturers	X Needs transformers	X Low efficiency
X High price	X Low efficiency	
X Thick panels		

Thin-film panel technology is advancing very rapidly, leading to increasing efficiencies and other improvements, and additionally, its costs are lower; hence, thin-film panels have been selected for the PV array in the proposed network.

PV array and installation A PV-based electricity production system typically consists of a string or an *array* of solar panels, called a *PV array*, which is connected to increase the power that can be delivered. PV arrays are installed in many ways, for example, ground-mounted or built into the roof or walls of a building. Additionally, the angle at which a PV module (or array) is installed—called the tilt angle—influences the power produced. A solar panel that is tilted perpendicular to sunlight typically receives more light on its surface than an angled solar panel. Moreover, the tilting is also dependent on the location; in general, the optimal orientation without non-tracking is nearly horizontal near the Equator, toward the south in the northern hemisphere, and toward the north in the southern hemisphere (Chang, 2009).

Numerous studies have explored the optimum tilt angles at various locations on the basis of many factors such as predicted data, temperature, and seasons (Chang and Yang, 2012; Zhao, 2010; Tang, 2010). Moreover, many solar panels and arrays are equipped with mechanical systems called solar trackers that tilt a solar panel throughout the day, thereby following and tracking the sun's movement; this significantly enhances early morning and late afternoon performances. Trackers are especially effective in regions that receive a large portion of sunlight directly; on the other hand, they have little value in diffuse light. In general, tracking is most beneficial at sites between ±30°latitude, with the benefits reducing at higher latitudes due to the sun dropping low on the horizon during winter months. However, trackers are expensive and they require energy for their operations, which may not always be available especially in such LVDC islanded networks; moreover, it may not always be possible to use them due to location constraints. Trackers are thus not always applicable (Benghanem, M., 2010). Hence, the solar panel that will be used in this study will not have solar tracking, that is, they will not be self-directing panels. The location constraints during the actual implementation of this project are as yet unknown and cannot be reasonably predicted. Hence, in this thesis, it is simply assumed that the PV panel will be placed at the optimum position with the optimal tilt at the chosen location.

Solar cell efficiency In general, the conversion efficiency (η) of a solar cell is given by the following equation:

$$\eta = \frac{P_m}{E \times A_c}, \tag{1}$$

where P_m is the maximum power from the cell (W); E, the input light irradiance (W/m^2); and A_c, the surface area of the solar cell. Moreover, solar cell efficiencies are measured and specified, by convention, under standard test conditions (STC)—temperature of $25°C$ and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrum. Thus, for example, a solar panel with 15% efficiency and area of 1 m^2 will produce approximately 150 W of power under STC. It is important to note that in practice, commercial PV panel module ratings are typically given for STC. The efficiency of a solar cell is further dependent on several factors such as the wavelength of light, temperature (output decreases as temperature increases), dust and debris accumulation (decreases the output), air mass variations, shading (decreases the output), and reflection.

In this thesis, for simplicity, the effects of temperature, dust, reflection, and other factors are ignored; it is also assumed that the PV panels are not shaded.

Calculation of solar power output In this thesis, the PV output has to be calculated for two different purposes, and hence, two different methods have been used accordingly. Firstly, in the sizing algorithm, the predicted PV array output must be known in order to calculate the required PV array and battery sizes. To obtain the PV output, the peak-sun-hours (PSH) method has been used (Weixiang et al., 2005). PSH, or just sun hours, refers to the number of hours in a day in which the standard solar irradiance of 1 kW/m^2 is experienced; more precisely, it is the length of time in hours at a solar irradiance level of 1 kW/m^2 needed to produce the daily solar radiation obtained from the integration of irradiance over all daylight hours (IEEE, 2007). The PSH for a day can be determined simply by taking the average solar irradiation for the day and dividing by 1000; note that since the integration is not performed accurately, this gives an approximate value but it has been considered sufficient for the purposes of this thesis. The PV output is then simply *PSH* × *PV array size* since the PV array size is given under STC—1 kW/m^2—just like PSH.

Secondly, the control algorithm, in practice, does not need the PV output to be calculated; in a practical scenario, the real-time PV output is given as an input into the algorithm (for example by the PV converter through a communication interface). However, in this study, the PV output has to be calculated for the *simulation* of the control algorithm. This calculation has been performed simply by taking the manufacturer's nameplate rating (which is given for STC) and applying the following formula:

$$PV\ Power\ Output = \frac{Rated\ Output \times Irradiance\ Data}{1000}\ W$$

The PV power output calculated in this manner has then been used for the simulations of the control algorithm presented in this study.

2.1.3 Solar irradiation

Historical irradiation data Solar irradiance E is the amount of solar power striking a given area and is given in W/m^2 (Prof. Dr. Quaschning, 2013). The irradiance measured over a period of time, or, its integral over a time period is, referred to as solar irradiation or insolation H (Wh/m^2). A nearly constant 1.36 W/m^2 (called solar constant) of solar irradiance strikes the earth's outer atmosphere but this includes all wavelengths. Silicon PV modules use only the part of the spectrum from 0.3–0.6 μm. Additionally, the irradiance striking the earth is decreased by various atmospheric factors as well as the climate and location. Only a part of the extraterrestrial beam irradiance reaches the earth's surface directly; it is estimated that the total irradiance striking the earth on a sunny day is approximately 1000 W/m^2 (the basis for the PSH method).

Solar irradiation data provide information on the amount of energy striking a surface at a location on the earth during a particular time period, H (Wh/m^2). Many organizations have and continue to obtain irradiation data based on satellite measurements, such as (Helioclim, 2013) and National Weather Service, United States. Moreover, several databases of irradiation data are available, and quite a few websites and authoritative organizations provide time series of historical solar irradiation data for free and open access, for example, the SoDa service, which is supported by the European Commission, and National Renewable Energy Laboratory, which is owned and funded by the US government. Where solar irradiation measurements are not easily available for various reasons (high equipment costs and calibration requirements), estimations of solar irradiation data by using models have often been proposed (for example, Muzathik et al. (2010)).

The amount of solar radiation received is highly variable due to weather patterns and the changing position of the sun. Many other factors also influence the amount of solar radiation reaching the earth's surface, such as clouds, local geographical features, the time of day, season, and pollution. Solar irradiation data reflect this variability, and its availability can be used to design and analyze practical PV-based systems.

The global solar radiation on a horizontal surface has two components—direct beam radiation and diffuse radiation. Direct beam radiation refers to the direct radiation from the sun, while diffuse radiation is scattered out of the direct beam by molecules, aerosols, and clouds. On clear days, the diffuse radiation is approximately 10% to 20%, while it is as high as 100% for cloudy skies. Further, tilted planes have another component—radiation reflected from the ground (approximately 20% of the global irradiance (Prof. Dr. Quaschning, 2013)). The sum of the direct beam, diffuse, and ground-reflected radiation arriving at a tilted plane is called total or global solar radiation. Depending on the type of the measuring station, either all the components are measured, or some are measured and the remaining calculated (several methods have been presented in the literature, for example, Liu and Jordan (1960).

Figure 4 shows the total monthly irradiation data for the year 2004 at two locations, latitude 0° and latitude 60°, that is, corresponding to the Equator and much higher north, for example, Helsinki (the Arctic Circle is at 66°), respectively; the effects of season and location can be clearly seen. At latitude 60°, the monthly irradiation decreases to almost 0 during the winter months—December and January—and increases to as high as 6000 Wh/m^2, which is higher than the highest amount for the Equator during summer. These trends clearly demonstrate the effects of long hours of darkness in winter and daylight in summer at latitude 60°. In contrast, the irradiation never decreases to less than 4000 Wh/m^2 at the Equator and is much more consistent; the small variations in the levels can be attributed to the effects of rain and cloud cover. These trends lend credence to the intuitive idea that the power output can be expected to be more reliable near the Equator than near the poles. A more detailed analysis will be presented in Chapter 3.

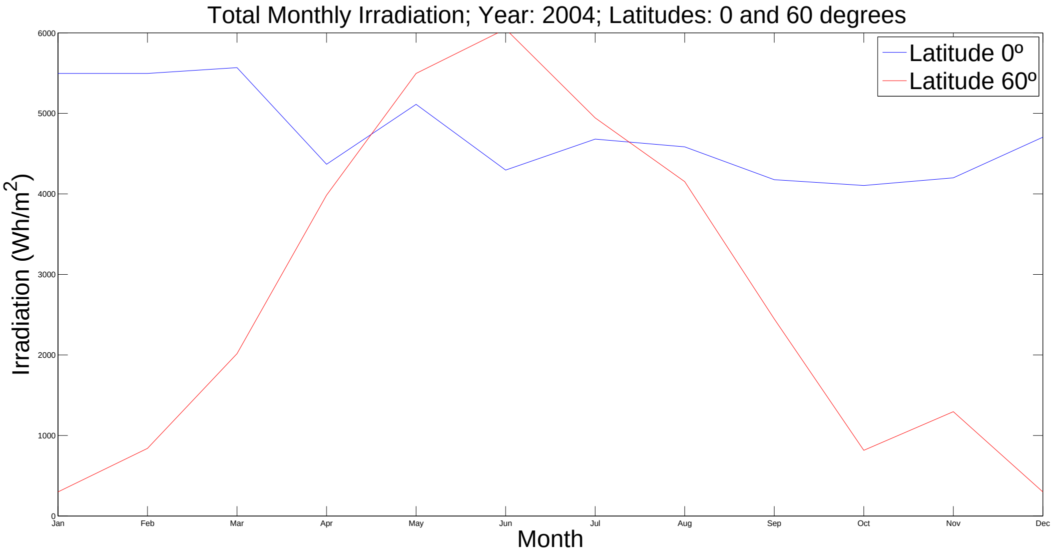


Figure 4: Total monthly irradiation data for the year 2004 at two locations—latitudes 0° and latitude 60°, corresponding to the Equator and much higher north.

Forecasted irradiation data In addition, solar data forecasts are also an invaluable resource for both sizing and control. However, solar data forecasting is not an easy problem since it is weather-dependent, and several researchers have attempted to improve its accuracy and reliability. Many types of forecasting methods have been proposed in the literature, including statistical methods such as ARIMA and neural network-based methods (Yona et al., 2008; Huang et al., 2012; Heinmann et al., 2006). Such forecasting algorithms and methods typically forecast solar irradiation for very short periods (called now-casting and typically for a few hours), short periods (short-term forecasts for up to 7 days), or long periods (long-term forecasts that give monthly or annual estimates). Beyond 7 days, the reliability decreases tremendously and any generated data may not be of much value. Note that forecasted solar irradiation data are typically not available for free.

Solar irradiation data collection All the solar irradiation data used in this thesis was obtained from online resources (via the SoDa service) which gives time series data of daily, monthly, and yearly solar irradiation data for the period 1985–2005 for free and open access. In the simulations in this thesis, only the data for inclined planes has been considered, for consistency; this also ensures to a certain extent that the values are neither under-estimated nor over-estimated. Concentrating solar systems use only direct irradiation, whereas non-concentrating systems also use diffuse irradiation; further, tilted planes are much more common in practice. Hence, the data of the global component—that is, the sum of the diffuse, direct, and reflected components—is used, unless otherwise mentioned. In the case of inclined planes, data is available for free for only one year—2005. Additionally, the data has not been recorded in some cases (given as -999), but irradiation values on top of the atmosphere are available. In all such cases, the unrecorded values have been replaced by the corresponding values for the top of the atmosphere (this does not result in serious simulation errors).

2.1.4 Interfacing with LVDC island networks

PV arrays can be connected or interfaced to the grid with or without a converter. However, converters (or inverters) are commonly implemented because they can be used to draw maximum DC power from the array. Most of the existing researches have been conducted into optimum inverter connections with AC grids, while a few have focused on converters and DC connections. In the LVDC islanded network that is being considered, the PV array will be connected to the network through a DC/DC converter that will also be used to enable maximum power point tracking (MPPT; a method to extract maximum possible power). Further, the PV converter is able to communicate the current power, voltage, and current statuses reliably and quickly and also accept control instructions and act accordingly. The nominal voltage should be as close as possible to the voltage of the DC network voltage as possible, 750 V. PV power production is not reliable and can vary significantly depending on the climatic conditions; hence, an important functionality of the PV array for maintaining the power balance in the network is that its production should be controllable, that is, it should be possible to maximize it or constrain the production.

2.1.5 Summary

The renewable power source used in this study is solar energy, and the PV array uses thin-film technology. The solar irradiation dataset used in this study for testing and simulation purposes consists of the global component of solar irradiation falling on an inclined plane over the year 2005. The irradiation values given in the solar dataset are used to calculate the PV array outputs required for conducting simulations and to determine power output variations with locations. Further, the PV arrays are connected to the DC mains via a DC/DC converter that is not only able to communicate its power statuses quickly but also receive control commands and act on them reliably.

2.2 Electricity storage

2.2.1 Introduction

Due to the high variability of power production from PV arrays and the isolation of the network, backup power supplies are required to meet load requirements reliably. Such backup power is typically supplied by batteries, which, naturally, should be rechargeable. The basic function of the battery is to supply power when the system load exceeds the power output from the PV array (IEEE, 2007). In addition, batteries are either recharged by the PV array or discharged to supply load, depending on the energy and power balance statuses of the network during the time period under consideration.

2.2.2 Storage types

Today, many types of rechargeable batteries with different chemical combinations are available, such as lead-acid, nickel cadmium (NiCd), lithium ion (Li-ion), and nickel metal hydride (NiMH). In general, lead-acid batteries are popular for their low costs, mature technological levels, high discharge rates, low maintenance requirements, and recyclability. Stationary lead-acid batteries, which are designed for deep discharges, are commonly used as large backups to power supplies. Such deep-cycle lead-acid batteries are designed to be regularly deeply discharged, typically to 50% to 70% of its capacity. Due to the unreliability of PV power production, deep-cycled batteries are important to enable the LVDC island network to supply power reliably. Hence, deep-cycle lead-acid batteries are used as the additional backup power supply source.

2.2.3 Lead-acid battery characteristics

Battery capacity refers to the amount of (usable) energy that a battery can store at the nominal voltage, and it is usually expressed in terms of the current that can be supplied by the battery under normal conditions (Ah). The state of charge (SOC) expresses the current capacity of the battery as a percentage of the total capacity, while the depth of discharge (DOD) is a measure of how deeply a battery has been discharged. It is important to note that the higher the DOD—or, the deeper the battery discharge—on an average, the shorter the battery cycle life; simply put, deeper discharges shorten battery life. As a result, it is not advisable to discharge batteries too deeply, and the commonly recommended DOD is not more than 50%. Controls are often employed to protect the battery from being over- or under-charged, which typically include power conversion subsystems (inverters or converters). A charge controller may also incorporate additional functions such as discharge termination, regulation voltage, and status indication. (IEEE, 2008)

Batteries have specific charge and discharge rates, which must be considered in the sizing and control algorithms. The discharge rates, expressed as C-rate, measures the rate of discharge of a battery relative to its maximum capacity; a discharge rate of 1C implies that the entire battery will be discharged in 1 h. For a 200 Ah battery, a discharge rate of C/2 means that the battery will be discharged in 2 h with a discharge current of 100 A. Other parameters of interest in this thesis are the nominal voltage (V) and the charge voltage (the voltage that the battery is charged to when charged to full capacity). It is also important to understand that very rapid discharging and charging rates, although attractive, can damage the cells; the maximum continuous discharge and charge currents (recommended) are typically set by the manufacturer as preventive measures.

Lead-acid batteries also self-discharge at a rate that typically depends on the storage or operating temperatures. However, the effects of self-discharges have been ignored in this thesis in order to simplify the analysis. Further, sulfation (the crystallization of lead sulfate) occurs when a battery is not used or charged for long periods of time, leading to reductions in its capacity. This may not be a significant risk in this network, because batteries are expected to be required to charge regularly given the variable nature of the PV power supply. Nevertheless, it must be noted that undercharging—not allowing the charger to restore the battery to full charge—limits battery life, and continuous operations at a partial SOC can lead to sulfation. The control algorithm must attempt to prevent undercharging and must attempt to restore the SOC as soon as possible; this implementation has been considered in this thesis. Note that sulfation can be a significant problem since it affects the charging cycle, resulting in longer and less efficient charging and higher battery temperatures; at the same time, desulfation methods can be used to reduce the sulfation that may have occurred.

Further, there is an additional complication. The capacity of a lead-acid battery is not fixed; it varies with the discharge rate in accordance with Peukert's law (Doerffel and Sharkh, 2006) that gives an empirical relationship between the discharge rate and capacity. Nevertheless, in this thesis, the capacity is considered to be an input from the battery management system which manages charge balance issues, and, for simplicity, these variations are not considered in the simulations.

2.2.4 Battery energy management system

Modern batteries are equipped with battery management systems (BEMSs) that monitor, manage, control, protect, and communicate the state of the battery (Pop et al., 2008). The basic task of BEMSs is to ensure that the battery energy is optimally used and any risks of damage are prevented. Typically, the charging and discharging processes are monitored, controlled, and communicated. Parameters such as voltage, SOC, DOD, current, temperature are monitored, and additional calculations based on these parameters may also be performed. Moreover, recharging is managed efficiently and the battery is protected from surges and other unsafe operating conditions. In this thesis, it is assumed that a BEMS exists and that it communicates the required parameters to the control software on a regular basis. Batteries can be connected to the network with or without DC/DC converters. If a converter is not used, the battery charges depending on the voltage in the network and explicit control instructions are not required. However, in this network, DC/DC converters are used (see Fig. 3), and further, the battery converter, with the EMS, communicates the current battery statuses reliably and quickly, while also being able to accept control instructions and act accordingly.

2.2.5 Summary

The LVDC island network uses solar power for power production, and this causes problems of reliability of power supply. Hence, a lead-acid battery is used as the storage device to either supply or absorb balance power, depending on the situation. The battery capacity and management have a huge impact on the system availability and reliability. High battery capacities can dramatically increase the number of hours of power supply, and efficient management of the resources can reduce losses and improve network performances. Larger batteries will cycle deeper less frequently, thereby increasing the system availability and battery life. However, the larger the battery, the greater the risk of sulfation. Nevertheless, in general, increasing the battery capacity increases system availability more cost-effectively than increasing the PV array size. (IEEE, 2008)

The battery is also important from the network control point of view, since controlling the battery SOC by charging or discharging is an important method to maintain power balance as well as to ensure voltage regulation. In the algorithms introduced in this thesis, battery parameters such as battery capacity and charge and discharge rates are considered as input parameters entered by the network operator before beginning the network operations. The battery bank is connected to the LVDC bus with DC/DC converters, and it incorporates a management system that communicates the current battery statuses reliably and quickly, while also being able to accept control instructions and perform the required actions.

2.3 Electricity consumption

2.3.1 Introduction

Consumption behavior is an important aspect of network planning, analysis, and control since the entire purpose of the network is to meet the consumption demand. Moreover, the quality of the sizing as well as control ultimately depends on the nature of the customer connections and the resulting customer behaviour. The load demand of customers in a rural area, who may never have used electricity before, may be much lower than the load demand of customers in an urban area, who may be regular and dependent users of electricity. Similarly, the reliability expectations may be completely different—some customers may require electricity for running their businesses, while some customers may not be as dependent and more tolerant to losses in power supply. The type of load being supplied may also differ dramatically; for example, some customers may require connections for refrigerators, some others may desire internet connectivity, while some customers may be satisfied with just lighting loads.

This project is meant to be implemented in populated areas comprising small villages that are spread randomly around the area of the island network. It is difficult to anticipate the exact consumption behaviors and characteristics of the customers who will use the network since it depends on the exact location where the project will be ultimately implemented, the nature of consumption and consumers, the type of load requirements, and the ground conditions at that location and period of time. Therefore, due to the variability in the load type, it is challenging to implement the sizing and control perfectly and in such a manner that all possible loads are encompassed. Clearly, some kind of a generalized approach is preferable, especially at this preliminary stage; this approach can then be adapted according to the requirements.

Hence, in this thesis, certain general load types and their logical classifications have been proposed, which have then been used to control the network; this is discussed in more detail in Chapter 4. The basic intention has been to build the algorithms such that variations in the load profile do not impact the efficiencies, operations, and results as far as possible.

2.3.2 Types of loads

From the viewpoint of the nature of electric supply, two types of loads have been considered in the thesis:

1. **AC Loads:** These loads comprise most household appliances and equipment. A single or three-phase converter will be used for the DC/AC conversion and the voltage levels will be approximately 230 V.
2. **DC Loads:** Mostly lighting loads with a voltage level of 48 V.

Typical loads Typical loads refer to the most common loads that may be used by the customers. At the individual level, the customers of this network are most likely to have requirements for lighting, fans, internet, television, and refrigeration. At the community level, the typical loads may be doctor's clinics or hospitals, schools, street lighting, and loudspeakers. Note that some of these loads could be further classified as the most critical or essential loads of the network.

Flexible loads An important aspect of the load usage in this study is *load flexibility*—the idea that not all loads need to be supplied regularly and that there can be some flexibility in the load usage. Such flexibility may differ for different customers and the loads may have to be chosen accordingly using some kind of pricing-based user-side prioritization (user takes the decision to disconnect loads, typically on the basis of pricing) or power-supply-availability-based operator-side prioritization (the network operator disconnects loads depending on the power supply availability). For example, some customers may not require the regular usage of refrigerators, but they may need lighting and fans at night; similarly, other customers may wish to prioritize television sets over washing machines. Loads such as refrigerators, television sets, and washing machines are examples of flexible loads whose usages are not critical and can be prioritized.

Load prioritization Due to the variable nature of the power supply, lowered reliability, and the nature of the loads, it may not be possible to supply all the connected loads. In such a situation, supplying some loads is more preferable than supplying none. The loads that can be disconnected are determined by prioritizing the loads. In other words, when the total load energy demand cannot be met, some loads must be disconnected from the power supply and the choice of the loads for disconnection is based on *prioritization*. Prioritization works only if there are loads in the network that are not critical and can be disconnected; since load flexibility has been assumed, in this network, load prioritization is a meaningful method. Such prioritizations may be online and real-time by the customer or may be determined and fixed prior to the network operations (with the option of changing it at regular periods), if required; this thesis considers the latter.

Another alternative is to perform load shedding wherein a part of the network, comprising many loads, is deliberately disconnected in order to ensure that the entire system does not collapse. Load shedding is common in many developing countries since demand often exceeds supply especially in the summer season; it is also common to communicate load shedding periods in advance to the customers. If forecasts of power production and balance can be made with reasonable accuracy, the communication of such information must be considered during the operations of the LVDC islanded network as well. The actual classification of loads and the mechanism of load prioritization used in this thesis are discussed in detail in subsequent chapters.

It is assumed that the loads can be disconnected quickly, reliably, and accurately, as and when required. Further, while the load profile is given as an initial input to the algorithm for sizing, the real-time load parameters are regularly communicated by the load converters to the control algorithm. In addition, forecasted load profiles must be given as inputs to the control algorithm so that it can make the necessary tweaks required for optimal operations; this aspect is not considered directly in this thesis and must be addressed in the future.

2.3.3 Typical load curve

In this thesis, the average load peak power is considered to be approximately 800 W. For simulation purposes, a typical load profile scaled from a typical Finnish customer's load curve has been considered. Figure 5 shows a practical load demand curve of a single Finnish customer living in row-and high-rise apartments without heaters for 1 year. Figure 6 shows a plot of the same load demand for 1 day. The load curve data is taken from real data given as hourly indexes and with the peak power as approximately 800 W; further, a confidence interval of 95% has been considered. Note that this load data has been used in all the simulations presented in this thesis, but simulations with other loads were also performed for verification purposes.

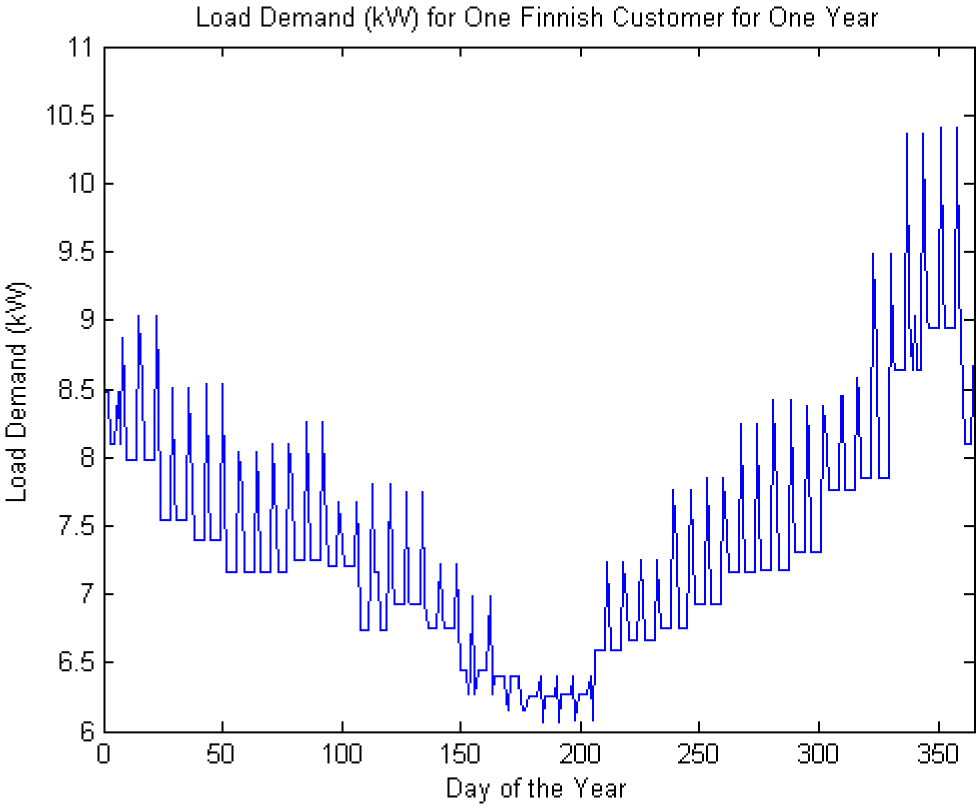


Figure 5: Load consumption (kW) for one Finnish customer for one year. (Note: The load peak power is approximately 800 W.)

Figure 5 somewhat approximates the possible load behaviour of customers closer to the Equator, but with the months inverted! Note that the total load demand increases during the winter months (the two ends in the figure) and decreases toward the summer (middle of the year)! This happens in Finland because less lighting and heating are required in summer. For a customer in the equatorial or tropical regions,

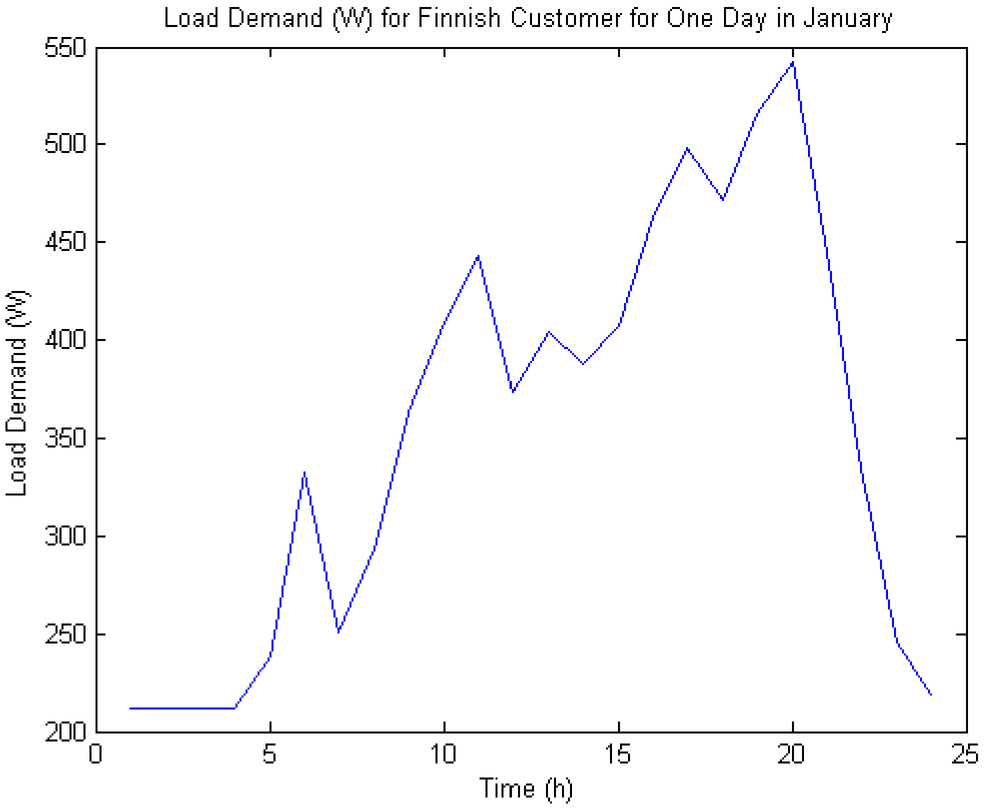


Figure 6: Load consumption (kW) for one Finnish customer for one day in January. (Note: The average load peak power is approximately 800 W).

the situation would be somewhat reversed, with greater load demand in the summer than in the winter. Figure 5 shows the load demand of the Finnish customer for one day; the load demand is low at night, but it increases in the morning with a perceptible spike during the morning hours, and there is a subsequent further increase toward the evening before it decreases again.

2.3.4 Summary

The nature of loads and the consumption behavior are very important since they determine the power balancing requirements; however, they differ with the location and customers. Nevertheless, some generalizations can be made about them and a general control algorithm can be built. Further, both DC/AC and DC/DC load converters communicate all relevant information to the control algorithm at regular intervals. Since the power supply is variable, load prioritizations and disconnections are important tools that are used by the control algorithm proposed in this thesis. Further, forecasts of load consumption are critical data that can be used to optimize the power and energy balancing.

The basic problem addressed by the thesis is illustrated in Fig. 7. During many days of the year, especially during the winter months, the solar irradiation (before converting to electricity) is considerably less than the load demand. This gap is partially met by using large PV arrays that can increase the amount of available power, but this is an expensive and sometimes impractical solution. A more reasonable approach is to also use battery to supply the balance power. Another advantage of using a battery is that when the produced power is more than the load demand, it can absorb the excess power and hence balance it. The problem addressed by this thesis is the control of the battery SOC, PV power supply, and loads in such a way that power balance is achieved and maintained at all times.

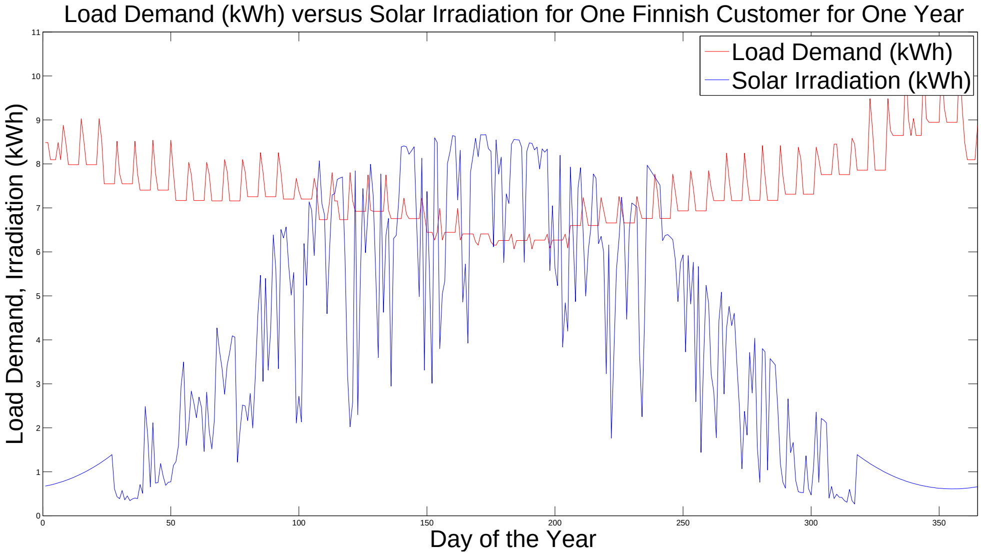


Figure 7: Load demand (kWh) versus solar irradiation (kWh) for one Finnish customer for one year. This thesis proposes an algorithm to ensure that they are balanced and that the two curves (blue and red) coincide; to ensure this, a battery whose state of charge is controlled is employed, and/or loads are disconnected depending on the conditions.

2.4 Conclusions

The renewable power source used in this study is solar energy and thin-film PV technology is used for the PV array. The PV arrays are connected to the DC mains via a DC/DC converter that is not only able to communicate its power statuses quickly but also receive control commands and act on them reliably. A lead-acid battery is used as the storage device to either supply or absorb balance power, depending on the situation. The battery capacity and management have a huge impact on the system availability and reliability. Controlling the battery SOC by charging or discharging is an important method to maintain power balance as well as to ensure voltage regulation. The battery bank is connected to the LVDC bus with DC/DC converters, and it incorporates a management system that communicates the current battery statuses reliably and quickly, while also being able to accept control instructions and perform the required actions.

The nature of loads and the consumption behavior are very important since they determine the power balancing requirements. However, they differ with the location of the network and the nature of the customers' requirements and practices. Both DC/AC and DC/DC load converters communicate all relevant information to the control algorithm at regular intervals. Since the power supply is variable, load prioritizations and disconnections are important tools used by the control algorithm proposed in this thesis.

In this manner, this thesis considers a bipolar 750-V LVDC network that is powered by thin-film PV panels with rechargeable lead-acid batteries to supply loads that can be flexible and prioritized, if required. Further, the basic problem addressed by the thesis is the control of the battery SOC, PV power supply, and loads in the network in such a manner that power balance and voltage regulation are achieved and maintained at all times.

This chapter has laid the foundations for subsequent discussions into the development of the EMS itself and related concepts. The three main elements of the LVDC microgrid network—power production, energy storage, and load consumption—have been discussed with particular focus on their applicability to the LVDC island network being considered. In the next chapter, the efficient and effective sizing of the components in the network will be discussed.

3 PRODUCTION CAPACITY: PLANNING and ANALYSES

3.1 Introduction

In this thesis, production capacity planning and analyses refer to investigations into the ability of the LVDC island network—basically, the power production system—to reliably supply a certain amount of power to a certain number of customers for a certain time period. Capacity planning involves solving the problem of the power production capacities needed to reliably supply power for a certain time period, while capacity analysis involves an investigation into whether the sized system can supply power, and if yes, for how many hours. In other words, capacity planning addresses the question: What should be the sizes of the PV array and battery for the given network parameters and location? On the other hand, capacity analysis attempts to answer the question: Given PV array and battery sizes, how many service hours can be reliably guaranteed at a specific location? Such capacity planning may not seem to directly affect the control algorithm, but, nevertheless, it is important because the answers impact network reliability and functionality; accurate sizing implies smoother and more optimal control. Moreover, reasonably accurate sizing improves the testing of the control algorithm. Similarly, capacity analyses are important from the network operator's viewpoints, for example, in the case of the service guarantees that can be made to the customers of the network.

In the considered LVDC island microgrid, the two largest system components are the production and storage components, and their sizes, or capacities, must be determined reasonably accurately first; it is also useful to know the sizes of the cables, converters, and other component, but the PV array and battery bank are the most important since they typically dictate the sizes of the other components. These two components must be sized carefully, optimally, reliably, and cost-effectively; in addition, it is important to perform the sizing early since not only control but also other aspects of network planning, such as protection and communication planning, can then be carried out effectively. Reasonably accurate estimates of their capacities can be crucial from the viewpoint of other network planning aspects such as costing, power, and reliability as well.

In this chapter, first, previous research approaches to sizing are described. Subsequently, an algorithm for accurately determining the PV and battery capacities is presented; the accuracy of the proposed algorithm is then supported by simulation results which are described and discussed. In the final section, an algorithm to determine the number of service hours that can be guaranteed by the network at any location in the world is presented along with the obtained results. The chapter is then concluded with a brief discussion on the limitations of the approach and the potential areas of further research.

3.2 Capacity planning

3.2.1 Research background

Numerous researches have been conducted on the sizing of PV-battery standalone systems in the last few decades, and several analysis methods have been proposed and developed. Early analysis methods (Solar Power Corp., 1978) focused on the concept of the number of autonomous days (NADs) in order to ensure that the power supply was completely reliable; however, this somewhat simple approach oversizes the system and is uneconomical, especially in the case of large systems. Ofry and Braunstein (1983) proposed the loss of power supply (LOPS) probability concept as a method to optimize the sizes of the PV array and battery storage system, especially from the viewpoint of cost. Instead of using the NAD concept, they defined reliability as the total number of hours in which the consumer's power demand is more than the power supply.

Chapman (1987) employed the loss of load probability (LOLP) concept, which is a widely used reliability measure in capacity planning (Wang et al., 1977), to propose a noncomputerized sizing technique that enables sizing for the required LOLP, given the load demand and insolation data. Gavanidou & Bakirtzis (1992) considered LOLP as another design objective to be minimized, along with the capital investments, and employed the tradeoff/risk method to design an autonomous system. Borowy & Salameh (1994) considered a standalone hybrid wind/PV system and calculated the optimum size of a PV array; subsequently, they extended their research to battery banks by using the LOPS probability concept (Borowy & Salameh, 1996). Shrestha & Goel (1998) conducted studies into the optimal sizing of a PV system on the basis of statistical models. Conti et al. (2002) proposed a multi-objective optimization approach that uses fuzzy logic to avoid the disadvantages of both NAD and LOPS concepts. In 2006, Markvart (2006) used the time series of irradiation data in place of LOLP in order to size PV systems.

Markvart et al. (2006) also succinctly summarized the objectives and procedures for sizing. According to them, the basic objective of sizing procedures is to consider the relationship between the sizes of the PV array and battery which deliver energy to the load with a certain reliability of supply that can be tolerated by the user: the results of the sizing procedure are often summarized in the form of a *sizing curve*. Since the key parameter is supply reliability, it must be satisfactorily defined, and LOLP is most often used for this purpose. IEEE (2008) and IEEE (2007) provided methods for properly sizing the PV array and battery, respectively, in PV-battery standalone systems. In their methods, the sizing ensures that the load demand is met in a cost-effective manner and the system performances and operating lifetimes are improved. The PSH method of sizing is used, and the systems are sized based on the worst-case solar radiation, load consumption, and system losses. In addition, the basis for the system sizing is the current of the PV module. The guide recommends the use of LOLP. Khatib (2010) listed and discussed the general procedures and guidelines for designing the system components of standalone PV systems; in addition to recommending the LOPS concept, current was proposed as a suitable parameter for sizing the PV array since it does not depend on temperature, unlike voltage and power.

In this thesis, the concept of NADs has not been used; instead, it has been assumed that there should be reliable power supply for 24 h. In addition, the DES method has been used. In DESs, the operation of a system is modeled as a discrete sequence of events in time; each event is supposed to occur at a particular instant in time and marks a change of state in the system. (Banks et al., 2009) DESs can be event-based or time-based; in time-based simulations, the system is simulated at predefined time steps even if nothing happens, whereas in event-based simulations, the system is updated only when an event occurs. In this thesis, the state of the network must be checked at regular time intervals, and hence, time-based DESs have been employed. There are no changes in the system between consecutive time intervals that may be as high as 1 h for energy balancing and as low as <1 s for power balancing. Basically, the system states are updated after each chosen time interval, and the situation and conditions are checked.

The output data from a simulation directly corresponds to the outputs that can be recorded from the real system. Simulation models contrast with optimization models in that they are “run” rather than solved. The model is run using the given particular set of input and model characteristics, and the simulated behavior is observed; a set of scenarios is then evaluated and a good solution is recommended for implementation. Simulations have several advantages, and the relevant ones among them are as follows: (1) New ideas and hypotheses can be explored and tested for feasibility without disrupting the ongoing operations of the real system; (2) Testing is easy; (3) Time can be compressed or expanded, as per the requirement; (4) Insights into the interaction of variables and the importance of variables to the system can be obtained; and (5) "What if" questions, which are particularly useful in the design of new systems, can be answered. In this manner, simulation is a reasonable approach because it mimics what happens in a real system (or the perception at the design stage). Further, a DES is ideal for analyzing this network since it operates over a definite time period and experiences changes in its state and conditions at discrete time intervals. Of course, simulation modeling and analyses can be time-consuming and expensive, but this is not a serious disadvantage in this type of relatively smaller DC networks. (Banks et al., 2009)

In order to properly size the PV array and battery in a standalone PV system, two pieces of information are critical—accurate load and solar irradiation data. The more accurate the load and solar irradiation data, the more accurate is the system sizing; in contrast, inaccuracies may lead to over- or under-sizing. In this thesis, it is assumed that accurate load and solar irradiation data are available and are accurate (Chapter 2). Moreover, since the use of MPPTs is assumed and not considered explicitly in this thesis, it is not independently sized; it is simply assumed that the MPPTs will be sized based on the array wattage. These systems also commonly employ controls to protect the battery from being over- or undercharged as well as power conversion subsystems (inverters). However, in this thesis, the sizing of any system controllers, inverters, wiring, or other system components is not considered.

In this thesis, the PV array and battery are sized for 24-h service times; this is not a (serious) restriction and the algorithm can be modified to allow the user to change the number of required service hours (this has been left for a future study). Further, the effects of losses have been neglected.

3.2.2 Problem statement

To optimally size the two largest components of the given LVDC Island Network—PV Array for Production and Lead-acid Battery Bank for Storage—in order to improve the performance, cost-effectiveness, and lifetimes of the network

3.2.3 Methodology

Battery The battery is sized first because it is a critical component and its sizing has to be reasonably accurate for optimum reliability. This is because the battery's backup essentially decides the NAD, that is, the number of autonomous days in which the load demand can be satisfied by the battery alone. Moreover, the PV array must not only meet the load demand but also charge the battery, and since these two operations must ideally be performed simultaneously, it is preferable to know the battery size before the PV array size.

The simplest approach is to consider the annual solar data and then size the battery to meet the load demand for the maximum continuous time period for which the PV array cannot supply power. So, for example, assume that all 365 days have some hours without sunlight or with insufficient sunlight. The value of the maximum uninterrupted non-sunlight period can then be determined and the battery can be sized accordingly. However, if such a simplistic approach is employed, the battery will be under-sized; the battery's recharge capability may not be sufficient for it to recharge quickly after the discharge, and this will cause problems if the next non-sunlight period is too close. Of course, at the same time, some loads could be disconnected and critical loads could be given more autonomy than non-critical loads. The amount of compromise that is required can be made by the control algorithm. Nevertheless, this is not a good solution because emergencies leading to the lack of sufficient PV production are not predictable, and for reliability, it is preferable to avoid under-sizing, especially in the case of batteries.

In many approaches, as discussed previously in Section 3.2.1, the NAD is given as a design criterion and the battery is sized accordingly. However, in this study, the initial approach is to consider that the power supply is always available for all loads; hence, the NAD has not been considered, or, rather, the NAD has been considered to be the time period being investigated. Further, since reliability is a key parameter, it is assumed that the PV array will be sized sufficiently to *at least* meet the average daily power requirements of the load under normal conditions and charge the battery *simultaneously*. At the same time, the battery sizing methodology assumes that no power is available from the array, and hence, the resulting battery capacity should be adequate to meet the typical load requirements.

The inputs to the algorithm are the network voltage; the load profile data (including the number of customers) and hourly solar irradiation data for the considered time period; battery charge and discharge rates; and the minimum SOC of the battery. The idea used here is to assume a minimum battery capacity as a starting point; either a reasonable assumption can be made for this starting point, or it can be determined analytically. Beginning with this battery capacity, the network is simulated for the time period in question and it is verified if the battery SOC decreases to less than the minimum SOC SOC_{min}. As soon as $SOC < SOC_{min}$, the battery size is incremented and the simulation is restarted. The battery size is then chosen to be the minimum battery capacity for which the SOC never decreases to less than SOC_{min}. Note that the event can be updated at time periods specified by the user, and the only potential restriction is the availability of irradiation data at those intervals. In this thesis, 1-h intervals have been used.

PV array The PV array has two basic functions: (1) Supply power to loads and (2) Charge the battery. Charging the battery is not required once the battery is charged to its maximum point, and even otherwise, complete charging from the minimum level may not be required in many situations. Nevertheless, for reliability, the worst-case scenario should be considered, and the sizing should consider the power required for fully charging the battery as well as for supplying the load, even though this may lead to over-sizing. Subsequently, the optimum size can be revised by real-time simulations, if needed (not done in this thesis).

The PV array is sized to replace the ampere-hour (Ah) in the battery consumed by the load and to supply the load demand. This is done by simply adding the average load demand for a day and the maximum battery SOC that can be charged.

Algorithm

Aim To determine the optimum capacity of the battery and PV array

User-input data Hourly solar irradiation H kW/m^2 for the time period; number of customers N; hourly load data for a year for one customer, L Wh, for the time period (or, all the loads separately); network voltage level V; battery charge and discharge rates (B_{Ch} and B_{Dch}, respectively); and minimum and maximum SOCs of battery (SOC_{min} and SOC_{max}, respectively).

The algorithm proposed in this thesis is given as follows (Algorithm 1), and the flowchart is given in Fig. 8:

Algorithm 1 Algorithm for sizing PV array and battery

```
Battery
  1. Obtain user-input data.
  2. Initialize $SOC_{max}$.
  3. Begin Simulations from time = 1 to timeperiod in steps of 1.
      (a) If $SOC(time) = SOC_{max}$, do not charge battery.
      (b) If $H > 0$ and $SOC(time) < SOC_{max}$, charge battery.
      (c) If $H = 0$, discharge battery to meet load demand.
      (d) If $SOC(time) = 0$, $SOC_{max} = SOC_{max} + 5$. Repeat from Step 3.
  4. Else, battery capacity required $= SOC(time)$.

PV Array
  1. Determine the average load demand for an hour.
  2. PV capacity = Load demand + Battery capacity.
```

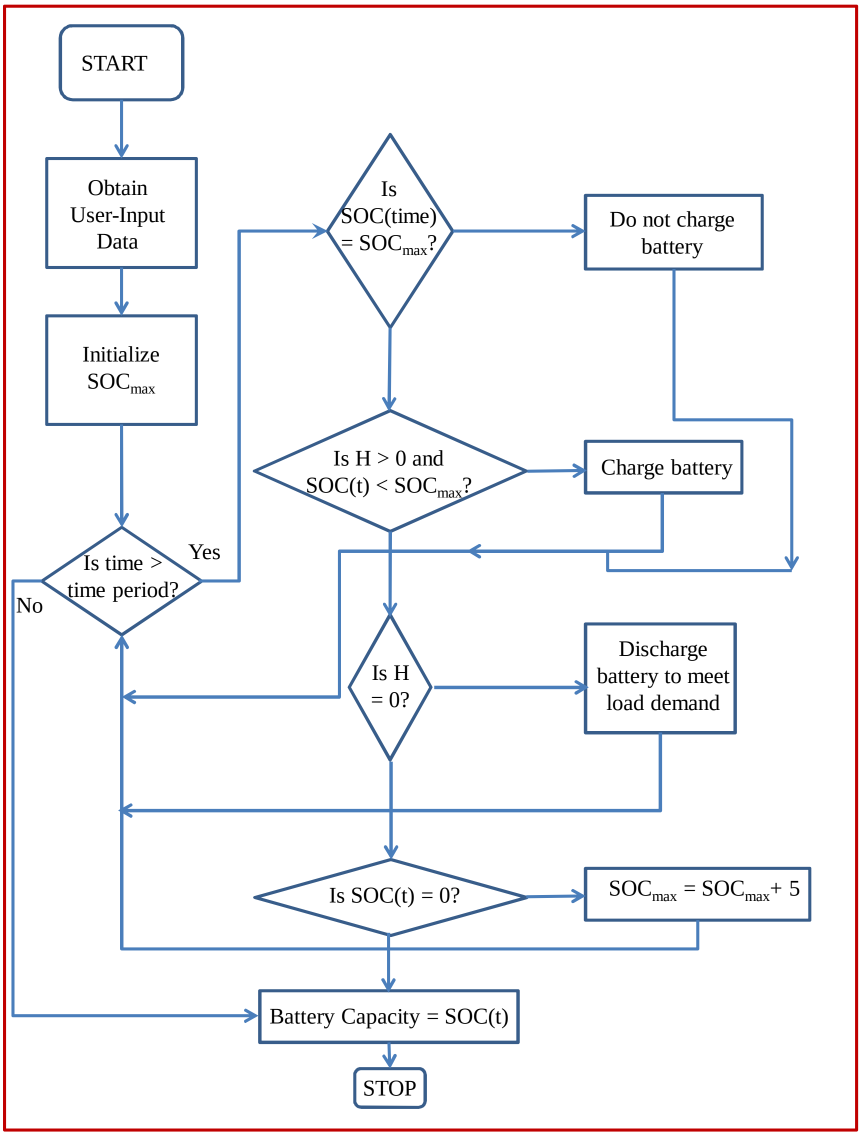


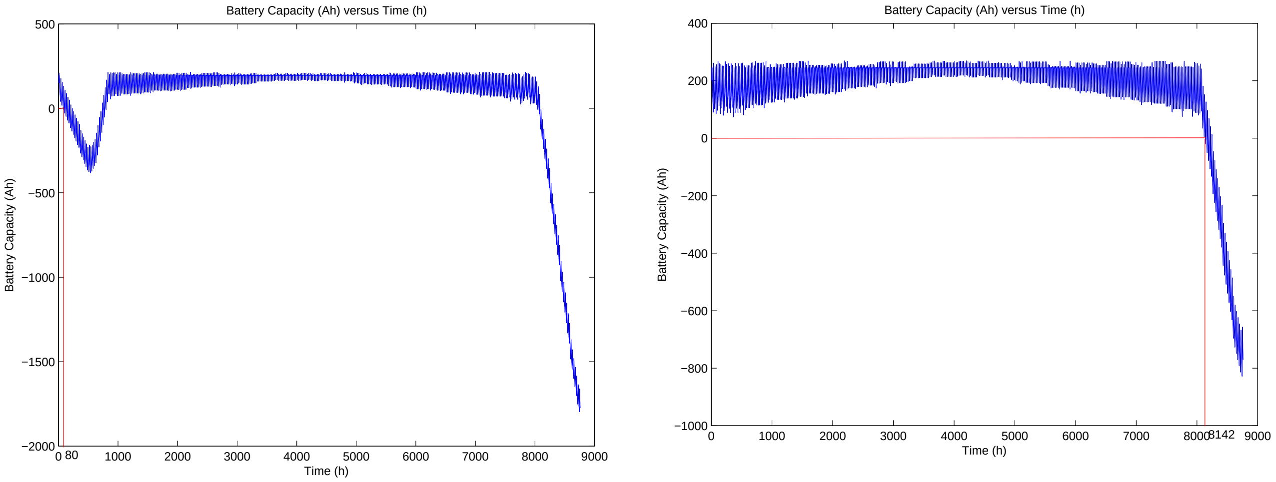
Figure 8: Flowchart for sizing PV array and battery.

This algorithm was implemented in Matlab© , and the results are given in the next section.

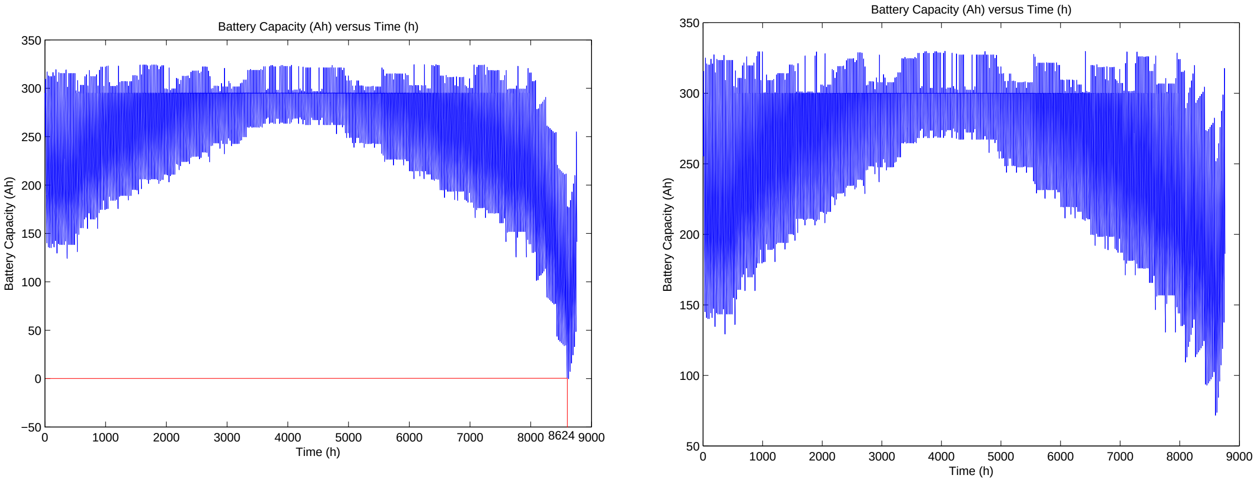
3.2.4 Results and discussion

For the simulations, the following data was chosen: time period = 1 year, or, 8760 h (8760 simulation steps); number of customers = 20; the hourly solar irradiance for an entire year for latitude 60° was taken as per Section 2.1.3 ; the load profile was a typical Finnish load profile, as discussed earlier in Section 2.3.3; $SOC_{min} = 0$; and B_{Ch} and $B_{Dch} = C/10$.

Figures 9a–9b show the variations in the battery capacities with time. In Fig. 9a (left), the initial battery capacity is low, and hence, by the 80^{th} day of operation, the SOC becomes less than SOC_{min}: $SOC(80) < SOC_{min}$. In Fig. 9a (right), the battery capacity is increased, and now, the SOC becomes less than SOC_{min} only by the 8142^{nd} day. In Fig. 9b (left), $SOC(8624) < SOC_{min}$. Finally, in Fig. 9b (right), the battery capacity is at the level where it never goes below zero throughout the operation period.



(a) $SOC(80) < SOC_{min} = 0$ and $SOC(8142) < SOC_{min} = 0$.



(b) $SOC(8624) < SOC_{min} = 0$ and $SOC(time) > SOC_{min} = 0$.

Figure 9: Battery capacity versus time for various initial battery capacities.

For the given parameters, the obtained battery capacity is $300\,Ah$ $(225\,kWh)$, and the PV array size is $28.657\,kW$. If it is assumed that the peak power $800\,Wh$ is demanded by the load at every hour, the energy demand per hour would be equal to $800 \times 20 = 16\,kWh$. The battery capacity per hour would then be $\frac{16\,kWh}{750\,V} = 21\,Ah$. However, the obtained required battery capacity is as high as $300\,Ah$ $(225\,kWh)$. Why is it so much higher? The reason is that the battery is not charged immediately after discharging, which means that if there were 10 hours of continuous darkness, $21 \times 10 = 210\,Ah$ $(157.5\,kWh)$ would be needed to be charged. At 60° latitude, there are often 15–20 hours of darkness, and hence, the abovementioned result of $300\,Ah$ $(225\,kWh)$ seems quite reasonable for the latitude. In contrast, if the same parameters are applied at 0° latitude (solar irradiation data is changed), the required battery capacity decreases to $95\,Ah$ $(71.25\,kWh)$. In this manner, the obtained results seem quite reasonable.

3.2.5 Limitations and future studies

This algorithm is somewhat over-simplified and requires some modifications to improve the accuracy of the estimation; in particular, not all concepts and ideas have been considered here. For example, consider the second condition in the battery sizing: “If $H > 0$ and $SOC(time) < SOC_{max}$, charge battery”. Here, it is assumed that the power production is sufficient to supply the load and charge the battery, but this may not be true; there may be enough power production to meet the load demand but not to charge battery. Similarly, in the case of the condition “If $H = 0$, discharge battery to meet load demand”, the battery SOC may not be at a sufficient level to meet the load demand. These factors may cause some inaccuracies, which may perhaps not be significant, but, nevertheless, should be kept in mind. Moreover, the use of daily averages of the load demand leads to inaccuracies in the PV array capacity; this can be improved by conducting DESs for the PV array as well. Further, the energy required to overcome system losses and inefficiencies has been neglected in this study. However, this is very important and must also be included in future studies. Other system components—cables, system controllers, inverters, wiring, and protection devices—must also be correctly sized in the future.

3.3 Capacity analysis

3.3.1 Introduction

Capacity analysis, as mentioned previously, refers to the ability of the planned capacity to reliably meet the load demand for the required service hours. There are many ways of approaching this problem, such as, for example, addressing the following two questions: (1) How does the guaranteed service hours change as the distance of the network location from the Equator increases (or, as the PV power availability changes)? (2) How many customers can be supported by the network at a given location? In this thesis, the question of service hours at the given location is considered, since knowledge of tolerances to the loss of load can improve the system design, especially with respect to the cost.

In this section, the effects of the geographical location on the service hours have been investigated. *Service hours* is defined as the minimum period of time per day for which uninterrupted power supply can be guaranteed to the customers. Many variables influence the service hours, such as the number of customers, PV array and battery capacities, load data, weather conditions, solar irradiance levels that depend on the location, functioning of other network components, network losses, and other network parameters. Here, a general method to determine the minimum number of service hours at any location has been derived. The general algorithm gives an average answer. Subsequently, practical solar irradiation data at different latitudes were obtained (in the manner described in Section 2.1.3) and the effects of the location on the service hours were examined.

3.3.2 Problem statement

Given the production and storage capacities, to determine the number of service hours that can be guaranteed at any location

3.3.3 Methodology

The number of customers, PV array output power under STC, battery capacity, battery charge and discharge rates, battery minimum and maximum SOC, load data, solar irradiance data at the location, and network voltage are assumed to be input by the user. The functioning of other network components, network losses, and other network parameters are neglected. Moreover, for simplicity, load prioritization during subnormal or emergency situations—or, in other words, unexpected situations leading to lack of sufficient power supply—is not considered here, and only normal operations are considered. In the analysis of the effects of the geographical location on the service hours, all the factors and parameters (including air mass) other than the solar irradiance data are assumed to be identical in order to ensure that the comparisons are valid.

The PV array output is calculated using the PSH method mentioned in Section 2.1.2. Subsequently, the average PV production and load demand for a day are calculated. Simulations are then conducted for 1 day; these simulations are not real-time and are conducted on the basis of average values. Note that this is purely for simplicity, and the simulations can be extended to any time period, as per the requirements. Finally, it is assumed that when the PV production is available, the first preference will be for charging the battery as soon as possible and secondly to supply the load. Again, this is also for simplicity and the analysis can be extended to load prioritization with real-time simulations.

3.3.4 Algorithm

Aim To calculate the service hours for *any* location given user-input data

User-input data Hourly solar irradiation data H W/m^2 for the time period; number of customers N; hourly load demand data for a year for one customer, L Wh, for the time period (or, all the loads separately); network voltage level V; battery size (maximum SOC) SOC_{max}; battery charge and discharge rates (B_{Ch} and B_{Dch}, respectively); minimum SOC of battery, SOC_{min}; and PV array size PV_P.

The algorithm proposed in this thesis is then given as follows (Algorithm 2):

Algorithm 2 Algorithm for calculating the service hours for *any* location

```
1. Obtain the user-input data for the location.
2. Determine the total peak sun hours for the entire year for the location, $PSH_Y$.
3. From $PSH_Y$ and $PV_P$, determine the possible output energy from the PV array for the entire year, $PV_E$ kWh: $PV_E = PV_P \times PSH_Y$.
4. Determine the average PV energy production for a day: $PV_{E(day)} = (PV_E)/365$.
5. From the load data, determine the load energy for the entire year, $L_E$ kWh, and then determine the average load demand for a day, $L_{E(D)}$: $L_{E(D)} = L_E/365$.
6. Begin simulations for 1 day (1 to 24); $counter = 1:1:24$
    (a) If PV energy is exhausted $(PV_{E(day)}(counter) = 0)$, end the loop and record the counter.
    (b) If the battery capacity is not full,
        i. Charge battery: $SOC = SOC + B_{Ch}$.
        ii. Supply load (as much load as possible without becoming negative).
        iii. Obtain PV energy for next hour (= PV energy in this hour - energy required to charge battery and supply load).
    (c) If the battery capacity is full,
        i. Supply load.
        ii. Obtain PV energy for next hour (= PV energy in this hour - energy required to supply load).
    (d) Repeat from Step (a).
7. Service hours = counter + time for which battery SOC can supply power.
```

Results

Simulations using the general algorithm and real solar irradiation data were conducted at various locations with different latitudes. Only the solar irradiation data was changed and all the other parameters were kept constant in order to facilitate effective comparisons. The solar irradiation dataset was obtained in the manner described in Section 2.1.3—hourly data for the global component of the solar irradiation dataset was obtained for the year 2005. The latitude was varied from 0° to 65° in steps of 5°. Additionally, the effects of natural landscape were taken into account, at least to some extent. For example, areas that comprise deserts were excluded from the analysis since rainfall is less in such regions, leading to less cloudy weather and skewed results; moreover, Similarly, as far as possible, all the areas were chosen such that they have the same elevation from sea level, thereby avoiding altitudinal variations. These factors have resulted in *deliberate* longitudinal variations in the locations. Since the SoDa service gives free data only for some longitudes (-66° to 66°), some latitudes (for example, 15°, 20°, and 25°, which point to areas in African deserts or the Atlantic ocean) have been omitted.

A period of a year—365 days—has been considered, and hourly data has been taken from a single year, 2005. Now, it is natural that the service hours would be different for different days, and hence, for comparison, the average number of service hours has been considered; in other words, the number of service hours is calculated using $\frac{total\ service\ hours}{365}$.

Figure 10 shows the results of the simulation. The service hours increase from the Equator (0°) towards the Tropic of Cancer (22.5°) until 30°; this is possibly due to the higher amount of rainfall and cloud cover in the equatorial regions. The service hours clearly decrease as the latitude increases beyond 30°, which, as expected, is due to lesser sunlight hours. The slight jump between latitudes 55° and 60° is probably due to slight inaccuracies in the solar irradiation data. Although there is no solar irradiation data beyond 65°, the number of service hours is not 0 because the battery supplies the load.

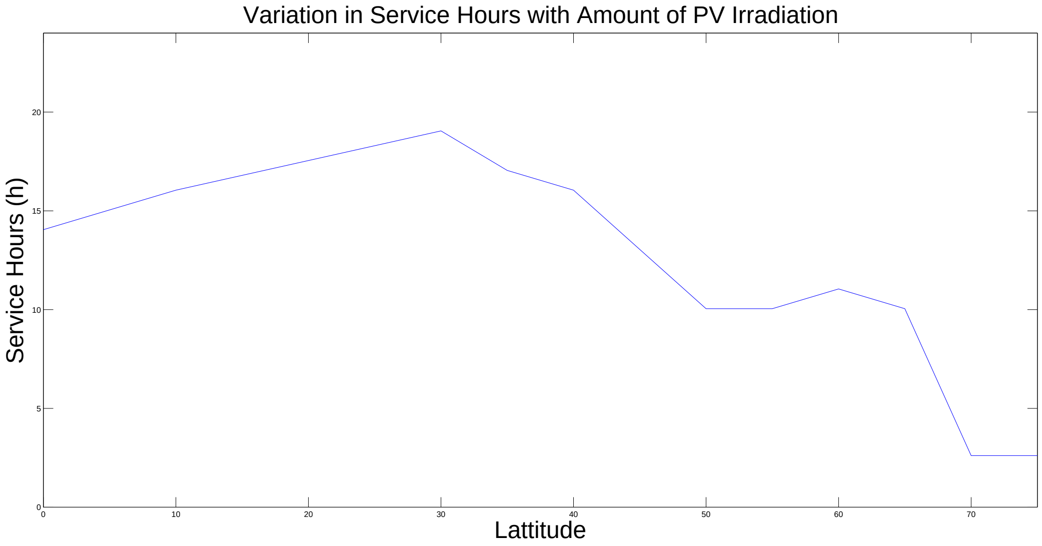


Figure 10: Latitude versus number of service hours. The service hours increase from 0° towards the Tropic of Cancer 22.5° until 30° and then decreases.

3.3.5 Limitations and future studies

For simplicity, load prioritization during subnormal operations (when neither the PV array nor the battery can meet the load demand) is not considered here, and only normal operations are considered. Further, for more accurate results, more latitudes (perhaps in steps of 1) should be included.

3.4 Conclusions

In this chapter, two capacity issues—planning and analysis—have been considered. In the first part, the problem of capacity planning—the determination of the required PV array and battery capacities—was examined and solved. The proposed algorithm successfully obtained reasonably accurate battery and PV sizes under different load and sunlight conditions.

In the second part, the problem of capacity analysis—the number of service hours that can be guaranteed at a location—was investigated. First, a general method to determine the service hours at any location in the world, given accurate solar irradiation data, was proposed and demonstrated. Subsequently, the method was applied to different places located at various latitudes. The algorithm clearly demonstrated the variations in the number of service hours that can be guaranteed to a customer when the network is located at different latitudes.

The algorithms used were introduced, and the results obtained from their implementation in MATLAB© were subsequently presented and discussed. Finally, the limitations of the approaches and the future studies that can be conducted to further improve the results were proposed.

Overall, the sizing estimations are preliminary, and some work is still required to improve the estimation accuracies and to eliminate the limitations of the proposed algorithm. In addition to losses, the algorithm must also consider control concepts such as load prioritization. Further, the results of the approaches, although reasonable, have not been compared with those of other studies; such comparisons must be made in the future in order to test the efficiency of the algorithms and to verify their improvements and advantages and disadvantages. Moreover, the sizing of system controllers, inverters, wiring, and other system components is a pending task.

Nevertheless, the estimations are reasonable and practical, and they provide a good basis for proceeding to write algorithms to control the power and energy balances of the network.

4 ENERGY MANAGEMENT SYSTEM: PRINCIPLES AND FUNCTIONALITIES

4.1 Introduction

4.1.1 Energy management systems

As mentioned in Chapter 1, Introduction, an EMS is basically a system of computer-aided tools and operations used to monitor, control, and optimize the power production and/or transmission efficiencies and overall network performances, and they are facilitated by a robust communication system that regularly communicates the network system and component statuses. Efficient and optimal EMSs have been developed previously for various kinds of networks, and several approaches have been proposed, but these have primarily focused on grid-connected systems that have the option of islanding, if required: Very few researches have been conducted into the development of an EMS for completely islanded LVDC microgrids whose power production is based on renewable (hence, variable) energy.

This chapter begins with a description of the essential requirements that any EMS for microgrids must typically fulfill as well as a brief listing of the key features of EMSs; simultaneously, when relevant, the discussion is expanded to LVDC island networks as well. The basic principles of operations of the EMS proposed in this thesis are then elucidated. An important aspect of network control in the completely islanded mode is the handling of subnormal and emergency conditions which must be elucidated before proceeding further into the core of the EMS. Hence, the type of emergencies that can be expected is now explained, and some of the approaches to deal with them are mentioned. This is followed by a description of the functionalities of the three elements of the network—PV array, lead-acid battery, and load—and the manner in which their operations are considered and controlled by the EMS. Finally, the chapter is concluded by summarizing the main points.

4.1.2 General requirements and functions

In this thesis, the term EMS refers to a collection of softwares and their paradigms that have been designed and developed to enable the proposed LVDC island network to function optimally. Optimal functioning of the proposed LVDC island network implies that (1) Customers receive uninterrupted power supply (for the guaranteed service hours); (2) There is no unbalanced power in the network; (3) The network is adequately protected; (4) Power quality standards are complied; and (5) Energy costs are optimized in the long term. The role of the EMS is to ensure that the network functions optimally without, or with minimal, user intervention; in other words, the network must function automatically and independently (Note that this thesis does not consider protection of the network.).

In general, EMSs for DC microgrids—when off-grid—must be able to perform independent operations such that the following requirements are fulfilled (adapted from Pedrasa & Spooner (2006) and Bhaskara & Chowdhury (2012)):

- *Autonomy*: EMSs must be able to respond to events autonomously using only local information.
- *Power Quality*: EMSs must be able to ensure that power quality requirements are satisfied.
- *Optimization*: EMSs must be able to optimize the energy usage.
- *Energy Balance*: EMSs must be able to maintain energy balance between supply and demand.
- *Voltage Regulation*: EMSs must be able to regulate voltages (and frequencies, in AC microgrids) within acceptable limits.
- *Response Speed*: EMSs must be able to respond quickly.
- *Emergencies*: EMSs must be able to handle subnormal and emergency conditions intelligently.
- *Communication*: EMSs must be able to accept data and send command signals (if communication infrastructure is present).

The EMS proposed in this thesis has been designed to satisfy all the abovementioned requirements. The methods adopted for satisfying these requirements will be elucidated in this and the subsequent chapter. Further, reliable EMSs for microgrids must comprise certain key features for enabling and ensuring optimal operations; they are listed as follows:

1. Effective control strategy (algorithm)

2. Efficient software implementation (of the strategy)
3. Reasonable handling of forecasting of production and load demand
4. Reliable communication
5. Reliably sized network components (only for testing purposes; in practice, the EMS must be able to respond irrespective of the size)

This thesis attempts to incorporate as many of these features as possible. Typically, reliable sizing of network components has been assumed to be an independent problem in most prior studies, but, in this thesis, the sizing of PV arrays and batteries has been considered (Chapter 3). Forecasting, however, has been considered only at a superficial level, and its efficient integration into the software has been left for future studies. Further, communication-related issues have not been explicitly solved in detail, but some basic ideas have been considered, for example, the nature of the data used by the softwares as inputs and outputs, acceptable timeframes for obtaining the data, and a basic communication structure; these are discussed separately in greater detail in Section 4.5. Similarly, protection-related issues have not been considered at all, and it is simply assumed that protection devices exist and act quickly and decisively; however, during the implementation of the project, it may be necessary to consider protection issues in greater detail, and in particular, to analyze their potential impacts on the control efficiency and reaction speeds.

4.2 Energy and power balance principles

In the operation of electric power systems, the main challenge is to ensure that the "electrical" storage in the system is negligible. This implies that the supply and consumption of electrical power must be balanced at all times. The load is changing all the time in ways that cannot be perfectly predicted, and hence, the production must follow the load in real time. Typically, the balance between supply and demand is performed using a hierarchical control scheme, with crude matching at the longer timescale (energy balance) and finer matching at the shortest timescale (power balance). (Kassakian and Schmalensee, 2011) Note that in the LVDC islanded network being considered, the production also includes the storage.

Thus, the fundamental principles of both energy and power balancing are simple: the power/energy production must meet and satisfy the load demand (losses should be considered as well). Power balancing must be performed instantaneously while energy (power × time) balance can be performed over longer periods of time (for example, daily). This balancing takes place under some constraints, for example, cost, efficiency, and reliability.

Mathematically, the balancing can be expressed by the following equation:

$$\int_{0}^{\mathrm{T}} min(Production + Battery - Load - Losses) > 0 \tag{2}$$

Equation 2 expresses the idea that over a time period $[0\ T]$, the total power supply at any particular point in time must always be greater than the load demand (and losses). However, as mentioned above, this balancing occurs under some constraints such as efficiency, costs, reliability, protection, and communication infrastructure. Hence, the balancing can also be expressed as follows:

$$(P_{PV} + P_{Batt.})_{constraints} = (P_{Load} + P_{Losses}) \tag{3}$$

$$(E_{PV} + E_{Batt.})_{constraints} = (E_{Load} + E_{Losses}) \tag{4}$$

In this thesis, the primary constraint considered is efficiency.

4.3 Subnormal situations and emergencies

Electricity production from renewable energy sources such as solar and wind tend to be variable, and hence, inherently unreliable. Moreover, island networks are isolated and cannot depend on other grids to compensate for the lack of power supply. These two factors imply that there may be situations in which the load demand cannot be met. Such situations are commonly referred to as subnormal situations in this thesis, and if the situation worsens, as emergencies (the exact conditions and classifications are given in the next chapter.). Energy storage devices such as batteries are a solution to reduce the occurrence of such situations, but they also have limitations such as cost, size, and maintenance. The occurrence and nature of subnormal situations depend on the production and storage capacities as well as the infrastructure selected for protection, communication, transmission, and control; for example, there will be no shortage of power production if the PV array and battery capacities are very high. However, this is not an economically feasible solution, and compromises may have to be made during practical implementations of the network, keeping in mind techno-economic constraints. Further, there are reasonable chances that losses in power supply will occur in the network, and the control algorithm must take adequate measures to reduce their impacts. Hence, before proceeding further, it is necessary to elucidate network situations wherein power supply may be lost (subnormal situations, including emergencies) and the possible approaches that can be implemented to mitigate their impacts.

In this thesis, the term “subnormal situation” refers to any situation in which the normal or typical functioning of a network is constrained by external factors which may be anticipated (for example, night-time, forecasted cloud cover or rainfall) or unanticipated (for example, storms) and controllable (for example, faults) or uncontrollable (for example, equipment malfunction). “Emergency” refers to a subnormal situation that is close to collapse. Typically, most subnormal situations are some variations of loss-of-power-supply situations but the root cause may often be different; for example, it may be due to weather conditions or faults.

The term emergency is used to imply both subnormal and emergency situations in the subsequent discussion in this chapter and practically used interchangeably. The exact conditions that define normal, subnormal, and emergency situations are elaborated in greater detail in Chapter 5. Here, the emergency situations are considered and are classified into situations depending on the root causes, and some proposed approaches are discussed.

Production emergency Production emergency refers to emergency situations in which, for some reason, the power production is not equal to the load demand (independent of other network conditions or parameters). In the network being studied, this implies that not only the PV array but also the battery cannot provide sufficient energy to meet the power (or energy) demands of the network. The basic reason for this emergency to occur is undesirable weather conditions at the location, especially over a period of time. Some emergency situations may occur regularly; for example, regular hours of darkness daily can lead to emergency situations if the sizing is inaccurate, for example, if the battery size is insufficient or it does not get charged sufficiently during the periods of sunlight. Similarly, some emergency situations may occur seasonally; for example, the production may be lowered during the rainy season alone. Some emergency situations may occur unpredictably, for example, unexpected rainfall, storms, and production equipment failures. The failure of production equipment can cause the production capacity to decrease or even stop; for example, batteries whose lifetimes may be approaching end-of-life will have decreased SOCs and DODs.

Predictable emergency situations can be handled by accurate sizing. However, it may be sometimes necessary to make compromises on the sizing, which may lead to emergency situations occurring on a daily basis. Such situations as well as other unpredictable situations (for example, inclement weather) can be handled by load prioritization and load disconnection. Note that the customers must know and understand the implications of load prioritization and despatch and their expectations must be set accordingly. Additionally, accurate solar forecasting data can be critical for anticipating and responding to emergencies. Battery end-of-life must be checked regularly to prevent or respond to emergency situations; further, the PV array must be inspected and maintained to sustain optimum power production.

Protection emergency Protection emergency refers to emergency situations in which power imbalances are caused by faults occurring in the network. Faults can also lead to secondary issues such as production and transmission failures. In general, it is expected that the protection equipment itself will be able to handle such emergencies and restore the network production and transmission. Hence, protection emergencies have not been addressed in this thesis. At the same time, the EMS may have to quickly respond at some level to ensure that the operations continue to be optimal in the remaining parts of the network. The impact of protection emergencies on the control of the network and how the algorithm can respond should be addressed in a future study.

Communication emergency Communication emergency refers to failures in the communication systems as a result of which there is either a time delay or information loss. The control system is significantly dependent on the communication infrastructure since it requires inputs from network components such as converters and other devices for calculations whose results determine the decisions and control signals that need to be returned to the network components (or elsewhere). A communication emergency leads to two problems: (a) The control algorithm receives/sends *incomplete or no information*, and (b) The control algorithm receives/sends *incorrect information.* In such a situation, the control algorithm may use such information and send incorrect control signals that may then have a cumulatively large effect on the network, leading to severe imbalances.

In the case of (a), if the control algorithm does not receive all the required information within the acceptable timeframe, it can assume that there is an emergency situation and start operating in the emergency mode. At the same time, it can start sending signals to the part of the network from which the communication is not received, till it receives a response. In the case of (b), the control algorithm can have some inbuilt error-check mechanism, which it can then use to verify the communication received. However, such an error check cannot cover all possible situations and is not a perfect solution; determining a more acceptable solution can be a subject for future study.

Another question is what actions should be performed if there is no communication for a long period of time, perhaps because of collapse in the communication infrastructure; arrangements for handling the network in the absence of communications must be considered in a future study. Note that when the control algorithm becomes aware of an emergency situation, the network operator is also immediately informed. Finally, here, it is assumed that the communication infrastructure and planning will have some measures for handling communication emergency issues, such as backup communication, and steps to restore communications will be taken as and when necessary.

Network component emergency Network component emergency refers to failures in network components, other than production and storage, that may cause the optimized control algorithm to lose efficiency; typical network components may be converters and cables. In this thesis, methods to address network component emergencies are not addressed directly, and this could be an important subject for future studies.

Miscellaneous emergencies Miscellaneous emergencies refer to any emergency situations that have not been listed previously; typically, these are unexpected unforeseen network conditions. Such emergencies may have to be handled in a different manner, and their analyses have not been included in this thesis.

4.4 Functionalities of network components

Most of the power in the network being studied is either supplied or absorbed by three main elements—the PV array, battery, and load—and power and energy balancing require their inputs and outputs to be analyzed and controlled. In general, the PV array always supplies power, while the load always absorbs power; in contrast, the battery both supplies as well as absorbs power. Further, the power outputs from the PV array and battery and the power input into the battery are controllable, while the load power demand can only be adjusted by disconnection based on prioritization.

Power flow and energy management problems have been studied previously, for example, in Jun et al. (2011), Lagorse et al. (2010), Riffonneau et al. (2011), and Locment et al. (2012). These researches have primarily considered various power system operation modes (typically multi-source) and different strategies. However, their studies are mostly related to power balance control without considering power supply restrictions or limitations. Wang et al. (2012) extended their researches to provide an interface for energy management that considers the possible limits imposed by the utility grid; limited PV production and load shedding have been considered to some extent. However, their research is also limited to grid-connected supplies and only considers occasional islanding. Completely islanded networks which lead to additional problems, especially those of reliability, service-hour restrictions, and optimization, and few researches have considered them. In such islanded networks, correct battery usage and load prioritization become even more important.

This thesis proposes power-system operation modes that encompass the various situations faced by an LVDC island network and considers power and energy management strategies for all possible scenarios. The PV array, battery bank, and load have different operation modes depending on the network conditions (normal operations or emergency operations). The control algorithm is designed based on this logical foundation to send control signals depending on the operation mode of the network components.

4.4.1 PV array

In the network, the power output from the PV array is P_{PV}, and it is within the range $0 \leq P_{PV} \leq P_{PVmax}$. P_{PV} is not directly controllable in the sense that it depends on the solar radiation; however, it can be limited if necessary. The PV array has the following modes depending on its state of operation. These modes are dependent primarily on the weather conditions and sometimes on the control signal.

Load Supply Mode: The PV array, in combination with the MPPT algorithm, produces as much power as possible and is able to meet all the loads: $P_{PV} = P_{PVmax} = Total\ Load\ Demand$

Limited Load Supply Mode: The PV array, in combination with the MPPT algorithm, produces as much power as possible but the power supply is not sufficient to meet all the loads: $P_{PV} = P_{PVmax} \neq Total\ Load\ Demand$ (But, $P_{PV} + P_{Bat}$ may be equal to the total load demand.).

Constrained Mode: In this mode, the PV array is constrained to output less power than the maximum power from the MPPT in order to balance power or energy: $0 \leq P_{PV} < P_{PVmax}$

Switchoff Mode: PV array is switched off and there is no power production from the PV array: $P_{PV} = 0$ (or less than an irradiation threshold (Wang et al., 2012)). This mode occurs either when there is no sunlight or when the control algorithm has to deliberately force the PV array to stop production.

4.4.2 Battery

The energy storage device—the lead-acid battery in this case—is employed as the backup power supply to compensate for the variable nature of the primary production source. However, a battery has limited storage capacity as well as charge and discharge constraints. In this thesis, three SOC limits have been defined: maximum SOC, SOC_{max}, minimum SOC, SOC_{min}, and least possible SOC, SOC_{least}. SOC_{max} refers to the maximum limit to which the battery can be charged; SOC_{min} refers to the minimum limit to which the battery can be charged normally; and SOC_{least}, the lowest possible limit, beyond which the battery should not be discharged under any conditions. The SOC is practically the most important parameter in network control, and the battery charges and discharges are used for controlling the network voltage and power balancing in this thesis.

Typically, the battery SOC will be in the range $SOC_{min} \leq SOC \leq SOC_{max}$ during normal operations and $SOC_{least} \leq SOC \leq SOC_{min}$ during subnormal operations. These ranges are not fixed limits for the two operations since subnormal situations are defined by the ability of the power supply to meet the load demand and not the SOC alone; in other words, such situations may occur even when $SOC \geq SOC_{min}$! It is assumed that all the three limits are specified by the manufacturer and entered into the software by the network operator before operations. An important difference between the PV array and battery is that the PV array power production is dependent on the weather conditions, whereas the battery energy utilization is dependent completely on the decisions taken by the algorithm.

Control signals are sent to the battery based on the decision taken by the algorithm, and the battery enters one of the following operation modes:

Charge Mode: In this mode, the battery is charged at the maximum charge rate:

$$ChargeRate_{possible} = ChargeRate_{max}$$

This happens when the PV production is optimum, that is, it can meet the load demand as well as charge the battery.

Limited Charge Mode: Battery is charged, but the charge rate is lower than the maximum charge rate because of non-optimum PV production:

$$ChargeRate_{possible} \neq ChargeRate_{max}$$

Discharge Mode: Battery is discharged at the highest possible discharge rate:

$$DischargeRate_{possible} = DischargeRate_{max}$$

Limited Discharge Mode: Limited discharge refers to emergency situations in which it is preferable to charge the battery as quickly as possible (while supplying *some* loads) rather than discharge it completely (and supply more additional loads). This mode is important because the criticality of the battery backup makes it more important to charge the battery quickly rather than supply all loads; this action is also better for the battery life. Here,

$$DischargeRate_{possible} \neq DischargeRate_{max}$$

SwitchOff Mode: Battery is switched off and neither charging nor discharging takes place. This happens when the SOC is already at the maximum limit ($SOC = SOC_{max}$); when SOC is at the lowest possible limit ($SOC = SOC_{least}; subnormal$); when SOC is at the minimum level ($SOC = SOC_{min}; normal$); or when the PV array output is sufficient to meet the load demand and losses ($P_{PV} = Load\ Demand + Losses$).

4.4.3 Load division and prioritization

Load division The basic function of any electrical network is to supply the power demanded by the various connected loads. However, loads utilize power and it is not always possible to meet the load demand. Load prioritization, load disconnection and load shedding are potential solutions (as discussed in Chapter 2). In this thesis, it has been proposed that the loads should be divided into three categories with certain priorities and further sub-divided into sub-loads with sub-priorities. The loads are then considered to have different operation modes that depend on whether the total load demand can be met or not and the consequent prioritization. The operation modes, load categories, and prioritizations are discussed below.

Normal Load Operations: All the loads receive power supply without any constraint.

Load-Constrained Operations: Only some loads can be serviced. The choice of the loads that can be serviced is based on the load category and their prioritizations, and this determines the operation mode as well.

1. *Critical-Loads Mode*: In this mode, only the critical loads are supplied. Critical loads are the most vital loads in the network, whose servicing may be a life-and-death issue. Examples of critical loads are hospitals (or, doctors' clinics), critical lighting (highways or bus stations), emergency services, triage centers, and disaster-response areas.
2. *Essential-Loads Mode*: Only essential loads are supplied in this mode. Es-

sential loads refer to loads that are not vital, but, nevertheless, are important. Typical examples of such loads are banks, ATMs, street lighting, schools, houses, and water-pumping stations. Critical loads are typically community loads, but essential loads can also be household loads such as lighting.

3. *Normal-Loads Mode*: Normal loads refer to any other loads besides critical and essential loads. Typically, these loads may be household loads such as fans, refrigeration, internet, and television.

Note that all these loads may or may not be present in the network application that is proposed, that is, small populated villages; for example, ATMs and hospitals may be absent in small villages. However, they have been mentioned because it is preferable to assume that these loads do exist, to consider them as input data, to build for them, and to then not use them in the calculations, depending on the situation.

All the three load operations are prioritized according to the scheme given below, which includes internal prioritization as well.

Load prioritization In the prioritization mechanism, the highest priority is given to Critical Loads. The second priority is given to charging the battery. The battery must be charged as soon as possible for two reasons: (1) The battery is not only the primary but also the *only* backup; (2) This will prolong the battery life; the battery is often cycled close to its least possible SOC during subnormal operations, and hence, it is urgent to charge it. After the battery is charged till at least the minimum SOC (and if possible, more), the third priority is given to Essential Loads and the final priority to Normal Loads.

In addition, all the loads may or may not have sub-loads, which implies that there is a need for internal prioritizations. To illustrate this, consider Critical Loads. First of all, there may be many critical loads with different criticalities; hospitals or medical services, for example, may be more critical than lighting loads. Hence, each load type has a "sub-Load Mode" which is referred to as Limited Critical/Essential/Normal Load Mode when all the loads belonging to that load type cannot be serviced. Moreover, each critical load may or may not have several loads. For example, hospitals/doctors' clinics may have several loads of varying importance (intensive care units are more critical than a waiting room!), whereas, in contrast, lighting loads could be grouped as one load that does not need any further sub-divisions.

Therefore, the category “Critical Loads” has the highest priority, and it is then subdivided internally into several sub-loads with sub-priorities; each of these sub-load is then divided again into super-sub-priorities. Figure 11 illustrates this mechanism. Top-level loads refer to the three main loads—critical, essential, and normal—and sub-loads refer to loads such as street lighting or households or hospitals, and super-sub-loads are the smallest loads such as fans, intensive care units, or refrigerators. Some super-sub-loads may be independent, for example, power supplies for communication devices or a transformer (if required).

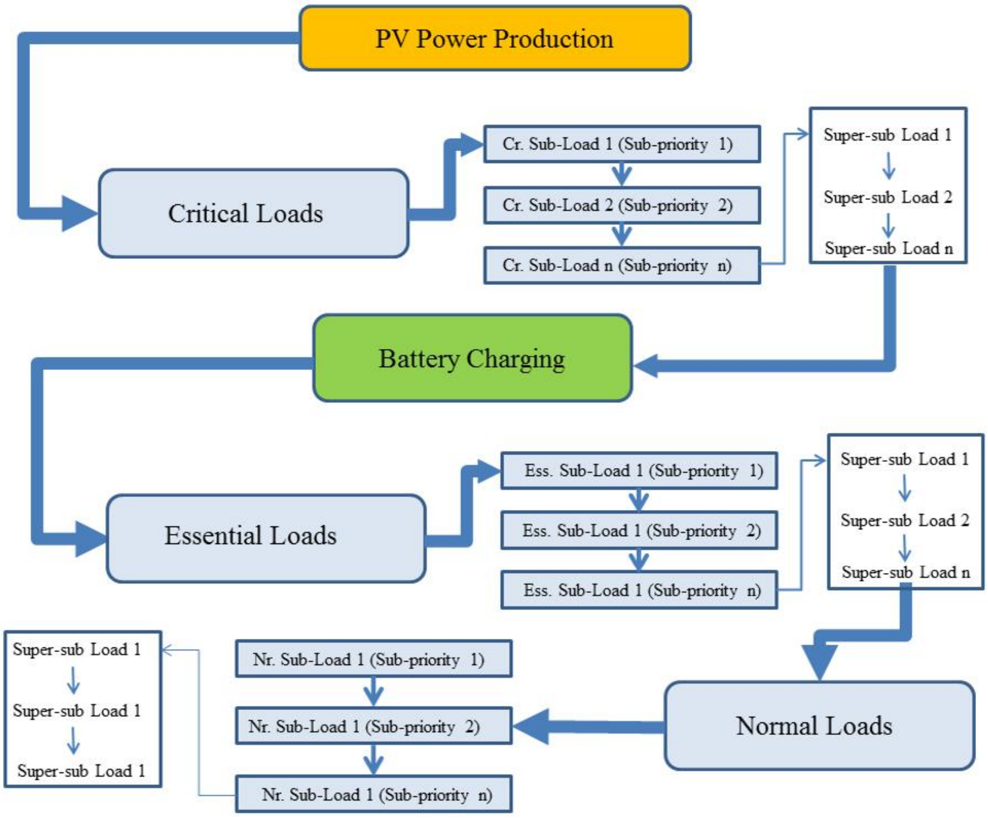


Figure 11: Load prioritization flow. The proposed EMS uses this mechanism during subnormal situations or emergencies to maintain power supply to at least *some* loads.

In this thesis, it is proposed that the main control algorithm handles the top priorities and the sub-priorities related to each sub-level load, but the load converter of each sub-load handles the super-sub-priorities (Fig. 12). This distributed control (“master-slave”) approach simplifies the control mechanism and reduces the burden on the main algorithm. Note that even if the load converter does not have provisions for intelligent computing, it is not problematic to integrate the priority-assigning algorithm into the main one.

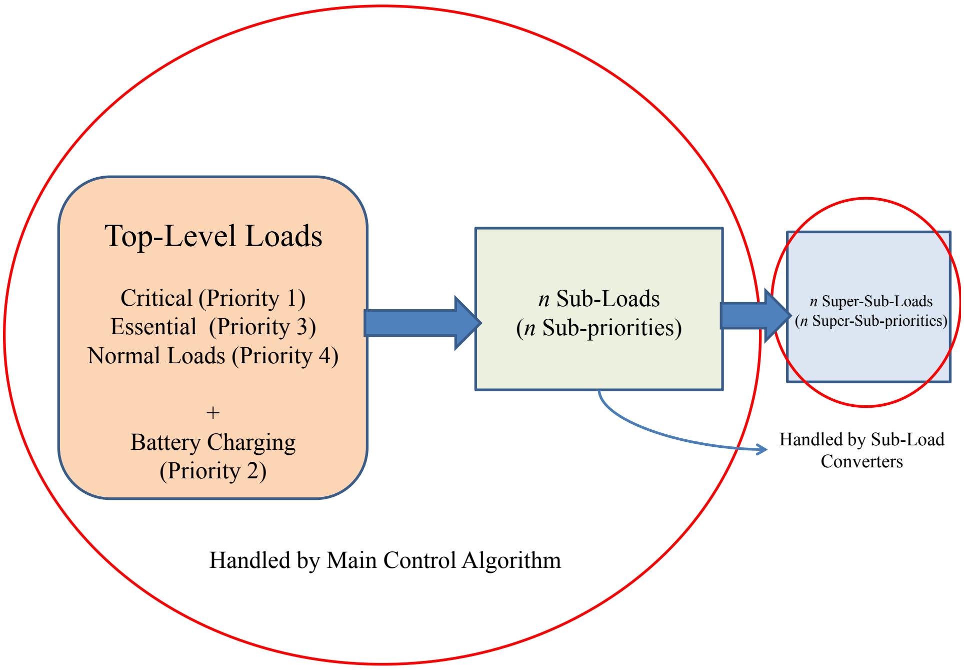


Figure 12: Load prioritization handling: the main control algorithm handles the top- and sub-level prioritizations, while each load converter handles its internal prioritizations. This simplifies the control and reduces the computational burden on the main algorithm.

Finally, each and every individual load prioritization must be input into the EMS before the operations begin. Typically, this should be done by the network operator on the basis of customer requirements, location-related issues, and technical or other constraints.

4.5 Information and communication technology (ICT) systems

4.5.1 Roles and requirements

ICT systems play a critical role in ensuring smooth control and efficient power and energy balancing of the network. The master-slave method employed in this thesis for power balancing is based on high-speed information transfers, especially during subnormal situations and emergencies. In particular, the ICT infrastructure must enable information and control commands from various parts of the network to be collected and transmitted quickly and reliably. Many previous researches have investigated communication requirements, especially for managing grid-connected microgrids during their islanding operations (Ding et al., 2009; Llaria et al., 2011; Calderaro et al., 2008) and have given useful suggestions; Ding et al. (2009), for example, suggested that the operation of microgrids should be implemented by the cooperation of various controllers. In addition, they have also recognized that the reliability and speed of ICT must be high during the operational control and energy management.

In this thesis, the existence of high-speed and reliable ICT infrastructure is assumed. Hence, in this section, only the aspects of communication that are relevant to the optimal functioning of the EMS is discussed. In addition, some remarks are made on the potential communication structure that will enable smoother distribution of information as well as control signals.

4.5.2 Information and control signals

In the network, the ICT system has two roles: (1) It must supply certain information to the control algorithm for its calculations, and (2) It must supply the appropriate control signals to various parts of the network. Further, in all the operations, speed and reliability are essential. The nature of the information required is listed in Tables 2–3. Note that information regarding power is strictly not required, since it can be easily calculated by the control algorithm from the current; nevertheless, it has been included for clarity.

Table 2: Input parameters required constantly by the control algorithm for its operations.

	Parameters Input to Control Algorithm			
PV converter	Voltage	Current	Power	–
Battery converter	Voltage	Current	SOC	SOH
Load converter	Voltage	Current	Power	–

Table 3: Output parameters sent constantly by the control algorithm.

	Control Signals			
PV converter	Switchoff	Constrained	Load Supply	–
Battery converter	Charge	Limited Charge	Discharge	SwitchOff
Load converter	Disconnect	Connect	–	–

An important question to consider is how quickly must these information interchanges happen. The basis for a solution is the requirement that the communication from production, storage, and load must arrive *simultaneously*; this is important because the calculations depend on all three information, and data arriving at separate times will lead to mixups and errors, and hence, incorrect control signals. Further, the speed of information arrival should not lead to the situation that the control system does not have enough time to perform all the calculations and send control signals. Finally, if the network costing is based on an electricity market, the time can also depend on how often the pricing is updated in the electricity market. In any case, this is an important question that must be addressed in subsequent researches.

4.5.3 ICT architecture

The ICT structure is an important part of the communication network; how should the various communication nodes be arranged for optimum communication? These issues have been considered in another study, but a preliminary idea is to use a master-slave approach wherein a master control delegates some control aspects to various subunits that are located at other parts of the network; these subunits may then delegate further to other subunits. Figure 13 shows the proposed ICT structure. The master control is located centrally and obtains information that is communicated by the local control devices. The local control devices, in turn, have delegated their functions to intelligent electronic devices (IEDs) that gather basic information and supply them to the more central local control. The master and local control may also process the received information before communicating it further. Such an arrangement is advantageous for the following reasons:

1. Even if one part of the network is disrupted, information flow to and from other parts can continue;
2. Communication workload is shared, thereby increasing communication speed;
3. It becomes much easier to detect the location of communication disruption; and
4. Emergencies can be handled better.

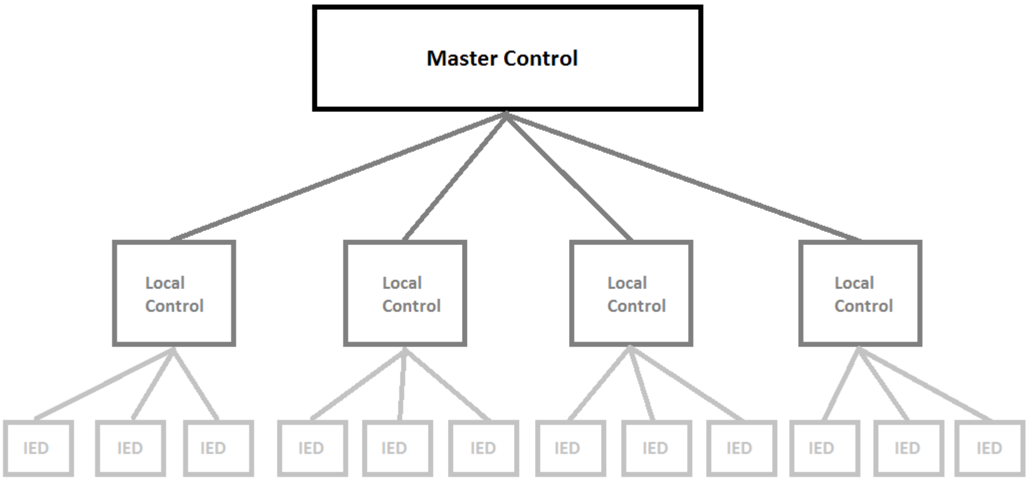


Figure 13: Hierarchy of information and communication technologies (ICT) structure; here, IED refers to intelligent electronic device.

4.6 Conclusions

In this chapter, the essential requirements of any EMS for microgrids were first elucidated and its key features were listed; the discussion was also expanded to include LVDC island network requirements, wherever there was a difference. The basic principles of operations of the proposed EMS were then elucidated. Subsequently, emergencies were introduced and explained in detail along with some approaches to deal with them.

The primary methods used to control the power and energy balance in the network, as well as to achieve voltage regulation, are the optimal control of the PV array power production and battery SOC along with appropriate load disconnections. However, it is important to formulate the logic for performing these actions in a systematic manner. Such a logical basis is presented subsequently in the form of the functionalities and operation modes of the network elements. Depending on the power balance status, these three elements of the network shift to the appropriate operation mode, which ensures both power balance as well as voltage regulation. In this manner, these three primary components can be controlled on the basis of the given paradigm of operations modes. Finally, the importance of ICT systems as well as the communication requirements were elucidated in detail. In addition, an appropriate ICT structure based on the master-slave approach has been proposed.

The proposed EMS was developed on the basis of the operation-mode paradigm, and its algorithm shall be introduced, along with the relevant simulation results, in the next chapter.

5 PROPOSED ENERGY MANAGEMENT SYSTEM

5.1 Introduction

In any electric network, the power production and consumption must be balanced continuously. Several methods have been proposed to achieve power and energy balances in both AC and DC microgrids, and these have been discussed in Chapter 1. In addition, voltage regulation must be performed at the customer end and in the DC bus in order to ensure the standard voltage quality. The network considered in this thesis is an LVDC island network, and hence, only the active components need to be controlled. The master-slave method (Karlsson and Svensson, 2003) has been adopted in this thesis to achieve power balance. In this method, power balance is achieved by controlling the vital elements of the island LVDC system—production, storage, and consumption—and relies on fast communication between the respective converters. The production is dependent on the weather conditions and is highly variable, but it can be controlled; for example, the PV array can be either constrained to produce less power than available, or its power output can be maximized. The consumption behaviour is variable but it can be controlled by prioritization and disconnection. Further, the storage elements can be controlled by sending the appropriate control signals to their converters. In general, the approach is to control the power flow by controlling the charging and discharging of the battery.

In this chapter, first, the various possible network conditions, the corresponding operation modes, and the actions taken to achieve power balance control are described in detail. Subsequently, the algorithm proposed for effective control, which follows the general guidelines given in Chapter 4, is introduced. This algorithm is designed to control the power balance under almost all circumstances. The algorithm was simulated for a sample network, and the results obtained from the simulations are presented and discussed. Finally, the chapter is concluded with a discussion on the methodology by which the algorithm can be extended to larger networks.

5.2 Power balance

In this island LVDC network, power balancing is performed at regular time intervals by collecting production, storage, and consumption data and making the appropriate decisions. Further, voltage regulation is performed based on the information from load converters. To perform these controls, two types of operations have been defined depending on the status of the network: *Normal* and *Subnormal* operations. The conditions that lead to the normal and subnormal operations as well as the control signals and responses determined by the algorithm are explained in the next section.

5.2.1 Normal operations

Normal operations refer to the network control setting when the power production and storage statuses are ideal—either the appropriately sized PV array, the battery, or both together are capable of supplying the loads. In the ideal case, the PV array can not only meet the load demand but also the battery charging requirements, if any, whereas, in the non-ideal case, the battery assists the PV array to meet the load demand, being allowed to discharge until the minimum limit. The battery SOC is required to remain in the following range: *Minimum SOC* $\leq$ *Battery SOC* $\leq$ *Maximum SOC*; in other words, when the battery goes into *Discharge Mode*, the discharging can happen only till *minimum SOC* is reached. In addition, the load demand for that time interval cannot be greater than the power that can be supplied by the battery, which is limited by the discharge rate (this can happen due to undersizing); in other words, the battery's discharge rate must allow sufficient power to be supplied to meet the load demand.

The control algorithm must first verify the following three conditions at the beginning of each iteration:

1. Is there enough power in the PV array, battery, or their combination, to meet the total load demand?
2. Will the battery SOC after the discharge be within the acceptable range ($>$ *Minimum SOC*)?
3. Is the battery's discharge rate able to meet the required load demand?

If these three conditions are satisfied, the network can be said to be operating *normally*. Further, on the basis of the PV power production status, two operation modes have been defined—*Optimal-Operation Mode* and *Sub-Optimal-Operation Mode*—in this study as follows:

1. *Optimal-Operation Mode:* PV production alone is sufficient to meet the load demand AND to charge the battery completely[1] (if required; charging, however, may not necessarily be at the maximum charge rate.).
2. *Sub-Optimal-Operation Mode:* PV production alone is *not* sufficient to meet the load demand AND to charge battery completely (if required)[2]. Note that, nevertheless, PV production + battery discharge ($SOC > SOC_{min}$) is sufficient to meet the load demand and, maybe, to at least partially charge the battery.

In both these modes, certain conditions must be checked, and actions must be performed on the basis of certain conditions and statuses. These conditions and actions are described below and also listed, for convenience, in Table 4.

Optimal-Operation Mode

1. Battery SOC is at its maximum limit: the PV array goes into *Load Supply Mode* and the battery goes into *SwitchOff Mode*.
2. Battery SOC is less than its maximum limit and PV production can charge the battery at the maximum charge rate: the PV array goes into *Load Supply Mode* and the battery goes into *Charge Mode*.[3]
3. Battery SOC is less than its maximum limit but PV production can charge battery only at charge rates lower than the maximum charge rate: the PV array goes into *Load Supply Mode* and the battery goes into *Limited Charge Mode*.

SubOptimal-Operation Mode

1. There is some PV production and it is sufficient to meet load demand but not to charge battery completely: the PV array goes into *Load Supply Mode* and battery goes into *Limited Charge Mode*.
2. There is some PV production but it is insufficient to meet load demand, and of course to charge battery as well: the PV array goes into *Limited Load Supply Mode* and battery goes into *Discharge Mode*.[4]

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[1] This corresponds to the abovementioned ideal case.

[2] This corresponds to the abovementioned non-ideal case.

[3] During normal operations and *Charge Mode*, the charging stops when the *maximum SOC* is reached.

[4] The discharging can happen only till *minimum possible SOC*.

3. There is no PV production: the PV array goes into *SwitchOff Mode* and battery goes into *Discharge Mode*.

Table 4: Normal Operations

Normal Operations	**PV**	**Operation Sub-type**	**SOC**	**PV Mode**	**Battery Mode**
$PV + Battery =$ $Load + Losses$	$= Battery + Load$	Optimal Normal	*max*	*Load Supply*	*SwitchOff*
			$min \leq SOC < max$	*Load Supply*	*Charge*
			$min \leq SOC < max$	*Load Supply*	*Limited Charge*
	$\neq Battery + Load$ $PV > 0$	Sub-Optimal Normal	$min < SOC \leq max$	*Load Supply*	*Limited Charge*
			$min < SOC \leq max$	*Limited Load Supply*	*Discharge*
	$\neq Battery + Load$ $PV = 0$		$min < SOC \leq max$	*Switchoff*	*Discharge*
$PV + Battery$ $\neq Load + Losses$	$\neq Battery + Load$ $PV > 0$	Emergency	*min*	—	—
	$\neq Battery + Load$ $PV = 0$		*min*	—	—

5.2.2 Subnormal operations

Fundamentally, the network is considered to be operating in the Subnormal setting either when the total load demand is not met, or if the battery is forced to cycle deeper than normal, that is, $SOC \leq Minimum\ SOC$. This can happen for a variety of reasons: neither the PV array nor the battery, singly or in combination, may be able to supply all the loads; or the network or power production may be disrupted in some manner; or the battery may have been cycled for too long in the previous time periods. Emergency situations are a typical reason for subnormal operations; their nature, impacts, and some resolutions have been discussed previously in Chapter 4. During subnormal operations, typically, the PV power production is zero (night) or insignificant (dawn or dusk or cloud cover); the battery SOC is too low; or, the battery's discharge rate is too small to meet the load demand in that time period. In addition, such situations can occur even when the PV power production and battery SOC are high, if the load demand is abnormally high, although this would mostly be a consequence of poor sizing.

In this case, the control algorithm does not have to verify any conditions at the beginning of each hour; quite simply, if the abovementioned conditions for normal operations (Section 5.2.1) are not met, the network operations revert to subnormal setting. Load prioritization is a key tool used for power balancing during subnormal operations and must be done carefully before the network operations begin; moreover, the control depends on fast load connections and disconnections, and the ICT systems must be able to handle this requirement capably. Once the subnormal operations have begun, several scenarios have to be considered. Note that the battery SOC will now remain in the following range: $Least\ Possible\ SOC \leq Battery\ SOC \leq$

$Maximum\ SOC$; hence, when the battery goes into *Discharge Mode*, the discharging will happen only till the *least possible SOC* is reached.

Unlike the case of normal operations, both the PV production and battery SOC statuses are used to define the two operation modes—*Optimal-Operation Mode* and *Sub-Optimal-Operation Mode*.

1. *Optimal-Operation Mode:* PV array and battery, singly or together, can meet the total load demand, but only if battery is cycled to below the minimum limit to the least possible limit; hence, $Least\ Possible\ SOC \leq Battery\ SOC \leq Minimum\ SOC$.
2. *Emergency-Operation Mode:* PV array and battery, singly or together, cannot meet the total load demand, even if battery is cycled deeply, and some loads have to be disconnected. $Least\ Possible\ SOC \leq Battery\ SOC \leq Maximum\ SOC$.

As in the case of normal operations, both these modes have several scenarios and actions that depend on certain conditions. These conditions and actions are described below and also listed, for convenience, in Tables 5–6.

Optimal-Operation Mode (Table 5)

1. There is some PV production: the PV array goes into *Limited Load Supply Mode* and battery goes into *Discharge Mode*.
2. There is no PV production: the PV array goes into *Switchoff Mode* and battery goes into *Discharge Mode*.

Table 5: Optimal-Operation Mode during Emergency Operations.

Optimal-Operation Mode (Subnormal)	**PV Mode**	**Battery Mode**	**SOC**	**Load Mode**
$PV + Battery = Total\ Load$	*Limited Load Supply* ($PV > 0$)	Discharge	$least \leq SOC < min$	All Loads
	$SwitchOff(PV = 0)$	Discharge	$least \leq SOC < min$	All Loads

Emergency-Operation Mode (Table 6)

1. There is some PV production: PV array goes into *Limited Load Supply Mode* and battery goes into *Discharge or Limited Discharge Mode* depending on its status (Table 6).

(a) *Critical Loads*:

  i. *Limited CL (LCL) Mode*: Only some critical loads can be supplied.
  ii. *Critical Loads (CL) Mode:* All critical loads can be supplied.
  iii. *Critical-Battery Load (CB) Mode*: All critical loads can be supplied power, and if $SOC < SOC_{min}$, battery is charged preferentially over supplying essential loads.

(b) *Critical and Essential Loads*:

  i. *Limited Critical-Essential Load (LCEL) Mode*: All critical loads and some essential loads can be supplied.
  ii. *Critical-Essential Loads (CEL) Mode*: All critical loads and all essential loads can be supplied.

(c) *Critical, Essential, and Normal Loads*:

  i. *Limited Critical-Essential-Normal Load (LCENL) Mode*: All critical and essential loads can be supplied power, but, battery goes into *Limited Discharge* mode if $SOC < SOC_{min}$ (as before).
  ii. *Limited Critical-Essential-Normal Load (LCENL) Mode*: All critical loads and essential loads and some normal loads can be supplied power.

Table 6: SubOptimal-Operation Mode during Emergencies with PV power. CL: Critical Loads; LCL: Limited CL; CEL: Critical-Essential Loads; LCEL: Limited CEL; LCENL: Limited Critical-Essential-Normal Loads.

Emergency-Operation Mode (Subnormal)	**PV Mode**	**Conditions**	**Load Mode**	**Battery Mode**
$PV + Battery \neq Total\ Load$	*Limited Load Supply* ($PV > 0$ *or* $PV = 0$)	$PV + Battery < Critical\ Loads$	*LCL*	*Discharge*
		$PV + Battery = Critical\ Loads$	*CL*	*Discharge*
		$PV + Battery < (Critical\ + Essential)\ Loads$ $SOC < SOC_{min}$	*CB*	*Charge (may be Limited)*
		$PV + Battery < (Critical\ + Essential)\ Loads$ $SOC \geq SOC_{min}$	*LCEL*	*Discharge (may be Limited)*
		$PV + Battery = (Critical\ + Essential)\ Loads$ $SOC \geq SOC_{min}$	*CEL*	*Discharge (may be Limited)*
		$PV + Battery < (Critical\ + Essential...$ $... + Normal)\ Loads$ $SOC \geq SOC_{min}$	*LCENL*	*Discharge*

2. There is no PV power production: The modes and operations are exactly as before, except that the PV array is now in *SwitchOff* mode.

It is important to note that charging the battery to at least SOC_{min} is given higher priority than the CEL and CENL modes; in other words, battery charging is assumed to be more important than supplying essential or normal loads (for more on this, refer Section 4.4.3 and Fig. 11).

5.2.3 Algorithm

In practice, the software is supplied data from battery, PV, and converters at regular intervals (see Section 4.5 on Communications). It then calculates fresh information and sends the appropriate control signals accordingly. Moreover, some data must be entered into the software before the network operations begin.

User-input data

Before Operations

Required network voltage level V_{nw} V; Required DC load voltage $V_{L(dc)}$ V; Required AC load voltage $V_{L(ac)}$ V; Number of Critical Loads, $Loads_C$; Priorities for each Critical Load, $Pr_{C1} - Pr_{CLoads_C}$; Number of Essential Loads, $Loads_E$; Priorities for each Essential Load, $Pr_{CE1} - Pr_{CLoads_{E1}}$; Number of Normal Loads, $Loads_N$; Priorities for each Normal Load, $Pr_{N1} - Pr_{NLoads_N}$; Time interval t; Minimum SOC SOC_{min} %; Maximum SOC SOC_{max} %; Least Possible Battery SOC SOC_{least}

During Operations

PV array power and voltage, SOC[5], Battery current and voltage, Load power and voltage (from all loads)

Methodology The algorithm first checks the voltages from all the loads and verifies if the voltages are regulated with the acceptable limits (±10%, typically). If any load, or loads, requires voltage regulation, the required power to regulate the voltage is added to the load demand of that load. Subsequently, the SOC and power production statuses are verified. Depending on these statuses and the type of load that requires the voltage regulation, the algorithm makes a decision to supply more power from the battery, constrain PV production, or to disable the loads.

Note that for voltage regulation, the power reference would be obtained by the following calculation:

---

[5] This algorithm does not consider SOH and DOD presently, but they should be considered in the future.

$$Power = (Acceptable\,Voltage - Current\,Voltage) \times Current$$

Moreover, it may not be possible to supply the entire required power immediately because it will be limited by the weather conditions and battery discharge rate.

Algorithm Preliminary

1. Obtain all user-input data
2. Determine total emergency, priority, and normal loads, and total loads.
3. Assign appropriate priorities.
4. Begin operations.
5. Receive data from converters.
6. Check all voltages. Does any (or many) load(s) need to be regulated?
    (a) If yes,
        i. VoltageFlag = 1. Note the loads that need to be regulated, including their priorities and type (AC/DC).
        ii. Add required power to the load that needs to be regulated and the total load demand.
    (b) If no, VoltageFlag = 0.
7. Check the following conditions:
    (a) Is total power production (PV Power Production + Battery) >= than Total Load Demand (Load Demand + Losses)?
    (b) If some load demand needs to be met by battery discharge, can the battery discharge meet it?
    (c) Will meeting the load demand reduce the SOC to less than SOC_{min}?
8. If all the answers to (7) are Yes, *Normal Operations*. If No, *Subnormal Operations*.

Normal operations

1. *Condition 1*: If (PV Power Production$\geq$ Total Load Demand) and (Current SOC = Maximum SOC)
    (a) Control Signal: SwitchOff Battery!
    (b) Control Signal: Supply Load from PV!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s). Power = (Acceptable Voltage - Current Voltage) $\times$ Current.
2. *Condition 2*: If (PV Power Production$\geq$ Total Load Demand) and (Current SOC < Maximum SOC)
    (a) Control Signal: Charge Battery!
    (b) Control Signal: Supply Load from PV!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s). Power = (Acceptable Voltage - Current Voltage) $\times$ Current.
3. *Condition 3*: If (PV Power Production$\geq$ Total Load Demand) and (Current SOC < Maximum SOC) and (Discharge Rate < Maximum Discharge Rate)
    (a) Control Signal: Limited Charge Battery!
    (b) Control Signal: Supply Load from PV!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s). Power = (Acceptable Voltage - Current Voltage) \times Current.
4. *Condition 4*: If (PV Power Production $\geq$ Total Load Demand) and (Current SOC $\leq$ Maximum SOC)
    (a) Control Signal: Limited Charge Battery!
    (b) Control Signal: Supply Load from PV!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s).
5. *Condition 5*: If (PV Power Production < Total Load Demand) and (Current SOC $\leq$ Maximum SOC)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: Limited Load Supply Mode!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s).

6. *Condition 6*: If (PV Power Production = Total Load Demand) and (Current SOC $\leq$ Maximum SOC)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: SwitchOff Mode!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s).

Subnormal operations (PV Power Production < Total Load Demand)

1. *Condition 1*: If (PV Power Production + Battery > Total Load Demand) and ($SOC_{least} \leq SOC_{now} \leq SOC_{min}$)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: Supply Load from PV!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s).
2. *Condition 2*: If (PV Power Production = 0 and Battery > Total Load Demand) and ($SOC_{least} \leq SOC_{now} \leq SOC_{min}$)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: SwitchOff!
    (c) If VoltageFlag = 1, Supply appropriate power to the required load(s).
3. *Condition* 3: If (PV Power Production + Battery < Critical Loads) and ($SOC_{least} \leq SOC_{now} < SOC_{min}$)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: Limited Load Supply: Some Critical Loads!
        i. Assign Critical Loads according to priority.
    (c) If VoltageFlag = 1, Supply appropriate power to only some critical load(s) in order of priority.
4. *Condition 4*: If (PV Power Production + Battery = Critical Loads) and ($SOC_{least} \leq SOC_{now} < SOC_{min}$)
    (a) Control Signal: Discharge Battery!
    (b) Control Signal: Limited Load Supply: All Critical Loads!

   (c) If VoltageFlag = 1, Supply appropriate power to as many critical load(s) as possible in order of priority.

5. *Condition* 5: If (PV Power Production + Battery < Critical + Essential Loads) and ($SOC_{least} \leq SOC_{now} < SOC_{min}$)
   (a) Control Signal: Limited Charge Battery!
   (b) Control Signal: Limited Load Supply: All Critical Loads!
   (c) If VoltageFlag = 1, Supply appropriate power to only critical load(s) in order of priority.

6. *Condition 6*: If (PV Power Production + Battery < Critical + Essential Loads)
   (a) Control Signal: Discharge Battery!
   (b) Control Signal: Limited Load Supply: All Critical Loads and Some Essential Loads!
      i. Assign Essential Loads according to priority
   (c) If VoltageFlag = 1, Supply appropriate power to all critical load(s) and as many essential loads as possible in order of priority.

7. *Condition* 7: If (PV Power Production + Battery = Critical + Essential Loads)
   (a) Control Signal: Discharge Battery!
   (b) Control Signal: Limited Load Supply: All Critical and Essential Loads!
   (c) If VoltageFlag = 1, Supply appropriate power to all critical load(s) and as many essential loads as possible in order of priority.

8. *Condition* 8: If (PV Power Production + Battery < Critical + Essential + Normal Loads)
   (a) Control Signal: Discharge Battery!
   (b) Control Signal: Limited Load Supply: All Critical and Essential Loads and Some Normal Loads!
   (c) If VoltageFlag = 1, Supply appropriate power to all critical and essential load(s) and as many normal loads as possible in order of priority.

9. Iterate for next loop.

5.3 Energy balance

Energy balancing follows exactly the same principles mentioned above, but the energy balance is verified over larger time intervals, typically days. In addition, the approach is to use forecasted load and production data and make preliminary adjustments to the supply statuses, control signals, and information to the user. Only a few tweaks need to be made to revise the above algorithm to include energy balancing, and hence, the methodology has not been included in detail. Energy balancing algorithms that will include forecasting will be investigated and written in the future.

5.4 Results and discussion

Normal operations The simulations were conducted using the following data. The total number of customer connections = 20; this was divided into 1 Critical Load, 8 Essential Loads, and 11 Normal Loads. The peak power of the customers = 800 W. A section of the network used for the simulations is shown in Fig. 14.

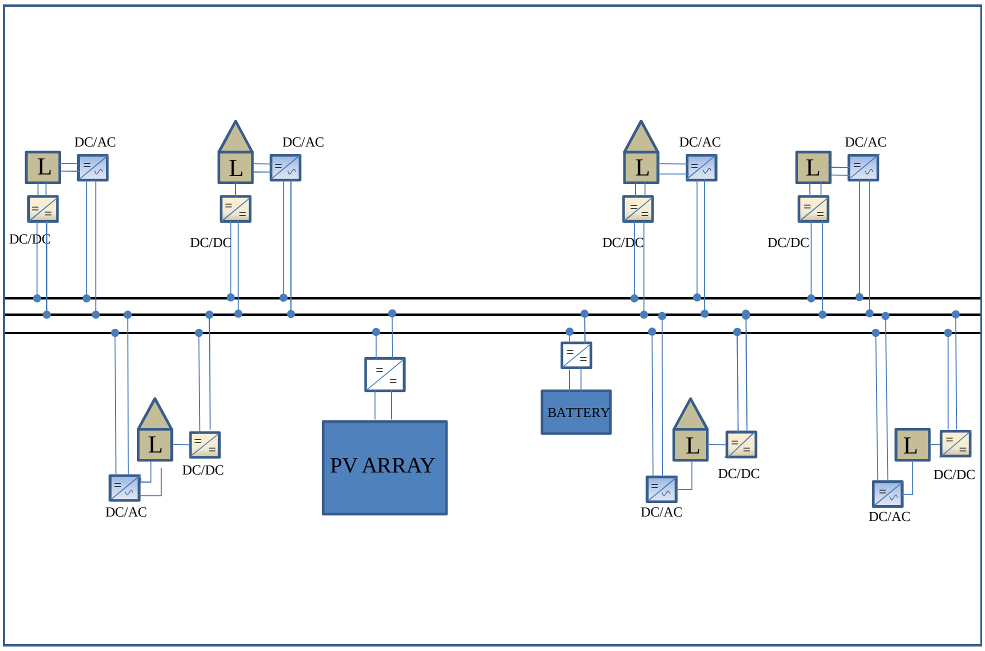

Figure 14: Sample network for simulations.

The load profile was taken, as mentioned in Section 2.3.3, from a Finnish customer's load profile. The same load profile was used for all types of loads; this is a restriction, since, in practice, the load profiles for different loads would be different. The solar irradiation data was taken for 60° latitude using the SoDa service in the manner mentioned in Section 2.1.3.

The remaining input parameters are listed as follows:

Network Voltage = 750 V; Time interval = 100 ms; PV array size = 500 kW; Battery capacity = 600 Ah $(450\ kWh)$ = Maximum SOC; Minimum SOC = 70% ; Least Possible SOC = 50%; Maximum Charge Rate = C/10 = Minimum Charge Rate.

Under these conditions, the network operated normally, and no load disconnections or prioritizations were required. Power and energy balancing and voltage regulation were performed without any production problems. Figure 15 shows the simulation results for a period of 100 ms. The PV power production, total load demand, and battery SOC statuses are illustrated in the figure. In this figure, the PV production is deliberately reduced to zero and then increased at random intervals in order to demonstrate the battery SOC response; in practice, 100 ms is too short a time for such drastic variations, which would, instead, typically occur through the day. The battery SOC is given as a percentage of the battery capacity.

The figure shows that the PV power production is sufficient to charge the battery as well as to meet the load demand during some periods. The battery SOC is charged and increases to 100% when there is PV power production. When the PV power production is low (or nil) and unable to meet the load demand, the battery is discharged to SOC_{min}—70%—which is one of the criteria for normal operations. Note that there are some situations where the PV power is more than total load demand as well as battery charging requirements. In these cases, the PV production is constrained for power balancing.

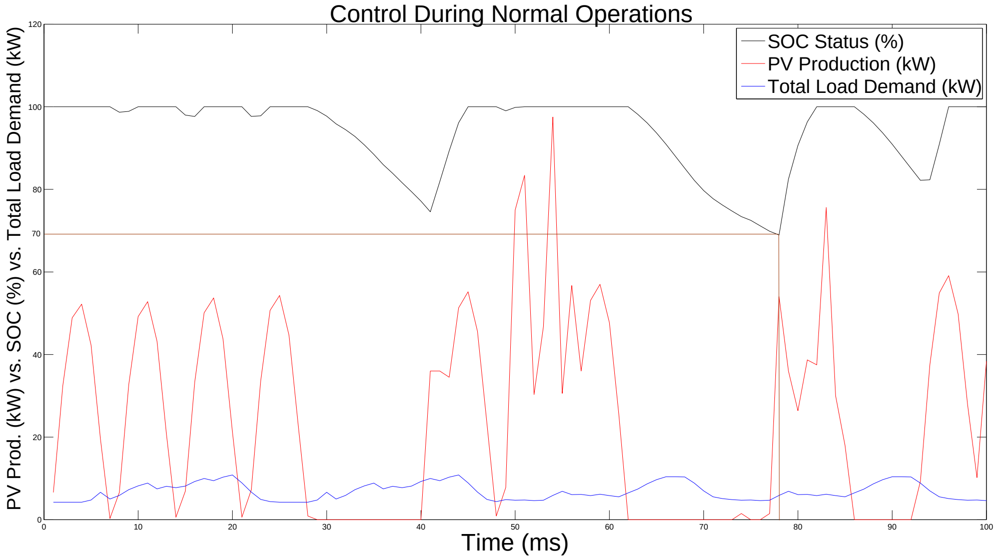

Figure 15: Power balancing during normal operations. PV production, SOC statuses, and total load demand are shown. Note that the PV power production is deliberately reduced to zero and increased at random intervals; in practice, 100 ms is too short a time for such drastic variations (they would, instead, occur through the day).

Figure 16 shows the voltage regulation during the normal operations. In LVDC networks, acceptable voltages are approximately $\pm 10\%$ of the network voltage, and the voltage should not be allowed to increase or decrease beyond these levels. Note that in the proposed algorithm, the allowed range is an input by the network operator (since the regulations may be different across the world.) In order to demonstrate voltage regulation, random voltages were generated from one part of the network; most of these voltages were maintained close to the network voltage of 750 V, but some voltages were allowed to be outside the range $[750 - 10\% \times 750 \;\; 750 + 10\% \times 750] = [675 \;\; 825]$. The randomly generated input voltages are shown in Fig. 16 as a red line. In the figure, the blue line shows the regulated voltages. The figure clearly shows that the voltages outside the allowed limit are regulated and the LVDC standards for voltage regulation are met.

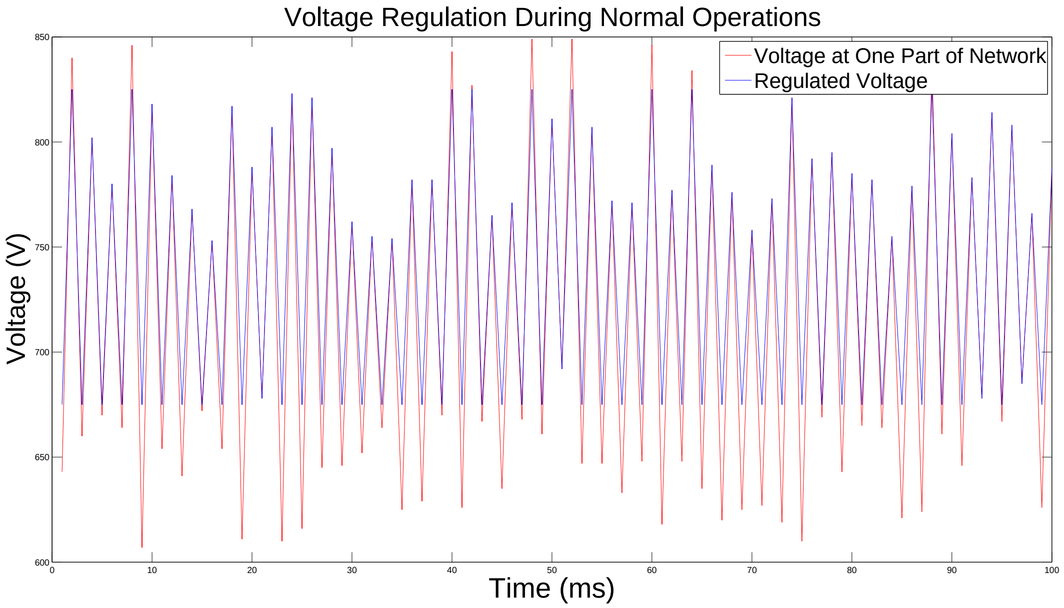

Figure 16: Voltage regulation during normal operations. The red line represents randomly generated voltages some of which are forced to be outside the allowed limits ($[750-10\%\times750\ \ 750+10\%\times750]=[675\ \ 825]$). The blue line represents regulated voltages.

SubNormal operations In order to force the network to operate subnormally, the battery capacity was reduced to 300 Ah ($225\ kWh$) and the PV array size was reduced to 300 kW. Moreover, the number of critical loads was increased to 3 and the number of essential loads was reduced to 11. The simulations were conducted again. The results are shown in Fig. 17.

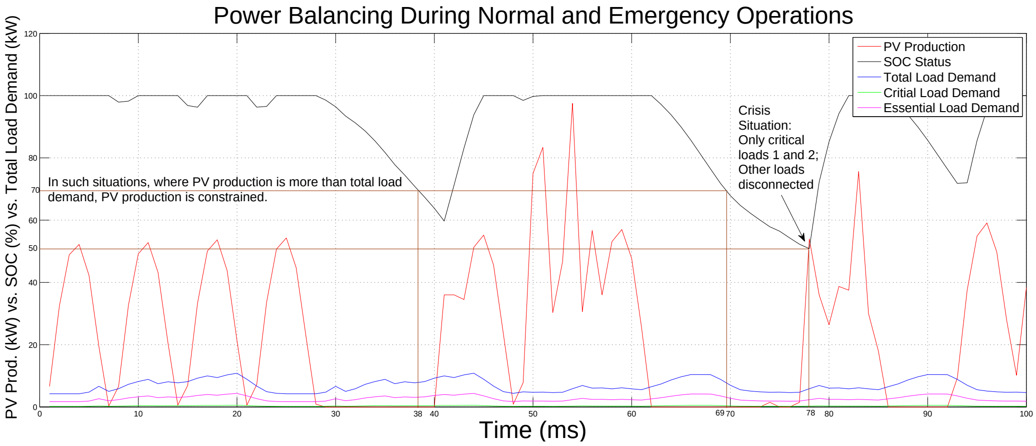

Figure 17: Power balancing during normal and subnormal conditions. Note that battery SOC now decreases to almost 50%, i.e., the battery is forced to cycle much deeper. Moreover, not all load demands are met when the battery SOC is close to 50%. The arrow points to crisis situations where only Critical Loads 1 and 2 are connected and the other loads are disconnected.

In this figure, it is noticeable that the battery SOC is now cycling to 50% capacity during some periods (SOC_{least}). The network operates normally till 38 *ms*, but now, the power available is too low and the battery is forced to cycle deeper, up to 60%. However, the PV production increases suddenly, and the battery is able to quickly recharge back. When the time reaches 69 *ms*, the situation is worse. Suddenly, there is no PV production for a long time (63–77 ms), and the battery is forced to start cycling deeper and deeper from 70% all the way to almost 50%. The battery is restricted from cycling below 50% and there is no PV power; clearly, the available power cannot meet all loads. The control algorithm sends signals to disconnect all the loads, and only critical loads 1 and 2 are supplied power (Critical load 3 has lowest priority). Luckily, at this time, the PV power production has restarted. This means that all other loads can be reconnected in the order of prioritization. From the figure, the battery SOC now begins to increase and reaches 100% again; the emergency situation has passed and normal operations can begin again. Note that there are some situations where the PV power is more than total load demand as well as battery charging requirements. In these cases, the PV production is constrained.

In all these calculations, the peak power of a single customer has been considered to be 800 W. This may, however, be higher in other circumstances. Higher peak power would imply that the load demand is higher. As a result, there could be more losses of power supplies in more parts of the network, which may have to be accounted for in some manner, maybe by increasing the sizes of the PV array and/or battery or by changing the number of service hours guaranteed to the customer.

5.5 Application to larger networks

This algorithm can be applied to larger networks with more customers by using a master controller and many local controllers. The basic idea is to implement many local control algorithms at various parts of the network, rather than having one big algorithm that controls all the information. These local controllers handle the individual power balancing and voltage regulations and report their statuses to a master controller which verifies the information that all the situations are normal. In the case of emergencies, the responsibility of the master controller increases and it may have to take more decisions, for example, to prioritize and disconnect the load. Such a master-slave approach is similar to the ICT architecture proposed in Section 4.5.

The algorithms presented in this thesis primarily deal with power and energy balances. Hence, the algorithm considers power consumption by the loads at a general level and does not address internal voltage or current requirements/variations within the load unit; it is assumed that the load converters will ensure required voltage regulation within the load unit itself and will communicate power consumption details on a regular basis to the main control algorithm. For example, if a household has many loads such as lighting, fan, and refrigerators, the control algorithm requires information regarding the total load demand of all these loads; individual loads are then assumed to be distributed, controlled, and regulated by the load converter. This decision affects the nature of prioritization, which will be discussed in a subsequent chapter, but it simplifies the control algorithm and also makes it possible to expand the network more easily.

5.6 Limitations and future studies

The successful operations and efficiency of the control and sizing algorithms proposed in this thesis have been demonstrated by simulations and results. The results clearly demonstrate that the LVDC network can be reasonably well controlled as well as sized using the outlined strategies. Power and energy balancing were achieved along with voltage regulation under all the circumstances considered. Nevertheless, several challenges still remain, and the algorithm and methodology can be improved in many ways.

The control is not perfect because forecasted data have not been considered for both the control operations and for simulations; the application of forecasted data will be investigated thoroughly in the future. In the control algorithm, load prioritization has not been assumed in the case of normal operations, but this could be assumed in order to charge the battery quickly; this can be important in circumstances where the battery needs to be charged really quickly. Since it may often be beneficial to prioritize the fast charging of the battery over some loads, the concept of *expendable* loads can be examined in a future study.

The algorithms presented here for the power balance control are based on technical control; in other words, the parameters being varied or changed are basically technical in nature. Another higher-level control has been proposed previously: *price-based control*. In price-based control, the customer's energy consumption is regulated by using price as the instrument of control. This is some kind of demand-side management in which the load consumption and load prioritization can be controlled by incentivizing the use of some loads and the non-use of some loads at certain times of the day. For example, Shevchuk (2012) has suggested that as soon as there is solar activity, consumption can be decreased and battery charged rapidly; this would prolong the battery life. In addition, load prioritization during emergencies can be achieved by incentivization. Further research is required, especially in the case of the control aspect of the energy management system. In particular, as discussed previously, price can be used as an instrument of control. However, this is dependent on the development of an "electricity market". In island LVDC networks, it is important and practically inevitable to have a good pricing mechanism and a smoothly functioning electricity market. Many researchers have argued that demand response should be used for electricity pricing in electricity markets in general. In future investigations, such a pricing mechanism could be developed and linked to control by giving incentives for load consumption.

A network comprising 20 customers has been considered in the simulations. This somewhat arbitrary figure is only for simplicity and does not severely restrict the control or sizing accuracies since larger networks would only require scaling up and expansion. The methodology for the network expansion has been suggested in Section 5.5; however, the ideas are preliminary and control and other issues—such as protection and load dispatch—must be explored in greater detail in a future study with more in-depth analyses. For example, in very large networks, the concept of load shedding—disconnection of entire areas—may be more critical than individual load disconnections. The necessity, implications, and consequences of such important emergency responses should be examined in detail in the future.

The typical peak power of a single customer connection is specified to be approximately 200 W in the beginning. Further, it is assumed to grow to around 800 W within a few years. This implies load growth which should, ideally, be considered in the network calculations, especially in the case of cost or loss analysis. Load growth, related cost parameters (such as interest and annuity), and other factors have been neglected in this thesis. The typical peak power of a single customer has been assumed to be 800 W in all the analyses. This may lead to overestimations, for example in the case of sizing, and load growth must be factored before actual practical implementation. Moreover, the same load profile was used for all types of loads; this is a restriction, since, in practice, the load profiles for different loads would be different.

Solar irradiation data is required and even critical in this thesis for planning, analyzing, controlling, and optimizing the PV-based system. Further, the more accurate the solar irradiation data, the more accurate the results. In all the simulations, illustrations, and examples throughout this thesis, it is assumed that the solar irradiation data used is accurate and reliable. In other words, the software used for testing assumes that all user-input data are accurate, complete, relevant, and in accordance with the requirements. In other words, no error-checking code for incorrect data has been built so far; this should be done in the future prior to real implementation.

Deep-cycle battery life and capacity are affected by temperature. Batteries perform best in moderate temperatures unlike PV modules that work better at lower temperatures. As a result, it is often preferable to keep batteries indoors rather than leaving them subject to outside temperatures. Moreover, the exact voltage-to-battery-charge correlation is dependent on the battery temperature. Cold batteries will show a lower voltage when full than hot batteries. In this thesis, the effect of temperature on battery performance or life is not considered; however, this may be an important aspect to consider in the future. Most BMSs also indicate the state-of-health (SOH), which is the point that has been reached in the battery's life cycle. It reflects the general condition of a battery and its ability to deliver the specified performance in comparison with a fresh battery (Pop et al., 2008). However, in this thesis, battery life and SOH have not been considered; they should be considered in future studies, especially when planning long-term network operations.

5.7 Conclusions

The supply of uninterrupted electric power remains a challenging problem across the world, especially with increasing consumption and demand. The need for higher reliability has led to demands for more reliable network solutions than the traditional 3-phase AC distribution systems. Technical and economic developments during the last decade, especially in power electronics technology, have given the opportunity to develop competitive distribution systems based on low-voltage DC (LVDC) distributions. Island networks that are completely isolated from the main grid and operate completely independently and co-operatively have been considered for applications to remote areas that do not have electric power transmission and supply. However, islanded operations lead to various economic and technical issues such as power quality, voltage regulation, network stability, harmonics, reliability, protection, and control. Further, environment friendliness is important today, and renewable energy has been considered a viable alternative to conventional fuels. The energy production from renewable energy sources is variable, intermittent, and (usually) at comparatively low voltages, and they are practical for applications to smaller grids with fewer loads, such as microgrids; this also helps in reducing their implementation costs.

In this thesis, an LVDC islanded bipolar network using renewable energy sources has been considered; a PV array supplies the power to typical domestic customer loads, and a battery bank operates as the backup. The PV array uses thin-film technology, and they are connected to the DC mains via a DC/DC converter that is not only able to communicate its power statuses quickly but also receive control commands and act on them reliably.

Solar power causes problems of reliability of power supply, and hence, a lead-acid battery has been used as the backup. The battery can either supply or absorb balance power, depending on the situation. The battery bank is connected to the LVDC bus with DC/DC converters, and it incorporates a management system that communicates the current battery statuses reliably and quickly, while also being able to accept control instructions and perform the required actions. Further, both DC/AC and DC/DC load converters communicate all relevant information from the loads to the control algorithm at regular intervals; the loads are flexible and can be disconnected, if required.

In this manner, this thesis considers a bipolar 750-V LVDC network that is powered by thin-film PV panels with rechargeable lead-acid batteries to supply loads that can be flexible and prioritized, if required. Several challenges remain before the implementation of such an LVDC island network, such as protection, communication, and power balancing. Many studies have proposed and analyzed the applicability of solar power, wind power, other renewable sources, or their combinations to microgrids, and various real-world installations (primarily on-grid) have been implemented across the world. However, Most of these studies have focused on using microgrids as a backup to the main grid and completely islanded operations have rarely been considered due to the variability of the production. This thesis has focused on power and energy balancing and voltage regulation issues of completely islanded LVDC networks. The aim of this thesis was to develop a methodology—an Energy Management System—to control the power and energy balancing and voltage regulation of the network.

In order to design the control algorithm, a method to reasonably size the PV array and battery was first developed. This sizing is important because the EMS can use the obtained values for its preliminary analyses. The developed sizing method was based on DESs, and the proposed algorithm successfully obtained reasonable sizes for PV array and battery under different load and sunlight conditions. Further, the impact of the availability of sunlight hours at various locations was examined using another algorithm. First, a general method to determine the service hours at any location in the world, given accurate solar irradiation data, was proposed and demonstrated. Subsequently, the method was applied to different places located at various latitudes (thus changing the number of hours of sunlight). The algorithm clearly demonstrated the variations in the number of service hours that can be guaranteed to a customer when the network is located at different latitudes.

The proposed EMS is based on the master-slave/communication approach. Therefore, it relies on robust ICT infrastructure; in this thesis, a probable ICT structure has been proposed and the requirements from the ICT have been elucidated. In order to logically establish the principles of EMS operations, this thesis defined functionalities and operation modes of the network elements; these operations modes encompass all possible combinations of supply, storage, and load under all conditions and situations. Using this logical basis as the foundation, these three primary components were controlled on the basis of the given paradigm of operations modes. The EMS functioned by optimally controlling the PV array power production and battery SOC; in addition, the principles of flexible loads, load prioritization, and appropriate load disconnections were used to ensure that at least some loads continue to receive power at all times. The efficiency of the EMS was verified and demonstrated by conducting simulations with a section of the entire network; the EMS successfully and efficiently performed both power and energy balancing as well as voltage regulation.

Nevertheless, some researches that can further improve the EMS are still pending. Forecasts of load consumption are critical data that can be used to optimize the power and energy balancing; they should be incorporated in the future. Price-based demand-side management in which the load consumption and load prioritization can be controlled by giving financial incentives to the customer can be considered. Moreover, network expansion from smaller networks must be examined in greater detail with extensive simulations.

The control algorithm presented here has been developed with the intention of applying it practically to LVDC network implementations in real-time situations. The results presented here are for the Nordic situation since Finnish data has been used for all the analyses. However, the potential for islanded microgrids supplied by PVs will be considerably more in the southern regions, where the winters are not so problematic. Most of the practical implementations are intended to be in and around the tropical regions. In the future, this control algorithm will be implemented in onsite LVDC networks, and its efficiency in real situations will be demonstrated.

Completely islanded microgrids using renewable energy sources present numerous techno-economic challenges such as protection, communication, reliability, and power balance issues. Nevertheless, they are attractive because they can be employed to supply renewable-energy-based pollution-free electric power to isolated or remote locations comprising small loads, such as remote villages that have never received electric power supply. By using such completely islanded microgrids, such places can be supplied electricity in a cost-efficient and effective manner; this has important social benefits since the quality of human life will be improved. This thesis has taken a small but important step toward “replacing the candle” in villages by developing an efficient and robust EMS for LVDC networks.

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