PhD Dissertation

International Doctorate School in Information and Communication Technologies

DISI - University of Trento

DCT ENABLED SMART CONSUMER GRID MODEL

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April 26, 2017

Dedicated to
My parents &
my wife for her support through out my career endeavors
my kids Anaus, Zainab and Hassan

Abstract

Sustainable energy and energy harvesting has become a hot research area due to the shortage of fossil energy resources and burning fossil fuels release greenhouse gases in our environment, which is partaking in gradually increasing of surrounding temperature of our environment. Therefore, the penetration of various types of renewable/ distributed sources, onsite storage devices and DC powered appliances has recently focused attention towards DC power distribution in consumer grids to achieve the target of zero/positive energy buildings and communities. As compared to AC micro grid, many recent studies revealed that DC distribution has many advantages over the convectional AC distribution in term of high efficiency, integration of renewable/ distributed sources and storage locally. The objective of this dissertation is to propose reliable, cost-effective, sustainable, scalable DC consumer grid architecture which can integrate not only renewable/ distributed sources and storage, but also fully compatible with the convectional AC distribution network without any significant change or upgrade. In order to achieve this goal, we proposed the DC Transformer (DCT) enabled consumer grid model. The DC Transformer has been regarded as one of the most emerging technologies and it has many advantages over the convectional low frequency AC transformers such as high power density in small area, voltage regulation, reactive power compensation, fault detection and isolation etc. Apart from advantages, DCT required intelligent control algorithm and additional supervisory circuit makes it complicated and expensive. Therefore, in our proposed model we discussed the pros and cons of typical Solid-State transformer topologies already proposed and explained the topology used in the DCT transformer. Furthermore, in state of the art models, authors used three stages of grid operational modes, which is usually based on different factors such as the status of grid connections, State of charge of Battery storage and output power from locally available sources. However, we introduced four stages excluding buffering stage. All stages are depended upon the practical situations consumer grid may face during normal grid operations such as, DCT Isolation mode, if main grid and local generators are not available then how our proposed model would manage the locally available storage. Main grid interactive mode, we discussed the existing or convectional grid operational condition. In case of no local generator available and the AC main is the only source of power. Self-reliance grid operation, when the renewable energy sources are generating enough energy to fulfil demand side *power requirements. Moreover, we explain the safest transition technique from grid connected mode to self-reliance mode without effecting overall grid stability and reliability, called buffer state. Power sharing mode, in this mode we discussed how the locally consumer grid would share surplus energy with adjacent consumer grids without effecting or compromising its own stability. The purpose of proposing critical operational modes and defining the rigid criteria between transitions of each mode is to operate whole grid flawlessly in any real time condition. Moreover, we introduced Buffer stage in between the grid connected and self-reliance mode to take into account that renewable sources are stochastic in nature and to avoid any grid stability issue. The operational modes are among key techniques of our proposed architecture and the detail contribution of our proposed model is mentioned in section* 1.7.3. *Some practical issues related to the DC micro grid are also examined in detail, such as overall grid control algorithm, power management strategy, demand side management, fault isolation and rectification are highlighted and the solution of these issues also presented with detail simulation results. Furthermore, the state of art DC grid models are proposed for specific type of renewable source(s) such as PV, wind or combination of both. In our proposed architecture, we are not depending on any specific type of renewable and distributed source or storage. We proposed the standard interfaces for possible type of renewable /distributed sources, storage and grid connection. Therefore, by using the standard interface any type of the source and storage can be plug-n-play in PCmRC model. However, the main objectives are to maximize the exploitation of renewable-sources, to decrease reliance on fossil-fuel, to boost the overall efficiency of the grid by reducing the power-conversion losses and full management of end user demand in all possible forms. The simulation platform is designed in MATLAB/Simulink. Several types of case studies and simulation results show the effectiveness of the proposed power distribution and management model.*

Keywords

Home Energy Router (HER), Power Controlling Monitoring and Routing Center (PCmRC), DC transformer (DCT), Microgrid (MG), Distributed Energy Sources (DES), Sustainable Energy Sources (SES), Energy Storage (ES), AC-DC power convertors, DC power transmission, DC-AC power convertors, DC-DC power convertors, circuit breakers, distributed power generation, fuel cells, power generation faults, power generation protection, power transformers, secondary cells, solar cell arrays, wind power plants, AC transformer, AC/DC/AC conversion, DC microgrid protection, DC power system, DC-DC power converter, alternating current, batteries, coupled-inductor DC circuit breaker, coupled-inductor solid-state circuit breaker, direct current, fault protection, fuel cell, long-distance power transmission, solar panel, supply DC voltage, wind power generator, Circuit breakers, Circuit faults, Electricity supply industry, Inductors, Logic gates, Microgrids, Power grids, Switches

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Chapter 1

Introduction

In this chapter, the motivations and objectives of this dissertation would be presented and also describes the state of the art of AC/Hybrid grids architectures, progress in dc distribution and transmission systems, DC microgrids applications and smart energy management systems. A comprehensive review of the power converter topologies used in electrical distribution is provided, with an especial focus on residential consumer low-voltage distribution systems. The key challenges, a literature review and summary of contributions are also provided, followed by the dissertation outline and the scope of research.

1.1 Research background

The energy demand is growing day by day and global economy is fully dependent on the energy resources especially fossil reserves. Fossil fuels such as coal natural gas and petroleum are still the dominant energy resources and due to shrinking reserves the prices of convectional fuels are gradually increasing. On the other hand, renewable energy sources are abundantly available on earth and they are long lasting. The most attracting feature of renewable energy sources is generating complimentary energy without damaging our atmosphere with some initial installation cost. The initial installation cost for the renewable energy sources are reasonably higher than conventional fossil fuel generators but initial investment will be reimbursed depending upon energy utilization. As compared to fossil fuels, there is no shortage of renewable energy because it can be taken from the Sun, wind, water, plants, and garbage. According to the US energy department survey, the amount of sun-ray falls on the United States of America in a single day, containing same amount of energy which whole country utilized in whole year [9, 45, 132].

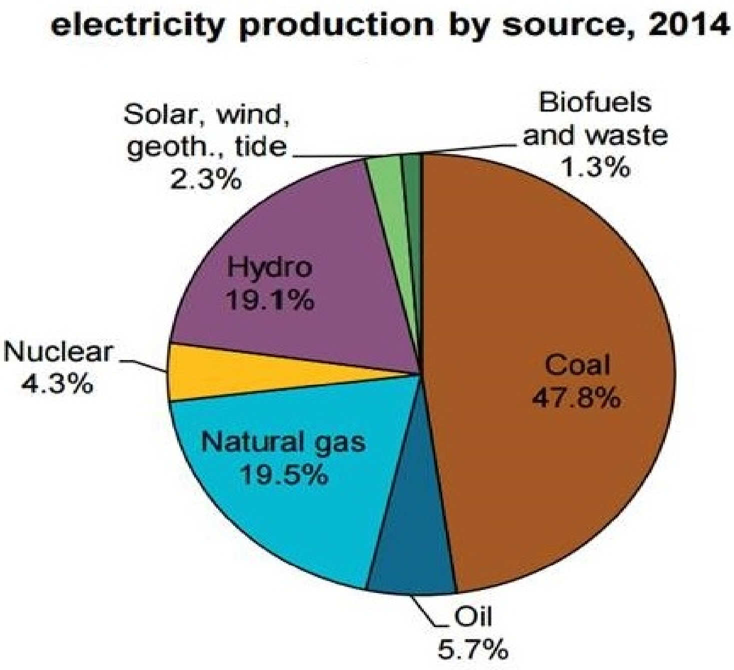
In order to meet the growing demands from last decade, focus is shifting towards renewable energy sources to decrease the dependency on the fossil fuels. Therefore, renewable energy sources are penetrating in our society to meet the growing demands and the consumption of fossil full generated electricity is decreasing gradually. The total electricity generated in 2014 by using fossil and convectional fuels was 9329TWh which is 0.6% less than the compared to 2013. Similarly, the generated value in 2015 was 9300TWh which is 0.2% less than the value in 2014 [2]. The power generated from renewable sources was 2.3% in 2014 as compared to total power production and this value became 7.5% in 2015, as shown in figure 1.1((a)), 1.1((b)).This is the reason many technologists became confident that by 2030, the worlds energy requirement would be provided solely by renewable & distributed energy sources [64].

Thus, renewable energy management, storage, transmission and distribution are the hottest topics of research. Many studies have been done and many researchers proposed different methodology to integrate power from renewable energy sources into the traditional AC utility grids [130]. The most effect way to integrate the different sources including AC utility grid is built, Microgrids (MG) because by using distributed MGs, renewable energy sources and storage can be integrated in any stage and there is no need to change the existing infrastructure of the power transmission and distribution network. The basic concept of MG is to use solid state technology instead of using bulky transformers to shift the voltage levels, integrates the sources and storage locally or near to the utility grid. The main advantage of the MG is that it can operate with or without AC maingrid power and it always consider AC maingrid as a backup power source, to avoid load shedding. In this way, consumer becomes prosumer, which can generate energy locally and can sell surplus energy back to main utility grid. In this way the cost of the electricity unit is also decreasing. The chart in figure 1.2((a)) shows that in Oct 2015 the oil prices have crashed but Hawaiis cost remain stable [47]. The MG based generation market is increasing gradually and tentatively it would reach to 12.7 billion at 2018, as shown in figure 1.2((b)).

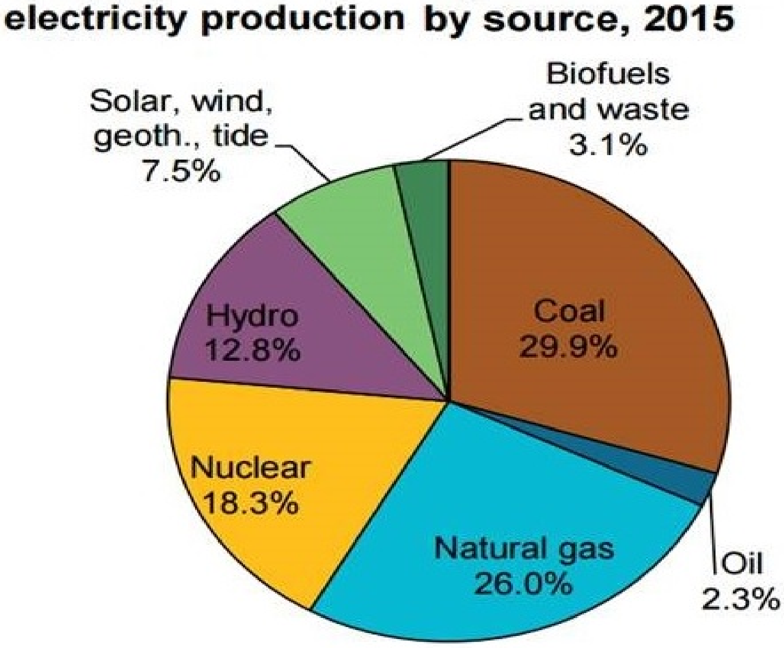
The MG can be considered as an energy hub and it integrates all type of sustainable and distributed energy sources and storage. However, modern MGs contain power converters instead of convectional electrical transformer. Therefore, all sources are rectified interfaced with common voltage bus with intelligent power electronic interfaces. There are different types of microgrids and each type of MGs having own advantages and disadvantages, the more details would be presented in next section.

1.2 Comprehensive overview on Microgrid architectures

As mentioned in above section, the concept of Microgrids arises and has become one of the hottest topics of renewable energy research. This field has been regarded as one of the 10 most emerging technologies by *“Massachusetts Institute of Technology (MIT)”* review in 2012 [108]. The Microgrid has the potential to solve our local generation, distribution and storage problems, which we are facing nowadays. The Microgrid is a future energy-distribution paradigm; consist of the several distributed micro-generation sources (such as PV, micro-turbine, wind-generator

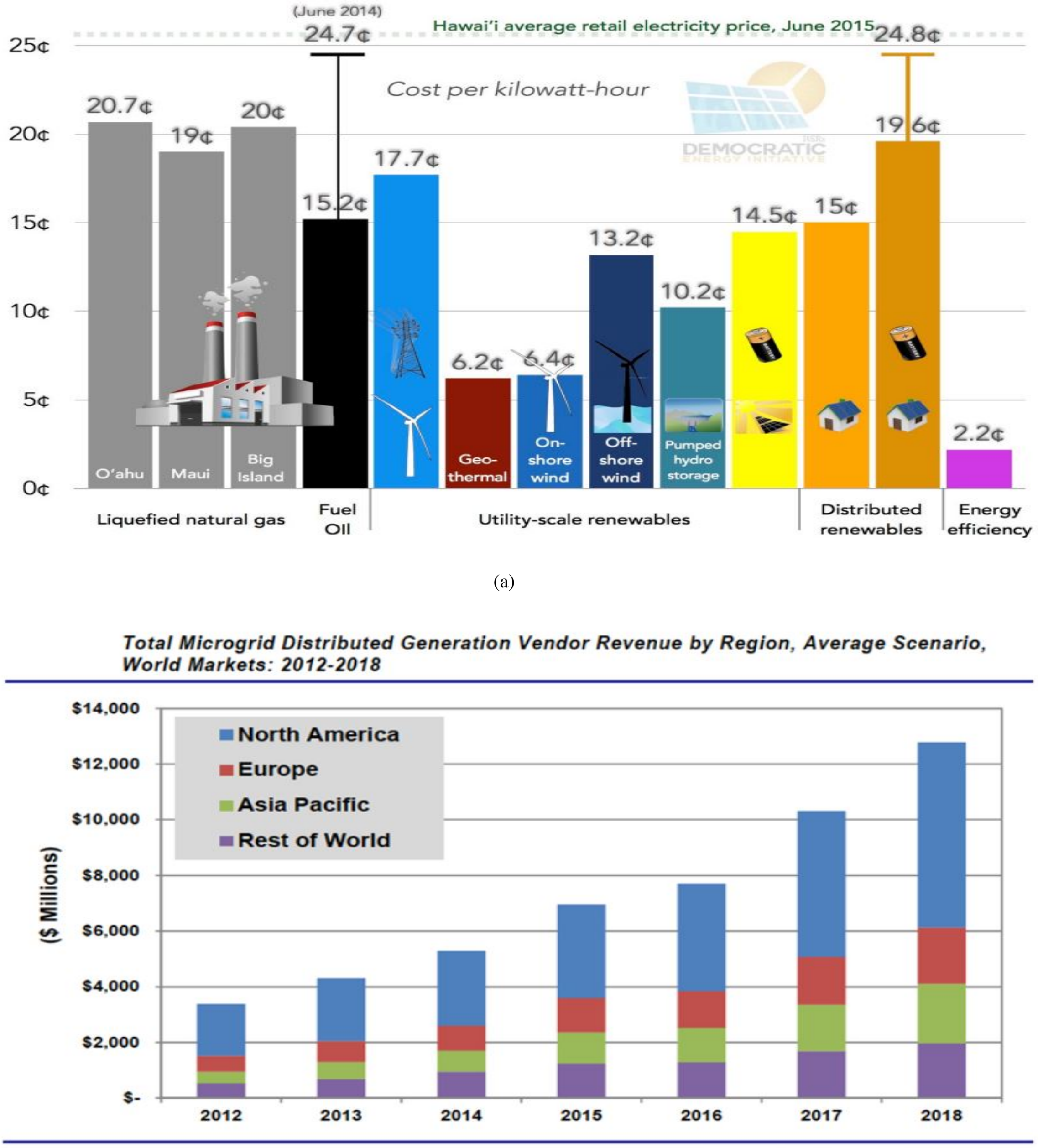


(a)



(b)

Figure 1.1: Energy generation statistics (a) In 2014 (b) In 2015



(a)

(b)

Figure 1.2: MG statistics (a) Cost of Hawaiian energy sources in June 2015 (b) World Microgrid generation market from pike research

etc.), combined with distributed storage (such as flywheel, ultra-capacitors, SMEs, batteries etc.), load management, regulation, peak leveraging local distribution systems and management strategies. Depending upon the nature of the distributed sources, type of the storage, power quality and consumer demand, the microgrid is significantly different from the convectional AC power generation and radial distribution system [79, 104].

The modern concept of power distribution based on the microgrids is highly promising on bases of the following main reasons. i) The transmission losses can be reduce up to $8 - 10\%$ [104]. ii) Local grid can be constantly monitored, in this way the power quality and reliability of entire grid will be increased. iii) Integration of variety of renewable sources at any stage in power generation plant becomes possible, with low carbon footprint. iv) Both type of short-term and long-term storage can be incorporated within grid and play important role in control and operation of a microgrid. v) It significantly contributes in reducing the effect of the natural disasters by rapid restoration capabilities. Basically, microgrids are divided into two main branches, namely; application and power distribution. In terms of applications, microgrids are divided into three main groups: i) Residential Microgrid, ii) Commercial Microgrid, iii) Off-grid or remote Microgrid (such as ships, aircrafts and military units) [54, 88, 142]. In terms of power transmission and distribution, AC Microgrid, DC Microgrid, and Hybrid (AC/DC) Microgrid are common.

1.2.1 AC Microgrids

From nearly more than half of century, there is well-established power generation and distribution system based on Alternate-current (AC). There are three main reasons of penetration of AC power widely in our society. Firstly, convectional fossil-fueled power plants generates AC power. Secondly, AC electrical distribution system can easily allow change in voltage levels (step-up or step-down) by using transformer as shown in figure 1.3. Thirdly, AC power protection and control devices are well established and available in reasonable cost. Many research studies have been proposed for AC microgrid system, such as multi-bus AC microgrid [52, 84], fast-acting AC microgrid design [147], power electronics based AC microgrid [25, 152], active damper control [141]. Moreover, several unified controllers and operational algorithms have been proposed for specifically AC Microgrid design [40, 70, 87]. However, the integration of renewable sources is still a big challenge in AC microgrids, because most of the renewable sources generate DC power and additional power converters required for managing energy storage [29, 67]. Furthermore, due to tough requirements of synchronization of frequencies, phase-angle and amplitudes, additional sophisticated power converters are required, making the whole system more complex and multiple power conversion causing significant power loss within the grid, as shown in figure 1.4.

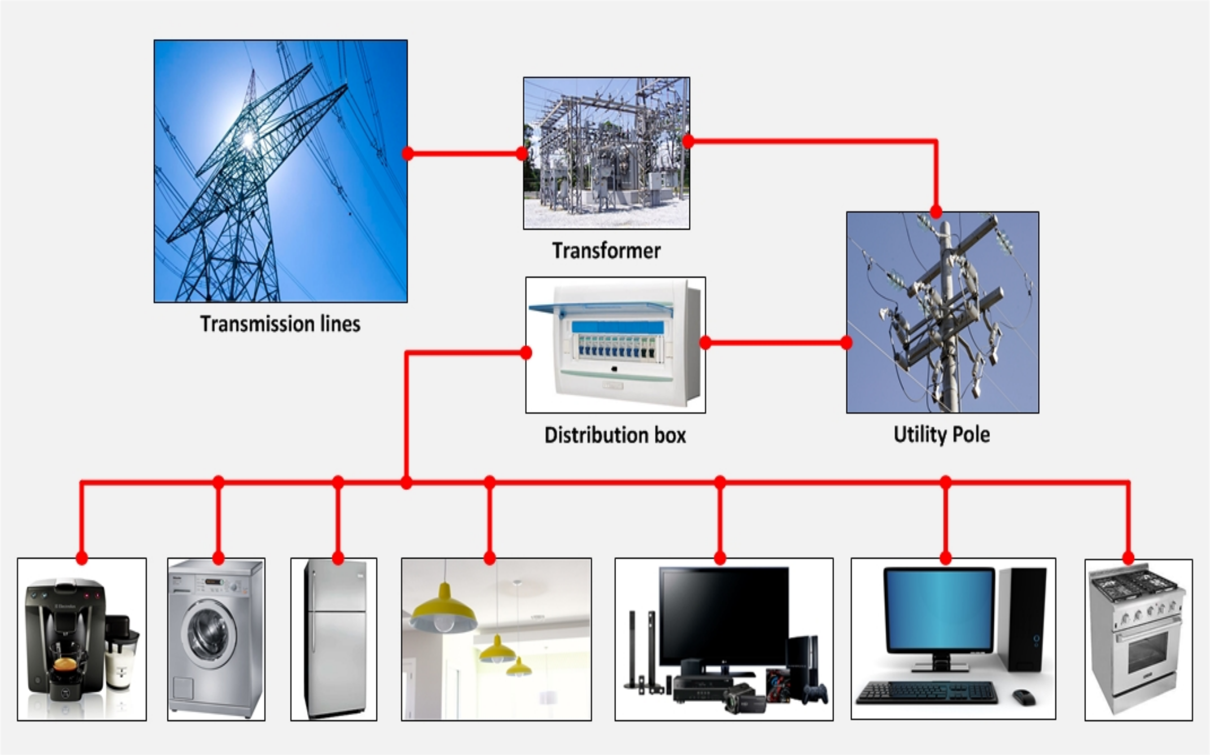


Figure 1.3: Typical layout of AC Microgrids

1.2.2 Hybrid Microgrids

The aim of the microgrid is to deliver reliable and high quality of power in an environmental friendly way. The one of the most important objective of the smart-microgrids is to facilitate renewable sources and energy storage without significant power loss [98, 107, 144]. In literature, researchers proposed microgrid architectures with provision of integration of AC /DC power generators, AC/DC load and storage management is called Hybrid Microgrid [6, 86, 87]. However, proposed models for hybrid grids required multiple power electronics converters for controlling power transfer between AC and DC grid side [140]. Moreover, sophisticated controllers required for interfacing of multiple voltage levels, phase-angle and frequencies of power sources. Therefore, overall power management, control, operation and demand-side management of AC/DC hybrid Microgrid become complicated and costly [87, 147].

1.2.3 DC Microgrids

Recently, DC grids are becoming more popular due to maximum utilization of renewable energy sources, integration of economical battery storage solutions and penetration of DC appliances in commercial, industrial and residential sectors. DC microgrids become alternative option and are gaining interest due to reduce number of power conversion required, ease of control, no reactive

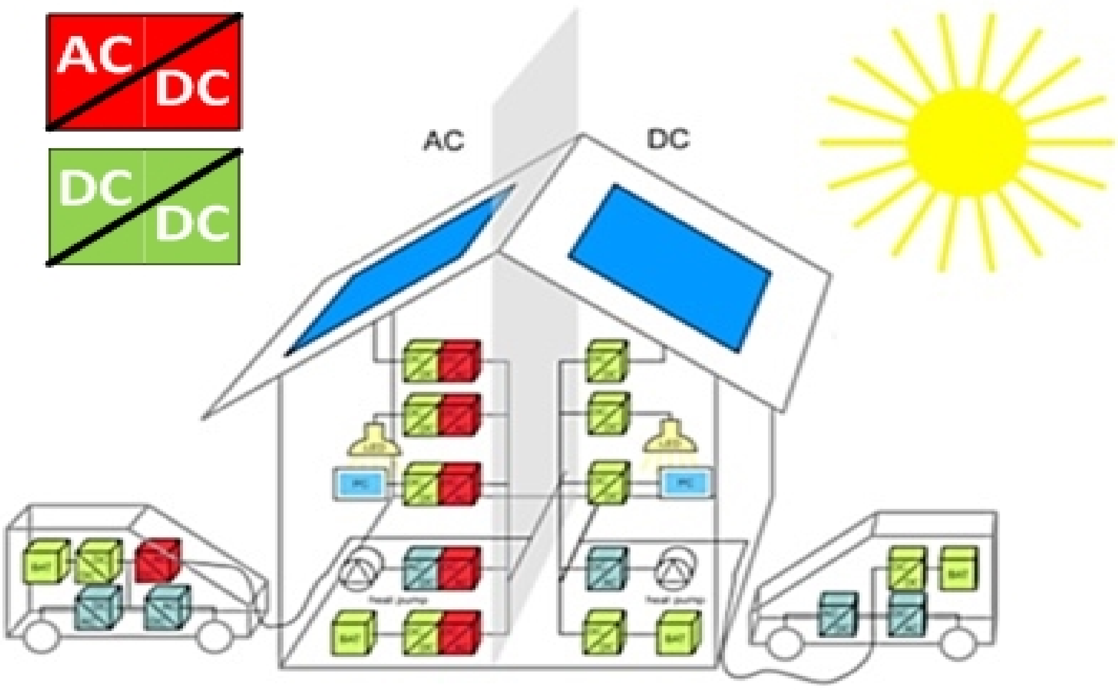


Figure 1.4: Difference between the AC and DC powered Microgrids

power factor issues and high power quality within cheap-cost. Moreover, a classical layout of the DC microgrid is also simple and consists of i) Grid-interface, ii) renewable generators, iii) demand-side management, iv) energy storage [54, 89]. This is the reason DC distribution seems promising and economical solution to integrate sustainable, distributed energy sources and storage devices as well as manage the power consumption of modern electronic appliances. Compared to AC distribution, DC to DC converters are more reliable and efficient than the AC to DC converters [35, 116]. Following are the list of advantages of DC power grid over a convectional AC power grid.

- Mostly, renewable sources generates DC power except wind turbine, however the output power of wind turbines consist of variable amplitude and frequency of AC power. Typically output of wind generator is converted into DC power before transmission.
- Nowadays, mostly appliances (such as LED lights, smart-phones, and computers) operate on DC power. Therefore, DC microgrid will reduce the conversion losses by eliminating power-inverter between DC source and DC load.
- There is no need to consider frequency synchronization and reactive power issues, between different DC power sources. Therefore, it leads the high power quality within reasonable cost.

- Energy storage can be directly coupled with the DC distribution bus without additional power converter. Therefore, surplus stored energy can be utilized without significant loss.

- Among DC/DC converter is more efficient and cost effective then same wattage of inverter. Therefore, whole system cost and energy loss can be reduced because power-inverter is required for solely Grid connected operation.

- Very few components used in DC microgrid, hence mean time between failure (MTBF) of DC microgrids is usually high [124].

1.3 DC Microgrid test bed and applications

Energy and environmental issues are the main focus of researchers and this is the reason several studies have been done related to effect of coal/ oil based generation plants, greenhouse gas, depletion of fossil fuel reserves and prediction of future energy demand. This is the reason not only microgrid projects implemented by academic research level but also private companies also supporting such projects [19]. In Japan, NEDO (New Energy and Industrial Technology Development Organization) implemented four DC microgrid projects [68] between 2003 to 2007. The U.S. Department of Energy (DOE), the Electric Power research Institute (EPRI), the California Energy Commission (CEC) focus on implementation of microgrids through which to make sure reliable, efficient and secured power distribution [16, 60, 99]. EU also spend 4.5 million euros funds within 5th Framework program $1998 - 2002$ on Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids and 8.5 million euros funds within 6th Framework program $2002 - 2006$ [60]. The Virginia Tech state university proposed and implemented scaled version of DC mcirogrid named Energy Control Center (ECC) [36]. Similarly, University of California state university research center FREEDM (Future Renewable Electric Energy Delivery and Management) not only proposed the DC-zonal distribution architecture but also implemented scaled model called IEM (Intelligent Energy Management) [124, 125, 138]. The Lawrence Berkeley National Laboratory established CERTS (Consortium for Electric Reliability Technology Solutions) microgrid test-bed located in American Electric power (AEP) company Walnet test facility completed in 2010 [66, 101].

In several other applications have been reported in which DC microgrids has been successfully implemented, including Naval ships, air crafts [14, 31], commercial data-centers [18, 113, 148], residential buildings [119, 120] and communities [28, 42, 101, 112, 124].Moreover, lots of studies have been done in the area of DC microgrid protections [12–14, 90, 92, 94, 114, 115], intermittent distributed energy storage [148, 149], grid-connected operations [34], autonomous operations, communications, islanding operations [72, 113, 117].

1.4 Overview of DC Microgrid controls

In DC microgrids has more complex control as compared to the convectional AC distribution system [77, 135]. In convectional AC distribution magnetic transformer is used to change the level of the voltages and Electric loads are directly connected to power line from main distribution box, as shown in figure 1.3. However, in DC microgrids power electronics technology would be used to change the voltage levels and electric loads would be connected to the main DC bus via power electronics interface, which enables the provision to integrate multiple sustainable and distributed sources and storage at any level. Therefore, extensive studies have been done on DC microgird control and it is divided into three major categories i.e. centralized control autonomous/ distributed controls [95] and hierarchical controls.

1.4.1 Centralized control method

The centralized control consists of master-slave configuration for successful grid operation real-time, reliable and fast communication link is required between the central controller (master) and connected peripherals (slaves), this control method is fast, efficient and economical [8, 85]. The bidirectional communication link is used for telecommands and telemetries of all connected slaves. The main purpose of the centralized control system is to control and monitor all activity centrally and reduce the processing on the slave or distributed nodes, in order to reduce the cost of each node. Therefore, each slave node do not have ability to manage power itself, all slaves required instructions from central controller for every action. However, the main drawback of centralized control is the communication link between master and slaves, overall reliability solely depends upon this link. In case of communication-fault or delay in data-packets would affect entire grid performance [30, 37]. Moreover, significant upgrades are required in central controller on each integration of distributed storage and generators. In term of overall grid operation and control point of view, the high system reliability and expandability is not achievable in centralized control method.

1.4.2 Autonomous or distributed control method

There is no dedicated communication-link required between nodes within the grid. Each terminal is intelligent and monitor the microgrid parameters, which is solely DC bus voltage in case of DC microgrid. In literature, many techniques have been proposed for distributed control of DC microgrid, such as Droop control [52, 72, 105], unified distributed control [97], DC-Bus Signaling [23, 63, 117, 118, 131], MDB Signaling [30, 149], Active load sharing control [8, 140], AC-signal modulation over DC voltage, circulating current method [63, 136], Multi-agent based control [128, 140], sliding mode control approach [50], Fuzzy Control and Gain-Scheduling

Technique [69]. However, the processing on each node, size, and cost of entire system will be increased drastically and continuous monitoring of SOC (state-of-charge) of battery-storage become complicated [151, 154, 155]. Moreover, overall grid control become slow, fault correction and isolation become complex [30].

1.4.3 Hierarchical control method

The advantages of both central and distributed control methods are combined in hierarchical control [57]. In hierarchical control like centralized control, all modules or nodes are connected through bidirectional communication link to the master controller [96] However, the control algorithm is more intelligent and robust like distributed or autonomous controller [58]. The local module or node can operate by itself based on the information available locally without any command from the master node, in case of delay or broken communication link. Due to communication link, the fault rectification and isolation become easy and each node is synchronized with the centralized controller. Therefore, the power management is not dependent solely on the central controller like centralized control method and local controller can manage the power independently which helps to increase the over all grid reliability. Moreover, the system level power management also become possible and fast due to the communication link. These days, several industrial and commercial communication protocols and methods are available for effective implementation of hierarchical control system such as Z-Wave, Zigbee [62], Power line communication (PLC) [27], Controller Area Network (CAN Bus) MOD Bus [80], Ethernet and WIFI [156]. Each protocol having its own advantages and disadvantages, protocol would be selected depending upon the user or design requirements. However, in hierarchical control each node became complicated and difficult to manage because the overall architecture is similar to the distributed or autonomous control system and adding the centralized control command and control required more processing power and robust algorithm design, which increases the chances of malfunction.

1.5 DC Microgrid bus standard voltages

This is one of the important parameters of DC microgrid, which has to be standardized. All control parameters, load requirement and protection systems are associated with DC microgrid operational voltage. As compared to AC distribution bus voltage, the DC microgrids must have the standard voltage because currently DC appliances are categorized into several voltage levels from $1.5V$ to few tens of DC voltages. Several studies have been conducted for selecting optimized DC bus voltage including $12V$ [101], $24V$ [112], $48V$ [100], $125V$ [116], $230V$ [7], $270V$ [150], $325V to 380V$ [100], $400V$ [106, 127], $700V$ [23, 39], $+/-170V$ [68]. Moreover, bipolar DC microgrids are also gaining interest because of less number of components and a simple DC to AC converter design can be used to drive AC powered loads [68]. In telecom sector for data-centers, $380V$ has been accepted [36, 116] and it may be used for residential and commercial DC microgrids. However, now some industrial DC distribution standards defined under EMerge Alliance [4] and European Telecommunication Standards Institute (ETSI) standard. The ETSI (EN $300132-3-1$) standard allows up to 400VDC for DC powered ICT equipment to be used in data centers. Moreover, IEC System Evaluation Group (SEG) 4 is also recommending DC voltage standards for low voltage DC (LVDC) distribution up to 1.5KVDC [1]. The sub DC buses are used to power up the consumer side and drive both high power AC/DC loads up to 300V and low voltage sensitive DC appliances up to standard 24VDC [1, 4].

1.6 Overview of DC Transformer concept

Power generation, transmission and distribution are the key areas of the power system and in all these areas, power transformer is the main fundamental component and play vital role [59, 135]. Transformers used to increase the voltage level before transmission to enable high efficiency over the long transmission distance [22, 121]. In recent technological advancements in the field of semiconductor materials, now high voltage and current solid state devices are available in reasonable cost [20, 153]. Therefore, instead of using convectional magnetic transformer, high power converter can be used and power electronics converter can be used for high power transmission and distributions. Moreover, due to high efficiency and reasonable cost, it is replacing the convectional bulky electrical transformer and empowering future grids. DC transformers, solid-state transformer or power electronics transformers are the modern form of convectional transformers with additional features such as in-system protections, harmonic isolation, small size, reduce weight, small foot-print, fault tolerance etc [55, 138, 159]. This technology is already being used from last decade in high voltage direct current (HVDC) transmission systems and also in flexible alternate current transmission systems (FACTs) including unity power factor controller, static synchronous compensator and static var compensator etc.

The solid state transformer is a type of power converter which is replacing the traditional $50-60$Hz power transformer by converting any AC or DC input voltages [83, 139]. The basic operation of the solid state transformer is to change the input AC ($50-60$Hz) into DC voltages and then convert it into high frequency AC voltages (frequencies usually in the range of few kilo hertz), after that these high frequency voltage is passed through the high frequency transformer to change the voltage level i.e. step up or step down, after passing through the high frequency transformer this voltage shaped back to the $50-60$Hz AC voltage to drive the load. The reason to change the low frequency voltage into high frequence in order to reduce the transformer weight and volume. The typical configuration of the solid state transformer is shown in figure

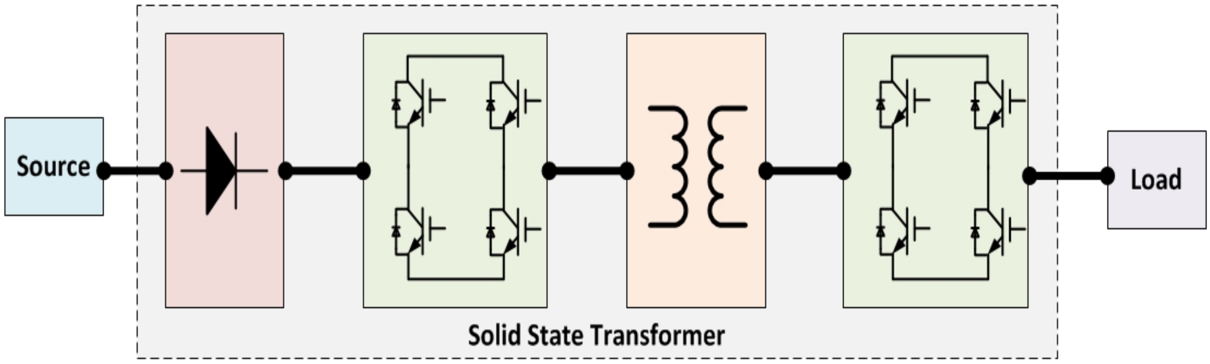


Figure 1.5: Configuration of Solid State or DC Transformer

1.5.

Extensive topologies have been proposed for solid-state transformers such as Dual half bridge (DHB) [43, 49], Series resonant Converter (SRC) [26], Cascaded Buck-Boost (CBB), Combine half bridge (CHB) [3], Dual active bridge (DAB) [159], L-Type half bridge [38], IEM [137, 158], ECC [36], IUT [78], Gen-1 SST [138], PSM-ZVS PET [110]. However, all above proposed topologies and models are used for AC-AC and AC-DC bidirectional conversions. Moreover, few of them can be used for DC-DC conversion such as DHB, SRC and DAB, but they do not meet the basic PCmRC power management requirements. DHB provides less reactive power because of single end isolation [26]. In SRC, due to active components the operating range of the converter becomes limited and control becomes complicated. The DAB topology is unsuitable for LVDC applications due to the limited range of voltage regulation.

1.7 Research gaps and objectives

1.7.1 Key challenges of DC microgrids

As discussed in above section, extensive studies has been conducted on dc distribution, AC/DC or DC/AC converter design, different centralized and distributed control techniques for residential and commercial DC microgrids. Beside advantages, DC microgrid also associated with several issues and challenges. Following are the list of issues associated with DC microgrid system and summarized the short-coming in the state-of-art proposed models in Table 1.1.

Grid Architecture and Control methods

Several DC grid architectures and control theories have been proposed and implemented in commercial data-centers [18,106], residential buildings [28,42], OFF-Grid and remote sites [14]. In terms of architecture and control, DC microgrids can be divided into two main categories such as centralized control and autonomous or distributed control [104].

- **A centralized controlled DC microgrid**, consists of master-slave configuration for successful grid operation real-time, reliable and fast communication link is required between the central controller (master) and connected peripherals (slaves), this control method is fast, efficient and economical [8]. However, the main drawback of centralized control is the communication link between master and slaves, overall reliability solely depends upon this link. In case of communication-fault or delay in data-packets would affect entire grid performance [30]. Moreover, significant upgrades are required in central controller on each integration of distributed storage and generators. In term of overall grid operation and control point of view, the high system reliability and expandability is not achievable in centralized control method.

- **In autonomous or distributed control method**, there is no dedicated communication-link required between nodes within the grid. Each terminal is intelligent and monitor the microgrid parameters, which is solely DC bus voltage in case of DC microgrid. In literature, many techniques have been proposed for distributed control of DC microgrid, such as Droop control [52,72,105], DC-Bus Signaling [23,117,118], MDB Signaling [**?**], Active load sharing control [8,140], AC-signal modulation over DC voltage, circulating current method [136], Multi-agent based control [140]. However, the processing on each node, size, and cost of entire system will be increased drastically and continuous monitoring of SOC (state-of-charge) of battery-storage become complicated [155]. Moreover, overall grid control become slow, fault correction and isolation become complex [30].

DC Protection system

Along with good control technique, proper protection system also play significant role in successful DC microgrid operation. As compared to AC protection system, the availability of wide-range of DC circuit breakers and other protection devices in economical cost is still a big challenge [12,15,146]. In AC power system the circuit breaker after sensing fault, activates the mechanical switch at zero crossing. In contrast with AC power system, DC current never goes to zero, so during circuit breaking operation destructive arcing is occurred, which may shorten the DC circuit breaker lifespan. By using solid-state switch instead of using mechanical-switch, arcing can be reduced. Indeed power electronic device can provide high-speed switching and arc-less operation, but solid-state switch causes significantly high on-state losses and heat dissipation as compared to zero-loss mechanical switches [13, 92]. Therefore, extensive studies have been done in DC protection system and researchers proposed different techniques in order to overcome this problem. Some of such efforts are hybrid fault current limiting circuit breaker [129], GTO (Gate-Turn-Off) breaker [92], RLD snubbers [13], Capacitor DC Circuit breaker (CDCCB) [13, 16], Hybrid-electro-mechanical circuit breaker [147], Ultra-fast IGCT breaker [94], Circuit breaking on AC side [146], Zonal Multiple fuse protection [114] etc. Beside all above studies, the biggest challenges associated with DC breakers in contrast to AC circuit breakers is that they are relatively too expensive, slow activation time, short lifespan and high maintenance cost [115, 147].

AC Maingrid and Backup generator integration

The main motivation behind DC microgrid is to reduce dependency on fossil fuels and maximized the utilization of renewable energy sources within local grid. However, due to inconsistent and stochastic nature of renewable sources [45, 102], integration of AC maingrid or backup power generation become indispensable part of DC microgrid. Therefore, overall DC microgrid reliability depends upon backup power supply. Hence, sophisticated bi-directional AC-DC converter required for interfacing with AC maingrid [36].

Compatibility with Existing infrastructure

The main motivation behind DC microgrid is to reduce dependency on fossil fuels and maximized the utilization of renewable energy sources within local grid. However, due to inconsistent and stochastic nature of renewable sources [45, 102], integration of AC maingrid become indispensable part of DC microgrid. Therefore, overall DC microgrid reliability depends upon backup power supply. Hence, sophisticated bi-directional AC-DC converter required for interfacing with AC maingrid [36]. The most important aspect of DC microgrid is the compatibility with the existing infrastructure. Another objective of the compatibility is to share on-site generated surplus power with adjacent utility grids. Therefore, proper standardization is needed to define for power transfer between adjacent grids and also with main distribution grid in economical and environmental friendly way [44, 87].

DC Transmission and Distribution

The main reason for AC power system is still viable due to efficient and economical transformation of AC power at different levels and multiple node distribution over long distance [87]. Although, the voltage source converter (VSC) can be used for DC transmission and distribution [87], however VSC is not simple and economical compared to AC electric transformers.

DC Bus voltage selection

This is one of the important parameters of DC microgrid, which has to be standardized. All control parameters, load requirement and protection systems are associated with DC microgrid operational voltage. Several studies have been conducted for selecting optimized DC bus voltage including 12V [101], 24V [112], 48V [100], 125V [116], 230V [**?**], 270V [150], 325V to 380V [100], 400V [106, 127], 700V [23, 39], +/- 170V [68]. Moreover, bipolar DC microgrids are also gaining interest because of less number of components and a simple DC to AC converter design can be used to drive AC powered loads [68]. However, in telecom sector for data-centers, 380V has been accepted [36,116] and it can be used for residential and commercial DC microgrids.

Selection of Communication protocol

Internal and external communication is the most vital constituent of any microgrid, primarily for uninterrupted power transfer and fault reporting aspects. In literature, depending upon usability communication protocols have been proposed such as TCP/IP, Ethernet Power-link [8], Power line communication (PLC), GSM/GPRS [82], CAN Bus [8], Mod Bus, ProfiBus, LVDS RS485 link, SCADA [105], DBS Signaling [117, 118] etc. However, in DC microgrid communication protocol is depend upon the microgrid architecture and control technique. Therefore, selection of appropriate communication protocol is also a big challenge.

Grid stability and reliability

The DC power distribution may cause following stability and reliability issues for both DC microgrid and the connected AC maingrid.

- **Non-Sinusoidal current:** As discussed earlier, AC maingrid or backup power generator is integral part of the DC microgrid. The power from AC maingrid or backup generator has indeed to be convert into DC, before inserting in DC microgrid. The easiest and most economical method to convert AC into DC power is to use *"Diode bridge-rectifier"* However, diode rectifier technique introduces non-sinusoidal current and low frequency harmonics on AC grid side, which may cause power quality issues [115].

- **Ground loop-currents and Neutral shifting:** AC grid neutral point and Ground potential of DC bus are tightly couple through rectifier diode; resultant DC rail will start picking lowest potential of AC neutral-side and start shifting from Zero to Negative DC voltage. Furthermore, loop current starts flowing between the DC bus and power converter, which may cause oscillations on DC negative rail [15, 146].

- **Electric field confinement:** The next challenge associated with DC distribution is the confinement of electric-field within DC bus, which may cause safety issues [15].

- **Voltage sag:** It is a short duration of voltage dip occurred on main voltage bus by activating heavy power load. This momentary dip in voltage causes malfunctioning or damage to sensitive electronics load [15, 109].

- **DC capacitance discharge and shunt-fault isolation issues:** In DC power supply, capacitors are used for smoothing and filtering the ripples ride on the DC voltage. Moreover, capacitors are directly coupled on the converter outputs and with DC buses, which is used to provide short-term energy storage for grid. However, during shunt-fault capacitors discharge heavy current, which produces high EMC, thermal and mechanical damages to grid [12, 13]. Therefore, proper shunt protection system required for DC microgrid.

- **High-Voltage Semiconductor material:** In contrast with AC distribution transformers, voltage source converter (VSC) required for DC distribution and transmission system. Therefore, the limitation associated with the HVDC and MVDC distribution network is the availability of high voltage power-semiconductor switches to design VSC for HVDC transmission [159].

Integration in Existing infrastructure and power sharing with neighboring grid

The most important aspect of DC microgrid is the compatibility with the existing infrastructure. The main objective of the compatibility is to share on-site generated surplus power with adjacent utility grids. Therefore, proper standardization is needed to define power transfer between adjacent grids and also with main distribution grid in economical and environmental friendly way.

AC powered Load

In early 19th century, AC power system started replacing the DC power system, because AC power generation and distribution is much easier than DC. Therefore almost, every electronic appliances available in market is designed for AC power input, even though it can be operate solely on DC power [**?**, 112]. However, we still have few critical inductive load that require AC power for normal operation. In order to fulfill AC load power requirements, sophisticated DC/AC power inverter is necessary for DC microgrid [36, 111]. This is another potential challenge associated with future DC microgirds, in order to accommodate high wattage AC load.

Lack of standards for DC microgrid

The DC micro grids (transmission and distribution) have several advantages and benefits over convectional AC power grids. However, as we have seen most of the areas related to DC microgrids are still under-research and needed to be standardized. Therefore, lack of availability of guidelines, standards and experiences causes difficulties in the implementation of DC micro grid system [82, 133, 147].

Necessity of Scalable and Standard grid architecture

Currently, around 1.5 billion population is still living in un-electrified houses and electricity demand increasing day by day [82]. Therefore, implementation of distributed micro grid has become inevitable, because it reduces the installation cost, maximizing the on-site generation through distributed sources (like Bio-mass, Bio-gas, PV, wind etc.) and fulfilling our energy needs in environmental friendly way. Hence, micro grids can handle all type of energy storage, loads, distributed and backup generations independently. Although, lots of studies have been done and researchers proposed numerous architectures, control and operation theories related to future micro grid model. However, in order to meet growing energy demands and electrification of embryonic areas, extensive research explicitly in scalable and standard micro grid model is required [133].

Table 1.1: List of some State of art DC micro grid models

Author (s)	**Grid reliability**	**Operational Modes**	**Fault detection Isolation**	**Load management**	**Grid Installation cost**	**Additional converter**
Xu She [122]	Distributed	Grid connected only	Not available	Available	Low	Required
Hiroaki [68]	Single point	Grid connected only	Available	Available	Too high	Required
Dong Dong [36]	Single point	Grid connected and off grid	Available	Available	Too high	Not required
Xunwei [155]	Distributed	Grid connected only	Not available	Not available	Low	Required
Dong Chen [30]	Distributed	Grid connected only	Available	Available	Too high	Required
Chi Jin [65]	Distributed	Grid connected and off grid	Available	Available	Too high	Required
Amir [74]	Distributed	Grid connected only	Available	Available	Too high	Required

1.7.2 Key contributions

PCmRC is DCT enabled design, which has several advantages over state-of-art AC-DC SST based design. The key advantages are summarized as follows:

- The state of art models usually design for solely grid connected and off grid operations. However, PCmRC consumer grid model equally operational in both scenarios without changing any control algorithm. However, in case of off grid mode the amount of renewable and distributed energy available locally must be equal or more than the load connected with the consumer grid for sustainable grid operation.
- Most of the state of art DC grid models are proposed for specific type of renewable source such as PV or wind or Fuel cell or combination of both. In our proposed architecture, we are not depending on any specific type of renewable and distributed source. Moreover, we proposed the standard interfaces for possible type of renewable and distributed sources.
- In proposed model, we classified the loads in term of critical and non-critical which is totally depending on the consumer. In this way, consumer can configure high priority load and make sure the continuous supply power for critical loads during power shortage due to main grid failure or worst weather conditions.
- DCT has dedicated port for low voltage DC and AC powered appliances, which would lower down the number of power converter counts within grid.
- There are four stages of grid operational mode which are designed to maximize the exploitation of renewable / locally available distributed sources and reduce the dependency on the AC main grid without effecting overall grid stability and reliability.
- The storage can be integrated directly on main DC and LVDC buses via standard interface and there are predefined level for storage charging and discharging autonomously as per the bus voltages, which reduce the complexity of continuous monitoring of SoC.
- Each DCT is equipped with transformer which provides magnetic isolation in between the main DC bus and consumer side buses and DCT isolation switch. On detecting any abnormal condition, respected DCT would go in DCT isolation mode by switching off all ports and activate the DCT isolation switch. In this way, the respected DCT(s) completely isolated from the main DC bus and other DCTs can work normally.
- There are built-in protection system for under/over voltage and short circuit current in each port, which eliminates the need of any additional protection system for DC grid.
- There is standard DCT module is used to enable the PCmRC consumer grid mode. Therefore, more than one DCT module can be cascaded in order to meet the consumer power

requirements. In this way, scalable power distribution system can be designed and desired number of redundancy can be achieved.

- The standard and scalable architecture would lead to lower down the production cost and MTTR (Mean time to repair) also minimized because all module pin to pin compatible and by replacing DCT module the whole grid would be operational within short time in case of fault.
- This architecture is perfectly integrated in the convectional AC power distribution infrastructure and allows dynamic power sharing from locally available sources and also permits to integrate storage at any level of distribution system.

1.8 Dissertation outline

The focus of the dissertation is preliminary on covering state of art technologies, DC micro grid proposed architectures, research gaps, our proposed power management strategy, design methodology, overall architecture of our proposed model and application of our proposed model on community level and residential level. This dissertation consists of six chapters and the overall organizational chart of the dissertation is shown in Figure 1.6.

$Chapter 1$ consist of the motivation and background of this research along with the detail overview of the state-of-art DC micro grid architecture. Then provided the DC micro grid test beds and real world applications and implementations. Furthermore, explained the different DC micro grid controls, Dc bus voltage standards, outline the key challenges associated with the DC micro grid and highlighted few key contributions.

$Chapter 2$ introduces the complete system description and detail explanation of the key features of DCT enabled consumer grid model including DC Transformer topology, load classification, demand side management, fault protection, isolation, islanding, grid connected operations, compatibility with existing infrastructure, standard interfaces for sources and storage.

$Chapter 3$ proposes overall control algorithm used to control, SoC of storage, grid connected, islanding, off-grid operations, sustainable and distributed sources. In this chapter, we explained the primary and secondary control loops along with the complete operational control flow chart of demand side energy management.

On the bases of the above power control and demand side management strategy, we divide the application of consumer grid model into two categories $1)$ community level in which we explained the power management strategy on large scale, which is elaborated in $Chapter 4$ and $2)$ we proposed the lighter version of grid model named **HER** (Home Energy Router) for residential grids, which is elaborated in $Chapter 5$.

$Chapter 4$ provides the comprehensive overview of DCT enabled PCmRC consumer grid

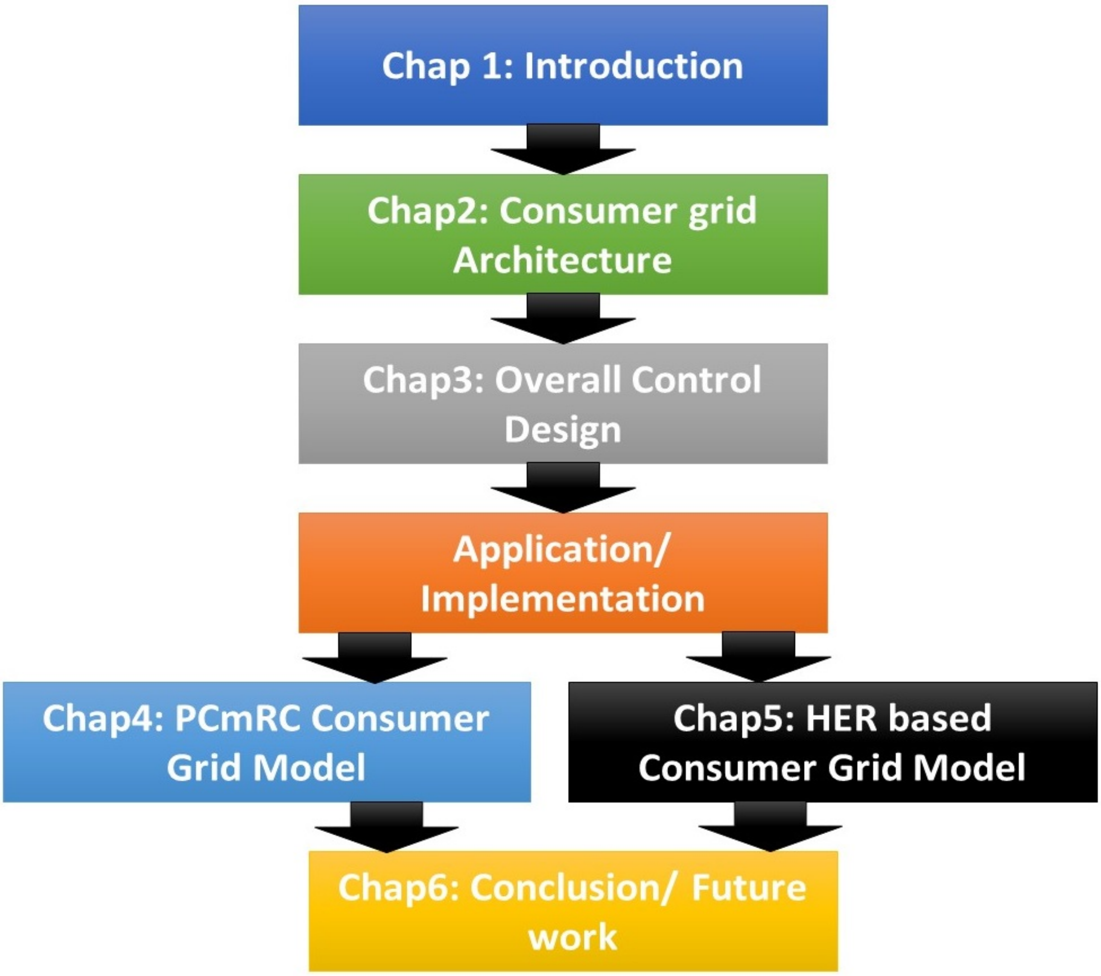


Figure 1.6: Organization of the dissertation

model on large scale. Furthermore, we explained the possible real time operational modes on the bases of availability of power and load management strategy with seamless switching in between modes. Finally, elaborates the key simulation results just for verification of our proposed grid model

$Chapter 5$ propose the typical residential consumer grid model and power management strategy with limited sources and storage along with the simulation results for verification purpose.

$Chapter 6$ concludes the dissertation and proposes the future work.

Chapter 2

System description and consumer grid architecture

2.1 Introduction and motivation

In last decade, the industrialist, government think-tanks and academia researchers recognized the importance of distributed generations, power transmission efficiencies by decreasing the transmission distances and need of sustainable/ environmental friendly sources. Sustainable energy sources are contributing significantly in distributed generating system and market share increasing day by day. According to the survey report that 19% of the global energy generated from renewable sources including 13% from biomas and 3.2% from hydroelectricity [24]. The renewable sources including solar, wind, geothermal, biofuel, contributes another 2.7% [33] of total generation. In United States, the renewable sources generated around 8% of the total energy generated in 2010 [56]. Therefore, the microgrid based power generation plant getting popularity and both AC or DC microgrids test beds are implementing around the world.

The term AC and DC microgrids are dependent upon the way through which power is distributed and managed within grid. The optimum selection of the type of microgrid is based on loads input power. From nearly more than half of century, there is well-established power generation and distribution system based on Alternate current (AC) [67]. Moreover, AC load protection and control devices are matured and available at reasonable cost [84]. However, the convectional AC power system is currently facing lots of challenges by increasing number of distributed energy sources. In ideal scenario, if the local consumer grid fully powered by using sustainable and distributed sources then there is no provision available in existing AC power system to operate whole grid on renewable energy sources. The another challenging issue associated with convectional power distributed system is to handle the DC storage to overcome the power fluctuation due to stochastic nature of renewable sources. The integration of renewable sources and modern electronic appliances are still a big challenge in AC microgrids, because most of the renewable sources and appliances work on DC power and additional power conversion is required for managing small DC storage [34]. Due to additional power converters required to power up the loads, the integration of sources and storage may increase the overall installation cost and decrease the reliability of the grid. A typical block diagram of AC and DC microgrids is shown in the Figure 1.4. In the layout of AC and DC micro grid, a photovoltaic cell and battery can be connected to DC mains by using dc/dc converters. DC appliances can be connected directly with DC mains whereas a DCAC inverter is required for AC powered loads. From the power management perspective, a DC micro grid has advantages over an AC micro grid due to reduce number of power conversion steps required, ease of control, elimination of reactive power factor issues and high power quality at low cheap-cost [42].

2.2 DCT enabled PCmRC consumer grid description

In order to mitigate aforementioned problems, PCmRC based DC microgrid architecture has been proposed in this section. The PCmRC is scalable and standard model of future consumer grid, which can be integrated into existing infrastructure without any significant change. It can handle AC/DC loads and energy storage. It also helps in solving grid stability problems and maximizes exploitation of renewable sources within consumer grid. The topology used in the DCT module supports bidirectional and multilevel DC to DC conversion, which can be used to interface the high DC voltage bus with low-voltage battery storage without any additional power converter. In this way, the overall power converters count and energy loss can be reduced within grid. In PCmRC, DCT module can regulate the voltage on both high and low side with embedded over voltage and short-circuit current protection on each terminal. Therefore, there is no need to install additional expensive DC protection system, which helps to lower down the overall grid operational cost. The most important feature of DCT enabled consumer grid is the independent and similar control with and without AC maingrid connection. It means there is no significant difference in control and operation of overall PCmRC consumer-grid in grid-connected, islanding and off-grid modes. The motivation behind standardized grid model is to reduce the production cost and fault rectification time.

2.2.1 Overview of PCmRC model

The envisioned DCT enabled consumer grid model is shown in Figure 2.1. The PCmRC is a scalable and standard model of a futuristic prosumer grid, which can be integrated into existing infrastructure without any significant modification. The proposed consumer grid architecture consists of one main DC voltage bus and sub DC buses. The main DC bus operates in the range of 350V to 400V DC with nominal voltage of 380V DC, used for electrical distribution

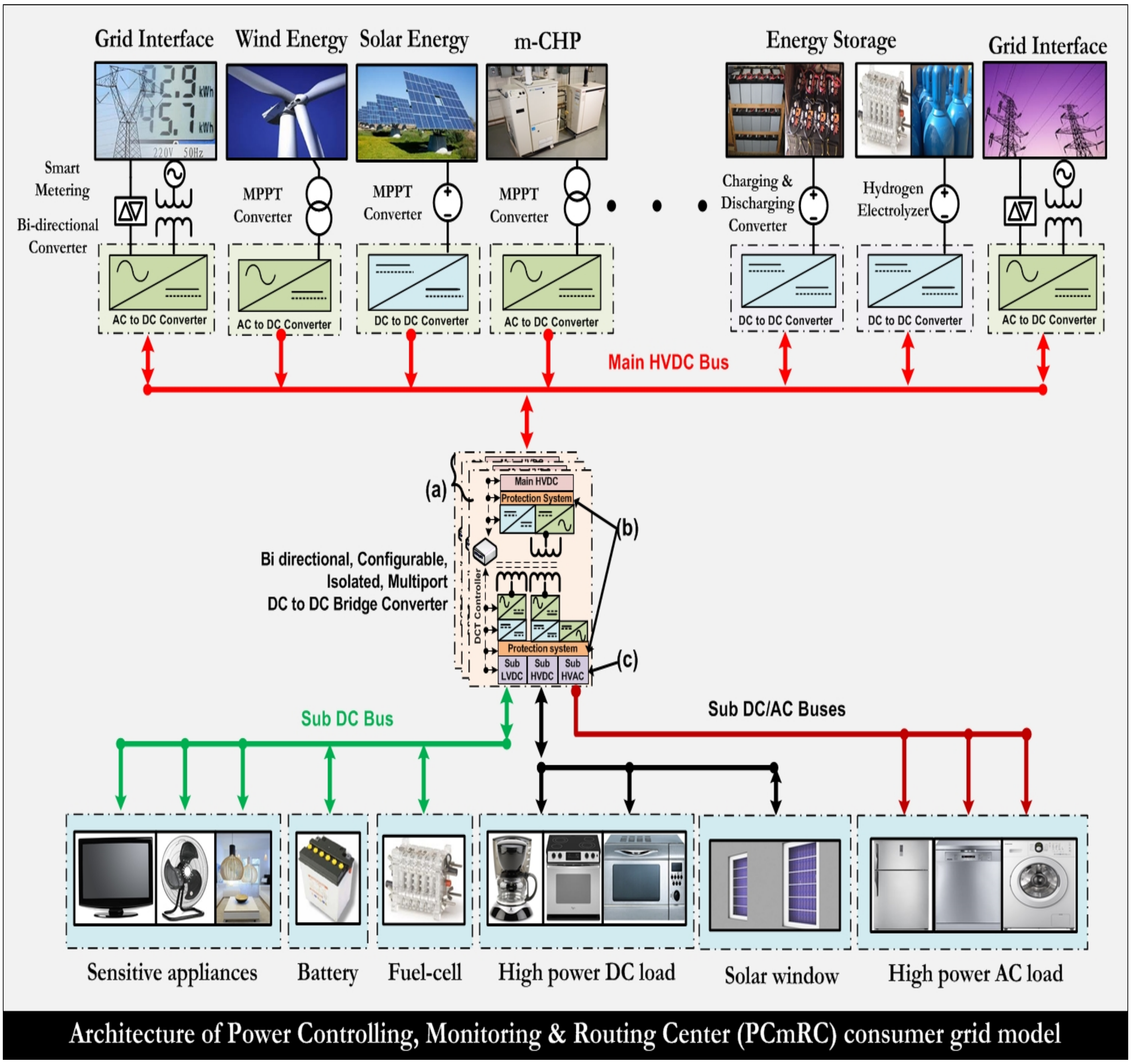


Figure 2.1: DCT enabled PCmRC consumer grid Architecture

and integration of high power local generators, storage and AC main-grid. This DC distribution voltage level is selected to comply with industrial DC grid standards such as EMerge Alliance [4] and European Telecommunication Standards Institute (ETSI) standard. The ETSI (EN $300132-3-1$) standard allows up to 400VDC for DC powered ICT equipment to be used in data centers. Moreover, IEC System Evaluation Group (SEG) 4 is also recommending DC voltage standards for low voltage DC (LVDC) distribution up to 1.5KVDC [1].

The sub DC buses are used to power up the consumer side and drive both high power AC/DC loads up to 300V and low voltage sensitive DC appliances up to standard 24VDC [1, 4]. The DCT is the key component of the PCmRC consumer grid architecture. The DC main bus is directly connected to the DCT terminal and it can be considered as an interface bridge between the main DC bus and sub DC buses on consumer side. The DCT is the “Hub” of all activities including controlling bidirectional power flow, on-site low voltage storage management, grid protection, both (main and sub) DC buses voltage regulation and fault isolation. Therefore, there is no need to install an additional expensive DC protection system, which helps to lower down the overall grid operational cost. The motivation behind standardized grid model is to reduce the production cost and fault rectification time. More detail regarding LVDC consumer grid power management will be discussed in chapter 4.

2.2.2 Overview of DCT topology

The Solid state transformer is the one of the critical transmission devices used in flexible alternating current transmission system (FACTs) [93, 123]. The main motivation behind solid state transformers is to apply the state-of-art power electronics technology [41] to achieve high operating frequency to reduce the foot-print (volume) of the transformer without effecting the power handling capacity. Figure 2.2 shows the full Triple-active-bridge (TAB) topology of the DCT under consideration. The DCT topology comprises of main DC bus interface and two sub DC bus interfaces. The main DC bus interface is directly connected to the main DC bus i.e. 350V to 400V DC and handle the bi-directional power flow between the main DC bus and sub DC buses in order to regulate the bus voltages. The sub HVDC interface is used to handle high voltage DC storage and non-critical DC or AC powered loads. The sub LVDC interface is used to handle the low voltage storage and critical sensitive electronic appliances. Thus, the DCT can be considered as a three port energy router and this characteristic makes it suitable to enable capability for handling both high and low voltage DC storage and DC or AC loads with better performance as compared to conventional AC or DC microgrids.

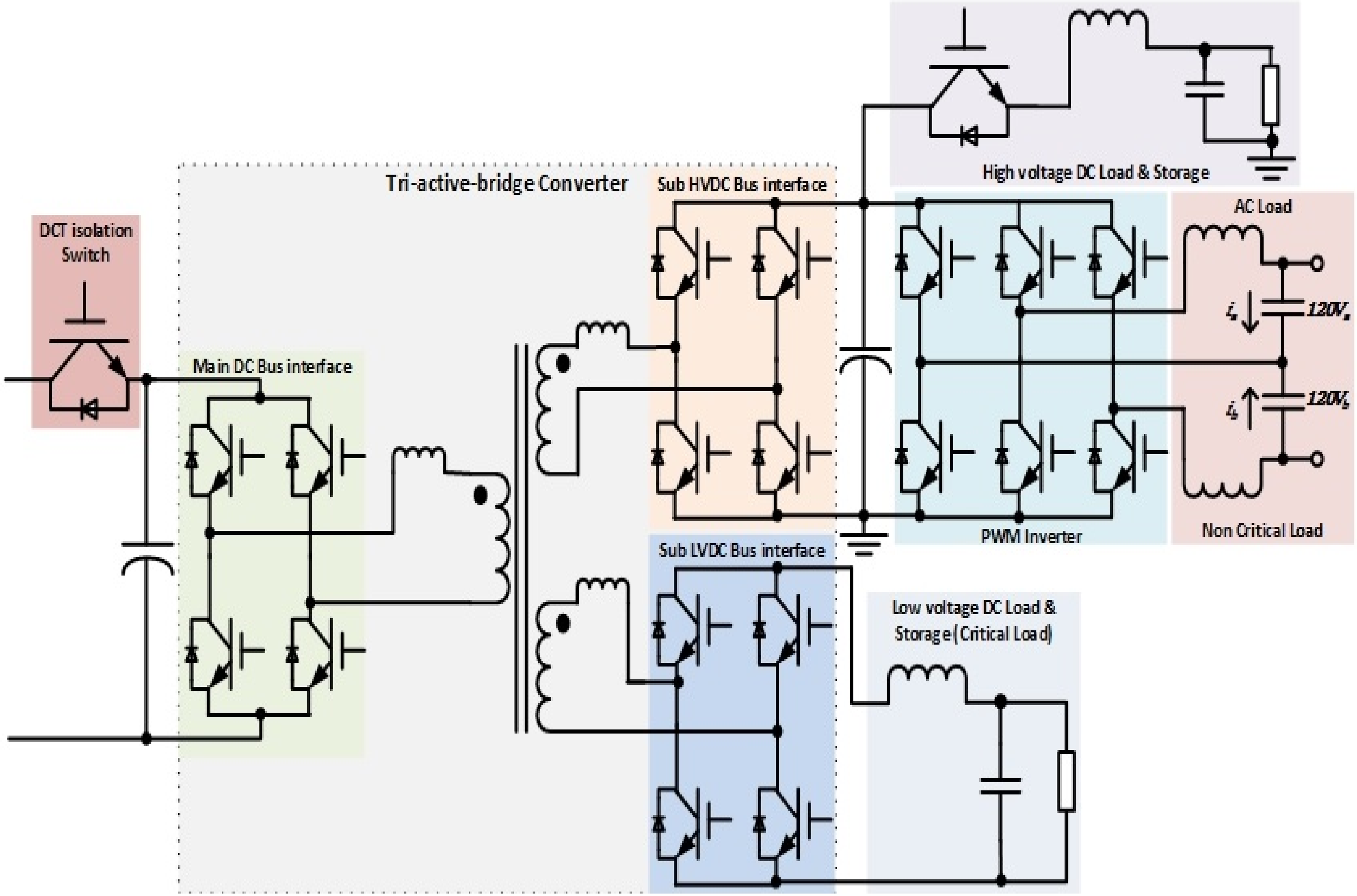


Figure 2.2: DCT enabled PCmRC consumer grid Architecture

2.2.3 Interfaces for sources and storage

Figure 2.3 shows the standard interface of renewable, distributed sources, storage and bi-directional AC main grid for backup power. All sources and storage modules share a common main DC bus through a power electronics interface. The reason for using a standard interface is to assure the entire grid reliability and scalability of the consumer grid. Every interface operates autonomously and there is no impact on grid performance and control algorithms due to increasing or decreasing the number of renewable sources, storage and AC maingrid connections. The PCmRC consumer grid model always maximizes the exploitation of renewable sources and only takes balance power from main AC grid, if required to avoid load-shedding. Therefore, the PCmRC ensures the "plug-and-play" function of all types of micro sources, storage and main grid connections. PCmRC manages available power either only from main grid in the absence of renewable distributed energy sources or only from renewable sources in the Off-grid Islanding condition without any upgrading.

2.2.4 Load classification and demand side energy management

The main function of the local generators and storage system is to ensure the reliable and continuous supply of power to loads by reducing the dependency on AC maingrid. Therefore, demand management is the key category for microgrid control. The unique power distribution scheme used in PCmRC depends upon the priority level of the load and can handle both AC and DC power loads connected to the consumer grid [112, 143]. The priority level is defined as per the consumer requirements and it is divided into two categories such as critical and noncritical loads. In worst case scenario, during a main grid fault, limited generation from renewable sources and the energy storage is also not enough to fulfill all power requirements of the consumer gird. Then PCmRC makes sure continuous power supply for only the critical loads and switched off the noncritical loads. In this way, PCmRC allows consumers to configure the priority level of the loads depending upon the importance and utilize the energy storage in more efficient way.

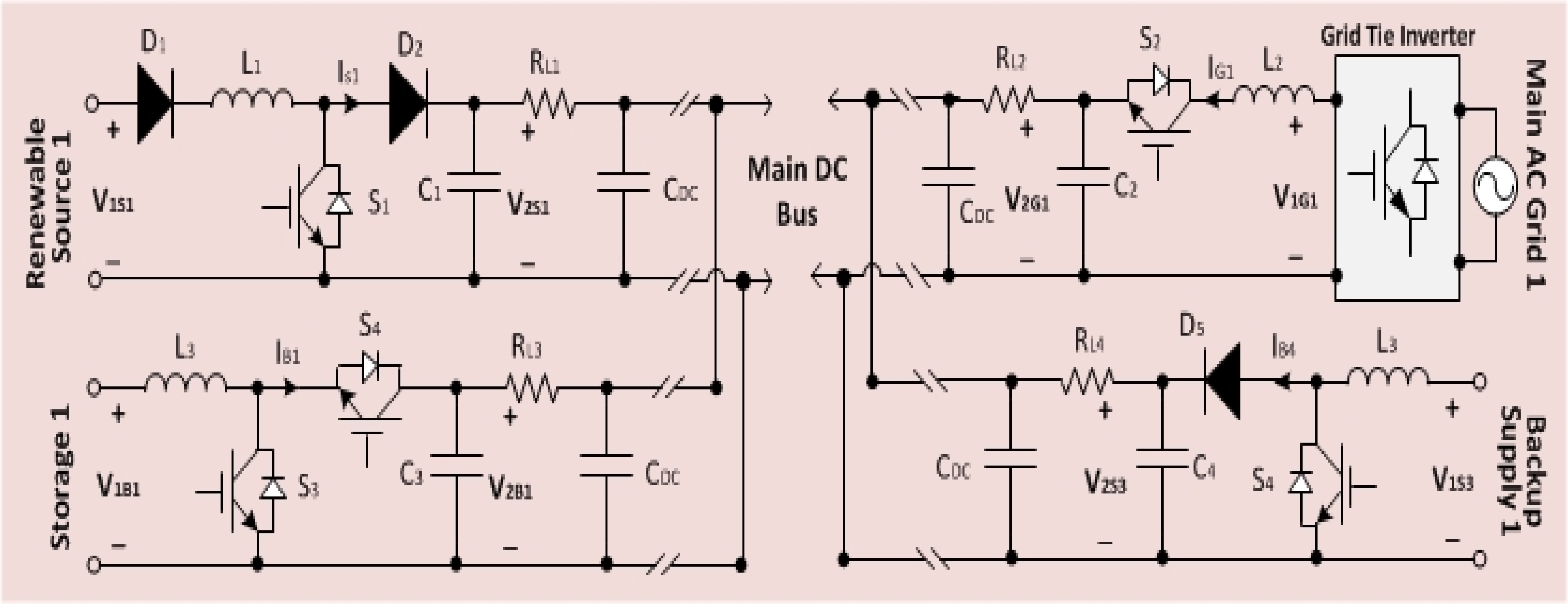


Figure 2.3: DCT enabled PCmRC consumer grid Architecture

2.2.5 Fault Protection

As discussed earlier, the DCT module is used for power distribution and demand side load management. Each DCT continuously monitors both main bus interface and sub DC bus interfaces. On detecting any anomalous situation such as over under voltage and short-circuit current, the respected DCT(s) immediately switch-off and isolate the fault within the grid. Moreover, battery storage can be directly coupled on the sub LVDC bus (24V) without any additional converter. Therefore, it has voltage-sag ride through capability, which increase the overall reliability and protection for sensitive electronic loads.

2.2.6 Islanding and Grid connected operations

Off-grid and remote power systems are independent from utility power grid such as remote telecoms sites, military bases, check-posts, aircraft, ships, detainee and training centers [53, 61, 88]. Since, all sources and storage are plug-and-play; the PCmRC intelligently manages available power either only from main grid or solely from renewable sources (if any). Therefore, during main grid fault (weak-islanding) or in the absence of utility grid, PCmRC manages power solely coming from renewable sources and available storage without any upgrade.

2.2.7 Compatibility with existing infrastructure

As mentioned above, all sources and storage are plug-and-play. If there is no renewable source and storage connected, then PCmRC will start taking power from maingrid. Furthermore, PCmRC can manage power requirements with or without renewable sources, storage devices and grid connection. Therefore, in existing infrastructure where the primary source of power is only AC maingrid, PCmRC can drive entire DC microgrid on AC maingrid perfectly without any additional up-gradation or change in grid control algorithm.

2.2.8 Single and parallel DCT operations

The main advantages of DCT module enabled PCmRC-grid model includes i) Standard architecture leads toward lower down the cost and fault tracing time. ii) High level of reliability can be achieved by introducing multiple level of redundancy. iii) Wide range of demand-side power requirements can be fulfilled by cascading multiple modules together and power system can be configured easily as per consumer demand [103, 126].

DCT is a bi-directional and configurable DC-to-DC converter module, which is responsible to regulate both High-voltage and low-voltage DC buses, protects from any type of fault and continuously manages storage.. Single or Multiple modules of DCT can be cascaded in parallel, in order to fulfill load requirements. DCT inputs on both side is DC voltages, therefore, there is no issue of frequency synchronization or factor factor corrections. DCT modules are distributed as per load requirements and autonomously control and manage entire grid.

2.2.9 Overview of overall grid stability and reliability

The PCmRC consumer grid mode overcome the all issues associated with the overall power distribution stability and reliability for both DC microgrid and the connected AC maingrid.

- **Non-Sinusoidal current:** As discussed earlier, AC maingrid or backup power generator is integral part of the DC microgrid. The power from AC maingrid or backup generator has indeed to be convert into DC, before inserting in DC microgrid. The easiest and most economical method to convert AC into DC power is to use *"Diode bridge-rectifier"* However, diode rectifier technique introduces non-sinusoidal current and low frequency harmonics on AC grid side, which may cause power quality issues [21, 46, 90]. This is the reason, in PCmRC consumer grid model DCT is used as a bidirectional Triple active bridge topology and all sources are connected through the power electronics interface as shown in figure 2.3, which prevents main grid reliability issues.

- **Ground loop-currents and Neutral shifting:** AC grid neutral point and Ground potential of DC bus are tightly couple through rectifier diode; resultant DC rail will start picking lowest potential of AC neutral-side and start shifting from Zero to Negative DC voltage. Furthermore, loop current starts flowing between the DC bus and power converter, which may cause oscillations on DC negative rail [15, 17, 71, 81, 146]. This is the reason, instead of using diode rectifier, in PCmRC model the grid interface is connected through controlled power converter and it would be used to acquire the balance power only from main grid.

- **Voltage sag:** It is a short duration of voltage dip occurred on main voltage bus by activating heavy power load. This momentary dip in voltage causes malfunctioning or damage to sensitive electronics load [15, 48, 109]. In PCmRC model, battery storage is directly coupled with without any central communication interface and it charge and discharge autonomously. Therefore, it has voltage-sag ride through capability and suitable for sensitive electronic loads.

- **DC capacitance discharge and shunt-fault isolation issues:** In DC power supply, capacitors are used for smoothing and filtering the ripples ride on the DC voltage. Moreover, capacitors are directly coupled on the converter outputs and with DC buses, which is used to provide short-term energy storage for grid citeDCProtectionMaqsood, samuelsson2005speed. However, during shunt-fault capacitors discharge heavy current, which produces high EMC, thermal and mechanical damages to grid [12, 13, 91]. Therefore, proper shunt protection system required for DC microgrid.

This is the reason, in PCmRC consumer grid model DCT module is used for power distribution and management. DCT is continuously managing the power requirements of connected loads. Therefore, each DCT is continuously monitoring both high voltage and low voltage DC bus and on detecting any anomalous situation, respected DCT immediately switched-off. In this unique technique, DCT not only detects fault accurately, but also isolate the fault.

Chapter 3

Overall control algorithm design

3.1 Overview and motivation

The conventional AC microgrid usually operates in two modes such as Grid connected mode and islanded mode [5, 87] and it has different control and operation methods for both scenarios. However, in DC consumer grid the mode of operation is slightly different, for example the utility grid is connected through the AC-DC bi directional converter and depending upon the bus voltage, the interface converter allows to exchange of power either with utility grid to consumer grid or vice versa [11, 107, 144]. The motivation behind the DC consumer grids is to make feasible the integration of renewable sources and storage at any stage in the consumer grid without sophisticated DC-AC inverters. But in most cases all renewable generators and sources have finite power handling capability, unlike the utility grid interface which has capability to handle infinite power capacity.

Therefore, in DC microgrids intelligent utility-power regulation is required and it is also treated as a finite power link just like other renewable sources and storage, using this interface for only balance power or backup supply in the absence of local sustainable generators and storage. To demonstrate the DCT enabled PCmRC consumer power management strategy and detailed control scheme is outlined in this section. The main DC bus must be well maintained and operates between the rigid upper and lower limits. In case of any anomalous condition the DC bus voltage can collapse the whole DC microgrid operation. Therefore, a robust and reliable control and management scheme required for the effective and sustainable consumer grid operation. The overall flow chart of PCmRC consumer model is shown in the Figure 3.1, which is fully compatible for Off-grid and conventional grid connected grids operations. The PCmRC consumer grid consists of the following terminals.

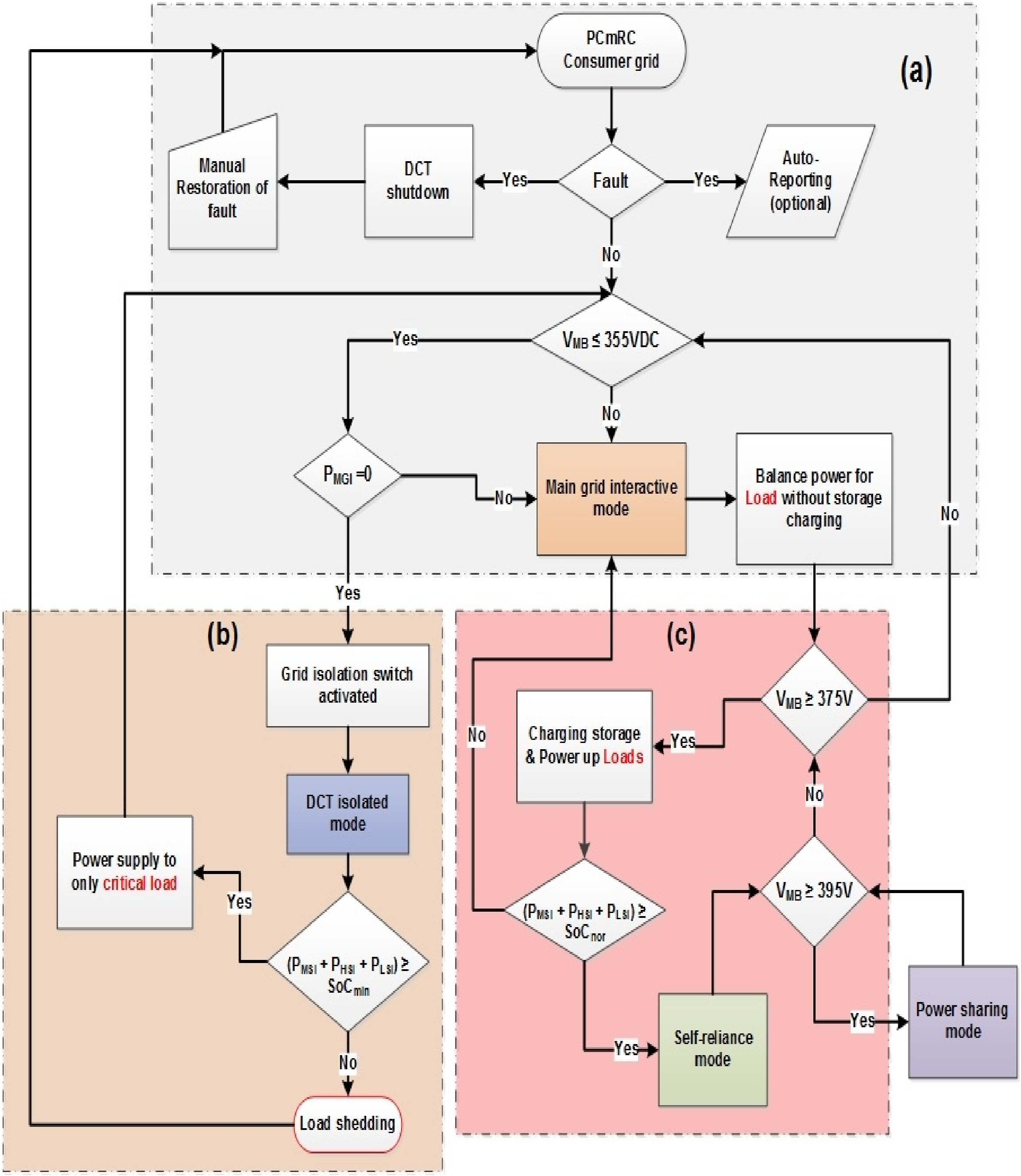


Figure 3.1: The overall operational control flow chart of PCmRC consumer grid model (a) in case of grid connected mode without local generators (as per convectional consumer grid) (b) In case of DCT isolated mode (c) in case of the off-grid mode.

3.2 DCT control

The DCT is the brain and hub of all power management in the PCmRC model. It provides 24V on sub LVDC bus and 300V on sub HVDC bus for high voltage DC and single phase AC output for conventional AC loads. The three stage DCT control diagram is presented in Figure 3.2 and symbols used in the control diagram are presented in Table A.1.

The DCT converts AC to AC for step-up or step-down voltage as the conventional electrical transformers but in a more efficient way with embedded protection and small footprint. As shown in Figure 2.2, the DCT consist of three I/O ports with high frequency transformers, DC to DC, AC to DC and DC to AC conversions. In normal operation, the power is transferred from the main voltage bus to the sub voltages buses and the sub LVDC/ HVDC H-bridge works as a control rectifier (AC to DC). The d-q vector control diagram of single phase rectifier is shown in Figure 3.2((a)). Both high voltage DC main bus and power factor are controlled by a dual loop controller and manage the real and imaginary values of the current and voltage. The outer and inner loop of d-axis component is controlling the active power control loop (both voltage regulator and current loop) and the q-axis is controlling the reactive power control loop and its reference is set to zero (i_{sqref} =0) for unity power factor operation [123].

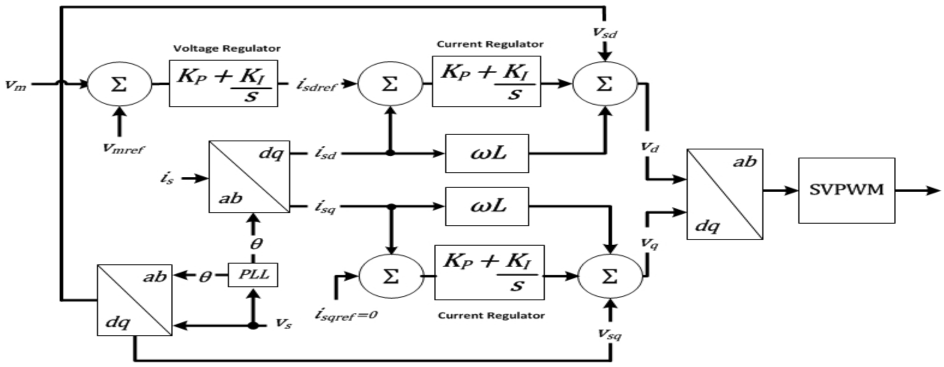
The Triple-active bridge topology used in the DCT offers zero voltage switching, less stress on switches and bi-directional power flow. The difference in the phase shift determines the power transfer between the main DC bus to sub DC bus [157]. Therefore, phase shift control is used in DC to DC conversion stage as shown in Figure 3.2((b)). The power transfer is controlled by configuring the phase shift on both primary H-bridge and secondary H-bridge side, which regulates the sub DC voltage bus to the appropriate voltage levels as given by following Eq 3.1 and Table A.1.

$$P_{Output} = (V_h)/2Lf\varphi(1-\varphi) \tag{3.1}$$

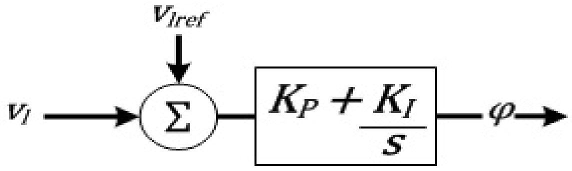
The inverter stage uses the capacitor current feedback control for better voltage output by sensing the current from output capacitor [123, 125]. The inner loop is controlled by the capacitor current and output AC voltage is controlled by convectional PI controller as the outer loop, as shown in Figure 3.2((b)). A split phase inverter topology is used in the DCT, which supports 120V and 240V AC voltages regulated outputs as shown in Figure 2.2.

3.3 Storage control

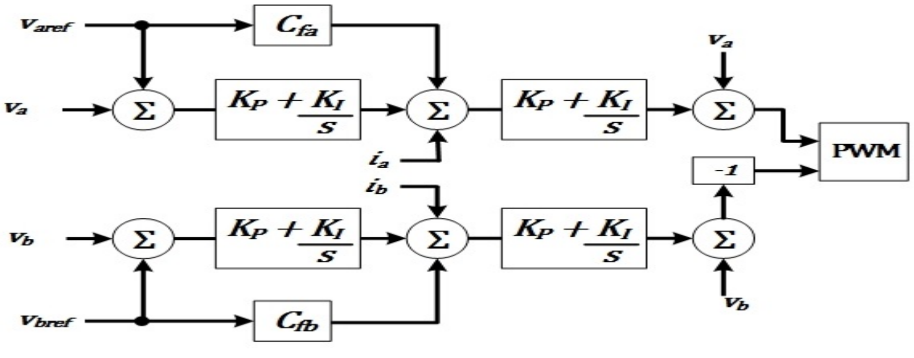
The DCT enabled PCmRC architecture can accommodate both distributed and local energy storage. The distributed energy storage is connected on the main DC bus and local (low voltage) battery storage is connected on the sub DC buses. However, the distributed energy storage is considered as a backup source and it operates autonomously. The interface diagram of the



(a) High voltage AC to DC control stage



(b) DC to DC control stage



(c) Sub voltage DC to AC inverter control stage

Figure 3.2: Control diagram of proposed DCT (a) High voltage AC to DC control stage (b) DC to DC control stage (c) Sub voltage DC to AC inverter control stage

energy storage is shown in the Figure 2.3, which allows the bi-directional flow of the current depending upon the SoC of the battery and mode of operation of the PCmRC grid.

In this section, we will discuss the operation of DCT controlled locally connected battery storage. The operation of the battery storage connected on the sub DC buses is dependent upon the State of charge (SoC$_{bat}$) of the battery. The PCmRC allows consuming of storage power up the loads as long as SoC$_{bat}$ is within limits, as shown in the Figure 3.3((a)) (SoC$_{min}$ $\leq$ SoC$_{bat}$ $\leq$ SoC$_{max}$). Therefore, PCmRC operates the locally connected battery storage in three modes i.e. charging, discharging and standby. The PCmRC always charges the battery storage in only self-reliance and power sharing modes and standby in maingrid interactive mode. It exploits the locally available storage in DCT isolated mode to power up the critical loads only. The PCmRC only charges the locally available storage from surplus power generated by the renewable sources and never charges the storage from maingrid supply just to reduce the consumption and dependency on maingrid, moreover, it helps to reduce the carbon emissions. The detail control flow diagram including battery management is shown in Figure 3.1.

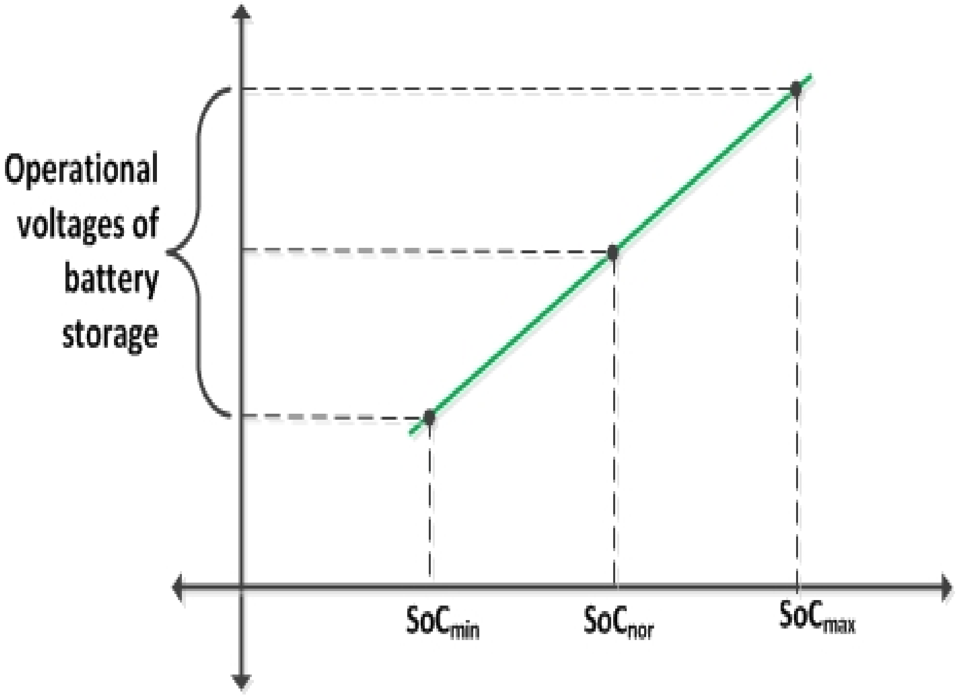
In worst condition, when the renewable sources are not available and PCmRC consumer grid is operating in islanding condition then locally connected storage regulates the sub LVDC bus and system operates in DCT isolated mode. As shown in the Figure 3.3((b)), the outer voltage loop is cascaded with the battery current inner loop, until the SoC$_{bat}$ reaches down and equals the SoC$_{min}$ to avoid over discharging of the battery storage.

3.4 Sustainable sources control

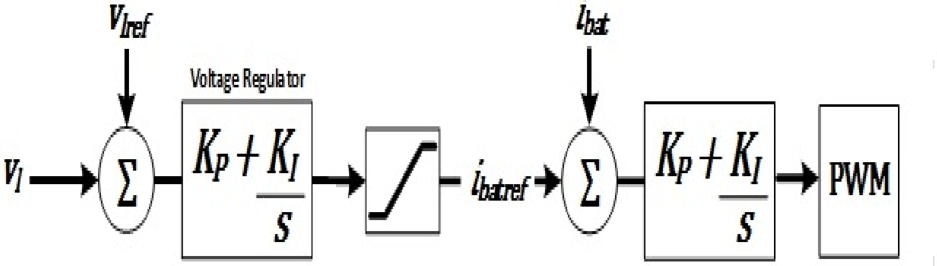
The key feature of the PCmRC consumer grid architecture is to manage any number of renewable and distributed sources. However, all types of sources are connected to the main and sub DC buses through standard interface circuit, as shown in Figure 2.3. As per control point of view in PCmRC, all type sources are classified into two group i.e. renewable and non-renewable source. The rectified output of renewable source is connected to the boost converter. The boost converter operates in the maximum point tracking (MPPT) mode, which shown as a MPPT block in Figure 3.4(a). In order to achieve effective control and optimum operation of MPPT both current and voltage are sensed on individual renewable sources [76, 102].

3.5 Distributed sources control

For non-renewable sources, MPPT is switched off and only power tracking is done by sensing output current and voltage of the individual source. Usually, back generator sources have slow dynamic response, therefore a dual control loop technique is used for fast tracking [155]. The outer loop is the power control loop and the inner loop is the current control loop, as shown in



(a)



(b)

Figure 3.3: Simulation waveform of Grid connected mode (a) Minimum and maximum Battery SoC imits and optimum operational point (b) Battery SoC control diagram in Sub LVDC bus voltage tracking mode

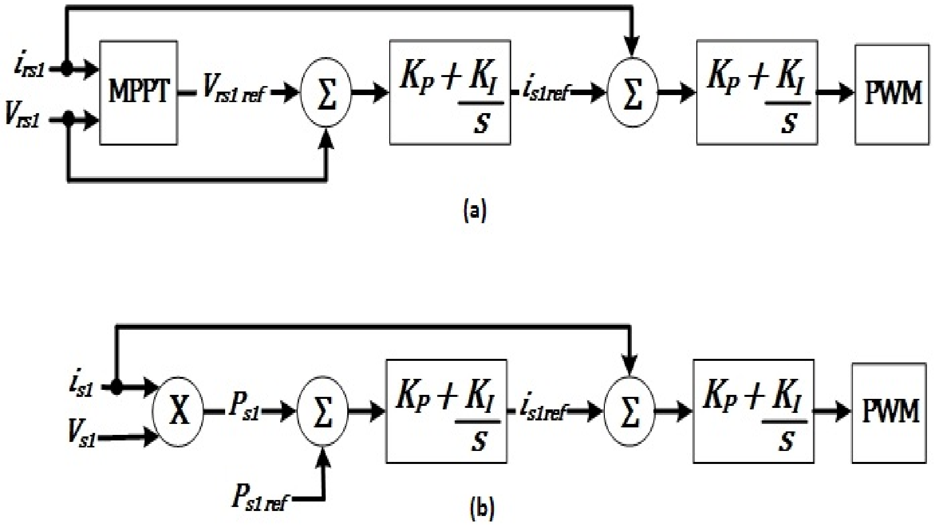


Figure 3.4: Control diagram of sources (a) Renewable source control diagram (b) Non-renewable source control diagram

the Figure 3.4(b)

3.6 Grid connected and islanding control

PCmRC considers maingrid connection as a finite energy source and maingrid is always connected through the standard interface to the main DC bus like any other sources, as shown in Figure 2.3. Therefore, multiple grid connections can be interfaced to the PCmRC in order to increase the redundancy, reliability and power sharing requirements with the adjacent grids. Moreover, the PCmRC control algorithm would be same for grid-connected islanding and off-grid operations without any upgrade. In case of convectional power distribution where the maingrid is the only source of power and there is no local generator available, the PCmRC can manage the maingrid power to power up only loads, as shown in Figure 3.1(a). Therefore, PCmRC architecture is perfectly compatible with existing systems because in a convectional power distribution system the maingrid is the only source of energy. If there is no source available locally and consumer grid is operating in islanding mode the PCmRC will provide power only to critical loads, until the storage depletes, as shown in the Figure 3.1(b).

3.7 Off-grid control

As mentioned above, PCmRC treated grid-connection is just like any other source and is plug-and-play. Therefore, if there is no grid-connection or consumer grid installed at a remote location where there is no existing power distribution infra-structure then PCmRC will operate the whole consumer grid on locally available sources and storage. However, the local generators must supply enough power to fulfill load requirements, as shown in the Figure 3.1(c).

3.8 Critical and non-critical load control

In the early 19th century, AC power system started replacing the DC power system because AC power generation and distribution is much easier than DC. Therefore, almost every electronic appliance available in market is designed for AC power input, even though it can be operated solely on DC power [112, 114]. However, we still have few inductive loads that require AC power for normal operation. In order to fulfill AC load power requirements, a sophisticated DC-AC power inverter is required in DC microgrids [15]. To overcome this potential problem, the topology used in the DCT has capacitive feedback inverter stage for handling the AC powered load the detail control diagram is shown in figure 3.2((c)). Excluding DCT isolated mode, PCmRC always ensures continuous supply to all type loads including critical and non-critical connected to the consumer grid.

Chapter 4

Overview of DCT enabled PCmRC power management strategy

4.1 Introduction and motivation

Zero or positive energy buildings and communities are a promising and realistic concept. According to article #9 of the Energy Performance Buildings directive (EPBD) [32] member states shall ensure that by the end of 2020 (2018 for public buildings) [10], all new buildings are nearly zero-energy [28,73]. The full exploitation of renewable sources and efficient integration of storage devices with effective and reliable consumer grid control model is required to realize Zero/ positive energy buildings and communities [75, 145]. Each house or building is considered as a microgrid, in this way each microgrid is responsible to generate its own power by using distributed and sustainable energy sources. Due to the penetration of DC appliances in our society, DC microgrids are gaining interest for two following main reasons.

- Most renewable sources generate DC power.
- DC storage can be integrated at any level without additional power converters, which decreases the grid overall installation cost and increases the reliability.

However, the major drawback of all time of renewable sources is that they are stochastic in nature, because of this we cannot rely totally on the renewable sources for all time. In order to overcome this problem, the proposed consumer grid model never depends upon any specific type of renewable or distributed source. The PCmRC consumer grid model provides a standard interface for all type of renewable sources, storage, local generators and AC maingrid interfaces, as shown in Figure 2.3. DCT enabled PCmRC utilizes the micro-sources available locally and to avoid load-shedding always takes balance power from the AC maingrid. Therefore, this futuristic model is perfectly compatible with the existing infra-structure without any upgrade or modification. Figure 2.1, shows the model of the proposed concept of the DCT enabled Power controlling, monitoring and routing center. The DCT module is connected between the main DC distribution bus and sub DC buses are connected on the consumer side. There are two main purpose of the main DC bus, firstly to integrate all zonal microgrids (DCT modules) onto the same bus and secondly to integrate the large scale generators, back-supplies and main grid connections. In this way, all zonal dc microgrids can share power locally because the load of each consumer grid is not constant and in case of any distributed zonal grid being unable to utilize the storage locally then it can share the surplus power with other zonal microgrids via AC maingrid interface. The more important factor is in DC microgrid there is solely one control parameter i.e. DC bus voltage to consider [7,116], therefore, if the bus voltage starts to drop then each zonal microgrid starts pumping surplus power getting from locally generated sources and storage to share DC bus for regulating the main DC bus voltage up to optimum level. However, in this paper only one consumer grid model is discussed and this concept (model) will be the same for the other zonal consumer grids.

All DCT modules use modified-droop control technique to manage the main and sub DC buses voltage (this will be discussed in detail in this chapter). The main DC bus will operate between 350V to 400V, if the main bus voltage crosses lower limits then all connected DCT modules operate in isolated mode. In isolated mode, each DCT only uses the power from micro-sources and storage connected on the sub DC buses, switched-off the non-critical loads ensuring continuous supply to critical loads until the storage will drain or local generator will stop generating required power. The most critical part of the LVDC consumer grid is the SOC (State of charge) management of the storage. Typically the battery storage is less than the overall power requirement of the load connected to the consumer grid. The traditional droop control uses battery storage as a switch between automatically charging and discharging mode. To avoid this condition, the storage will switch to constant charging mode when the main DC bus voltage reaches 380VDC, which will be discussed in detail in Self-reliance mode. It means the power requirement of the loads is less than the surplus power generated by the renewable energy sources. In order to operate the DCT module as an intelligent energy router, it must be operating in different operational grids condition. Most researchers propose 03 stages of grid control as discussed in [122, 155]. However, in PCmRC consumer grid model we propose four stages (excluding buffer stage), in order to get effective control on power flow and increase the overall grid reliability. The different operational modes are shown in Figure 4.1.

4.2 DCT isolated mode

In DCT isolated mode, the power required by the load is greater than the locally available power and the whole grid is operating in islanding or off grid condition, as mentioned in Eq

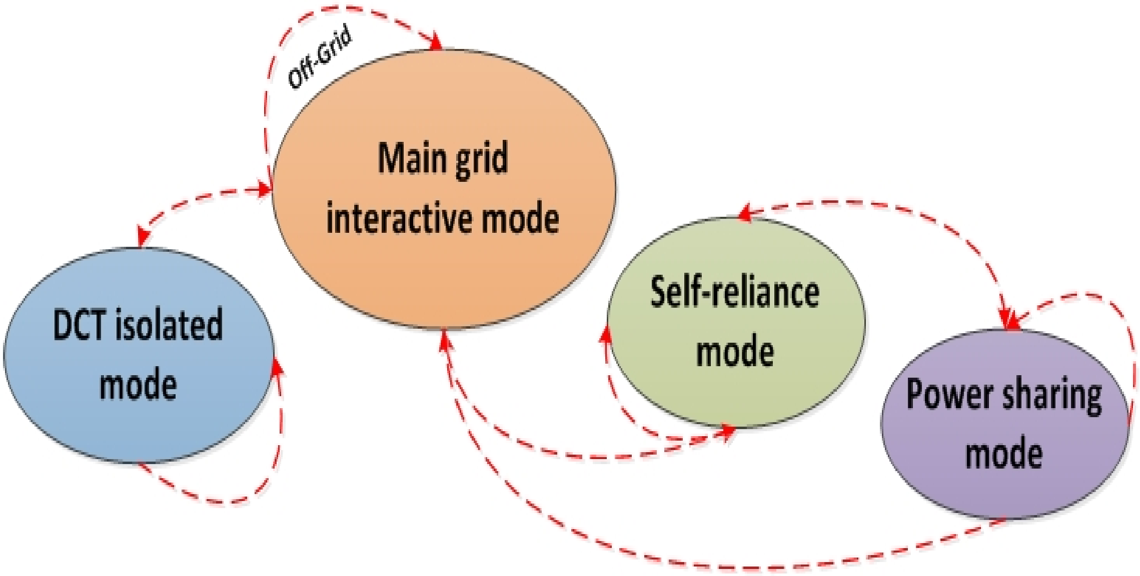


Figure 4.1: PCmRC operational modes flow diagram.

4.1. Therefore, the main bus voltage is starting to decrease until it reaches to the point A, as shown in Figure 4.2. Then each connected DCT starts working in isolated mode and there will be no power flow from sub DC bus to main DC bus. In this mode, each DCT module switches off the non-critical AC and DC loads so that the sub HVDC bus voltage becomes "Zero volt", if there is no storage connected on the sub HVDC bus. The locally available storage is solely utilized to operate only critical loads connected on sub LVDC bus, until the storage depletes or back-supply grid interface starts delivering power to microgrid to avoid load-shedding.

$$\begin{gathered}(P_{SLO} \geq (P_{MSI} + P_{HSI} + P_{LSI}) \\ \because P_{RSI} + P_{DGI} + P_{MGI} = 0(P_{HLO} = 0)\end{gathered} \tag{4.1}$$

4.3 Maingrid interactive mode

In the main grid interactive mode, the output power (connected load) of the grid is greater than the generated power from renewable sources and local distributed generators. However, maingrid interface and storage is available. In this case, PCmRC will only take the balance power from the main grid to fulfill the load requirements and keep the sub DC buses within certain voltage limits as shown in Table 4.1. If the sub voltage buses operate in these operational limits then PCmRC will keep the storage isolated. In maingrid interactive mode, PCmRC operates grid in the region between point A and B, as shown in the Figure 4.2.

In this region, only balance power is taken from the maingrid interface just to power up the load connected on the sub HVDC and LVDC buses and storage is considered to take “Zero current”, as shown in Eq 4.2.

$$\begin{aligned}(P_{HLO} + P_{SLO}) &= (P_{RSI} + P_{DGI} + P_{MGI}) \\ &\because P_{MSI} + P_{HSI} + P_{LSI} = 0\end{aligned} \tag{4.2}$$

4.4 Self-reliance mode

If the output power or load connected to the grid is less than or equal to the power generated by the renewable sources and consumer-grid can fulfill demand side power requirements without taking power from the AC maingrid is called self-reliance mode. In this mode, PCmRC ensures the power supply to both critical and non-critical loads and balance power will be used to charge the storage connected to DC buses. In Figure 4.2, the region between point B and C is the self-reliance region and in this mode the energy storage is treated as a load, as shown in the Eq 4.3.

$$\begin{aligned}(P_{HLO} + P_{SLO}) \leq (P_{RSI} + P_{DGI} - P_{MSI} - \\ P_{HSI} - P_{LSI}) \because P_{MGI} = 0\end{aligned} \tag{4.3}$$

4.5 Power sharing mode

In case of storage fully charged and surplus energy generated by local generators the PCmRC will start sharing power surplus power to the AC main gird, which is called Power sharing mode. In this mode, the maingird is also treated as a load and balance power is sent to the AC main grid via grid-tie inverter as shown in Figure 2.3 and Eq 4.4.

$$\begin{aligned}(P_{HLO} + P_{SLO}) \leq (P_{RSI} + P_{DGI} - P_{MSI} - \\ P_{HSI} - P_{LSI} - P_{MGI})\end{aligned} \tag{4.4}$$

As discussed earlier the renewable sources are stochastic in nature and demand-side power requirements may increase exponentially which cause grid stability problems. To avoid such scenarios, PCmRC introduces a buffer state while moving from Main grid interactive mode to the self-reliance mode in order to meet the unpredicted load requirements and to increase the grid stability. The main reason to use this buffer state is that, in main grid interactive mode, the renewable sources and AC main grid both are used to supply power solely to connected loads and storage is kept isolated. As renewable sources output power increase gradually, as soon it becomes equal to the load power requirement the PCmRC enters in self-reliance mode at point

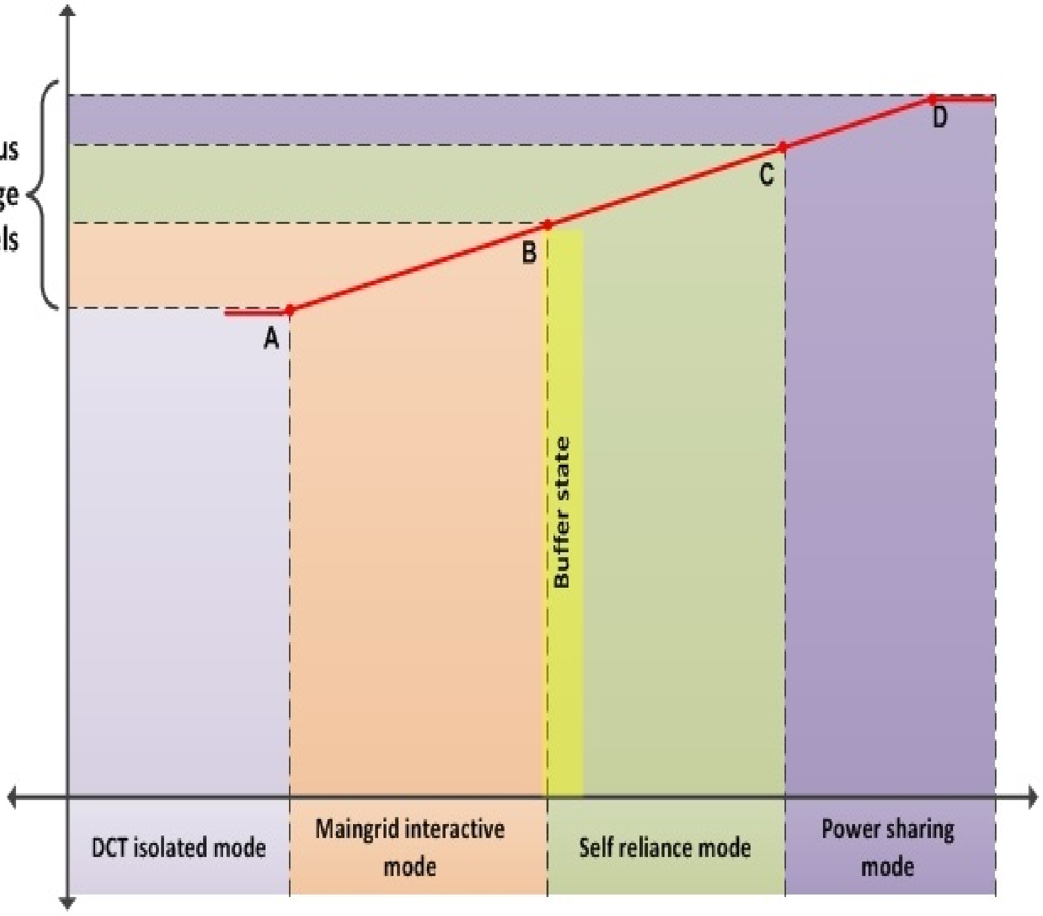


Figure 4.2: PCmRC operational modes graphical diagram.

B shown in Figure 4.2. But due to bad weather conditions or sudden increasing load power requirements the power generated from renewable sources might not be enough to meet that change and at that stage, storage is also not charged enough to compensate the deficiency of power. Therefore PCmRC introduces buffer state for smooth transition between the main grid interactive mode to self-reliance mode. Moreover, in buffer state, PCmRC also starts to charge the energy storage connected to the consumer grid. In Figure 4.2, the highlighted area is the buffer state and the bus voltages are mentioned in Table 4.1.

Table 4.1: List of key parameters of PCmRC Model

Mode of operation	**Main DC bus**	**Sub HVDC bus**	**Sub LVDC bus**	**Power flow**
DCT isolated	V_{MB}≤355VDC	V_{SHB}=0	V_{SLB}≤24.2V	Power coming from locally available storage only. High power AC /DC load is switched off.
Main grid interactive	360V≤V_{MB}≤375V	V_{SHB}≥280V	24.8V≤V_{SLB}≤25.9V	Power coming from renewable sources and AC maingrid. All types of storage are kept isolated
Buffer state	376V≤V_{MB}≤380V	280V≤V_{SHB}≤300V	26V≤V_{SLB}≤28.1V	Power coming from renewable source and maingrid. All types of storage are connected as a Load.
Self-reliance	381V≤V_{MB}≤395V	280V≤V_{SHB}≤300V	28.2V≤V_{SLB}≤28.8V	Power coming from renewable sources only. Maingrid is isolated. All types of storage are connected as a load.
Power Sharing	V_{MB}≫395V	V_{SHB}≫300V	28.8V≤V_{SLB}≤29.5V	Power coming from renewable sources only. Maingrid and all type of storage are connected as a load.

4.6 Evaluation of DCT enabled PCmRC consumer grid model

In order to validate the effectiveness and reliability of the DCT based consumer grid model and smart power management algorithm, a simulation platform is used by using average modeling technique. While simulation different load profiles, renewable and distributed sources output variations and behavior of storage in different grid operational condition would be demonstrated. In this section, we focused on grid transition between different modes, specially if whole grid is working on renewable or distributed energy sources and due to environmental or unpredicted change occurred. Moreover, we discussed the grid connected and off grid modes in details as well as in case of islanding mode if renewable sources also not enough to fulfill the demand side requirements then PCmRC behavior at the time of energy shortage and undergo in load shedding mode.

4.6.1 Overview of different scenarios

In order to verify the proposed PCmRC consumer grid model and power management strategy a simulation model of each control module is built in the Matlab/ Simulink based on the architecture mentioned in Figure 2.1. The average model technique is used instead of the switching model in order to cover large scale power system dynamics [134]. Moreover, average modeling technique speeds up the simulation without losing key characteristics of the system [51]. In the designed test cases and simulation platform, the power rating of the DCT Module is set under 5KVA to simulate typical residential consumer grid, other important parameters such as LVDC load is 750Watts, LVDC storage is 550Watts, AC load is 2.5KVA, AC main grid output voltage is 357V, HVDC bus voltage is 305V. Different scenarios of sources and loads profiles are simulated, however, due to page constraints only key waveforms are shown and explained in this section.

4.6.2 Grid connected mode without renewable sources and storage

When the entire consumer grid operates solely on the power coming from the maingrid, this is called maingrid interactive mode, in which no other renewable or sustainable source and backup generator is available locally. There are different possibilities to enter in maingrid interactive mode, a few of them are discussed in this section. As soon as the DCT detects the main DC bus voltage (V_{MB}) is less than 380V and V_{MB} is continuously decreasing up to 375V then to avoid load shedding, PCmRC enters in the maingrid interactive mode and regulates the sub DC voltage buses and powers up the critical and non-critical loads with power coming from the maingrid, as shown in Figure 4.3((a)). At time t=1.5sec, when the V_{MB} crosses the 375V threshold then Maingrid interface converter is switched-on and PCmRC manages the maingrid power to regulate the main DC bus voltage in between $360\text{V} \leq V_{MB} \leq 375$V.

Before entering in maingrid interactive mode, DCT keeps the sub LVDC bus voltage to $\leq$26Volts, in order to avoid low voltage storage charging. In Figure 4.3((b)), the storage was charged with a constant current of 20Amps. As soon V_{MB} decreases from 377V then immediately, the DCT regulates the sub LVDC bus to less than 26V and the control algorithm of PCmRC is designed in such a way that no storage will be charged on the low voltage side. If the sub LVDC voltage is less than 26V bus voltage, the PCmRC only powers-up the critical and non-critical loads, as shown in Figure 4.3((b)) 4.3((c)) 4.3((d)).

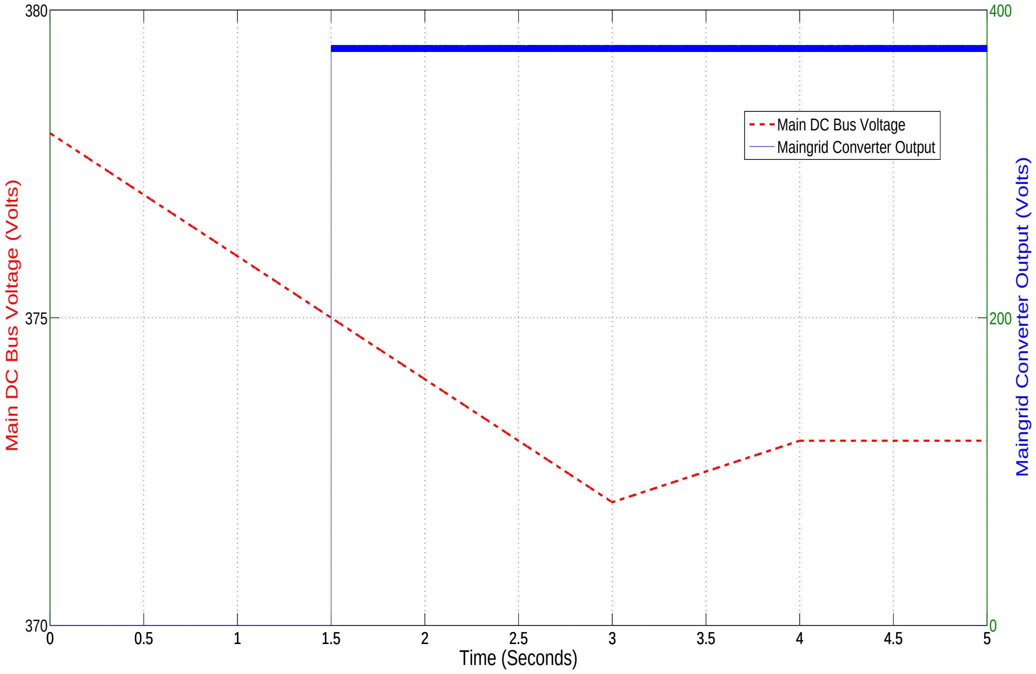
4.6.3 Weak Islanding mode with partial shading

In worst condition, a distribution system fault occurs and on-site renewable or distributed sources are also not generating enough power to operate entire grid in self-reliance mode. In this situation, if the consumer grid is already operating in maingrid interactive mode then if fault occurs and renewable sources are generating enough power to power up the loads then the DCT regulates the bus voltage in between maingrid interactive mode and buffer state, as shown in the Figure 4.4((a)). The DCT regulates sub LVDC bus voltage to less than 26V, as shown in Figure 4.4((a)). The main DC bus voltage is also within operational range, therefore AC and HVDC loads operates normally 4.4((b)), 4.4((c)).

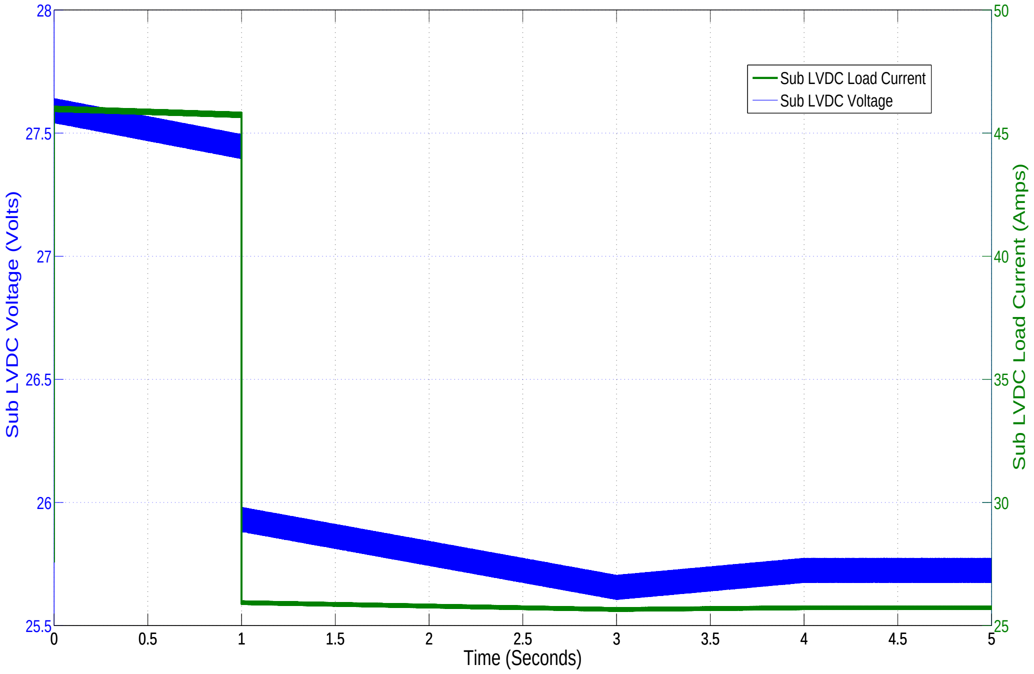
If the PCmRC is operating in DCT Isolation mode due to a maingrid fault and locally available sources generating power less than the rated values and storage are also not available the PCmRC regulates the bus voltages on available power coming from the locally available sources. In Figure 4.4((d)), PCmRC is managing available power to power up the critical loads and regulates the sub LVDC bus voltage within limits. However as is clearly shown in Figure 4.4((e)), 4.4((f)), as soon main DC bus voltage (V_{MB}) increases from 360V then PCmRC starts providing power to non-critical loads or sub HVDC bus. The control algorithm of PCmRC is designed in such a way that when the V_{MB} is higher than 360V and the slope of V_{MB} is negative then PCmRC switches-off the non-critical loads on V_{MB} $\leq$355V. However, if locally available sources start generating power and V_{MB} starts increasing from 355V, then to avoid switching PCmRC will power-on the sub HVDC side on V_{MB} $\geq$360V, as shown in the Figure 4.4((e)), 4.4((f)).

4.6.4 Peak surplus energy generation and on-site storage

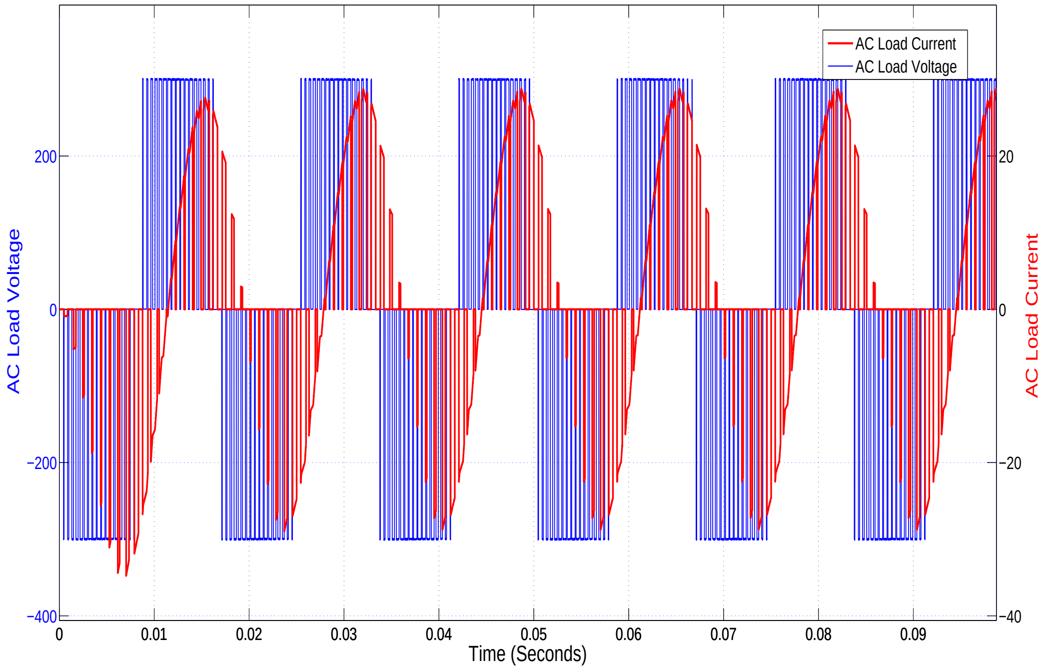
If the locally available sources are generating surplus power that is more than the consumer demand, the PCmRC will operate local consumer grid solely using on-site available sources called self-reliance mode. In Figure 4.5((b)), the slope of the V_{MB} is positive and even though sufficient surplus power is coming from the on-site generators, in order to increase the grid reliability and stability, PCmRC grid operates in buffer state and switch-off the maingrid converter


380
375
370
400
200
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)
Main DC Bus Voltage (Volts)
Maingrid Converter Output (Volts)
Main DC Bus Voltage
Maingrid Converter Output

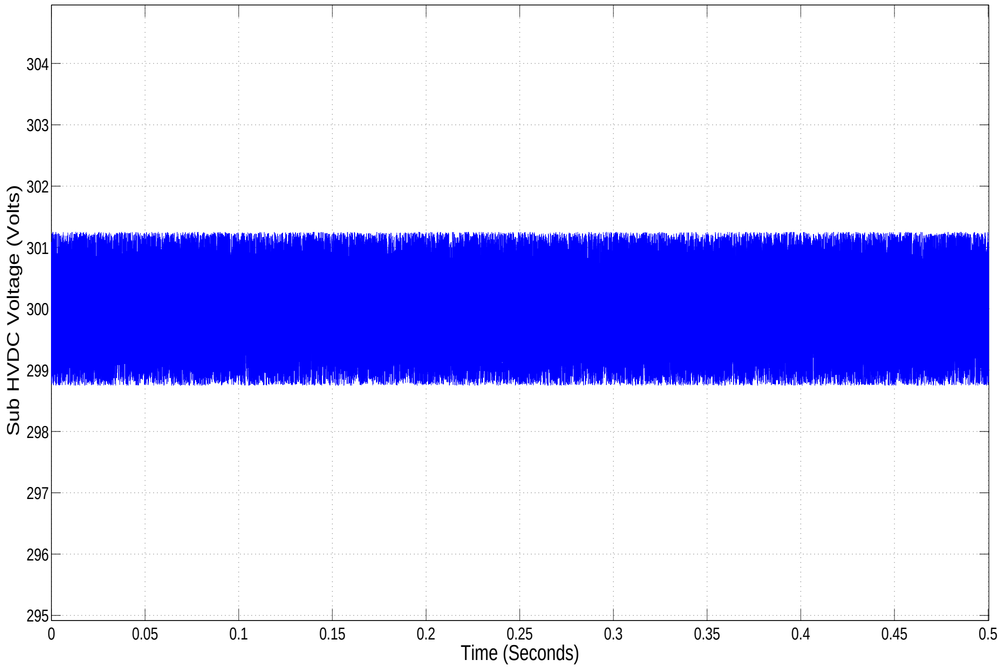
(a)


28
27.5
27
26.5
26
25.5
50
45
40
35
30
25
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)
Sub LVDC Voltage (Volts)
Sub LVDC Load Current (Amps)
Sub LVDC Load Current
Sub LVDC Voltage

(b)

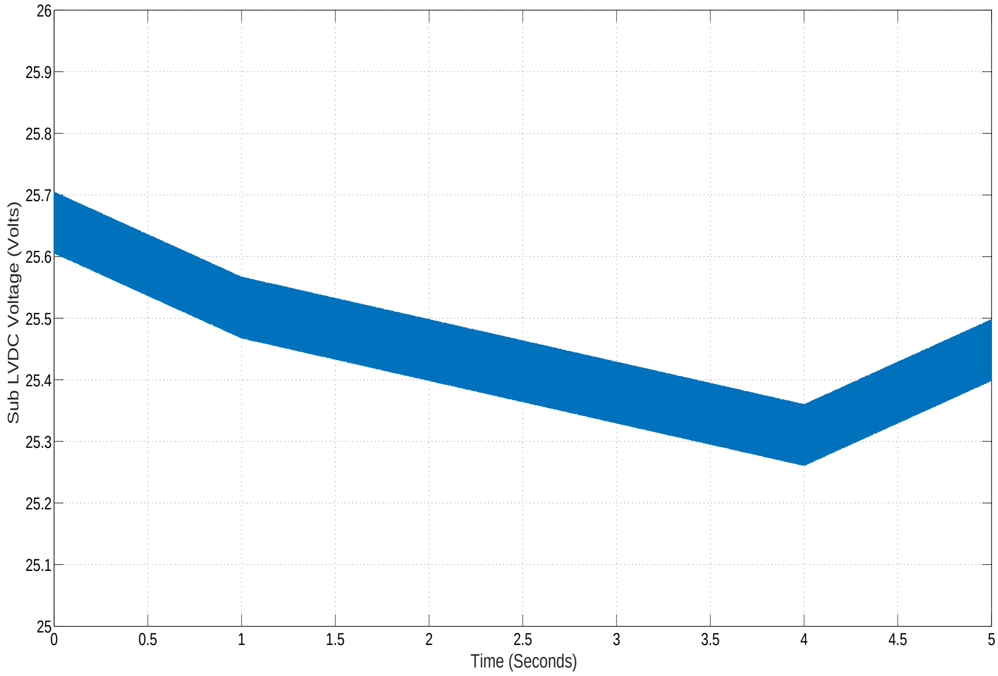


(c)

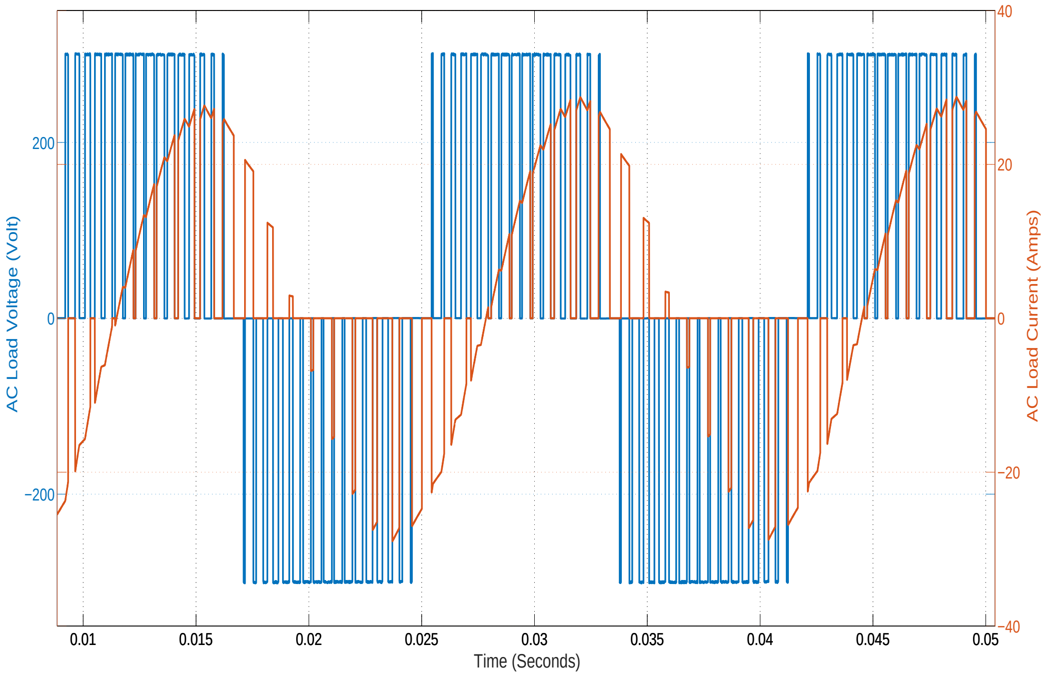


(d)

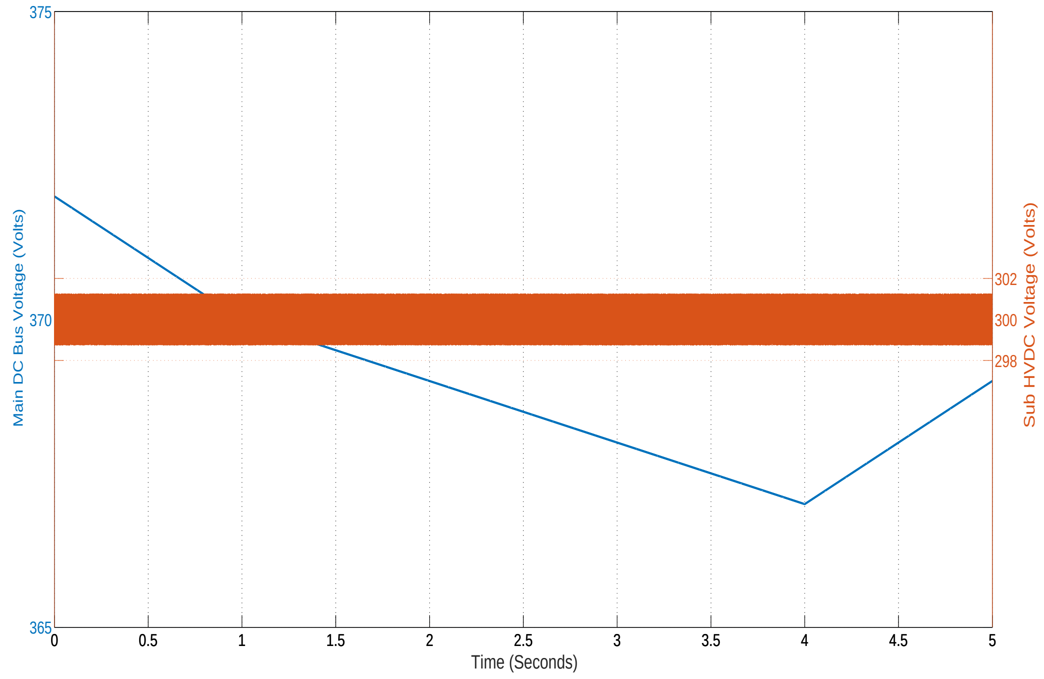
Figure 4.3: Simulation waveform during Grid connected operational mode (a) Main DC bus and Maingrid converter output voltage waveform (b) Sub LVDC voltage and Load current waveform (c) AC Load voltage and current waveform (d) Sub HVDC output voltage waveform


Sub LVDC Voltage (Volts)
26
25.9
25.8
25.7
25.6
25.5
25.4
25.3
25.2
25.1
25
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

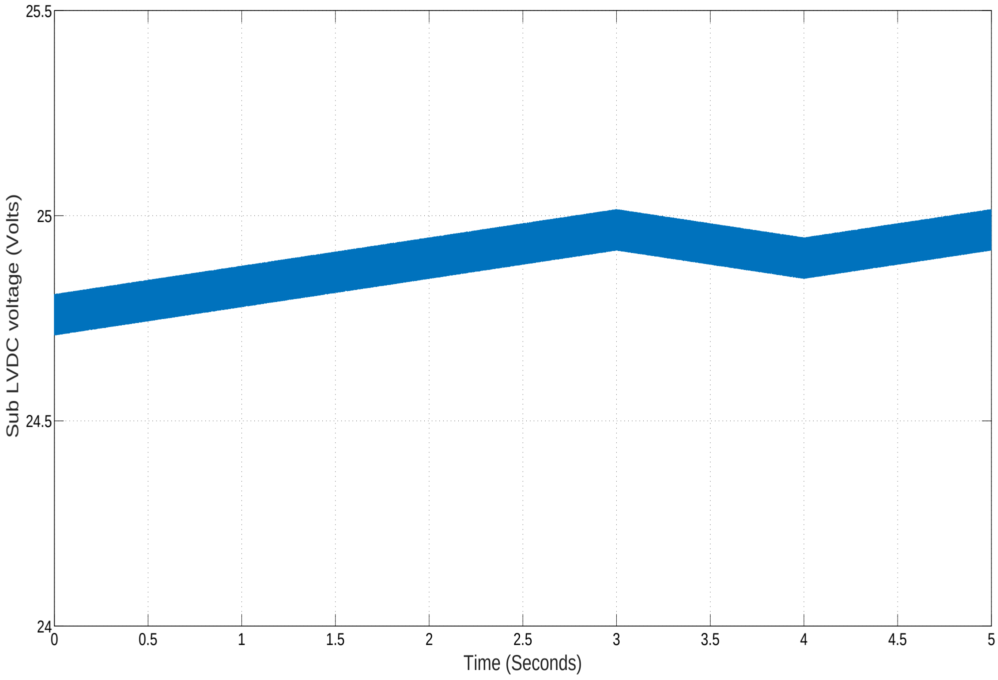
(a)


AC Load Voltage (Volt)
200
0
−200
AC Load Current (Amps)
40
20
0
−20
−40
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Time (Seconds)

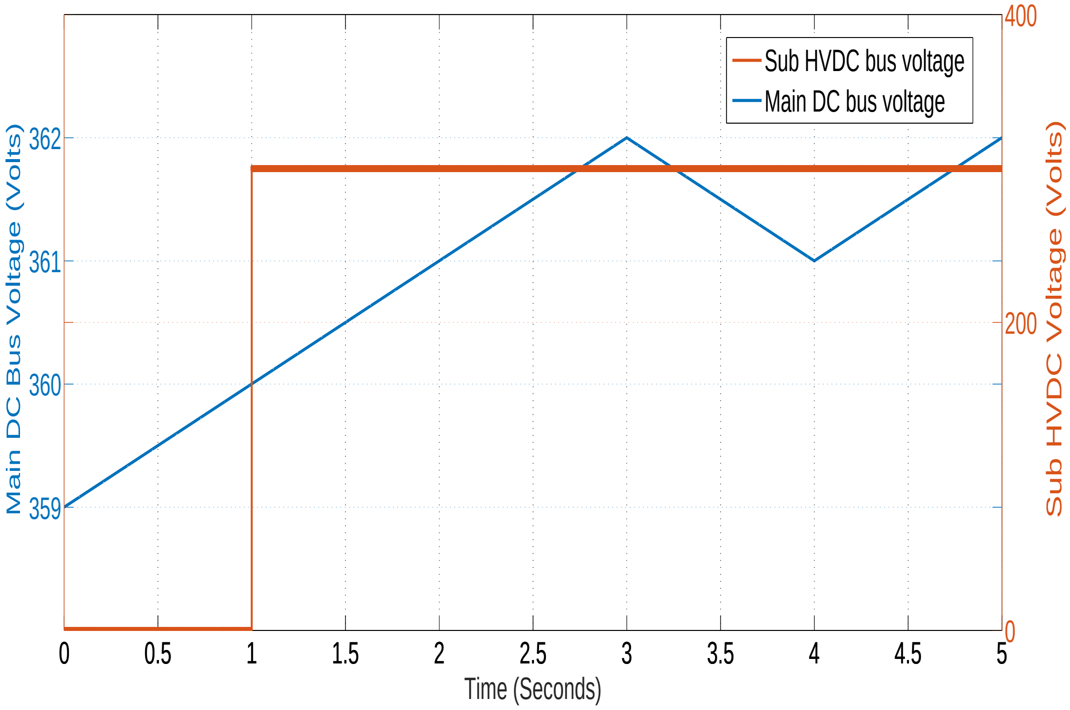
(b)


Main DC Bus Voltage (Volts)
375
370
365
Sub HVDC Voltage (Volts)
302
300
298
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

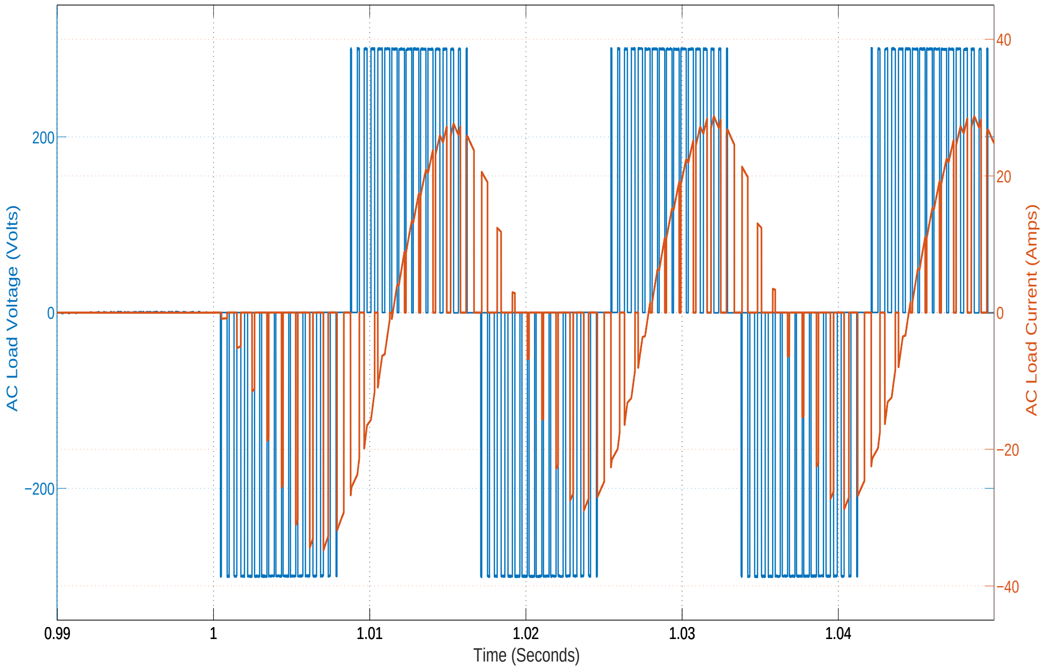
(c)


Sub LVDC voltage (Volts)
25.5
25
24.5
24
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

(d)



(e)



(f)

Figure 4.4: Simulation waveform during Weak Islanding mode (a) Sub LVDC bus voltage (b) AC load voltage and current (c) Main DC bus and Sub HVDC voltages (d) Sub LVDC voltage bus during DCT Isolation mode (e) Main DC bus and Sub HVDC bus voltage during DCT isolation mode (f) AC load voltage and current in DCT Isolated mode

after V_{MB} reaches to the 380V. However, in buffer state PCmRC starts charging the storage (at time t=2sec in Figure 4.5((a))) from the surplus energy to avoid any abnormal situation and ensure continuous supply for critical loads, as shown in the Figure 4.5((a)). During entire operation stable power outputs are available for non-critical loads, as shown in the Figure 4.5((c)), 4.5((d)).

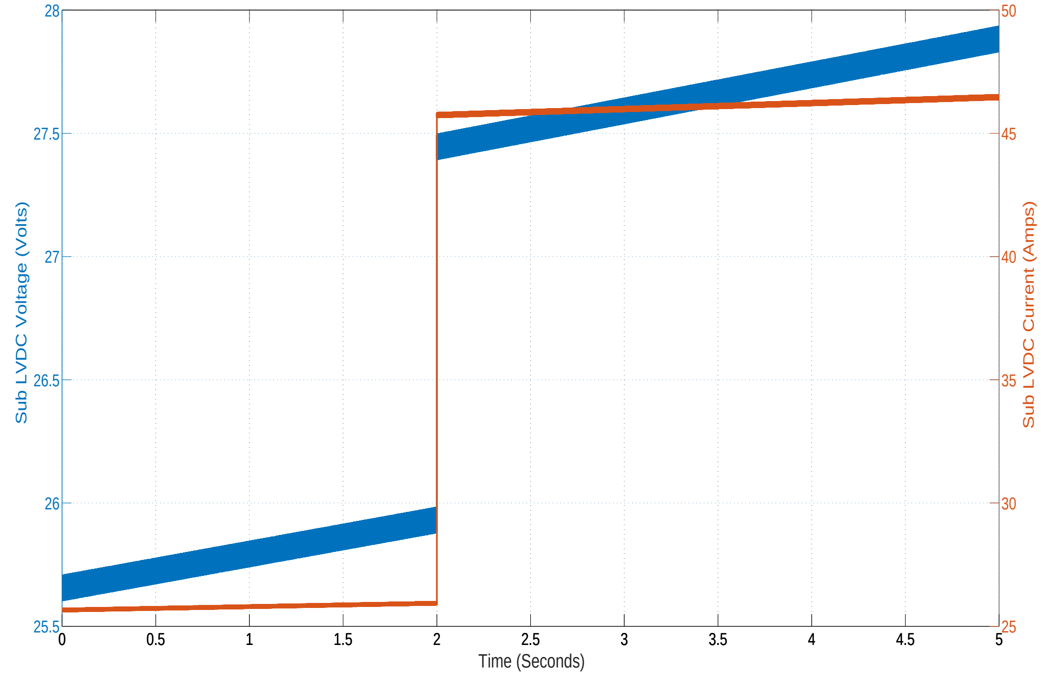
4.6.5 Off-grid mode with renewable sources and storage

In case of renewable/ distributed energy sources generating more than the demand side requirements the main DC bus voltage (V_{MB}) voltage starts increasing, as shown in Figure 4.6((b)). As soon the V_{MB} reaches to 395V, the PCmRC switches to power sharing mode and regulates the V_{MB} under 400V limits.

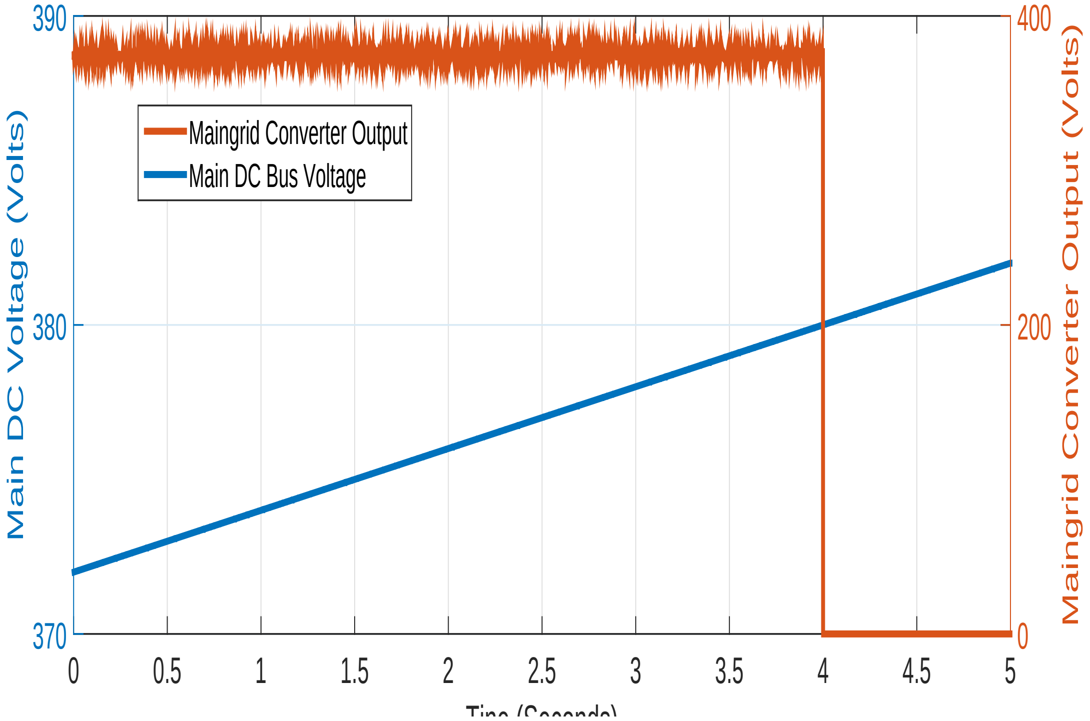
The surplus power which is coming from the renewable sources will be shared with the adjacent grid. Therefore, in order to share power to the adjacent grids the maingrid converter starts to control power flow from consumer grid to maingrid. This is the reason, in power sharing mode, the maingrid converter becomes load and the power flow through maingrid converter is presented with negative sign in Figure 4.6((a)). Similarly, PCmRC regulates the sub LVDC bus up to 29.2V on full load including low voltage storage connected to the sub LVDC bus as shown in Figure 4.6((a)). Sub HVDC bus and AC load operation can be seen in Figure 4.6((c)), 4.6((d)).

4.6.6 Load shedding of Non-Critical loads due to in sufficient on-site sources

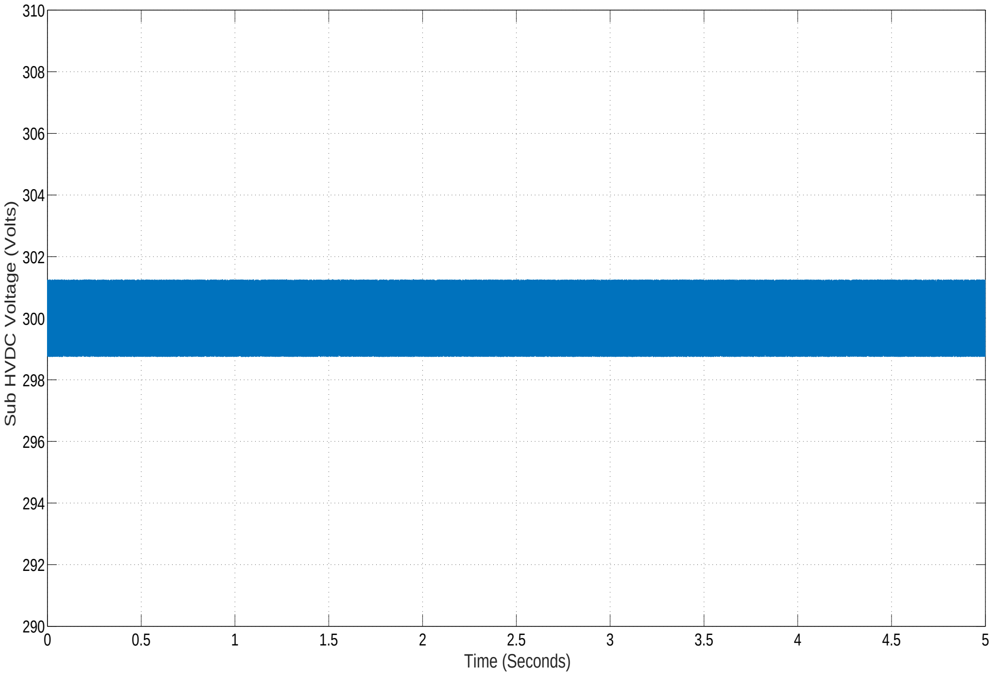
If the consumer grid is operating in islanding mode and on-site generators are also not generating enough to power up loads then main DC bus voltage (V_{MB}) slope becomes negative, as shown in the Figure 4.7((b)). The control model of PCmRC is designed in such a way that if the V_{MB} reaches to 355V or less, then each DCT connected to the main DC bus goes into the high-impedance by activating the DCT isolation switch as shown in Figure 2.2. If the DCT isolation switch activated then DCT switches-off the non-critical load (as shown in the Figure 4.7((c)), 4.7((f))) and operates in DCT isolation mode, as shown in Figure 4.7((a)) . In DCT isolation mode, PCmRC utilizes the low voltage storage ensure continuous supply for only critical loads without any interruption, as shown in Figure 4.7((e)). In Figure 4.7((d)), at t=2.5sec, as soon V_{MB} drops to 355Vat the same time PCmRC activates the low voltage storage to discharge on sub LVDC side which is shown with a negative sign in Figure 4.7((d)). Moreover, the sub LVDC bus voltage level rises proportionally to the storage voltage and will continue supply power to the critical load until the storage ends or again PCmRC starts operating in maingrid interactive mode.


Sub LVDC Voltage (Volts)
Sub LVDC Current (Amps)
28
27.5
27
26.5
26
25.5
50
45
40
35
30
25
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

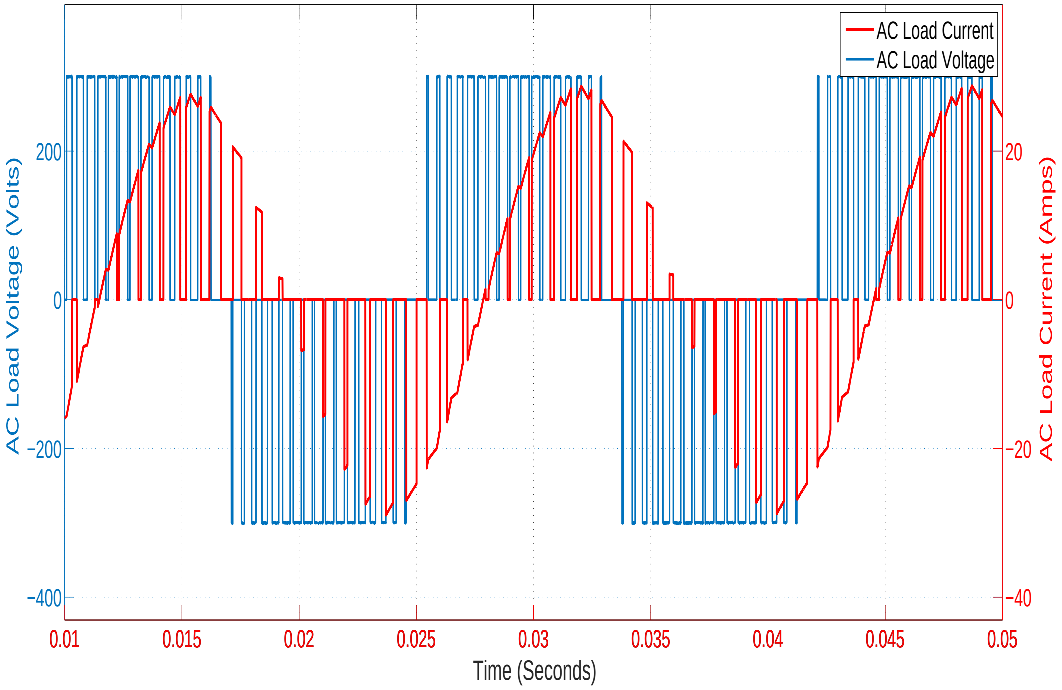
(a)


Main DC Voltage (Volts)
Maingrid Converter Output (Volts)
Maingrid Converter Output
Main DC Bus Voltage
390
380
370
400
200
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

(b)

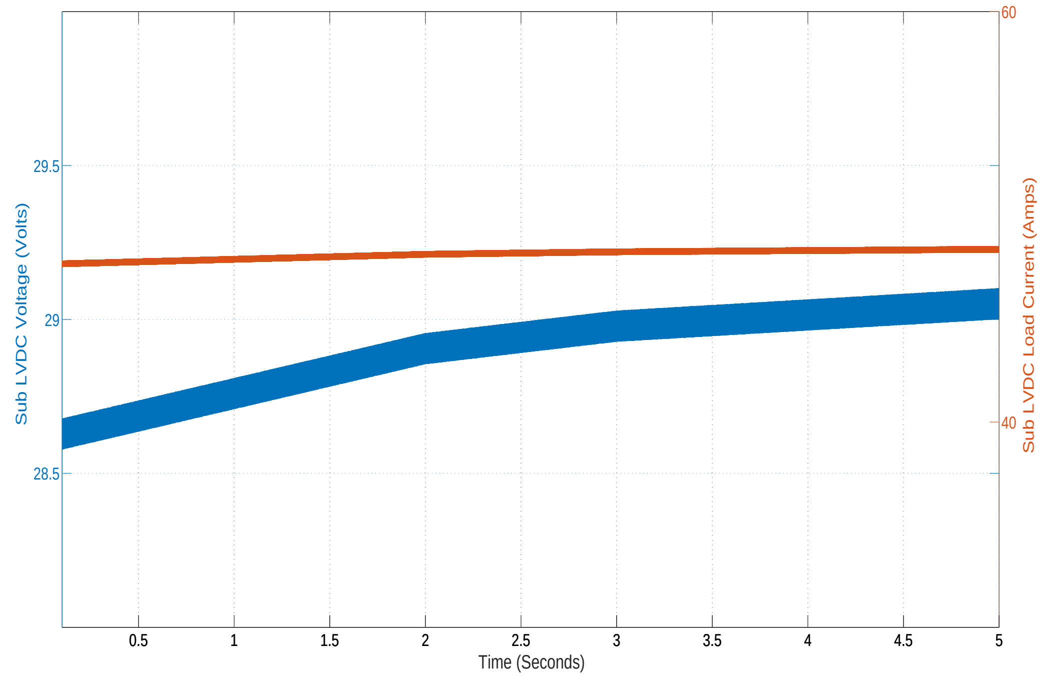


(c)

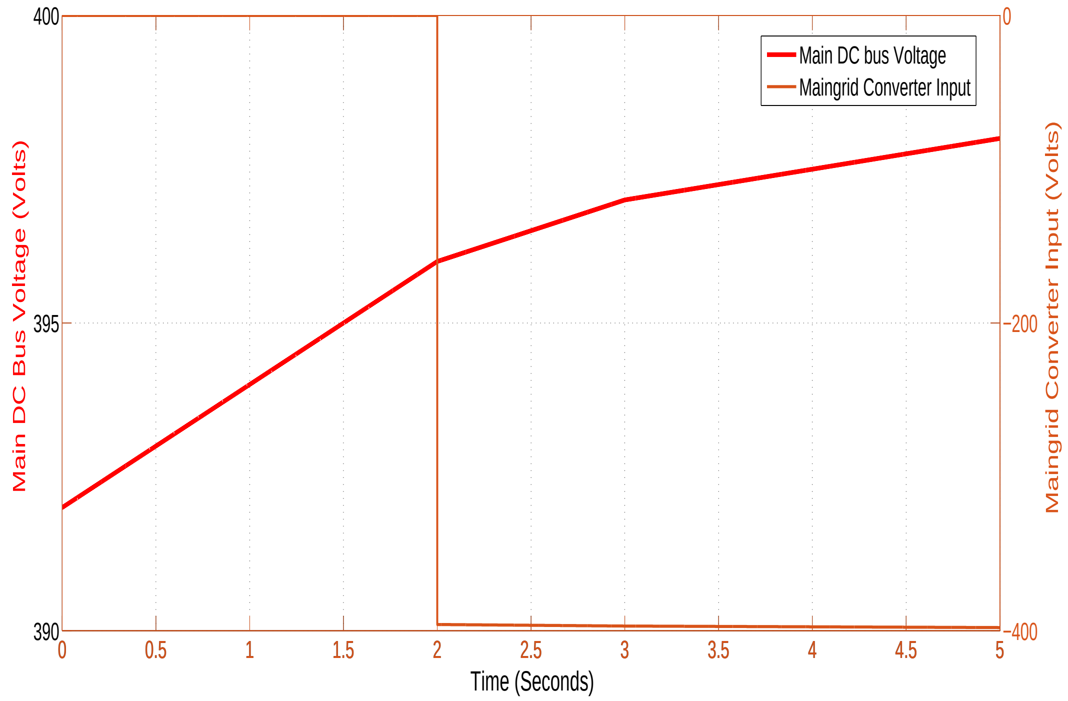


(d)

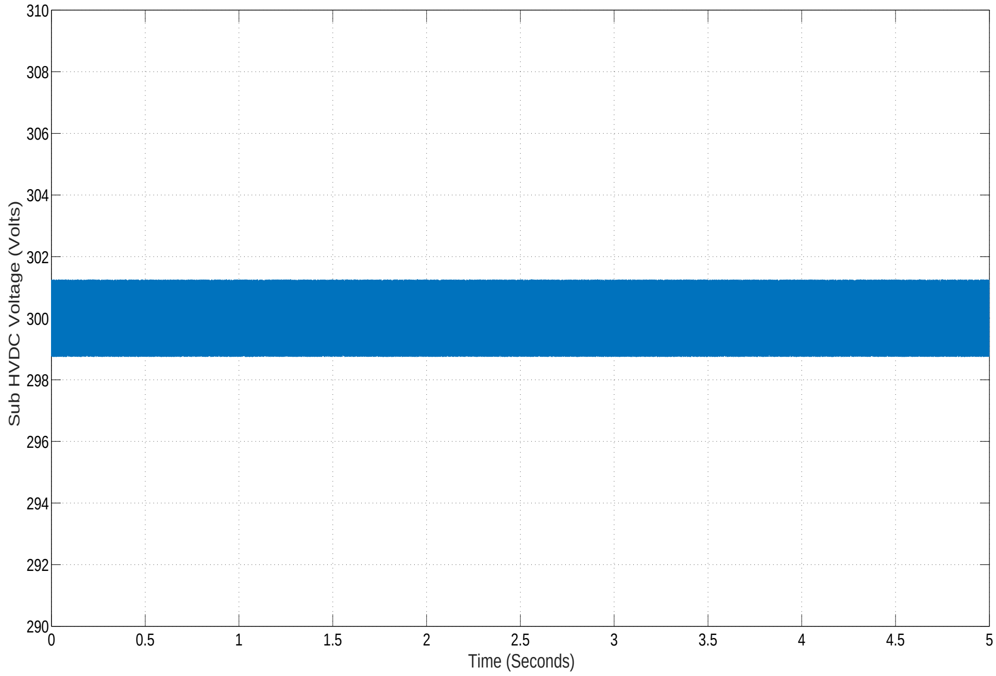
Figure 4.5: Simulation waveform during Self reliance mode (a) Sub LVDC voltage and current (b) Main DC bus and AC Maingrid converter output voltage (c) Sub HVDC bus voltage (d) AC Load voltage and current


Sub LVDC Voltage (Volts)
29.5
29
28.5
60
40
Sub LVDC Load Current (Amps)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

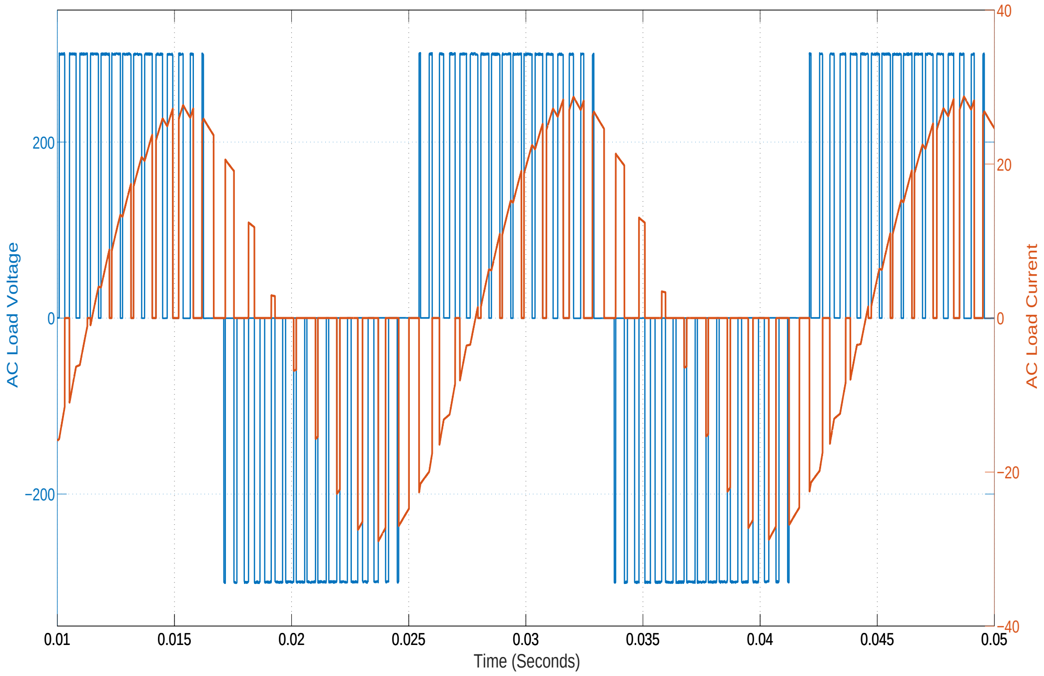
(a)


Main DC bus Voltage
Maingrid Converter Input
Main DC Bus Voltage (Volts)
400
395
390
0
−200
−400
Maingrid Converter Input (Volts)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

(b)



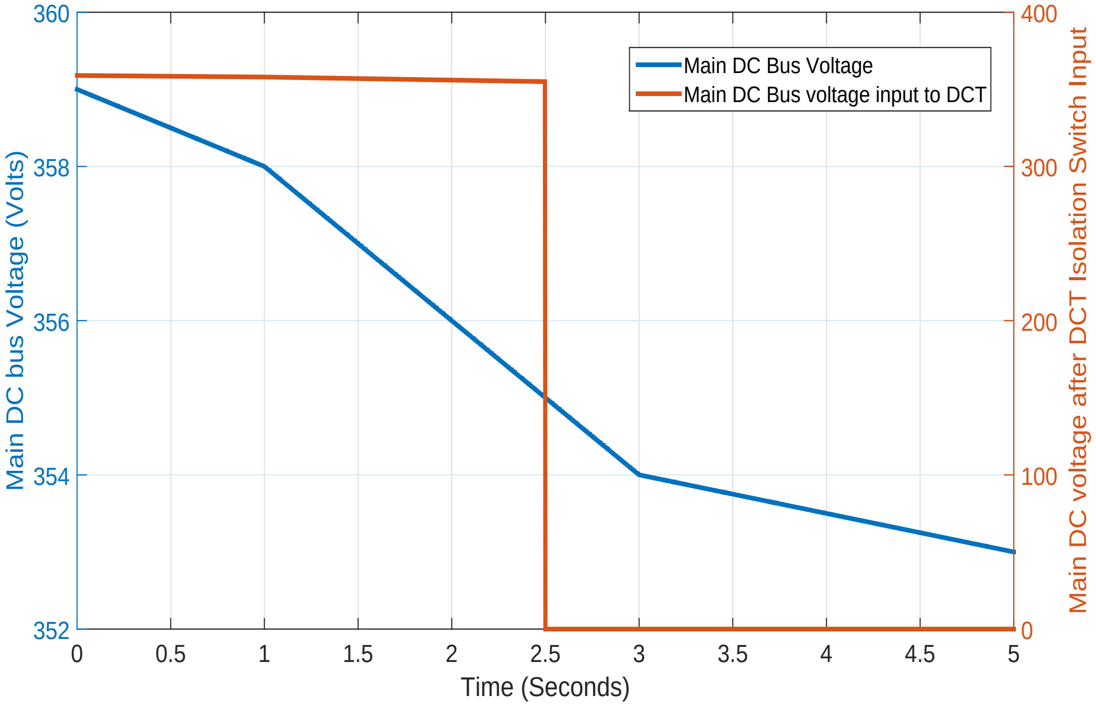
(c)



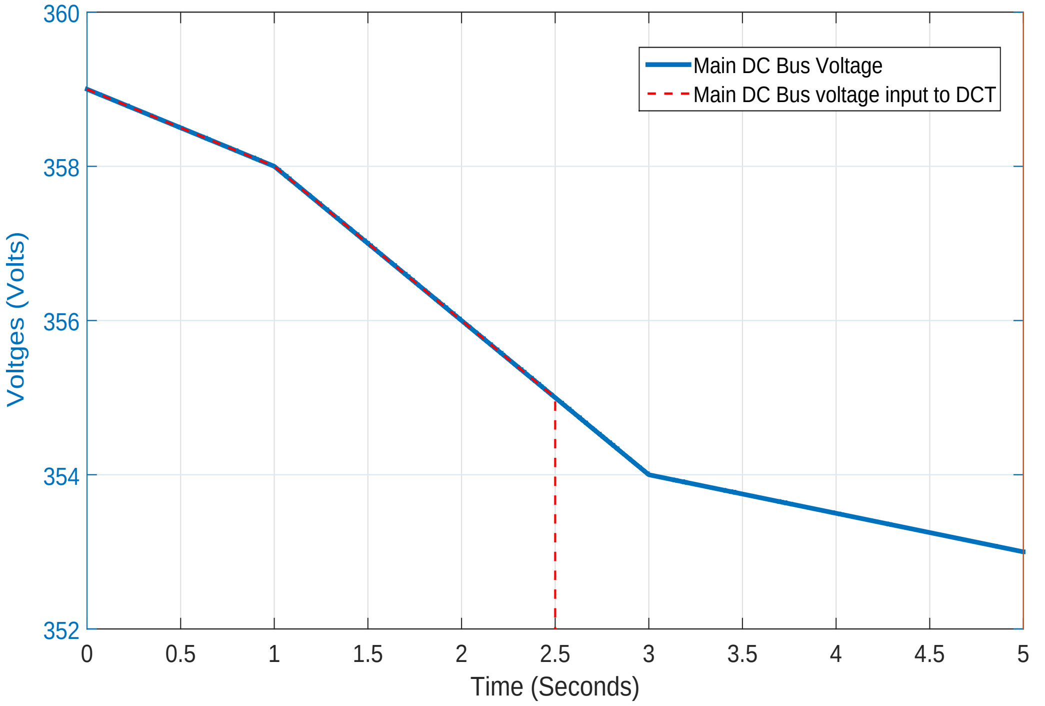
(d)

Figure 4.6: Simulation waveform during power sharing mode (a) Sub LVDC voltage and current (b) Main DC bus and AC Maingrid converter input voltage (c) Sub HVDC bus voltage (d) AC Load voltage and current

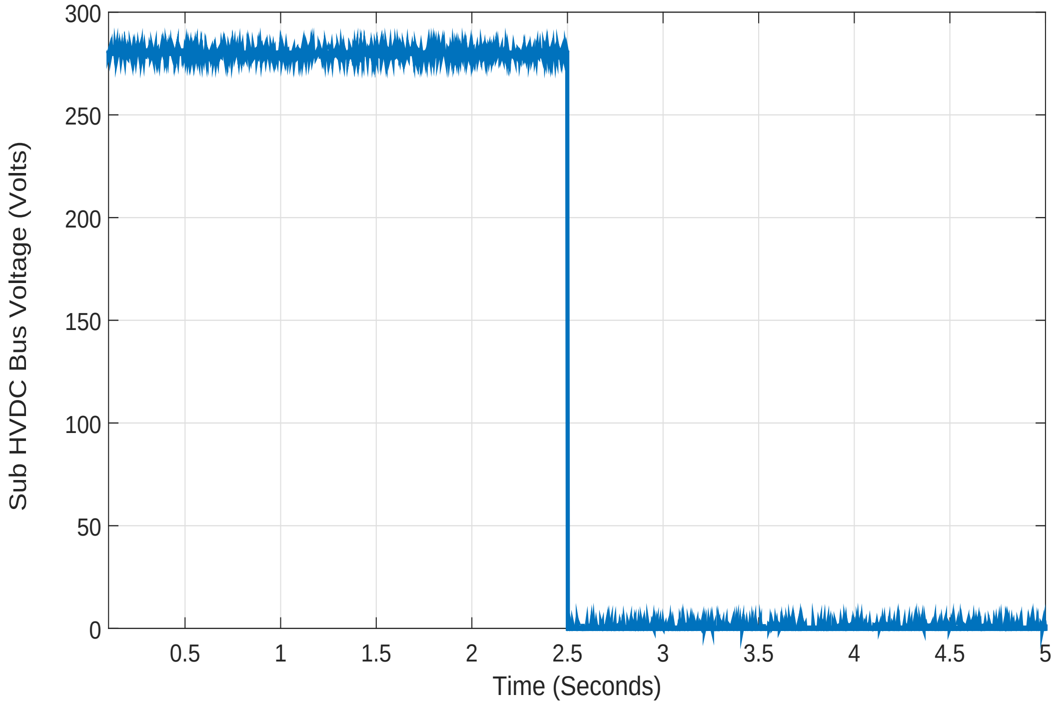
]


Main DC bus Voltage (Volts)
360
358
356
354
352
Main DC voltage after DCT Isolation Switch Input
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)
Main DC Bus Voltage
Main DC Bus voltage input to DCT

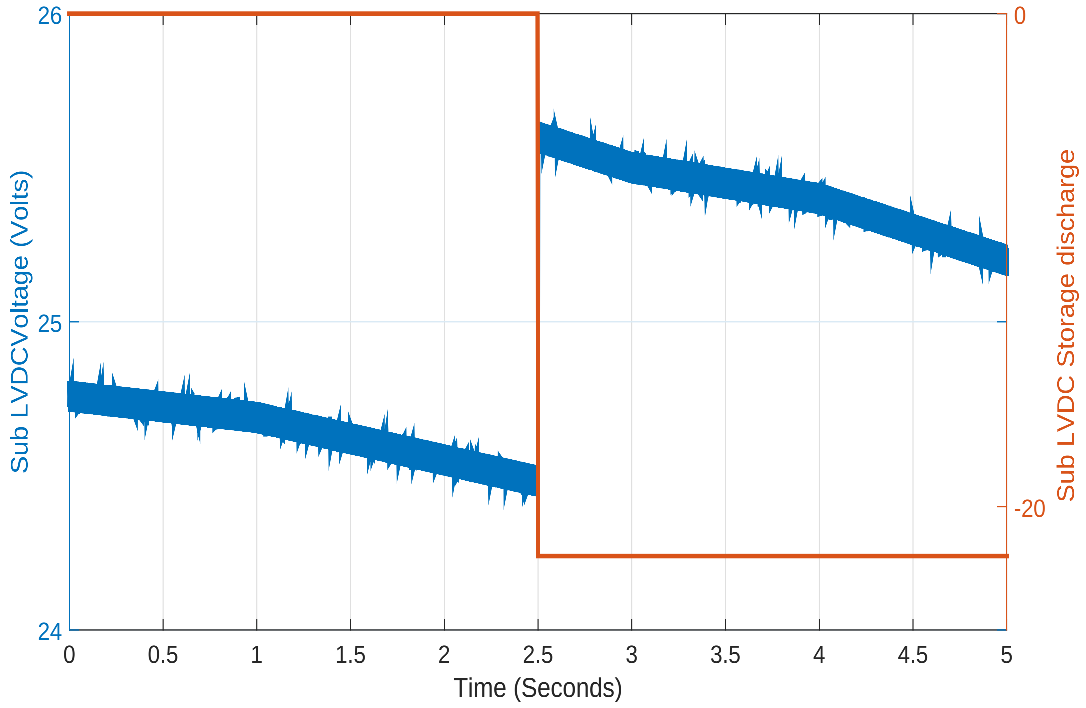
(a)


Voltges (Volts)
360
358
356
354
352
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)
Main DC Bus Voltage
Main DC Bus voltage input to DCT

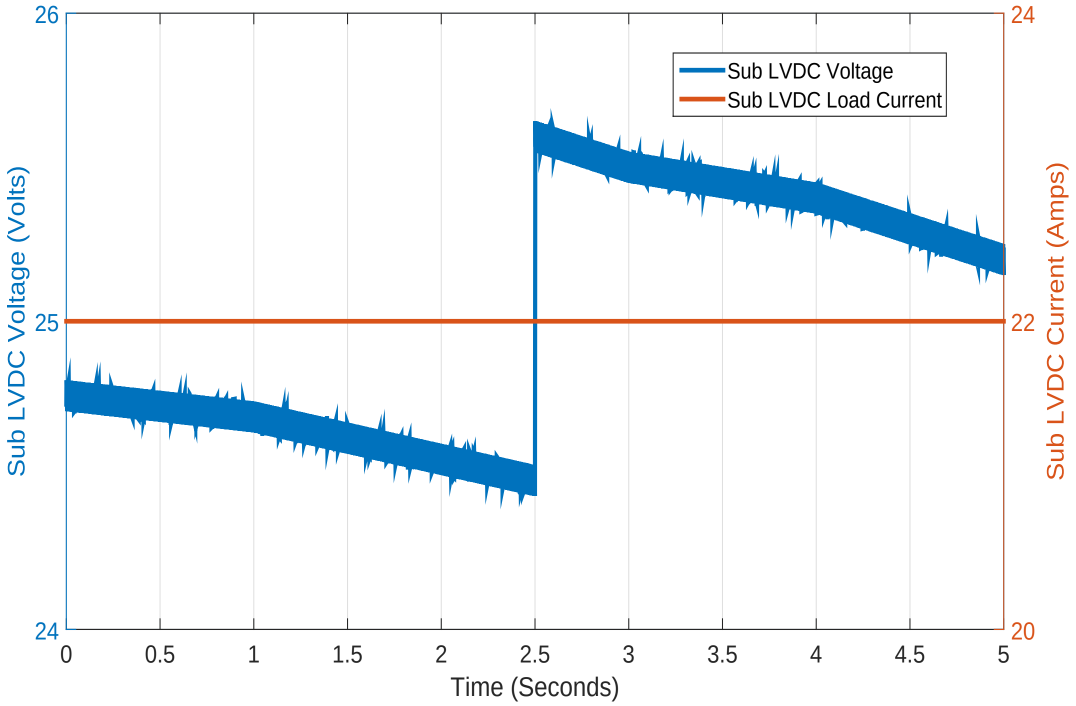
(b)


300
250
200
150
100
50
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Sub HVDC Bus Voltage (Volts)
Time (Seconds)

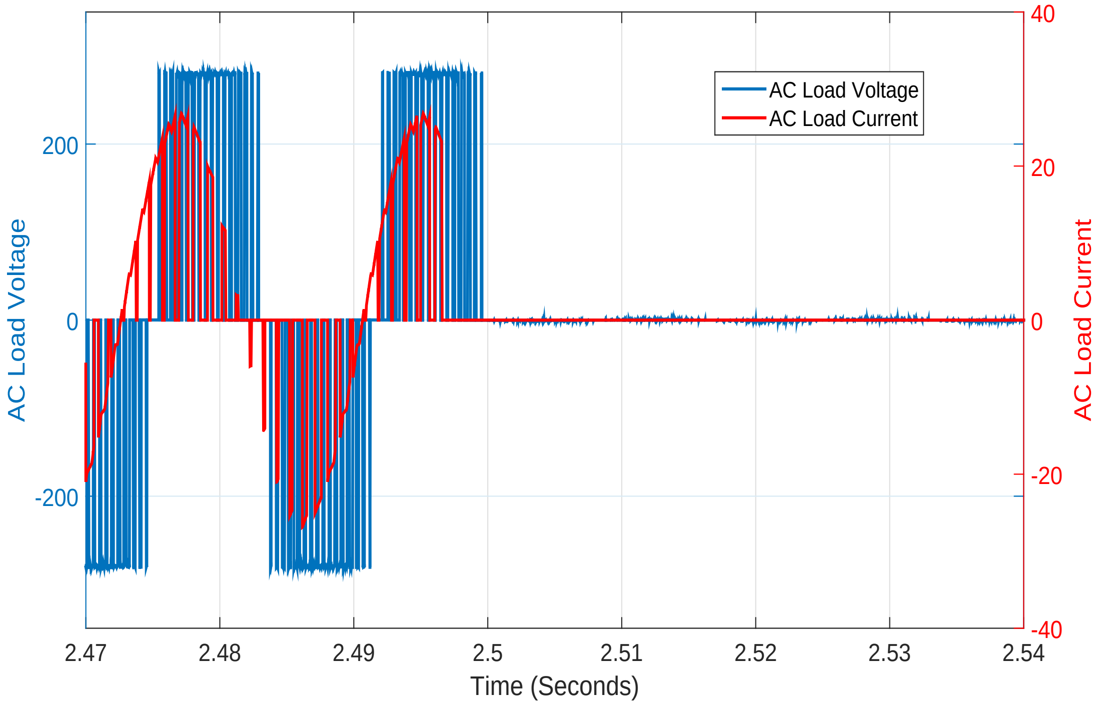
(c)


26
25
24
0
-20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Sub LVDCVoltage (Volts)
Sub LVDC Storage discharge
Time (Seconds)

(d)



(e)



(f)

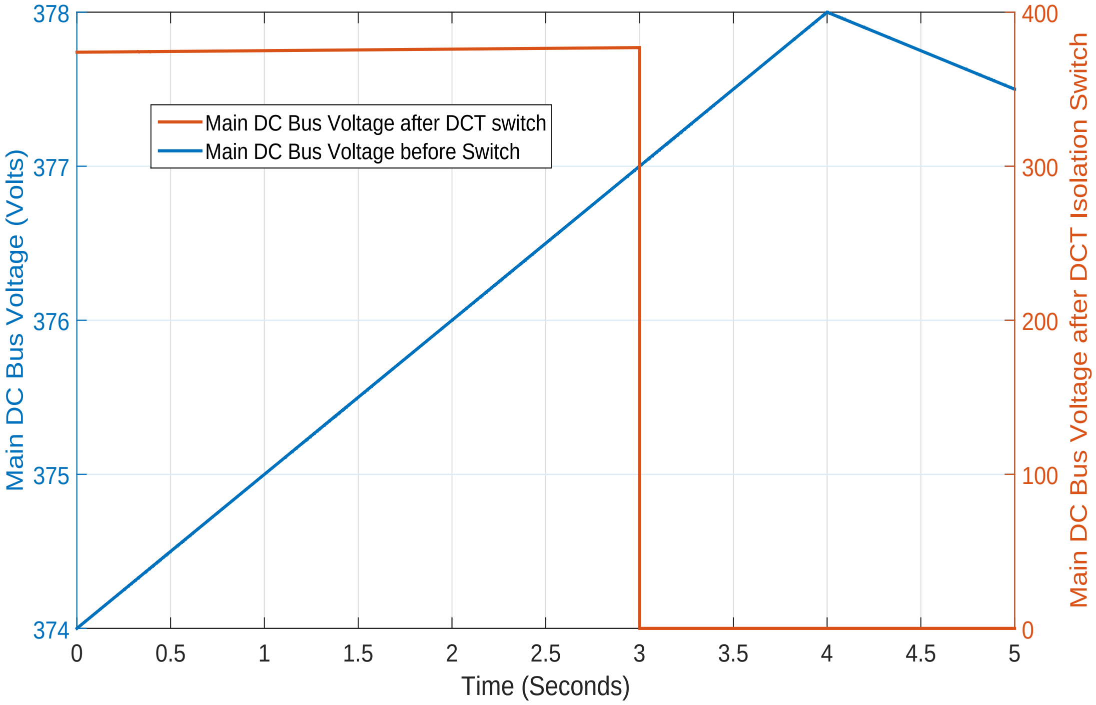
Figure 4.7: Simulation waveform of mode transition from Main grid interactive to DCT Isolated mode (a) Main DC bus voltage before and after the DCT isolation switch (b) Main DC bus voltage (c) Sub HVDC voltage waveform (d) Sub LVDC bus with low voltage storage discharge (e) Sub LVDC bus voltage and current (f) AC Load voltage and current

4.6.7 Load shedding due to fault occurs on demand side power system

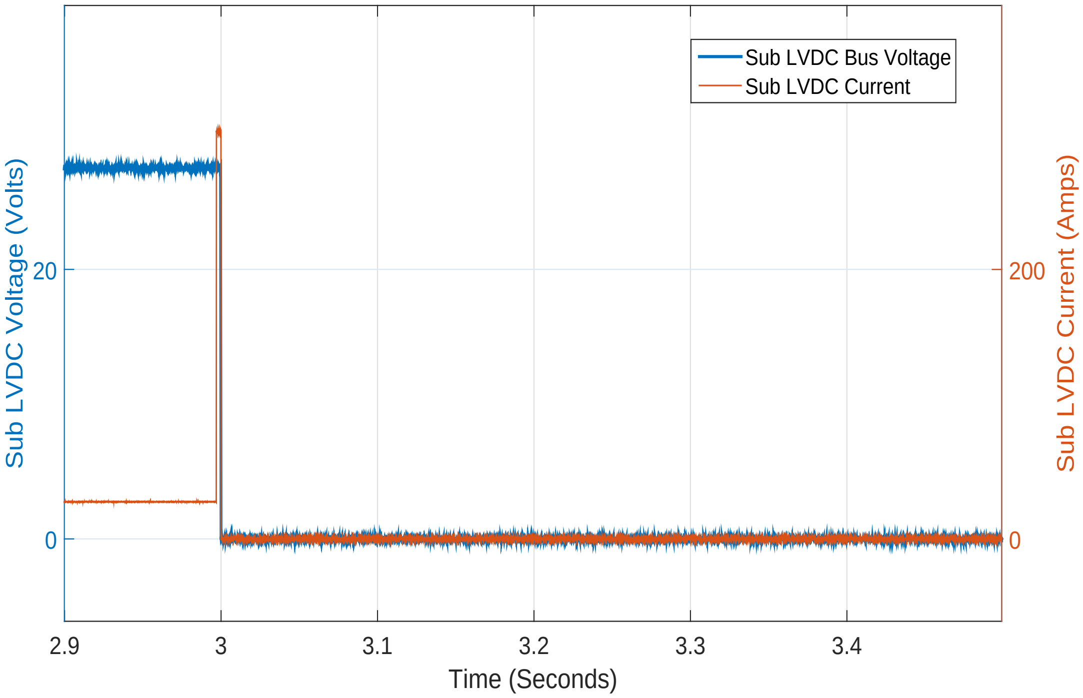
In case during normal grid operation any fault occurs on consumer side the PCmRC immediately shuts-off and isolates the respective DCT in order to ensure entire grid reliability. In Figure 4.8((b)), there is a high current spike generated on sub LVDC port, DCT immediately detects within $3 msecs$ and activates the DCT isolation switch and undergoes DCT isolation state. However, in DCT isolation state, the DCT shuts-off all input and output ports and disconnects from main DC bus, as shown in Figure 4.8((a)). Moreover, DCT switches-off sub HVDC bus and inverter output at the same time to avoid damage on consumer side as shown in Figure 4.8((c)), 4.8((d)). Hence, the respective DCT shuts-off all its Inputs/Ouputs and allow other adjacent DCTs work normally.

4.7 Conclusion

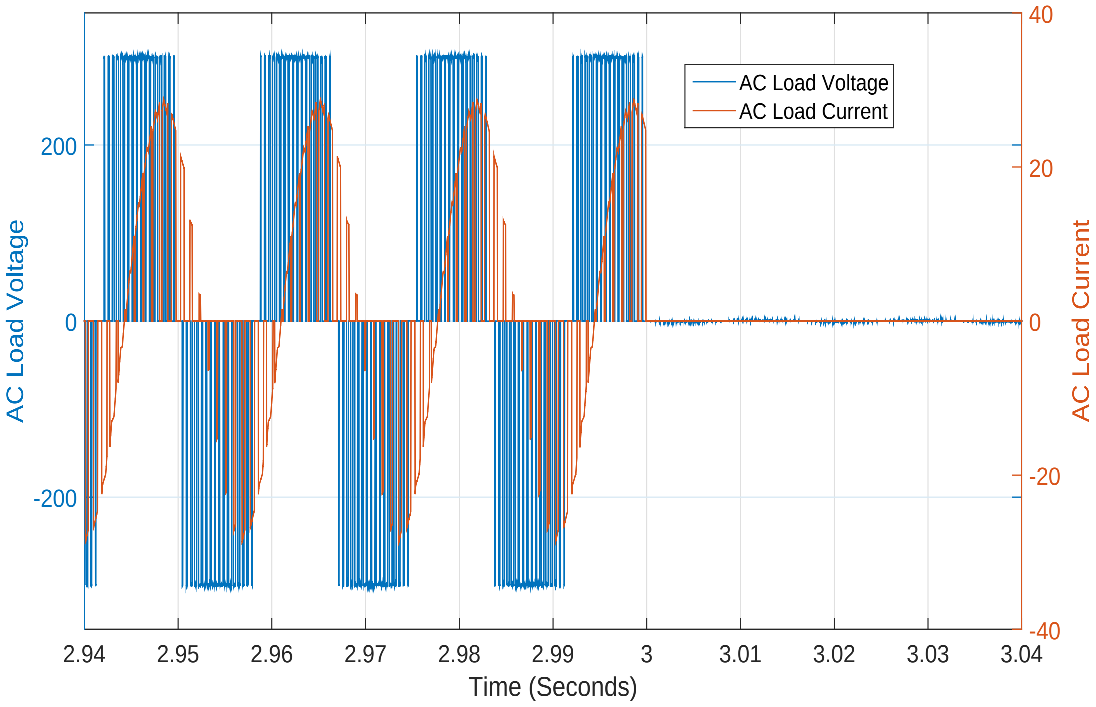
In this chapter, a unique power controlling, monitoring and routing strategy is presented, which is independent to the type of the available renewable distributed sources and storage. The proposed strategy provides seamlessly switching in between operational modes so that DC microgrid can operate in grid connected, islanding, off-grid, with or without on-site generators without any change in control algorithms, which enables the compatibility of the model in any sort of situation. A system model is constructed and key characteristics of the proposed model are examined by simulating various case studies, which validate the proposed concept of power management. Therefore, the DCT enabled PCmRC consumer grid model is a promising key component in modern power distribution of consumer grids.


Main DC Bus Voltage after DCT switch
Main DC Bus Voltage before Switch
Main DC Bus Voltage (Volts)
378
377
376
375
374
Main DC Bus Voltage after DCT Isolation Switch
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Seconds)

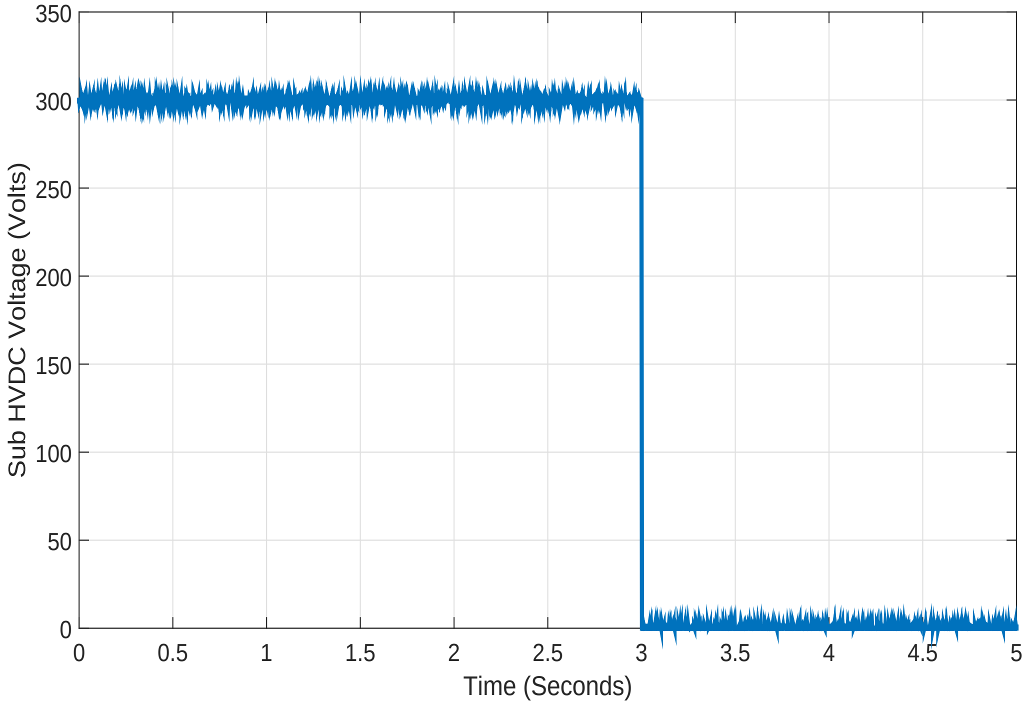
(a)


Sub LVDC Bus Voltage
Sub LVDC Current
Sub LVDC Voltage (Volts)
20
0
Sub LVDC Current (Amps)
200
0
2.9
3
3.1
3.2
3.3
3.4
Time (Seconds)

(b)



(c)



(d)

Figure 4.8: Simulation waveform during fault condition at consumer side (a) DC bus voltage before and after the DCT isolation switch (b) High current spike on Sub LVDC bus (c) AC Load voltage and current before and after the fault (d) HVDC bus voltage before and after the fault

Chapter 5

Scalable DCT enabled HER consumer grid power management strategy

As mentioned in previous sections, the renewable energy sources are seen as the best replacement of conventional fossil fuels. Nowadays, most of the domestic appliances and short-term or small storage usually work on DC power and many renewable/ sustainable energy sources also generate DC power. Therefore, there are several sophisticated power converters required to integrate DC appliances, sources and storage within convectional AC grid, which may increase the overall grid installation cost and decrease the grid reliability. This is the reason, DC powered microgrid is gaining popularity due to the less complexity, low energy losses and small number of converters. For instance, on-site generation and battery storage can be directly integrated in DC microgrid and solely DC-DC converter required to power-up DC appliances. However, existing infrastructure is based on AC distribution and few critical domestic appliances required AC power for normal operation. In this chapter, we would discuss the DCT enabled consumer grid mode based on the proposed distinctive approach to accommodate AC/DC powered load, sources and storage within DC microgrid without any additional power converter, known as Home Energy Router (HER).

5.1 Overview and motivation

In this paper we proposed novel distribution architecture based on HER (Home Energy Router) similar to the data router, in order to solve aforementioned challenges associated with DC microgrids. The detail HER system configuration is shown in Figure 5.1. the biggest advantage with the HER is that any type of load (either AC or DC) can be driven with any type of input source (AC or DC) without any additional power converter. The proposed HER based design can equally work either on 380V DC as well as 220V AC input power, in order to ensure compatibility with existing infrastructure. It can handle both high-power AC and DC loads with separate isolated bi-directional port for sensitive electronic appliances. Moreover, it can manage the bidirectional power flow solely in 380V DC distribution.

There is one grid-interface and two consumer interface ports are available in HER model. The grid interface port is capable to take power from convectional AC grid and also works on EMerge Alliance standard 380V DC for DC microgrids. However, the bi-directional power flow mode is only available in DC microgrids. The consumer interface ports are classified in term of voltage amplitude and power i.e. low-power and high-power ports. The high power port can be configured as 380V DC bi-directional port or 220V AC output port. If the high voltage port is configured into 380V DC, then 380V DC load or storage can be directly interfaced without any additional circuitry. If it configured as 220V AC then it can only drive the inductive or contact-current load and the bi-directional power flow mode is not enabled in case of AC power storage.

The low power port is configured either in 48V DC or 24V DC voltages based on the requirement of electronics appliances used in the DC microgrid. The output of the low power port is galvanic isolated from input and high power port. Therefore, in case of any fault either in maingrid or high-power port, there is no extra protection circuits required for sensitive appliances. Moreover, low-voltage storage (battery/ fuel-cell) can be interfaced directly with the low-power port without extra circuitry. The main features of the HER based AC/DC microgrid are follows.

1. The Grid interface port of HER module is compatible with both AC and DC power. Therefore HER is perfectly compatible with the conventional AC based existing infrastructure as well as future LVDC based microgrids.
2. Grid interface port and consumer ports are isolated, which increase the overall reliability of the grid.
3. HER can handle both AC and DC powered high-power loads with built-in overload and short-circuit protection. Therefore, there is no additional sophisticated DC to AC (inverter) required to operate inductive loads in DC microgrids.
4. There is dedicated isolated bi-directional port available in HER for sensitive low voltage electronic-appliances. The low-power port can monitor state-of-charge (SOC) for small DC storage without any additional circuitry.
5. Built-in overload and short circuit protection on each input and output ports. Therefore, there is no external expensive DC breaker or protection system required.
6. Optional Modbus communication link is provided for rapid fault identification and rectification. Moreover, each HER module works standalone and multiple HER module can be

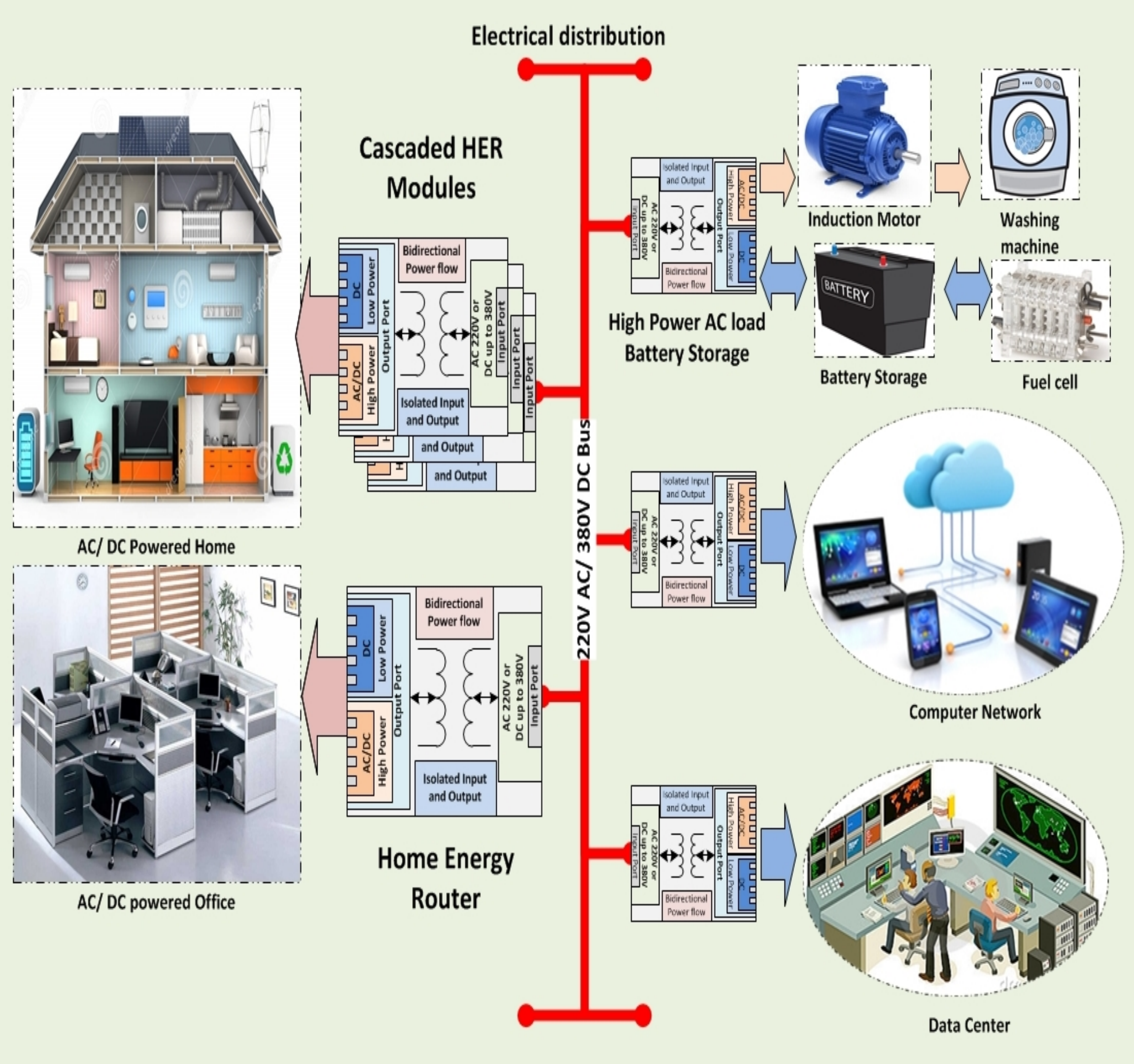


Figure 5.1: Home Energy Router System Architecture

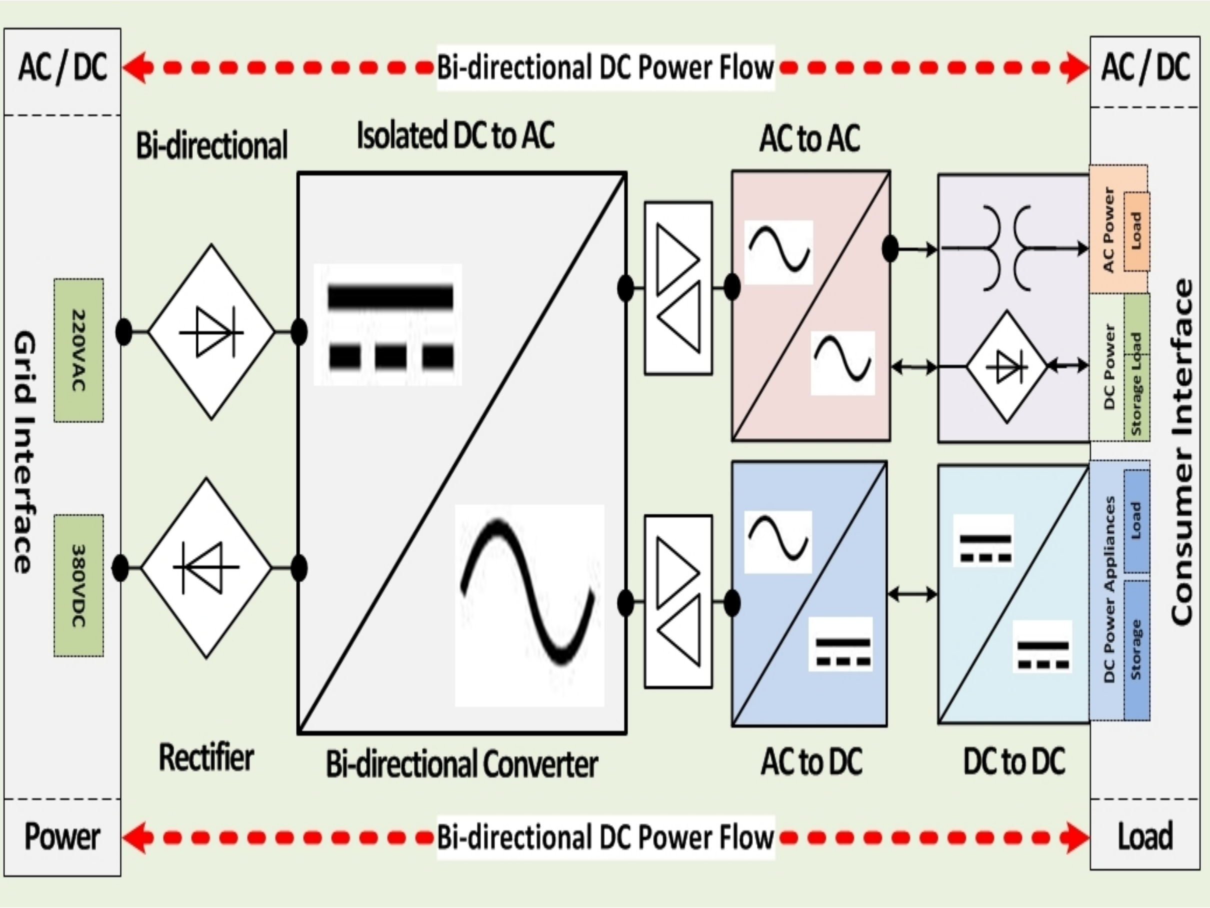


Figure 5.2: Internal Block diagram of Home Energy Router

configured in a network.

7. The class-II output power Bluetooth interface available for remote operations such as energy-metering and fault diagnostic or On/Off switching in case of HER installed in unreachable/ inaccessible area.

8. In case of night-saver meters, HER can be programmed to charge the storage and power up the heavy appliances at night time only.

5.2 Energy efficient smart home architecture

The HER model is based on DC power, which gives several advantages over conventional AC consumer-grid such as i) DC can be store easily at small scale. ii) Due to penetration of DC powered loads such as LED lights, smart-phones, LCD etc. in our societies, it reduces multiple power conversion losses. iii) Mostly renewable sources generate DC power; therefore integration of multiple sources became simple. iv) As compared complex parameters of AC power, the voltage's magnitude is the only control parameter in DC grid. v) In DC grid, high power quality without any harmonics and power factor correction unit. vii) There is no frequency synchronization required at any stage in DC powered grid.

5.3 HER interfaces

The internal block diagram of the HER module is shown in Figure 5.2. Following are the description of each block of HER model.

5.3.1 HER grid interfaces blocks

The input of HER module is connected with signal phase rectifier and full bridge DC to AC converter, which converts the input DC or low-frequency AC voltage into high-frequency 300V AC. Therefore, regardless AC or DC power, Grid power is rectified in first stage and then feed to the DC to AC converter as shown in Figure 5.2. In case of 380V DC input, HER module revert the surplus power back to grid-interface. Another advantage of DC to AC conversion is to get magnetic isolation between the maingrid and consumer load. In case of malfunctioning either on maingrid or consumer side would not be affected the overall performance of the system. Therefore, there is no need for additional protection system for sensitive consumer load.

5.3.2 HER consumer interfaces

The consumer port consists of two types of outputs i.e. high-power port and low-power port. The High-power has two selectable modes for AC and DC powered loads. However, the only DC power mode can use for DC storage for bidirectional power flow. Individual blocks are described as follows: .

1. High-power AC to AC block: This block converts the high frequency AC voltage into low frequency AC voltage (220VAC/50Hz), which goes directly to the output consumer port. This can be used to power-up inductive or constant-current loads.
2. High-power rectifier block: In case of DC microgrid do not require AC supply within grid. Then rectifier block can be selected to operate high voltage and high power DC loads. This rectifier block can handle the power flow in both direction and it can manage the DC load and DC storage at the same time.

The low-power port can deliver only DC power with configurable 24VDC or 48VDC voltages. Moreover, DC storage can be connected directly to the low-power port and it manages the SOC (State-of-charge) without any additional power management circuit. The output of high-frequency AC is connected to the AC to DC rectifier and then through configurable DC to DC buck converter, it can be used to power up low voltage sensitive DC low and small battery storage.

5.4 Scalable, standard and modular architecture

The main advantages of DCT enabled HER-grid model is the standard architecture leads to lower production cost and fault tracing time. Moreover, high level of reliability can be achieved by introducing multiple level of redundancy as shown in Figure 5.1. Therefore, wide range of demand-side power requirements can be fulfilled by cascading multiple modules together and power system can be configured easily as per consumer demand.

5.5 Standard plug-and-play interface for AC maingrid, on-site power sources & storage

In HER grid model, there are two buses consist of high voltage and low voltages, as indicated in Figure 5.2, all sources including AC maingrid and storage are plug-and-play like computer "USB–port". The renewable energy sources are in-consistence in nature and usually do not provide uniform power all the time, therefore intelligent Home Energy Router always maximizes the utilization of renewable energy sources and takes only balance power from the maingrid.

5.6 Compatible with existing infrastructure

As mentioned above, all sources and storage are plug-and-play. If there is no renewable source and storage connected, then HER will start taking power from maingrid. Furthermore, HER can manage power requirements with or without renewable sources, storage devices and grid connection. Therefore, in existing infrastructure where the primary source of power is only AC maingrid, HER can drive entire DC microgrid on AC maingrid perfectly without any additional up-gradation or change in grid control algorithm.

5.7 Dual Bus standards

HER consumer grid model uses two DC buses (i.e.300V to 380V) HV-DC bus and selectable (i.e. 12V to 48V) LV-DC buses. The advantage of selecting HV and LV DC buses are:

1. High voltage 300V to 380V DC is used for DC power distribution and as a drive for heavy loads.
2. High voltage DC reduces total harmonic distortion (THD) from 70% to 30%, if we change the voltage from 110V to 300V [112].
3. The design of power inverter (DC to AC) became simple with high voltage DC.
4. High voltage DC distribution is 7% more efficient then AC distribution in utility grid [7, 116].
5. AC maingrid and wind generator can be directly coupled on High DC bus.
6. Low voltage DC is used to drive sensitive electronic load.
7. Battery storage can be directly coupled on LV DC bus without any additional boost converter

5.8 Built in fault protection

In HER, DCT module is used for power distribution and managing power within the grid, each DCT is continuously monitoring current and voltages levels of both HV and LV DC buses. Therefore, on detecting any anomalous situation, DCT immediately switched-off and isolates the fault. In HER model, battery storage can be directly coupled without additional converter. Therefore, it has voltage-sag ride through capability and suitable for sensitive electronic loads.

5.9 AC and DC powered loads operation

The unique feature of HER grid model is the power distribution scheme depends upon the priority level of the load. Therefore, HER manages the critical and noncritical loads without any extra load management device. Moreover, HER can handle both AC and DC power loads connected to the consumer grid. In HER grid model, the load is classified into two groups based on the consumer requirements i.e. critical and noncritical loads. In worst case scenario, during maingrid fault, limited generation from renewable sources and without sufficient energy storage, HER makes sure continuous power supply for only the critical loads. Therefore, HER allows consumer to configure the priority level of the loads.

As mentioned in the previous sections, there are two DC buses HV and LV used in HER consumer grid. The low voltage DC bus can be used for low-power sensitive DC loads and battery storage. The high voltage DC bus can be used to power-up the high power DC loads as well as AC loads. In [100], author did series of experiments and on the bases of successful

Grid connection	5Kwatts
Solar Energy	2Kwatts
Battery storage	1.2Kwatts
DCT	5Kwatts
LV DC load	0.5Kwatts
LV DC voltage	24V
HV DC load	0.8Kwatts

Table 5.1: Simulation Parameters of Home Energy Router consumer grid model

results proposed that high DC voltage ($\gg 270$V DC) can be used directly to power up resistive type of AC loads. Furthermore, only few components required to convert 300V DC into to 220Vrms AC supply for inductive load as indicated in Figure 5.1.

5.10 Evaluation of DCT enabled HER consumer grid model

MATLAB/ Simulink is used for system level simulation of HER model. The basic model is constructed and simulated different operational scenarios in Simpowersystem toolbox. Figure 5.6 shows the input and outputs of embedded HER transformers. The input either AC/DC is rectified and feed to high-frequency transformer. Then the transformer‘s output of consists of high voltage and low-voltage outputs.

The output RMS voltages is shown in the Figure 5.7, the HVAC/DC output is rectified and then again converted into low frequency 220V AC voltage for inductive loads. However, the rectified DC voltages directly feed to high voltage DC loads.

The rectified low voltage output of the transformer is feed to DC/DC converter. The DC/DC converter can be configured into either 48V or 24V depending upon the consumer requirements. The simulated low voltage output is shown in Figure 5.7.

5.10.1 Overview of different scenarios

In order to evaluate the DCT enabled HER consumer grid model and power management technique simulated on system level by using MATLAB/SIMULINK tool. During simulation of HER average modeling technique is adopted to demonstrate the power controlling, monitoring and routing methodology, which include the bi-directional power flow between high voltage and low voltage side, Islanding mode and solely grid connected mode (without getting any power from renewable energy sources). For simplicity, we used single grid connection, single renewable source (which is solar energy) are connected with high voltage bus and small storage, fuel-cell are connected with low voltage bus of DCT. The main system parameters are listed in Table 5.1.

5.10.2 Peak renewable energy generation mode

In this mode, HER is not taking any power from maingrid and managing available power from locally generated by renewable sources. In Figure 5.3, the positive slope of main DC bus voltage is due to surplus power is coming from renewable source (which is solar energy in our case). HER is regulating voltage on main HV DC bus up to 395V DC voltage. On sub DC bus, when the LV DC magnitude increases from 25.9V (shown at 4.1sec), there is current spike which shows that DCT started to draw 700watts more to charge DC storage and regulates the LVDC voltage up to 27.9V, in order to keep floating DC storage voltage up to 28V.

5.10.3 Partial shading and Islanding mode

When the renewable energy source is not generating enough power and maingrid connection is temporary down, then HER will manage the available storage to power-up only critical electronic load. In Figure 5.4, the main DC bus voltage is gradually decreasing due to the absence of backup power from main grid and not enough power generated by renewable sources. Due to unavailability of power, DCT is switched-off the HVDC non-critical load output, therefore, in Figure 5.4 shows the negative slope of HVDC load voltage. The locally available 700watts storage is solely used to power-up LVDC critical load till storage ends. In Figure 5.4, the negative slope of LVDC load voltage indicates that as battery storage is discharging the LVDC sub DC bus voltage is also decreasing.

5.10.4 Grid connected mode in the absence of renewable sources and storage

In worst scenario, when renewable sources are not available and there is no energy storage left, then HER will only take that much power from main grid which is sufficient to drive only critical and non-critical loads. HER will not charge any type of storage in grid connected mode. As shown in Figure 5.5, the HER is regulating the main DC bus voltage around 350V and sub LVDC bus voltage around 24.2V and solely driving only 1300watt constant load (500watt LVDC load + 800watts HVDC load).

5.11 Conclusion

In the light of above discussions, DC microgrid may solve our on-site generation and storage integration issues and help to reduce the multiple power conversion losses within grid. Indeed, DC consumer-grids may be a better alternate option and prove more reliable and cost-effective than conventional AC grid in future. In order to overcome associated challenges with the LVDC distributions, HER would become integral part and play critical role in electrical distribution of zero/ positive energy building and communities. The HER will be the main component in the future Consumer grid, which will be responsible for grid-to-grid communication, real-time power metering, load management and integration of multiple renewable sources, energy storage and AC maingrid. According to current survey, around 39% of carbon emissions are due to residential power consumption [133], if residential consumers are started to exploit renewable energy sources then we will able to cut-down more than $1/3$ of overall carbon emissions. It will be a first step toward next generation sustainable empowering system for Smart-homes and Communities.

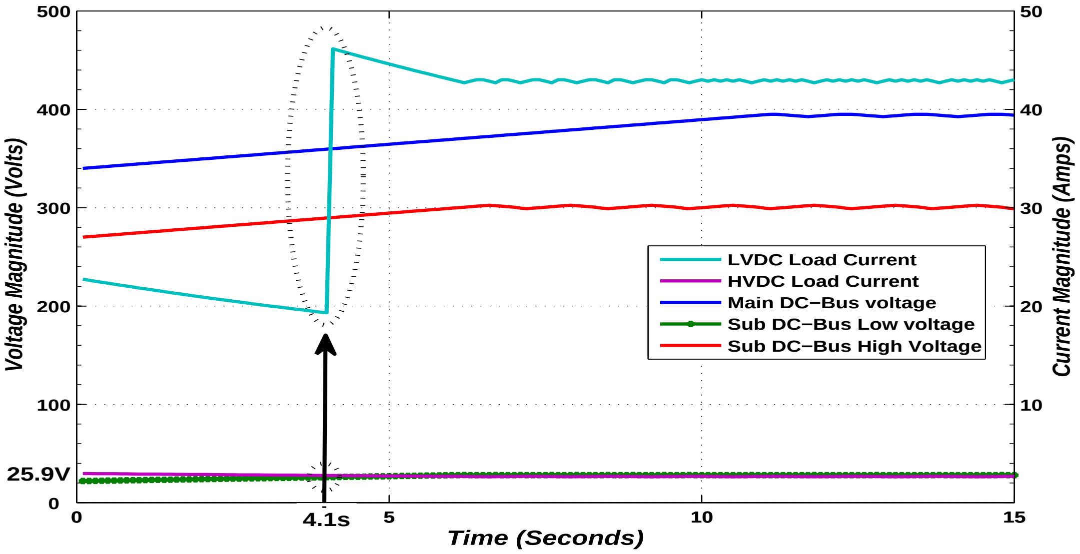


Figure 5.3: Power flow in HER during peak surplus energy generation mode

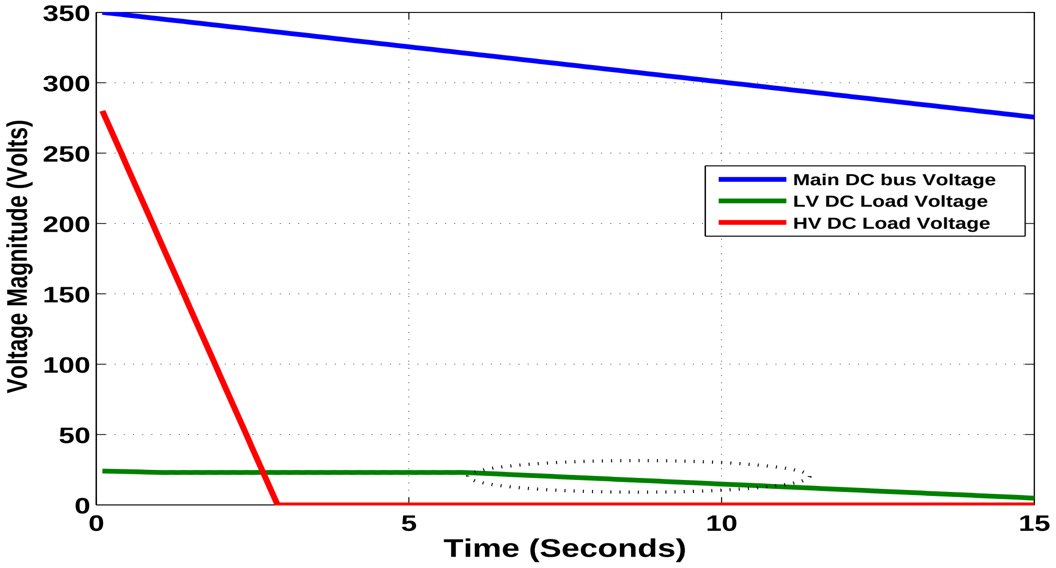


Figure 5.4: Power flow in HER during Partial shading and Islanding mode

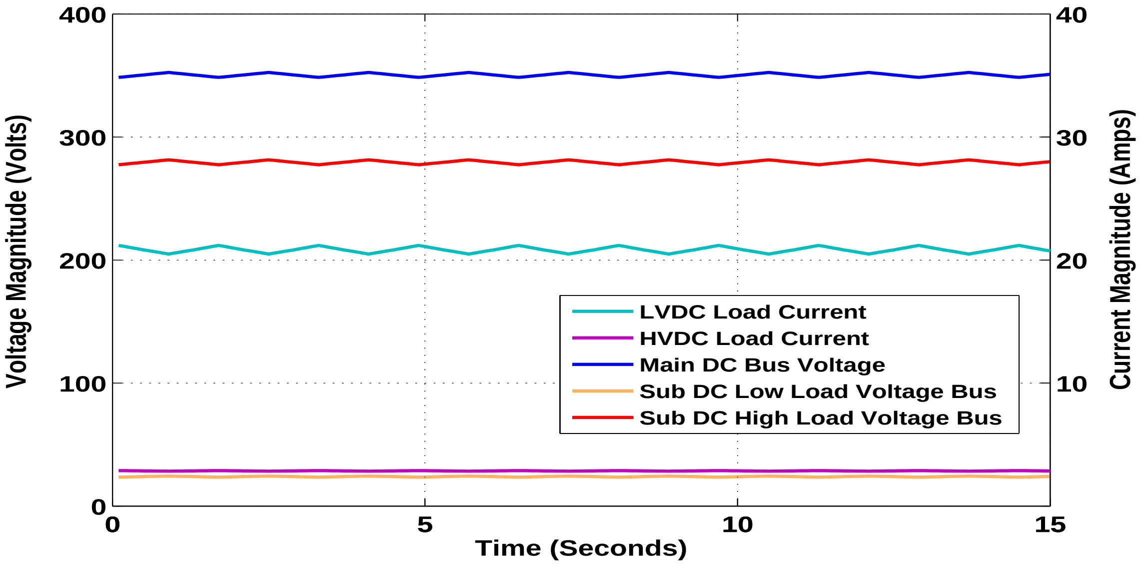


Figure 5.5: Power flow in HER during Grid connected mode without generators

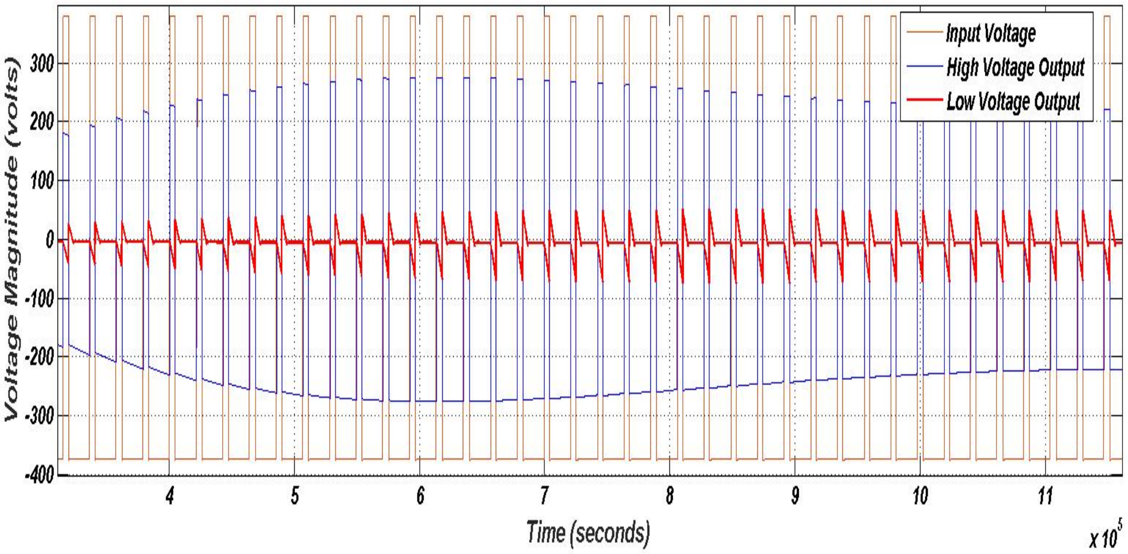


Figure 5.6: The Input and Output waveform of transformer embedded in HER model

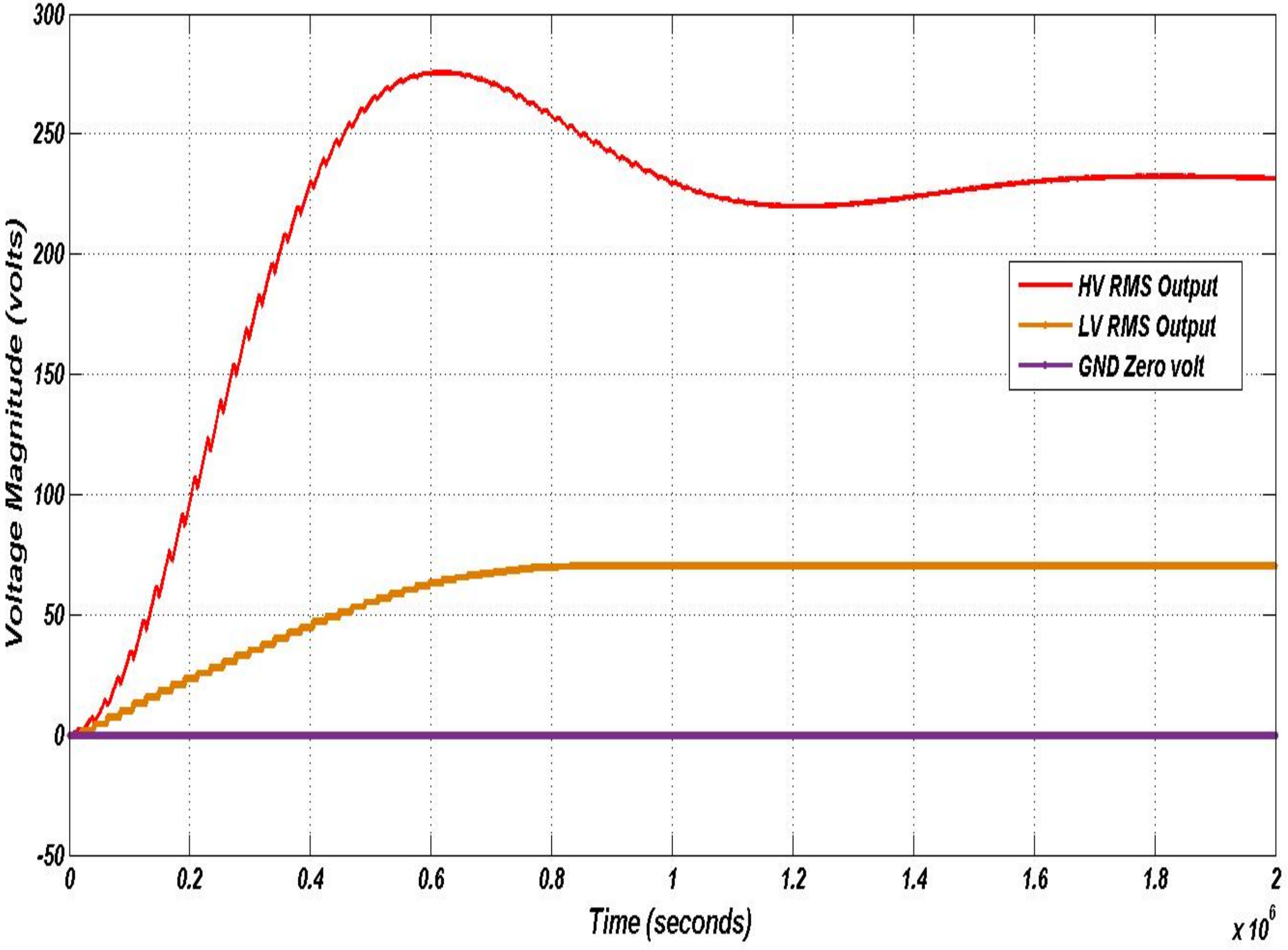


Figure 5.7: The RMS output voltages of HER transformer

Chapter 6

Conclusion and Future Work

In this chapter we summarizes the contribution of this dissertation along with the detail conclusions. Furthermore, we proposes the future work.

6.1 Conclusion

We proposed the power management technique for DCT enabled PCmRC consumer grid model. The major contribution is the DC Transformer, which is used for power conversion, control flow in bidirectional and AC/ DC load management. Furthermore, various operational modes, demand side management, control flow, standard scalable sources and storage interfaces are proposed, simulated and verified. In the proposed model, we mentioned the standard interface for different type of sources enabled the plug-n-play feature is investigated. In this dissertation, we not only presented the LVDC consumer grid model, in which locally available sources, storage can be integrated without significant change in the existing infrastructure, but also we explained the complete power management strategies in various situation which may occur during normal grid operation. The key contribution of the presented PCmRC consumer grid model is to allow any type of renewable or distributed source and storage regardless of its type and power rating at any stage without single change in control algorithm. Each source including main grid would be plug-n-play and there is no impact on normal grid operation by increasing or decreasing the amount of sources. However, for normal grid operation enough sources required to fulfill the minimum load requirements.

In this DCT can handle low/high voltage DC and AC powered load. Therefore, there is no additional power converter required and DCT also provides magnetic isolation between the main distribution bus and the consumer load and embedded over voltage and short circuit protection on each port, which assures the overall grid stability and reliability of the whole consumer grid and it eliminates the requirement of any additional supervisory system, which reduces the overall grid installation and supervisory system cost. While simulation, it has been proved that PCmRC consumer grid model equally operational in grid connected, islanding and off-grid conditions without a single change in control algorithm. However, in case of off grid mode the amount of renewable and distributed energy available locally must be equal or more than the load connected with the consumer grid for sustainable grid operation.

In presented model, the storage can be integrated directly on main DC and sub DC buses via standard interface and there are predefined levels of storage for charging and discharging autonomously. Therefore, it reduces the complexity of continuous monitoring of SoC and eliminates the possibility of fully drain of the battery storage, which enhance the life cycle of battery storage. There is standard DCT module is used to enable the PCmRC consumer grid mode. Therefore, more than one DCT module can be cascaded in order to meet the consumer power requirements. In this way, scalable power distribution system can be designed and desired number of redundancy can be achieved. The standard and scalable architecture would lead to lower down the production cost and MTTR (Mean time to repair) also minimized because all module pin to pin compatible and by replacing DCT module the whole grid would be operational within short time in case of fault.This architecture is perfectly integrated in the convectional AC power distribution infrastructure and allows dynamic power sharing from locally available sources and also permits to integrate storage at any level of distribution system. Therefore, the DCT enabled PCmRC consumer grid model would be a promising key component in modern power distribution of consumer grids.

6.2 Further scope of future work

In this dissertation, we already simulated and examined the over all grid power management strategies in different real world scenarios. However, the most important thing is to implement and deploy the scaled model DCT with two or more sources, at least one storage and two loads both critical and non-critical. There would be practical test need to be design to evaluate the scaled DCT model in grid connected and islanding modes with variable demand side power requirement. Proper investigation needed to be done related to overall stability when two or more DCT module run parallel. In order to validate the active power sharing control design without effecting grid stability.

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List of Publications

International Journals

Authors Syed Ashad Mustufa Younus, Matteo Nardello, Pietro Tosato, Davide Brunelli

Title Power Controlling, Monitoring and Routing Center Enabled by a DC-Transformer

Journal MDPI (Multidisciplinary Digital Publishing Institute) Energies 2017, ISSN: 1996-1073, VOLUME 10, ISSUE 3, pp. 403, doi: 10.3390/en10030403 March 2017

Abstract The penetration of various types of renewable sources and on-site storage devices have recently focused attention towards DC power distribution in consumer grids to achieve the target of zero/positive energy buildings and communities. To achieve this target, the most important component is the DC consumer grid architecture which can integrate not only renewable sources and storage, but also enable the implementation in any conventional AC distribution network without any significant upgrade. To this end, a unique DC Transformer enabled DC microgrid architecture is presented in this paper. The architecture, called PCmRC (power controlling monitoring routing center) is proposed to manage distributed energy sources and storage at any stage and also directly interconnects the DC consumer grid with the conventional AC power grid. This paper also investigates detailed control algorithms of each component and the DC Transformer topology in addition to proposing four unique stages of grid operational modes to enhance the overall grid stability in any operational condition. The main objectives are to maximize the exploitation of renewable sources, to decrease reliance on fossil fuels, to boost the overall efficiency of the grid by reducing the power conversion losses and demand side management in all possible forms. The simulation platform is designed in MATLAB/Simulink. Simulation results of several types of case studies show the effectiveness of the proposed power distribution and management model.

Authors Syed Ashad Mustufa Younus, Azhar Fakharuddin, Ahmad N. Abdalla, Muhammad Rauf, Nik Mohd Kamil, Salman Ahmad

Title A smart energy management system for monitoring and controlling time of power consumption

Journal Academic Journals Scientific Research and Essays , ISSN: 1992-2248, VOLUME 7, ISSUE 9, pp. 1000-1011, March 2012

Abstract Energy resources and their management is one of the prime challenges to the world especially low economy developing countries like Malaysia where the major contribution to energy generation is based on imports setting a considerable weight on the country economy. This overwhelming is causing affliction to policy makers and researchers. Domestic energy landscape has changed significantly over the years. From being an energy rich country a decade ago, Malaysia is slow and will soon be joining other countries that have to rely on imports in order to meet domestic demand. Hence, proper management of energy is a crucial issue that needs to be addressed to support the economy towards a higher growth trajectory. A holistic approach addressing the issues of energy supply, demand and pricing needs to be undertaken. In this research, a feedback and goal setting method is introduced in order to manage the high rise in peak demand. To obtain and monitor the desired mechanism, a high-tech system is proposed that involves some means of metering, display and communication layer having a live contact with the utility. A new package price is introduced here that might be of great user interest. This design is having an ability to be very effective in terms of electrical peak load management and a cost effective solution for different categories of users.

Authors Syed Ashad Mustufa Younus, Mirza Muhammad Amir, Dr. Roz Halliwell,

Title An Experimental Investigation Leading To Design Of Bi-Fuel System

Journal INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH, ISSN 2277-8616, VOLUME 3, ISSUE 11, NOVEMBER 2014

Abstract Since the beginning of time, energy has pervaded our earth. We rely on it to advance in any development. As the energy sources become scarcer, it is important to learn how to save and economize energy. A perfect energy should be cheap and efficient. Bi-Fuel system is such a concept, which combines the best of Diesel and Gas driven engines. Diesel driven engines though provide high power density but own the drawback of high cost and high on-site fuel storage. Gas driven engines provide low cost but own the drawback of low power density. A Bi-Fuel system is Compression ignited engine, which runs on the simultaneous combustion of Diesel and Natural gas. It works by introducing gas to the engine via various technologies and then electronically controlling flow dependent on output. This greatly extends the runtimes and limits the amount of diesel fuel that must be stored on site. This research work is about Bi-Fuel system.

International Conferences and Workshops

Authors S. Ashad Mustufa Y., Davide Brunelli

Title Model of scalable future consumer grid with residential power routing

Venue 9^{th} *IEEE International Workshop on Environmental, Energy and Structural Monitoring Systems (EESMS), 2015 (IEEE EESMS'15)*, Trento, Italy, July 2015

Abstract We present a distinctive grid-model for integration of renewable-sources, storage and AC-maingrid inside consumergrid known as Power-controlling-monitoring-routing-center. The main objectives are to maximize the exploitation of renewable sources, to decreases reliance on fossil-fuel, to reduce the powerconversion losses and full management of end-user demand in all possible forms. Simulation results show the effectiveness of the approach.

A unique distributed power management technique is proposed in this paper for DC microgrids. The PCmRC will be the main component in the future consumer grid, which will be responsible for grid-to-grid communication, real-time power metering, load management and integration of multiple renewable sources, energy storage and AC maingrid. Despite, the presented model can support the operation of whole range of consumer distribution system. Nevertheless, DCT enabled PCmRC may first be implement for residential application, which leads toward next generation sustainable empowering system for Smart-homes and Communities.

Authors Syed. Ashad Mustufa Younus, Davide Brunelli

Title Home Energy Router for smart consumer grids

Venue 9^{th} *IEEE International Symposium on Smart Electric Distribution Systems and Technologies (IEEE EDST'15)*, Vienna, Austria, Sept 2015.

Abstract Sustainable energy and energy harvesting has become a hot research area due to the depleting fossil energy resources and the need for lower carbon emissions. Nowadays, most appliances and short-term or small storage devices usually work on DC power and many renewable/sustainable energy sources also generate DC power. Therefore, there are several sophisticated power converters required to integrate DC appliances, sources and storage within the convectional AC grid, which may increase the overall grid installation cost and decrease the grid reliability. For this reason, the DC powered microgrid is gaining popularity due to reduced complexity, low energy losses and the small number of converters required. For instance, on-site generation and battery storage can be directly integrated in DC microgrid and solely DC-DC converter required to power-up DC appliances. However, existing infrastructure is based on AC distribution and few critical domestic appliances required AC power for normal operation. In this paper, we propose distinctive model to accommodate AC/DC powered load, sources and storage within the DC microgrid without any additional power converter, known as HER (Home Energy Router).

Authors S. Ashad Mustufa Y., Faisal Ahmed, Yannick Le Moullec, Paul Annus

Title Analytical evaluation of indoor energy harvesting technologies for WSNs with FYPSim framework

Venue 8^{th} *IEEE International Conference on Industrial Informatics and Computer Systems (IEEE CIICS'16)*, Sharjah, United Arab Emirates, May 2016

Abstract FYPSim is a framework that enables the modeling of various energy harvesting technologies and the sizing of energy storage technologies at the system level with application to wireless sensor networks. In this paper, we present the specific features of FYPSim related to energy harvesting exploiting indoor solar, indoor air flow, and indoor radio frequency energy sources. We also describe the models used for modeling hybrid energy harvesting and battery management. Our experimental results illustrate how FYPSim can be used to evaluate the above technologies in combination with Li-Ion batteries and super capacitors.

Authors S. Ashad Mustufa Y., John B., B. O'Flynn, R. Davies, P. McCullagh, H. Zheng

Title Design of a smart insole for ambulatory assessment of gait

Venue IEEE 12th International Conference on Wearable and Implantable Body Sensor Networks (BSN 2015), MIT, USA, June 2015

Abstract In this paper, we present the design and development of a smart insole that may be used to assess long term chronic conditions that affect the elderly population such as Stroke, Dementia, Parkinson's disease, Cancer, Cardiac Disease and Diabetes. This smart insole offers the potential for evidence base rehabilitation. The ICT solution detect the plantar foot pressure in a free living context through the integration of piezo sensors, micro-controller and Blue-tooth technology to empirically measure the pressure at important pressure points. The insole consists of 32 piezo sensors, 01 tri-axial accelerometers, temperature sensor and force sensor to automatically switch ON/OFF the insole. The accelerometers provide context for orientation. The design comprises two flexible PCBs encased in a padded layer, in order to protect the sensors and provide comfort to wearer.

Authors S. Ashad Mustufa Y., John B., B. O'Flynn, Declan D.

Title Design of smart integrated sensor systems for in-situ monitoring of marine environment

Venue International Conference and Exhibition on Smart Systems Integration (SSI 2016), Munich, Germany, March 2016

Abstract The COMMON SENSE project (CS) is a European Commission funded project under the FP-7 Framework. The aim of this project is to implement the EU marine policies i.e. Marine Strategy Framework Directive (MSFD), the Common Fisheries Policy (CFP) and the Integrated Maritime Policy. For this purpose, the scope of work under the CS project covers the development of the cost-effective, multi-functional, novel sensors, sensor acquisition system to the complete sensor data analysis and interpolation for in-situ measurement of marine environment. The core project research is based on the development of novel sensors for eutrophication, micro-plastic, underwater noise, temperature, pressure, concentration of heavy metals, pH and pCO2 according to MSFD descriptors 5, 8, 10 and 11. Moreover, the project will also focus on the data acquisition system, the deployments and analytical and process data and observations over a Common Sensor Web Platform (CSWP). CSP Smart Sensor Interface Architecture: The core project research is focusing on increasing the availability of standardized data on: eutrophication (phosphates, nitrates, nitrites, ammonia; concentrations of heavy metals (Pb, Hg, Cd, Zn and Cu); Microplastic fraction within marine litter; underwater noise; and other parameters such as temperature and pressure. This will be facilitated through the development of a sensor web platform and smart sensor unit. The overall block diagram of the Common Sensor Web platform. In order to integrate various sensors, we have not only proposed a standard and scalable sensor integration methodology, but also proposed the standard architecture of Common Sensor web platform (CSWP). The CSWP aims to connect sensors to the web platform, in order to make them available for various applications. The sensor layer consists of the actual hardware devices and the various kinds of communication protocols. The intermediary Sensor Web layer acts as a middle-ware and provides functionality to bridge between sensors and applications.

Appendix A

Symbol abbreviations

Table A.1: NOMENCLATURE

Symbol	**Definition**
P_{HLO}	The High power AC and DC Load output
P_{SLO}	The Low voltage sensitive electronics load Output
P_{RSI}	The Input Power from Renewable sources
P_{DGI}	The Input power from local distributed generators
P_{MSI}	The Input power from storage integrated with Main DC bus
P_{HSI}	The Input power from storage integrated with Sub HVDC bus
P_{LSI}	The Input power from storage integrated with Sub LVDC bus
P_{MGI}	The input power from AC main grid
V_{MB}	The Main DC Bus voltage
V_{SHB}	The Sub HVDC bus voltage
V_{SLB}	The Sub LVDC bus voltage
v_m	Secondary DC link voltage
v_{mref}	Secondary DC link voltage reference
i_s	Input primary current
i_{sd}	d-axis current
i_{sq}	q-axis current
i_{sdref}	d-axis current reference
i_{sqref}	q-axis current reference
v_s	Input primary voltage
v_{sd}	d-axis voltage of v_s
v_{sq}	q-axis voltage of v_s

Continued on next page

Table A.1 – continued from previous page

Symbol	**Definition**
V_l	Output side low DC bus voltage
V_{lref}	Output side low DC bus voltage reference
v_{sdref}	d-axis voltage reference
v_{sdref}	d-axis voltage reference
φ	Phase shift
V_h	Input side high DC link voltage
f	Switching frequency
L	Leakage inductance
i_{bat}	Battery storage current connected to sub DC bus
i_{batref}	Battery storage current reference
SoC_{bat}	State of Charge of battery
SoC_{nor}	Normal value of State of Charge
SoC_{min}	Minimum value of State of Charge
SoC_{max}	Maximum value of State of Charge
V_a	AC positive side output voltage
V_b	AC negative side output voltage
i_a	AC positive side output current
i_b	AC negative side output current
V_{aref}	AC positive side output voltage reference
V_{bref}	AC negative side output voltage reference
C_{fa}	Feedback capacitor for V_a
C_{fb}	Feedback capacitor for V_b
$C_{Linklow}$	DC Link capacitor for Low voltage
$C_{Linkhigh}$	DC Link capacitor for high voltage
i_{rs1}	Renewable source output current
V_{rs1}	Renewable source output voltage
V_{rs1ref}	Renewable source output voltage reference
i_{rs1ref}	Renewable source output current reference
i_{s1}	Back supply Non-renewable source current
V_{s1}	Back supply Non-renewable source voltage
i_{s1ref}	Back supply current reference
P_{s1}	Back supply power
P_{s1ref}	Back supply power reference

Appendix B

Key parameters for simulation

Table B.1: Key Simulation Parameters

Symbol	Definition
v_{sdref}	$380V$
i_{sqref}	0
V_{aref}	$120V$
V_{bref}	$120V$
V_{lref}	$24V$
i_{bat}	$22Amp$
f	$50KHz$
V_{rs1ref}	$375.5V$
V_{s1}	$359.5V$
C_{fa}	$100uF$
C_{fb}	$100uF$
$C_{Linklow}$	$42uF$
$C_{Linkhigh}$	$22uF$
$Transformerturnratio$	$12:10:1$
SoC_{nor}	60%
SoC_{min}	20%
SoC_{max}	90%