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CONTROL AND OPERATION OF DC MICROGRIDS

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SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2018

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted to higher degree to any other University or Institution.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Date

SUJAN ADHIKARI

To my Grandfather and Grandmother.

Acknowledgement

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Abstract

The utilization of DC microgrids in power industry has increased rapidly with the expansion in use of renewable energy sources (RES), energy storages and DC inherent loads. DC microgrid reduces the power conversion stages, does not require frequency, phase and reactive power control in its operation making it advantageous over AC microgrids. However, the cost-effective solution to renewable intermittency, system topology and standards for reliable, stable and efficient power supply still needs examinations through research. Control strategies, for economic solution to mitigate renewable intermittency in the system with inclusion of hybrid energy storage system (HESS), interconnection of microgrids with tie-line for reliable power supply and bipolar-type DC microgrids for high quality and high efficiency power supply, is proposed, implemented and elaborated in this thesis.

Energy storages are an option to solve renewable intermittency that can increase the utilization of RES into grid, changing the undispatchable generation to dispatchable. Energy storages can generate profit upon charging them when local electricity price lowers and can be discharged when the price is high. Choice of energy storage ranging from short term to long term is a key factor to address the compensation of load peaks, transients and to provide autonomy to the microgrids. Unfortunately, they cannot be achieved by a single energy storage, thus the need of hybridization of energy storages that have high specific energy and specific power is the solution for proper compensation of power fluctuation in autonomous microgrids. Upon review, it was also found that combination of lead-acid battery and supercapacitor compensate the gap of high energy density and high power density respectively and proved to be the best solution for hybrid energy storage applications and hence used as HESS in this research.

The conventional droop based decentralized control achieves static power regulation however, lacks to address frequency based autonomous power management for dynamic power control. Hence, a frequency coordinating virtual impedance concept has been explored in this thesis for the co-ordination control of an HESS in DC microgrids. It investigates power decoupling methods to better attenuate the ripple power by filtration. This research uses lead-acid battery and supercapacitor to form HESS and are connected to a common DC bus through bi-directional DC-DC converters. Battery converter can absorb low frequency power variations while supercapacitor converter can absorb the high frequency power variations. Battery supplies the long-term power demand and supercapacitor responds to the

short-term power fluctuations during transient process in this control approach. For the reduction of ripple power in battery, insertion of high order low pass filter for battery and high order high pass filter for supercapacitor converters instead of lower order low/high pass filters have been proposed. The effectiveness of the proposed concept is shown through simulation and experimental results.

The interconnection of DC microgrids for providing reliable power supply is particularly important in rural areas where utility grid is not available. Although, various researches are conducted in single entity, the interconnection of DC microgrid cluster is still novice in research. The interconnection of identical DC buses through tie-line and formation of microgrid clusters improves reliability of the system. To achieve power flow control through the tie- line, decentralized control approach has been proposed where the bus voltage of each microgrid in the microgrid cluster is controlled to ensure the regulation of bus voltage deviations. The use of decentralized control approach mitigates the issue of communication stress when the microgrid control areas are geographically distantly located. The decentralized control is accompanied by mode change based operation so that the distributed units like solar photovoltaic (PV) and energy storage system (ESS) in microgrids can adaptively adjust their operation modes depending upon the designated voltage level. By doing so, the bus voltage regulation (BVR) and power flow control is adjusted making each microgrid in the microgrid cluster autonomous. The power is generated/injected from/into microgrid when there is power surplus/deficit caused by supply-demand mismatch in particular microgrid. Tie-line power flow takes place in a microgrid, from another microgrid, due to the bus voltage decrement beyond the designated level caused by the increment in local consumption which could not be satisfied by the local generation and storages. The effectiveness of proposed decentralized control has been verified experimentally in the cluster of two microgrids.

Recently, bipolar-type DC microgrids have gained tremendous attention of researchers due to its advantages over conventional DC microgrids in terms of elevated level of quality, reliability and efficient power supply. Due to different loading in upper and lower terminals, voltage fluctuation from nominal value at respective terminals takes place and makes the system unbalanced. So, the control of parallel converters which interface distributed energy resources (DERs) and the topology of the converter along with voltage balancer play vital role in formation of efficient bipolar-type DC microgrid.

The bipolar configuration of converters in a DC microgrid can be formed by utilizing a converter to boost the input voltage and adopting a three-wire system by the means of voltage balancing circuit. Although many control schemes have been proposed for bipolar-type DC microgrids, they mainly focus on coupled microgrids with a centralized voltage balancer. The centralized voltage balancing technique is prone to deteriorate the system functionality due to the failure in communication links. Replacement of a centralized proportional-integral controller with multiple decentralized voltage balancers in a microgrid enhances the system reliability by removal of the communication links. This thesis proposes a decentralized control

for bipolar-type DC microgrids with a decentralized voltage balancing scheme for two battery energy storages. Droop control is implemented in this thesis for boost converters and voltage balancing circuits to realize decentralized power management for both load sharing and voltage balancing. The simulation results and experimental validations are provided to present the problem and associated solutions.

The proposed control strategies for operation of DC microgrid incorporating rooftop PV and HESS, interconnection of two DC microgrids consisting of PV and energy storages and bipolar-type DC microgrid consisting of two energy storages have been verified with Piecewise linear electrical circuit simulation (PLECS) software. Experimental cases have been carried out to validate the simulation studies with laboratory scale DC microgrid(s) prototype(s) developed at Water and Energy Research Laboratory (WERL), School of Electrical and Electronic Engineering, Nanyang Technological University.

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Acronyms and Symbols

Acronyms

AC	Alternating Current
BESS	Battery Energy Storage System
BIC	Bi-directional Interlinking Converter
BMS	Battery Management System
BRM	Bus Regulating Mode
BVR	Bus Voltage Regulation
CAES	Compressed Air Energy Storage
CC	Charge Controller
CP	Constant Power
CV	Constant Voltage
DBS	DC Bus Signaling
DC	Direct Current
DCL	Digital Communication Link
DERs	Distributed Energy Resources
DGs	Distributed Generators
DMS	Distribution Management System
DNO	Distribution Network Operator
EDLC	Electrochemical Double Layer Capacitor
EMS	Energy Management System
ESUs	Energy Storage Units
ETSI	European Telecommunications Standards Institute
FFT	Fast Fourier Transform
HESS	Hybrid Energy Storage System

HPF	High Pass Filter
HVDC	High Voltage Direct Current
IED	Intelligent Electronic Device
IEEE-SA	Institute of Electrical and Electronic Engineering Standard Association
KCL	Kirchhoff's Current Law
LBC	Low Bandwidth Communication
LCs	Local Controllers
LFC	Load frequency control
Li-ion	Lithium ion
LPF	Low Pass Filter
LVDC	Low-Voltage DC
MG1	Microgrid 1
MG2	Microgrid 2
MGCCs	Microgrid Central Controllers
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MTDC	Multiterminal DC systems
MVAC	Medium Voltage AC
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal Hydride
PCM	Power Control Mode
PCS	Power Converter System
PI	Proportional-Integral
PLECS	Piecewise Linear Electrical Circuit Simulation
PLS	Power Line Signaling
PM	Phase Margin
PR	Proportional Resonant
PV	Photovoltaic
PWM	Pulse Width Modulation
R & D	Research and Development

RES	Renewable Energy Sources
SC	Supercapacitor
SCESS	Supercapacitor Energy Storage System
SEPIC	Single-Ended Primary Converter
SMES	Superconducting Magnetic Energy Storage
SoC	State of Charge
STC	Standard Test Condition
UC	Ultracapacitor
VDC	Voltage Droop Controller
VRB	Vanadium Redox flow Battery
VSC	Voltage Source Converter
ZEBs	Zero-net-Energy Buildings
ZTDC	Zonal Type DC

Symbols

ω_c	Filter crossover-frequency
ω_{conv}	Converter frequency
ρ	Resistivity of conductive material
ε_v	Maximum allowable DC bus voltage deviation in droop control
A	Ideality factor
A_c	Cross-sectional area of a conductor
C	Capacitor
C_{dc}	DC network capacitor
C_{bus1}	Bus capacitor for MG1
C_{bus2}	Bus capacitor for MG2
C_i	Bus capacitor for i^{th} boost converter
C_{sup}	Supercapacitor value
d_{bat}	Duty ratio for the battery converter
D_i	Diode for i^{th} boost converter
d_{PV}	Duty ratio for the PV converter

e	Input voltage of boost converter
G_{bat}	Switching signal for the battery converter
G_{PV}	Switching signal for the PV converter
i_{ci}	Capacitor current of i^{th} boost converter
i_{Li}	Inductor current of i^{th} boost converter
i_{oi}	Output current of i^{th} boost converter
i_{dc}	Current injected into the DC network
i_{fl}	Full load current of the converter
i_L^*	Reference inductor current
I_{L_ba1}	Inductor current for a voltage balancing circuit of ESS1
I_{L_ba2}	Inductor current for a voltage balancing circuit of ESS2
I_{L_bai}	Inductor current at voltage balancing circuit of i^{th} converter in a bipolar-type DC microgrid
i_{L_baimax}	Maximum inductor current at i^{th} voltage balancing circuit of a bipolar-type DC microgrid
I_{L_boost1}	Inductor current of the ESS1 in a bipolar-type DC microgrid
I_{L_boost2}	Inductor current of the ESS2 in a bipolar-type DC microgrid
I_{o1}	Positive-half current of the ESS1 in a bipolar-type DC microgrid
I_{o1}^-	Negative-half current of the ESS1 in a bipolar-type DC microgrid
I_{o2}	Positive-half current of the ESS2 in a bipolar-type DC microgrid
I_{o2}^-	Negative-half current of the ESS2 in a bipolar-type DC microgrid
I_{ph}	Photocurrent
I_{PV}	Output current of solar PV
I_{rr}	Reverse saturation current at temperature T_r
I_{sat}	Saturation current
I_{sc}	Short-circuit current
i_{sup}	Supercapacitor output current
I_{tie}	Tie-line current
k	Boltzman constant
K_i	Temperature coefficient of short circuit current
L	Inductor

l	Length of conductive material
L_bai	Inductor at voltage balancing circuit of i^{th} converter in a bipolar-type DC microgrid
L_i	Inductor current for i^{th} boost converter
L_{linei}	Line inductance from source to the load bus of the i^{th} converter in a DC microgrid
n_p	Number of solar cells in parallel
n_s	Number of solar cells in series
P_{ac}	Rated power output, determined by power system operator from the microgrid to the AC utility grid
P_{bat}	Battery bank output power
P_{DG}	Power generation in the microgrid by DERs at MPPT state
$P_{ESS_{ch}}$	Maximum charging power of ESS units in the microgrid
$P_{ESS_{dch}}$	Maximum discharging power of ESS units in the microgrid
P_{load}	Local consumption
P_{load}^+	Positive-half load power of a bipolar-type DC microgrid
P_{load}^-	Negative-half load power of a bipolar-type DC microgrid
P_{PV}	PV output power
$P_{tie,i}$	Tie-line power
q	Electron charge
R_{bai}	Virtual resistance for i^{th} converter in a bipolar-type DC microgrid
r_{di}	Droop gain for the i^{th} converter in a DC microgrid
r_{dmax}	Maximum allowable droop gain for the converter in a DC microgrid
R_{dp1}	Virtual resistance for battery converter in MG1
R_{dp2}	Virtual resistance for battery converter in MG2
R_{droop}	Virtual resistance in HESS applications
R_{droopi}	Virtual resistance for i^{th} boost converter in a bipolar-type DC microgrid
R_i	Resistive load for i^{th} boost converter
R_{L1}	Resistive load in MG1

R_{L2}	Resistive load in MG2
r_{linei}	Line resistance from source to the load bus of the i^{th} converter in a DC microgrid
S	Solar irradiation
S_i	Switch for i^{th} boost converter
T_r	Reference temperature
T_s	Surface temperature of the PV cell
V_i^+	Upper-half capacitor voltage of the i^{th} converter in a bipolar-type DC microgrid
V_i^-	Lower-half capacitor voltage of the i^{th} converter in a bipolar-type DC microgrid
v_{ci}	Capacitor voltage of i^{th} boost converter
v_{MG}^*	Reference voltage for MG1 and MG2
v_{oi}	Output voltage of i^{th} boost converter
V_{bat}	Battery bank terminal voltage
V_{bo}	Output voltage of the battery converter
V_{bus}	DC bus voltage
V_{dc}	DC bus voltage for HESS application
V_{dc1}	DC bus voltage of MG1
V_{dc2}	DC bus voltage of MG2
$V_{dc,i}$	DC bus voltage of i^{th} microgrid
$V_{dc,j}$	DC bus voltage of j^{th} microgrid
V_{high}	Upper threshold voltage for utility, storage and generation dominating modes
V_{low}	Lower threshold voltage for utility, storage and generation dominating modes
V_{PV}	Input voltage of the PV converter
V_{PV}	Output voltage of solar PV
V_{PVo}	Output voltage of the PV converter
V_{ref}	Reference voltage
v_{sup}	Supercapacitor output voltage
v_{tie}	Tie-line voltage drop

$Y_{tie,ij}$	Tie-line admittance
$Z_{bat}(s)$	Equivalent impedance of battery converter in HESS application
$Z_{conv}(s)$	Real output impedance of converters in HESS application
Z_{droop}	Virtual output impedance in HESS applications
Z_{ESS}	Equivalent impedance for entire HESS
Z_{linei}	Line impedance from source to the load bus of the i^{th} converter in a DC microgrid
$Z_{sup}(s)$	Equivalent impedance of SC converter in HESS application
$Z_{tie,ij}$	Tie-line impedance

Chapter 1

Introduction

I have not failed. I've just found
10,000 ways that won't work.

—*Thomas A. Edison*

1.1 Background

The famous *battle of currents* which started in the late 1880s [1] was concluded by the eventual adoption of Alternating Current (AC) power system globally. The problem with Direct Current (DC) power system was that it could not be easily converted to higher or lower voltage levels allowing much longer transmission distances [1–3]. Power loss in AC transmission lines could also be significantly lowered by implementing very high voltage that could not be performed in DC power system at that time [1, 2]. However, the centralized AC power system standardized to transmit and distribute electricity has its own issues. The centralized generation system for producing bulk power require large infrastructure and are costly. Central generation plants are prone to attacks and can be unreliable and unstable during unforeseen events [4]. In addition, their environmental impact, inefficiency and sustainability issues has led researchers and policymakers to opt for Distributed Energy Resources (DERs) over central generation plants. DERs and loads are integrated in both grid connected and islanded mode conditions to form a microgrid [5–8].

Microgrid [5, 7, 9, 10] is a conceptual framework for interconnecting distributed generation, loads and energy storages. It exemplifies the advancement of current power systems as an autonomous unit of the main grid [11]. In addition, microgrids

improve the reliability, sustainability and make the system energy efficient [12] apart from their independent operation [13]. Microgrids are categorized as AC, DC [14] and hybrid AC/DC based on their function and structure [15, 16].

Renaissance of DC Microgrids

The DC system was obliterated by AC because of the fact that DC voltage regulation was not possible at that time and was inefficient and costly. This can be recalled by the fact in history, when Tesla's AC system won the bid in Chicago World's Fair in 1893 being USD 155,000 cheaper than General Electric's bid for electrifying the fair by Edison's direct current [1]. However, in the mid-1950s, high voltage DC was developed and is now an option instead of long-distance high voltage AC systems. The high voltage transmission has reduced the transmission loss from 30-50% in comparison with AC systems [17]. Also, the advent of power converters due to the development in semiconductor devices since 1970s [18] the DC system has seen a bit of a renaissance.

Along with the rise in use of renewable energy sources, prompt improvement in energy storage technologies and continuous advancement in power electronics in an economic manner, power industry has seen massive revolution in the use of power. A major shift from conventional AC distribution to the DC microgrid is seen in mostly in sectors such as transportation, data centers, military operations telecommunications, etc. [19]. A DC microgrid is beneficial because the Renewable Energy Sources (RES) like solar Photovoltaic (PV) and most of the energy storage technologies in market produce DC power which can directly feed most of the DC type residential loads [12]. In addition, efficiency can be enhanced by rapid battery charging of electrical vehicles, the use of which has been accelerated around the globe, by powering through high voltage DC bus. These traits of the DC microgrid in addition to its features like its ability to operate in the absence of frequency, phase and reactive control make it superior to conventional AC system [12]. Factors that have caused the paradigm shift from AC to DC as discussed above are elaborated as follows:

DC loads: At present, electricity need is fulfilled by AC but the development of semiconductor devices has increased the use of DC inherent loads. Computers, LEDs, electric vehicles, variable speed drives etc. utilize DC power for their operation. To feed these loads, the utility AC needs to be converted into DC using rectifiers. Since these loads are served through internal DC bus after front end rectification, such conversion account for power loss up to 32% [20] and the quality

of the power supply might be inadequate. Hence, there is the necessity of elimination of front end rectifiers to serve the DC loads through DC microgrid directly. About 50% of the losses of manufacturing plants can be minimized if the large rectifier/inverter motor drives are directly powered via DC bus [12].

Distributed Generators (DGs): DERs include diverse types of generators that can be either renewable or non-renewable type [21]. In recent years, there is an increasing use of renewable energy sources in the various electricity consumption sectors to achieve energy savings and reduce energy consumption. The installation and operational cost for the utilization of renewable energy resources has dramatically reduced due to the rapid technological development in past years, and the ecofriendly nature of renewable distributed generators over fossil fuel has driven the global interest towards investment in it in order to substitute fossil fuel and reduce carbon emission.

Approximately 1.1 billion of the global population lack accessibility to electricity as per World Bank's estimates. Majority of this population belong to areas where grids are simply not reachable [19]. Small scale microgrids with distributed renewable energy sources (RES) like rooftop PV and energy storages are the solution to electrify such remote areas. Moreover, the transmission losses of 6.5% due to geometrical location of source and load are eliminated [22]. On the other hand, customers' electricity bills do not include cost of transmission providing high quality affordable power [23]. Local surplus power generation by residents can be fed back to utility grid during peak demand to generate profit. Emerge Alliance (EA), a nonprofit open industry, has a vision to create Zero-net-Energy Buildings (ZEBs) to generate clean energy on-site in buildings equivalent to the energy they use lessening the economical, and ecological burden due to energy generation [24].

Storage systems: The intermittent nature of RES like solar and wind power might be disadvantageous and costly in comparison to other conventional energy resources [25–27]. The duration of intermittency in solar and wind power varies from short term to long term, short term ranging from seconds to minutes and long term being extended to months depending upon the factors like gusts and lulls, cloud movement, length of the day and seasonal weather changes [25–27]. Such variations in power can bring several problems like voltage surges and sags along with system frequency changes. To smoothen such intermittency, energy storages with fast ramp rate are the solution [28, 29]. Energy storages can generate profit upon charging them when local electricity price lowers and can be

discharged when the price is high [30]. They can increase the utilization of renewable energy into grid, changing the undispachable generation to dispatchable [30].

A key benefit of energy storages is that most of them available in market are of DC type and their integration to DC microgrid along with DC-type DERs to feed DC inherent loads can reduce conversion losses. Since their operation takes place in the absence of fossil fuels, DC type renewable DERs along with energy storages are an eco-friendly and energy secure technology [31]. The major reason to integrate energy storages with RESs in a microgrid is to provide high quality and consistent power supply.

The potential benefits of several factors for distribution of DC power through DC networks can be summarized but not limited to [32]:

- High efficiency: The local power systems are mostly comprised of distributed generations or storages that naturally produce DC power and have lesser AC to DC, AC to AC or AC to DC conversions making the power system highly efficient.
- High reliability: Fewer power conversions also make the system highly reliable since they require fewer electronic components resulting in low chances of failure.
- Low capital cost: Fewer power electronic components make the system less capital intensive and the capability of DC to carry higher current reduces conductor cost.
- Less complex and stable: The DC system has fewer power electronics components and does not require synchronization like AC system making the system less complex and more stable when subjected to internal and external disturbances.

The presence of potential storage buffer and power electronics between the AC grid and DC microgrid results in higher power quality and disturbance survivability.

1.2 Overview of DC microgrids

DC microgrid comprises various converters connected in parallel interfacing various distributed generation units (solar PV, wind turbines, fuel cells, microturbines etc.), and energy storages (battery, ultra- capacitor etc.). The schematic represen-

tation of generic DC microgrid is depicted in Fig. 1.1. DC-DC converter interfaces sources like solar PV, fuel cell and energy storages that are of DC-type to the DC bus while wind turbine and micro-turbines are interfaced to the DC bus by means of AC/DC converter. DC loads can be connected either directly or by means of DC/DC converter depending upon the voltage level of bus and the load. RES operate in Maximum Power Point Tracking (MPPT) mode.

Figure 1.1: Schematic layout of a generic DC microgrid

DC microgrid can be either operated in islanded mode or grid connected mode. The utility grid is interfaced with DC bus by means of Bi-directional Interlinking Converter (BIC) in order to operate in grid connected mode [33]. System operates in islanded mode during grid disturbances such as system frequency deviation and bus voltage fluctuation.

The functions of DC microgrid operation are to control the parallel converters involved to interface DG units, proportional load sharing and voltage regulation [34]. System stability of DC microgrids depends upon the system power balance and bus voltage regulation. The primary role of energy storages in DC microgrid with RES is to provide consistent quality of power supply by compensating the mismatch of power consumption and generation. The oscillating output of PV

power plants is usually regulated by Battery Energy Storage System (BESS) [35]. To acknowledge the compensation of transients and load peaks and to make the microgrid an autonomous unit, choice of energy storage has a significant role to play.

One of the first DC microgrid experimental prototype was developed in 2004 by Ito *et al.* [36] for 10kW system, after which rigorous research has been carried out for the demonstration of DC microgrid in residential households, telecommunication systems, data centers, etc. [37].

1.3 Obstacles to DC microgrid deployment

Some of the economic, technical and social hurdles observed by project developers while building the DC microgrid are [12, 19, 20]:

- Understanding of DC system: Despite many literature and research on improved efficiency and higher reliability of DC due to lower conversion losses, it is considered that AC has less power loss than DC in power system. Also, existing misconceptions are that DC is more dangerous than AC, and that it cannot be operated for long distance transmissions due to the lack of knowledge on advanced power electronic solutions like solid-state transformers to transform any electricity to AC or DC. Some form of hesitancy to approve DC projects can be seen from local authorities due to lack of references in safety codes and limited experience.
- Implementation of projects based on DC systems: The projects based on DC microgrids are limited to industry and academia which are relatively simple projects focusing on specific applications like telecommunication, data servers, or solar PV plus battery storage installations. Design and demonstration of large scale DC microgrid projects with diverse sources and loads should be promoted.
- Financial hurdles: It is difficult and cost intensive to replace AC rectifying elements and wide variety of DC bus voltages in off-the-shelf loads [12]. The extensive Research and Development (R & D) efforts for custom power electronics control and communication features associated DC microgrids increase the cost and project deployment time.

- Safety and protection devices: Identification, location and rectification of fault is very important for the continuous operation of DC microgrids. Addressing issues like grounding, types of faults ensure safe operation of DC microgrids. Proper protective devices should be designed based on the types of faults [37]. Awareness and mass production of such protective devices for DC systems in AC dominant distribution system market is a component of the socio-economic aspect in this case.
- Codes and standardization issues: The few existing standards for DC voltages that are available are 12V and 5V for vehicles and universal serial bus devices respectively [19]. For higher power, higher standard voltage is necessary. The telecom industry has settled in 48V standard [19]. European Telecommunications Standards Institute (ETSI) and the EMerge Alliance have standardized on 380V for DC distribution systems [19]. The Institute of Electrical and Electronic Engineering Standard Association (IEEE-SA) has number of activities for the utilization of DC distribution in various applications [38].

Although IEEE Standard 1547 is designed for AC system with RESs, some of the concept can be utilized for DC microgrid standards development since it is the standard for different operating modes i.e. grid connected or islanded and covers the requirements for acceptable voltage and frequency ranges and reaction of protective devices including power quality issues [37].

- Robustness of Control: The coordination of system units and interfacing power electronic converters in DC microgrid is achieved by various control methods i.e. centralized, decentralized and distributed control depending upon the communication links used. The development of robust control and energy management strategies for different applications is still an open area of research. A primary rule when conceptualizing a DC microgrid is that the system must be of generic type such that all generators contribute to the microgrid formation along with voltage restoration. Another key rule is that the network should be extendable such that the adding of new elements do not affect the network [39]. Above features form a reliable and stable DC microgrid prioritizing the generator and its control.

1.4 Objectives

The scope of this thesis lies on proposing decentralized control in DC microgrids for unipolar, bipolar and two bus configurations. The goal is to achieve better performance, which is summarized and expressed as follows:

- To propose DC microgrid with Hybrid Energy Storage System (HESS) consisting of battery and Supercapacitor (SC), using the SC to minimize high frequency oscillations and to extend lifecycle of the battery.

For standalone DC microgrids consisting of HESS, where centralized control is not viable and to provide control flexibility to conventional droop control, frequency coordinating virtual impedance concept is taken into consideration. The outcome shows the autonomous operation of DC microgrid achieving the complementary advantages of high energy density and high power density of battery and SC respectively to absorb both low and high frequency power fluctuations. Furthermore, the insertion of higher order filter is proposed and verified in order to reduce the ripple power in the battery.

- To develop decentralized control for two DC microgrids interconnected with tie-line.

Decentralized control scheme for managing power flow and maintaining DC bus voltage of DC microgrids connected with tie-line is still an open research. The bus voltages of DC microgrids act as an indicator for the power flow monitoring the supply-demand balance. The control scheme developed ensures the voltage stability during disturbances and tie-line power flow when a microgrid is deficit of power.

- To develop decentralized voltage balancing control for bipolar-type DC microgrids.

The decentralized control for bipolar-type DC microgrids with decentralized voltage balancing scheme is presently lacking. The control conflict due to two voltage balancing circuit is mitigated by applying droop based control for balancing circuit. The controller designed can converge the pole voltages to nominal value in short time after the transient response due to load change.

- To achieve autonomous operation and suitable distributed usage.

Either the microgrid operates in islanded mode or in interconnected system, this is a key criteria. It is of special prominence in case of microgrids with sources that are widely dispersed and difficult to be connected by communication network. The exclusion of communication links provide high reliability to the system since communication network failure may lead to system collapse.

- To provide experimental verification to the proposed schemes.

A suitable scaled down laboratory scale prototype has been developed for the test. The terminal voltages and currents sensed have been fed to the digital signal processors of the relevant DGs and ESS to realize the control scheme proposed for standalone and interconnected DC microgrids along with bipolar-type DC microgrid.

1.5 Thesis Contributions

The major contributions in this thesis are in the sphere of developing decentralized control strategies for unipolar DC microgrid with HESS, interconnected and bipolar-type DC microgrids. The control strategies developed are based upon generic principle and can be applied to DC microgrids with different types of DGs and operating characteristic.

a) Control of Hybrid Energy Storage System (HESS) in DC Microgrids

Rise in the demand and utilization of eco-friendly and renewable energy resources like wind and solar in electric grids come with a challenge of making the system unstable and delivering poor power quality primarily because of the intermittent nature of renewable energy sources and their variability. Such power variation can be decomposed into high and low frequency components. Energy storages with high power density and high energy density can be organized to cope up with low and high frequency components respectively. Frequency based power management approach is applied on a DC microgrid consisting of lead acid battery and SC along with solar PV generation. By shaping the virtual output impedance of battery and SC in frequency domain, the low frequency and high frequency components power fluctuations are absorbed. This concept can be applied to advanced power management strategies. The efficacy of higher order Low Pass Filter (LPF) /High Pass Filter (HPF) for battery and SC converter respectively with respect to the low

order filters has been investigated. Utilizing second order filters are expected to better attenuate the noisy output and ripple power in DC microgrid with HESS. The coordination of battery and SC along with the static and dynamic power sharing have been verified through experiments.

b) Control of two interconnected DC microgrids with tie-line

An ESS can address the renewable intermittency in an islanded DC microgrid enhancing the reliability and making the system more stable. In addition, the interconnection of neighboring DC microgrids for exchange of power can further enhance the reliability. Forming multiple DC microgrid clusters by connecting multiple identical DC buses via tie-line also aids in making the system more efficient and reliable. The primary challenge in interconnecting DC microgrids is keeping the system stable, since the involvement of multiple parallel converters in a DC microgrid cluster make the system unstable. A decentralized control approach for controlling the bus voltage of geographically dispersed microgrids in an allowable range can manage the power flow via tie-line across the microgrid. Such approach being decentralized, is void of communication stress. A mode adaptive decentralized control is adopted for seamless mode transition in operation modes of the microgrid. Thus, the distributed units can cope up with power flow control and Bus Voltage Regulation (BVR) providing autonomy to the interconnected microgrids. In case of power deficit, power is injected/generated into/from the microgrid caused by demand-supply mismatch in a particular microgrid. The generation sharing is facilitated by interconnecting the microgrids via tie-line in such case. In absence of power supply deficit, every microgrid operates as an autonomous unit curtailing the generation in case of surplus in power supply. The dynamic operation during variation in the source/load of microgrids has been evaluated maintaining the bus voltage.

c) Control of bipolar-type DC microgrids

Bus voltage is considered as a global carrier of information to designate system power balance in decentralized control of DC microgrids. Although, the three wire bipolar DC microgrid consists of three terminals and provide flexibility in the connection of loads through remaining wires even when one wire fails, it has certain challenges. Due to the different loading in upper and lower terminals, the bipolar DC microgrid gets unbalanced as the consequence of voltage fluctuation from nominal value at respective terminals. For this purpose, a voltage balancer is required in such microgrids. The use of decentralized control approach reduces the

communication stress on the state-of-the art proposed systems with central voltage balancer in bipolar-type DC microgrids. The decentralized voltage balancer can create control conflict when there exist two bus regulating units in the microgrid. An improved bipolar-type DC microgrid is proposed where decentralized control for parallel converters interfacing DERs is implemented with droop control based decentralized voltage balancing circuit. The control conflict between the two voltage balancing circuits involved to regulate the bus voltage have been mitigated by the proposed decentralized control for voltage balancing. The controller designed for bipolar-type DC microgrid can converge the pole voltages to nominal value in short time after the transient response due to load change.

1.6 Organization of the Thesis

This thesis consists of six chapters. The contents of this thesis are organized as follows.

this Chapter discusses the rapid increase in utilization of DC microgrids and the challenges associated with its development in the power industry, which is the motivation behind the writing of this thesis. The basic hardware topologies of DC microgrids have been discussed with illustrations highlighting the advantages and disadvantages of such commonly used existing topologies along with the reasons that have been the hindrance in DC microgrid deployment. Research objectives focussing decentralized control in DC microgrids are elaborated. Summary of major contributions have been pointed out.

Chapter 2, reviews the constituent of DC microgrids, compares various energy storage technologies and proposes hybridization of energy storage system with high specific power and specific energy as the solution to compensate the power fluctuation in autonomous microgrids that is not achieved by a single energy storage. The existing DC microgrid topologies have been summarized. The coordination control strategies of DC microgrids comprising of renewable energy sources, energy storages and HESS are elaborated.

Chapter 3, investigates decentralized control of DC microgrids and explores frequency coordinating virtual impedance concept for the co-ordination control of an HESS in DC microgrid. Power decoupling methods to better attenuate the ripple power by filtration have been investigated and the effectiveness of the proposed concept is verified through simulation and experimental results.

Chapter 4 discusses about the interconnection of DC microgrids to form a DC microgrid cluster with tie-line. It proposes decentralized control strategy for interconnection of two DC microgrids with tie-line. Mode adaptive decentralized control for these DC microgrids has been proposed where the bus voltage of each microgrid is controlled to ensure the regulation of bus voltage deviations. The effectiveness of proposed decentralized control has been validated experimentally in two interconnected DC microgrids.

Chapter 5, explores bipolar-type DC microgrids and decentralized voltage balancing control is proposed in bipolar-type DC microgrids. An improved droop control is implemented to mitigate control conflict due to two bus voltage controllers in a system and to validate the decentralized control of bipolar-type DC microgrid for both load sharing and voltage balancing.

Finally, in **Chapter 6**, this thesis is summarized and future research directions are recommended.

Chapter 2

Configuration and Control of DC microgrids

We're looking at it closely, but there are some obstacles. Some are technical; we need some control technologies. We'd like to see it more broadly implemented. From an economic standpoint, there's still a question of where and when they make sense.

—*Hareesh Kamath, ARPA-E*

*Energy Summit 2014, on technical
issues of microgrids*

This chapter reviews the configuration of DC microgrid topologies, classification of control strategies and the elements of DC microgrids. Desired control requirements have been identified and deployed from Chapter 3 onwards. Along with the control of power electronic converters for solar PV and battery, this chapter reviews the state-of-the-art in energy storage technologies and discusses the essence of hybridization of energy storage system in DC microgrids.

Figure 2.1: Equivalent circuit of typical PV module (a) Simplest model (b) Sophisticated model

2.1 Review on Constituents of DC Microgrids

2.1.1 Solar PV System

The simplest model of solar PV panel can be represented as a current source with an anti-parallel diode and series resistance R_s as shown in Fig. 2.1(a). The parallel diode is determinant of the I-V characteristics of the solar cell and the output of the current source is directly proportional to the solar irradiance. A sophisticated model can be represented with a shunt resistance R_{sh} in parallel with the diode [40] as shown in Fig. 2.1(b). The equations to represent the output current of solar cell are given as follows:

$$I_{PV} = n_p I_{ph} - n_p I_{sat} \times \exp \left[\frac{q}{AkT_s} \left(\frac{V_{PV}}{n_s} + I_{PV} R_s \right) - 1 \right] \quad (2.1)$$

$$I_{ph} = (I_{sc} + K_i(T_s - T_r)) \cdot \frac{S}{1000} \quad (2.2)$$

$$I_{sat} = I_{rr} \cdot \left(\frac{T_s}{T_r} \right)^3 \exp \left(\frac{qE_{gap}}{kA} \cdot \left(\frac{1}{T_r} - \frac{1}{T_s} \right) \right) \quad (2.3)$$

Where,

I_{PV} : Output current of solar PV;

I_{ph} : Photocurrent;

I_{sat} : Saturation current;

I_{sc} : Short-circuit current;

q : Electron charge;

A : Ideality factor;

k : Boltzman constant;

S : Solar irradiation;

V_{PV} : Output voltage of solar PV;

n_s : Number of solar cells in series;

n_p : Number of solar cells in parallel;

K_i : Temperature coefficient of short circuit current;

T_s : Surface temperature of the PV cell;

T_r : Reference temperature;

I_{rr} : Reverse saturation current at temperature T_r ;

The I-V characteristic of solar PV panel explained by (2.1)- (2.3) is depicted in Fig. 2.2. The curves are generated from MATLAB for module type SPR-305-WHT by SunPower, and the manufacturer specifications are listed in Table 2.1. I_{sc} corresponds to the short-circuit current which is obtained when the output voltage of PV (V_{PV}) is zero and V_{oc} corresponds to the open-circuit voltage of PV when the output current of PV is zero. I_{sc} and V_{oc} are the maximum values of current and voltage that can be obtained from a PV cell under Standard Test Condition (STC).

The power of the PV cell can be obtained by multiplying its output voltage and current. From Fig. 2.2, it can be seen that the power increases with increase in voltage of the PV cell reaching maximum point however, it further decreases from this maximum point. This point is termed as Maximum Power Point (MPP) and the corresponding current I_{mp} and voltage V_{mp} to achieve maximum power are indicated in Fig. 2.2.

Power Electronics for solar PV

The integration of solar PV to the DC bus is done by the means of interfacing converter termed as DC-DC boost converter. The schematic layout of DC-DC boost converter is shown in Fig. 2.3(a). The operating principle of the DC-DC boost converter is based on the periodic accumulation of energy and transferring

Figure 2.2: I-V characteristic of solar PV

Table 2.1: Solar panel parameters for SPR-305-WHT module

Parameters	Value
Number of series connected modules per string	1
Number of parallel strings	1
Irradiance at STC (W/m^2)	1000
Cell temperature at STC ($^{\circ}C$)	25
Open circuit voltage under STC (V)	64.2
Short circuit current under STC (A)	5.96
Photocurrent (A)	5.9602
Saturation current (A)	1.1753×10^{-8}
Ideality factor	1.3
Series resistance (Ω)	0.037998
Parallel resistance (Ω)	993.51
Voltage at maximum power point under STC (V)	54.7
Current at maximum power point under STC (A)	5.58

it through inductor L in the circuit with capacitor C and load. The operation of solar PV converter in DC microgrid can be classified as MPPT mode and Bus Regulating Mode (BRM).

Figure 2.3: Solar PV converter a) Schematic representation of DC-DC boost converter b) Controller for solar PV converter

During MPPT mode, the terminal voltage of PV panel is generated from the MPPT block as shown in Fig. 2.3(b) where, P_{PV} denotes the PV output power. The dual loop Proportional-Integral (PI) controller consists of outer voltage control loop and inner current control loop. The function of outer voltage control loop is to generate the reference current (i_L^*) for inner current control loop and is obtained by processing the difference of reference and actual terminal voltage of the solar PV. The inner current control loop consists of another PI controller to minimize the current tracking error and generate the duty ratio for the PV converter d_{PV} . PWM generates the switching signal (G_{PV}) for the power electronic switch S_{11} to

realize boost operation of PV converter.

In bus regulating mode, the reference output voltage of PV converter is tracked by a double loop PI-controller. The function of outer voltage and inner current control loops are same as explained above.

The relationship between the input voltage (V_{PV}) and output voltage (V_{PVo}) of the PV converter is expressed as in (2.4).

$$V_{PVo} = \frac{1}{1 - d_{PV}} V_{PV} \quad (2.4)$$

2.1.2 Energy Storage System

Several researches have been carried out in the area of energy storage and ESS. Depending upon the compensations for power fluctuations from seconds to hours, energy storage technologies are divided into short term, medium term and long term [41] including standalone systems [42]. Energy storage technologies can be classified into, as follows [43]:

- Mechanical Storage System: It comprises of technologies like hydro, compressed air and flywheel storage system.
- Electrical Storage System: Capacitors and Ultra capacitors fall in this category.
- Electromagnetic Energy Storage System: Superconducting Magnetic Energy Storage (SMES) represents this system.
- Electrochemical Energy Storage System: Traditional batteries and flow batteries represent this category.

Mechanical Storage System like Compressed Air Energy Storage (CAES) and hydro energy storages are able to provide energy for longer course of time ranging from hours to even days since they can store large amount of energy. However, the response time is slow [28].

SMES are highly efficient, up to 95%, with fast response time but the cost of refrigeration and superconducting wire make it very expensive [28]. They find their use in low energy high power applications.

Ultracapacitors carry long lifetime and are highly efficient. They have low energy density in comparison to lead-acid batteries and are costly. However, their fast

response provides short burst of power [28], thus, they find their use in low energy high power applications.

Researchers have paid high attention to chemical batteries lately. Traditional batteries like Lithium ion (Li-ion), sodium sulphide and flow batteries like vanadium redox have proved to be efficient by new technologies, Li-ion carrying nearly 100% round trip efficiency and sodium sulphide and vanadium redox providing 85% and 80% efficiency [44]. However, there will be a loss in the interface [28] since batteries store energy in DC and they need power electronic interface for energy conversion.

To have a better idea about the efficiency, specific energy, specific power, lifetime etc. of chemical batteries and ultracapacitors a literature survey is conducted and tabulated in Appendix A. References for the above mentioned parameters for widely used chemical batteries such as Vanadium Redox flow Battery (VRB), lead acid battery, Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH) and Li-ion along with SC are tabulated.

Based upon the summary tabulated in Table 2.2, Li-ion batteries are the best candidate for hybrid energy storage application in terms of parameters like efficiency and energy density. Besides high cost, Li-ion batteries are superior to other chemical batteries in every aspect. Supercapacitors show best performance in terms of power density, efficiency and lifetime (cycles). Combination of Li-ion and SC hence compensate the gap of high energy density and high power density and hence prove to be the best solution for hybrid energy storage applications.

Power Electronics for energy storages

The energy storage together with interfacing converter to the DC bus is termed as Energy Storage Systems (ESS). Bi-directional boost converter is illustrated in Fig. 2.4(a) for battery converter. The low voltage side is connected to the terminal of energy storage devices and the output side V_{bo} is connected to the DC bus. Converter operation signifies charging mode when S_{12} is modulated with PWM and gate signal (G_{bat}) of S_{11} is turned off. d_{bat} denotes the duty ratio generated by the inner current control loop for the battery converter. The discharging mode takes place when S_{11} is modulated in the PWM and gate signal of S_{12} is turned off. Two driver circuits to command integrated bipolar transistors (IGBTs) are required for this topology. This topology has the benefits of providing simple structure and low number of components utilized for its construction, which enhances the low cost operation. The two modes of operation for a battery converter are Power Control Mode (PCM) and BRM as shown in Fig. 2.4(b). The BRM in battery

Table 2.2: Tabulation of parametric comparison of different storage technologies

Storage Parameter	VRB Gen. 1	Lead-acid	NiCd	NiMH	Li-ion	Supercap.
Efficiency (%)	60..85	75..80	60..75	65..70	90..95	90..95
Temperature [°C]	+10..+40	-20..+60	-30..+60	-20..+60	-30..+60	-45..+60
Specific energy [Wh/kg]	10..30	25..40	35..65	60..90	90..180	5
Specific power [W/kg]		100..200	150..250	250..750	750..1500	2.5k..5k
Recharge rate [$\times C$]		0.1	0.2..1	0.2..0.5	0.8..1	$\gg 1C$
Self-discharge [%/ month]	3	3	10	10	5	>100
Lifetime [cycles]	12k..14k	500..1000	1500..3000	500..1000	1.5k..7.5k	0.5M..1M
Maintenance	High	High	Moderate	High	None	None
Initial cost		Low	Moderate	Moderate	High	Very high
Cycle cost [¢/kWh/cycle]	5..80	27	49	34	40	5.4

Figure 2.4: Battery converter a) Schematic layout of bi-directional DC-DC converter b) Controller for battery converter

converter is similar to that of PV converter explained above in 2.1.1.

The PCM corresponds to the generation of reference inductor current i_L^* for inner current control loop by dividing the battery bank output power (P_{bat}) with battery bank terminal voltage (V_{bat}).

2.1.3 Hybrid Energy Storage System

Energy storage forwards itself as a reliable technology for smoothing renewable intermittency. It does not use fossil fuel and is energy secure and eco-friendly [31].

The primary goal of integrating energy storages in microgrid with renewable energy sources is to provide consistent quality of power supply. Even though the power cost is minor, the energy cost for the existing storage technologies being deployed is expensive. Thus, their discharge time is thirty minutes at full power or even less [45].

Energy storages can be classified based on their ramp rate (kW/s), specific power (kW/Kg), life cycles, specific energy (kWh/Kg), etc. [46,47]. An individual BESS is not able to fulfill all the mentioned requirements [47]. Although various technologies have been deduced for BESS, they suffer from poor life span of less than 1000 full cycles which can further deteriorate in case of deep discharge cycles [35]. Lead acid battery being cost friendly are the dominant type of BESS. On the other hand, Li-ion battery that is one of the most efficient chemical battery is very expensive [35] and is available limitedly. ESS based on chemical battery is characterized by their specific energy but suffer from low power capacity compared to technologies like SC. A supercapacitor (SC), also termed as Electrochemical Double Layer Capacitor (EDLC) or Ultracapacitor (UC) [48] has high life cycle, low internal resistance, 10-100 times higher specific power compared to chemical batteries [49] and high charge/discharge efficiency [48,50]. On the flip side, chemical batteries like Li-ion have high charge/discharge efficiency with low rate of discharge and high specific energy.

The present energy storage system does not meet the characteristic of having high power density along with high energy density. High power density addresses power variations and high energy density provides autonomy to micro grids [51]. The need of energy storage system, which is able to provide both high power density and high energy density in microgrid is only possible by integrating two different energy storages having the above mentioned quality.

Research demonstrate that improved performance can be achieved by combining SC and batteries despite the presence of batteries with high specific power [35, 48, 52–54]. It is because large batteries have cost constraints. Also, cell voltage balancing degrade the capacity of battery packs overtime leading to battery system failure. Thus, to compensate the peak power demand, supercapacitors are opted. Other major factor for hybridization is the topology selection for power electronic interface [52, 53].

Power Electronics for HESS

An HESS having two energy storages can be categorized variously based on the

position and connection of converter interface and position of SC/battery. The power levels, control and application decide the best suited configuration. The configuration of HESS structure and topology of power electronic interface is reviewed in the following section [55].

A. Direct connection of HESS

The passive configuration of battery/SC HESS is shown in Fig. 2.5(a). The absence of power electronic converters reduces the cost and the ease of implementation making the system simple [50], but the power sharing between battery and SC is limited since there is no regulation of terminal voltage in such configuration. A power electronic interface in SC can aid in the complete utilization of energy of the SC [50, 53]. In addition, reduction in ripple of source current, better output voltage regulation and lower weight and volume can be ensured with the active HESS configuration [48, 50].

B. SC connected only to DC-DC converter

For effective utilization of SC energy, DC-DC converter is used to connect SC to the DC bus as shown in Fig. 2.5(b). Since the battery is in direct connection to the DC bus, voltage variation of DC bus cannot be achieved. This configuration lacks the presence of buffer between load and battery that might damage the battery [52, 53].

C. Battery only connected to DC-DC converter

The SC is connected to the DC bus directly as shown in Fig. 2.5(c) and acts as a low pass filter due to which the working range of SC is limited [52, 53]. Even during rapid change in power flow, the battery is protected in this topology since SC acts as buffer in such conditions [52].

D. Battery/SC cascaded by means of DC-DC converters

This topology is formed by using additional DC-DC converter between the DC bus and SC in Fig. 2.5(d). Addition of this DC-DC converter in the topology expands the working range of the SC. However, use of additional DC-DC converter means the topology becomes costly and it must handle the total load power.

E. Battery/SC in parallel with the DC bus

The DC bus and the battery/SC HESS are connected parallel in this topology as seen in Fig. 2.5(e). This parallel arrangement improves performance as the control of power flow can be performed as per the energy flow control [52]. Full utilization

Figure 2.5: Schematic layouts of different HESS topologies (a) Passive configuration for HESS (b) SC only connected to converter (c) Battery only connected to converter (d) Cascaded connection of battery/SC through DC-DC converter (e) Parallel connection of battery /SC to the DC bus

of SC voltage is achieved since the voltage can vary in a wide range [53]. The redundant nature of this topology ensures the reliability of the system and the ability of the system to operate even in case of failure makes it fault tolerant [52].

The proposed active topology is illustrated in Fig. 2.5(e). The output power of solar PV along with battery/SC HESS is realized through their respective converters. DC-DC boost converter is used to connect solar PV to the DC bus. To coordinate battery/SC HESS fully utilizing their benefits, the virtual output impedances for them are shaped into a frequency domain and are discussed in **Chapter 3**.

2.2 Review on Configuration of DC microgrids

Several hardware topologies of DC microgrids have been reported depending upon the specific application. The basic criteria lie in control flexibility, robustness and reliability. The basic topologies of DC microgrid can be classified into three categories [37]:

2.2.1 Single Bus Topology

Figure 2.6: Schematic layout of an unipolar DC microgrid

The single bus topology that is commonly used for DC microgrids has been shown in Fig. 2.6 and is effective in industrial applications. The DC bus in such configuration consists of positive and negative poles. One of the important factor in such topology is the selection of DC bus voltage level since the energy is transmitted over one bus voltage level [38]. Power transmission capability is enhanced by voltage level but the number of interfacing DC-DC converters is increased to meet the requirement of consumer voltage level [38]. Low voltage level limits the transmission capability to only in a short distance. However, it can be effective in remote rural areas where utility grid is not feasible. A 48V single bus topology

has been deployed in off-grid houses in rural areas of India [56]. A low voltage topology has been widely reported in various literatures [57–63] and is advantageous due to its simplicity and absence of asymmetry between two DC poles [38]. One of the disadvantages of such topology is the necessity of higher precision in

Figure 2.7: Schematic layout of a bipolar-type DC microgrid

circuit and control parameter design [37]. On the other hand, consumers have no redundancy on supply voltage level since they have to be powered with only one bus at a specific voltage level.

In order to mitigate this problem, Kakigano *et al.* [64] have proposed bipolar bus structure as shown in Fig. 2.7. Such topology consists of three wires with positive, negative and neutral terminals and the consumers can have flexibility to choose three voltage levels i.e. $+170V$, $-170V$ and $+340V$ respectively. During faults in one line, power can still be supplied by the other two wires, hence the system is reliable. The flexibility in supply voltage can cause system imbalance during unbalanced load connection. A voltage balancer circuit at source side is highly recommended for such system [65]. The control of such topology will be discussed in **Chapter 5**.

2.2.2 Multibus Topology

The single bus topology shown in Fig. 2.6 is the basis of multibus design. Multiple DC microgrid cluster configuration with redundant buses is an example of such topology [11, 66, 67]. The configuration of multiple DC microgrid cluster is illustrated in Fig. 2.8. In case of surplus or deficit of power, each microgrid is able to inject or absorb power from its neighbouring microgrids respectively. In case of failure, some corrupted buses can be automatically excluded from the system depending on the configuration of the microgrid. Local voltage deviation can be used as a tool to regulate the power flow and for the exchange of power between multiple DC buses.

Figure 2.8: Schematic layout of multibus DC microgrid

2.2.3 Reconfigurable Topology

The above mentioned topologies are examples of radial configurations and are not flexible during fault conditions. Several literatures have reported reconfigurable topology which consists of ring bus architecture [68], zonal configuration and multiterminal DC systems [39, 69, 70]. In ring bus configuration, two or more paths are present between the customers and the AC grid interface. To exclude faulty bus from the system, fast DC switches are placed at both ends of each DC bus which increase the flexibility of the system. The control of each bus and their interface with other neighbouring buses is executed by an Intelligent Electronic

Figure 2.9: Schematic layout of a DC microgrid ringbus topology

Device (IED) [68]. In case of failure of a bus, the IED identifies and excludes it from the system and renders an alternative path for power supply to the customer. Thus, in comparison to radial system, the ring or loop configuration shown in Fig. 2.9 has high reliability. Such system of distribution is particularly significant in industrial and urban areas. The disadvantage of such system is that if any fault occurs in the AC feeder, the DC microgrid system will be deprived of power supply.

Figure 2.10: Schematic layout of a multiterminal DC microgrid

A mesh type or Multiterminal DC systems (MTDC) illustrated in Fig. 2.10 consist of multiple utility grids interfaced with multiple DC buses through AC-DC converter. The availability of supplementary feeders for power supply to auxiliary parts of the system make MTDC more reliable than the loop or the radial DC grids. Similar frameworks are utilized in underground urban sub-transmission

and distribution systems and off-shore wind farms which are High Voltage Direct Current (HVDC) system [71, 72].

Figure 2.11: Schematic layout of a zonal DC microgrid

A Zonal Type DC (ZTDC) microgrid system shown in Fig. 2.11 where the distribution system has sub-division of number of zones with each zone having two redundant DC buses has been proposed in [69, 73] to make the system more reliable providing flexibility in load power supply. The higher number of switches make this configuration more flexible and suitable for distribution planning. The ZTDC grid can supply power to loads through different means like: exclusively from one bus and sequentially or simultaneously from multiple buses. Having said so, complication in the design and operation of the distribution system may arise from drawing power through multiple buses [74, 75]. ZTDC can find its application on ship board power systems [76].

2.3 Review on Control of DC microgrids

Control strategies for DC microgrids can be classified as centralized, decentralized and distributed depending upon the communication link [77–81] and are discussed as follows.

2.3.1 Centralized Control

Centralized control can be best understood by explaining three major classifications [82, 83]:

- Local Controllers (LCs) which are subdivided into microsource controllers and load controllers
- Central controllers
- Distribution Management System (DMS)

The aim of local controllers is to control the operating points of microsources and their power electronic interfaces with no communication link between them. Load controllers are used for demand side management and are installed at controllable loads. The objective of a central controller is to provide simple co-ordination of local controllers for the optimization of microgrid operation acting as an interface between the distribution management system and the microgrid. Management of the operation of low and medium voltage areas with multiple microgrid can be done using DMS or Distribution Network Operator (DNO) having several interfaced Microgrid Central Controllers (MGCCs). In case of microgrids participating in the market, Market Operators (MO) exist in the system. MO and DNO represent utility and are not the part of microgrids [83].

In case of small scale microgrids, master slave approach is employed [84, 85]. This type of control depends on the rapid communication amidst the source and load converters. One of the converter controls the DC bus voltage and is obliged to distribute power reference to other source converters [86]. This master converter, which acts as a voltage source converter, fixes the current references for other slave converters acting as current source converter as shown in Fig. 2.12. To avoid system failures, another module in the system acts as master if the master unit fails. The role of the master defines different ways of control. The master might be one fixed module or it might be arbitrarily chosen or the module bringing maximum current becomes master module.

Hierarchical control which consists of different control levels is often preferred for larger scale DC microgrids [77] as shown in Fig. 2.13. Such control consists of local converter control and a Digital Communication Link (DCL) based coordinated control. DCL based coordinated control is utilized to perform advanced energy management functions. For DC microgrid based application in data center

Figure 2.12: Schematic layout of master slave control

Salomonsson *et al.* [87] have proposed eight operation modes in centralized control to configure system units depending upon RES based generation and loading. Hierarchical control to achieve DC bus voltage regulation and charge/discharge based priority of batteries with different State of Charge (SoC) in standalone DC microgrid is proposed in [78] along with the study of load-shedding conditions. Adaptive droop control to achieve SoC balancing in primary control layer and supervisory control to coordinate different operating modes and recharge of multiple battery banks is proposed in [60]. Eventhough the centralized control provides opportunity to employ advanced control to achieve optimized and efficient operation, the drawbacks can be listed as follows:

- Single point of failure: If MGCC fails or any communication link in the system fails, the controller will not be able to relay the commands and the control objective cannot be achieved.
- Increased Cost: Even though the redundant communication links can be installed to increase the effectiveness of centralized control for critical appli-

Figure 2.13: General schematic layout of centralized control

cations, the system will not be cost effective.

- Reduced flexibility and expandability: The MGCC should be redesigned or reprogrammed even to increase the number of DGs in the system.

2.3.2 Distributed Control

The concept of distributed control has evolved due to the rapid development in communication technologies and information exchange algorithms [88,89]. The difference in distributed control in comparison with centralized control is that it does not consist of central controller. The local controllers communicate through DCLs as shown in Fig. 2.14 such that the important information is shared. Distributed control is resistant to single point of failure because the communication network remains effective even though there is failure in some communication links [77]. However, the modality of information exchange between LCs through DCLs is a challenge. In order to achieve coordination among distributed units through each other's data access directly to fulfill control objectives, consensus algorithm can be used [90].

Consensus algorithm is a simple agreement established in every local controllers

to sum up the algebraic differences of variable(s) of interest located at particular local controller and the local controller adjacent to it. Mathematically, for any given i^{th} local controller, it can be expressed as [77]:

$$\dot{x}_i(t) = \sum_{j \in N_i} [x_i(t) - x_j(t)] + b_i(t) \quad (2.5)$$

Where, $x_i(t)$ and $x_j(t)$ are the parameters of interest of i^{th} and j^{th} local controllers as mentioned above. Iteration j is carried out through all set of neighbours of i^{th} local controller and represented by N_i . And, $b_i(t)$ is the input bias of local controller and is optional. Any controller parameters adjust their values with respect to their neighbour values as $x_i(t)$ expressed in (2.5). Convergence of all parameters to common average value is ensured in some period if the communication network remains linked [91].

Figure 2.14: Schematic layout of distributed control

Consensus algorithms [62, 63, 92–94] have been employed to achieve distributed control in microgrids, recently. A consensus algorithm with sparse communication network is used in [63] and [92] to achieve a distributed secondary control diagram with dynamic averaging. For restoring voltage and enhancing current sharing accuracy, information is acquired only from neighboring converters rather than global information from all the converters. This also results in the reduction of communication stress on the system. The flexibility of the system is enhanced by

utilizing consensus algorithm to achieve plug and play activity.

$$r_{d,i} = r^* + \left(k_p + \frac{k_{ir}}{s}\right) (r - \bar{r}_{dci}) + \left(k_{pc} + \frac{k_{ic}}{s}\right) (i_{dci} - \bar{i}_{dci}) \quad (2.6)$$

$$r_{d,i} = v_{dc}^* - \underbrace{(r^* + G_{pir}(r_{ref} - \bar{r}_{dci}) - G_{pic}(i_{dci} - \bar{i}_{dci}))i_{dci}}_{\text{slope-adjusting-term}} + \underbrace{G_{piv}(s)(v_{dc}^* - \bar{v}_{dci})}_{\text{voltage-shifting-term}} \quad (2.7)$$

Figure 2.15: Control diagram proposed by Wang *et al.*

Where, v_{dc}^* is the DC bus voltage reference and v_{dci}^* is the voltage reference of i^{th} converter. r_{di} , r^* , $\bar{r}_{dci}$ and i_{dci} denote the droop coefficient, given reference value of droop coefficient, calculated average value of droop coefficients and output current of the i^{th} converter, respectively. The control parameters of the average droop coefficients and average current regulators are given by k_{pr} , k_{ir} , k_{pc} and k_{ic} .

The DC bus voltage is maintained by shifting droop curves keeping droop coef-

ficient constant. This phenomenon is called voltage shifting method [94] and is applied in [59, 62, 63, 92, 95]. The unequal equivalent output impedance gained by adding mismatched line impedance of the converters and the constant droop coefficient leads to inaccurate current sharing in parallel converters. This points the importance of regulating the average current controller further in case of rapid change of load current to maintain current sharing proportion. The droop coefficient is adjusted by adding slope adjusting term [94] to enhance current sharing accuracy in [63], however, its implementation to attain stability is complicated [94]. Wang *et al.* proposes three compensating controllers to enhance the dynamic performance due to fast changing load currents [94]. One of the controllers solves the problem of voltage deviation of DC bus caused by droop control and the rest two work to adjust the droop coefficient in order to achieve same equivalent output impedance, thus, eliminating the current sharing error. The governing equations for the control diagram presented by Wang *et al.* [94] in Fig. 2.15 are given by (2.6) and (2.7). Although the functions and objectives such as voltage restoration, output current sharing, SoC balancing can be achieved by distributed control and resembles with centralized control, the main drawback is the complex analytical performance analysis such as convergence speed, stability margins etc. due to communication delays and measurement errors.

2.3.3 Decentralized Control

In decentralized control, the DG units are controlled by making independent decisions based on the local variables without any communication links. It is performed by LCs as shown in Fig. 2.16. The most common type of decentralized control are DC Bus Signaling (DBS), adaptive adjustment of droop gain and Power Line Signaling (PLS) [77]. Decentralized control on the one hand has advantage of simplicity in control while on the other hand, it is disadvantageous because of lack of communication between system units and is highly affected by sensor inaccuracy.

DC bus signaling

The decentralized coordination method for DC microgrid control using DC bus as a communication link is termed as DBS. Due to the cumulative capacitance of every DERs interfacing power electronic converters, the DC microgrid bus is capacitive in nature as shown in equivalent circuit in Fig. 2.17 where P_{gen} , P_{load} and P_{bus} represent the generation, load and bus capacitor charging power, respectively.

Figure 2.16: Schematic layout of decentralized control

V_{bus} and C_{bus} denote the capacitance and voltage of bus capacitor respectively. Mathematical representation of system power balance can be expressed as (2.8) and (2.9). It can be seen from (2.9) that the change in bus voltage takes place due to the change in generation and consumption (load) power. If generation is higher than load power, bus voltage increases and vice versa. Hence, bus voltage acts as a global indicator for the system.

Figure 2.17: Equivalent circuit representing DC bus

$$P_{bus}(t) = P_{gen}(t) - P_{load}(t) \quad (2.8)$$

$$V_{bus}(t) \frac{dV_{bus}(t)}{dt} = \frac{1}{C_{bus}} (P_{gen}(t) - P_{load}(t)) \quad (2.9)$$

In other words, DBS obeys the concept of charge/discharge scheduling of individual distributed sources. Scheduling of sources is achieved by the operation dependence of DERs interfacing converters on DC bus voltage level affiliated to their charge/discharge threshold [96]. For the operation of multiple converters at

each threshold, voltage droop is implemented. Any change in the system causes the change in voltage level of the DC bus which enforces the converters involved in DC microgrid to switch to Constant Power (CP) or Constant Voltage (CV) mode [97]. In this way, source and storage converters in DC microgrid utilize DC bus voltage level to determine their mode of operation.

The details on implementation of DBS is provided in [77, 79] and [98] that was originally proposed by [97]. The converters in DC microgrid operate to fulfill two objectives, i.e. to regulate the deviation of system voltage and to regulate the power flow. This may lead to control conflict between the converters since at a time, only one operation mode is possible. Thus, the converters are classified as terminal regulating units and bus regulating units based on their control objectives [79]. Terminal regulating units serve as a constant power load/source in a microgrid. They include non-controllable DGs and loads working at MPPT. On the other hand, bus regulating units maintain bus voltage based on the information gained from feedback signal. They identify themselves as voltage source since they work on making the microgrid stable during power variations.

The operating modes are classified into utility dominating, storage dominating and generation dominating in [77] and [79] to highlight the DBS principle as shown in Fig. 2.18 [79]. It is considered that the microgrid consists of three possible sources i.e. DG, ESS and the utility and it consists of at least one bus regulating unit for system voltage stability. Hence, the modes are classified depending upon which terminal (generation, storage and grid) takes the responsibility of bus regulation. When the local DG and ESS power are unable to meet the local demand, the power deficit is imported from the utility grid. The interfacing converter acts as the bus regulating unit maintaining the system power balance as shown in Fig. 2.18(a). When the microgrid consists of sufficient power and energy reserve in its ESS, the renewable DGs work on MPPT to maximize energy harvest and the utility interfacing converter regulates power exchange with main grid according to power system operator. Such mode is termed as storage dominating mode and is shown in Fig. 2.18(b). The renewable DGs act as bus regulating unit in generation dominating mode, since the generation is higher than consumption and the surplus power is greater than ESS and utility capacity. In such case, the renewable DGs do not work on MPPT, but work to limit the generation maintaining the system power balance as shown in Fig. 2.18(c). The DC bus voltage is used to define the operation mode to enable adaptive and seamless mode transition through autonomous decision of DG, ESS and utility interfacing converters based upon

Figure 2.18: Operation mode classification and DBS principle (a) Utility dominating mode (b) Storage dominating mode (c) Generation dominating mode (d) Voltage range definition for mode transition

the information received from the DC bus voltage level. The mode transition can be summarized as in Table 2.3 [79].

Where,

P_{DG} : Power generation in the microgrid by DERs at MPPT state;

P_{ac} : rated power output, determined by power system operator from the microgrid

Table 2.3: Summary of mode transition in DC microgrids

Mode	Power status	Voltage range	Bus regulation
Utility dominating (Mode I)	$P_{ac} + P_{load} - P_{DG} > P_{ESS_{dsc}}$	$V_{bus} < V_{low}$	Utility units
Storage dominating (Mode II)	$P_{ESS_{ch}} < P_{ac} + P_{load} - P_{DG} < P_{ESS_{dsc}}$	$V_{low} < V_{bus} < V_{high}$	ESS units
Generation dominating (Mode III)	$-P_{ac} - P_{load} + P_{DG} > P_{ESS_{ch}}$	$V_{bus} > V_{high}$	DG units

to the AC utility grid. The value is zero during black-out.

P_{load} : local consumption;

$P_{ESS_{ch}}$: maximum charging power of ESS units in the microgrid;

$P_{ESS_{dch}}$: maximum discharging power of ESS units in the microgrid. The value is zero when ESS is fully discharged;

V_{bus} : DC bus voltage;

V_{high} : upper threshold voltage for utility, storage and generation dominating modes.

V_{low} : lower threshold voltage for utility, storage and generation dominating modes.

The selection of appropriate voltage level is a key criterion in DBS since it classifies the various operating modes. In case of higher difference between two adjacent partitioned voltage level, DC bus voltage fluctuation might exceed the permissible range. Even minute difference between them may lead to DC bus voltage ripples and sensor inaccuracy making the identification of operation modes difficult. For maximum utilization of energy at all times, the RES usually operates in MPPT mode. However, PV converter adapts voltage restoration mode when the local bus voltage exceeds the threshold value specified in [99], to maintain the bus voltage deviation induced by power surplus.

In order to increase the lifetime of the battery, the Energy Management System (EMS) for battery energy storages should be aware of battery manufacturer's specifications since frequent charge/discharge may deteriorate the battery. Also, the SoC equalization of energy storages and DBS should not be in conflict.

Adaptive adjustment of droop gain

The SoC between multiple ESS is balanced by using adaptive calculations of droop coefficient avoiding overcharge and over-discharge but, changes in the operation mode are not accounted. The ESS in a microgrid is usually regarded as a single entity from a control perspective, despite the ESS comprising of multiple Energy Storage Units (ESUs). The control of ESUs constitute two parts: Power Converter System (PCS) and Battery Management System (BMS) [100–102]. PCS is entitled to balance the SoC among different ESUs by controlling the converters whereas BMS equalizes SoC inside an ESU. References [100] and [101] propose SoC equalization method where the droop resistance r_{di} of the i^{th} ESU converter is directly proportional to the n^{th} exponent of SoC. This means that in charging condition, the r_{di} is directly proportional to SoC^n and during the discharge mode, they are inversely proportional to each other. The exponent n is adjusted to balance the speed of SoC balancing and it indicates the convergence factor. Although faster SoC equalization is achieved by a higher n , it degrades the voltage deviation further.

To mitigate this issue, a secondary control as shown in Fig. 2.19 has been proposed by [102] which balances the SoC between the ESUs and monitors control of charge/discharge.

A. Charge/discharge control

The power flow across individual ESU is determined and regulated by the control system on the basis of an assumption that DBS power management strategy is applied in the microgrid and the ESU operates as the droop controlled voltage source for the purpose of compatibility [102]. The droop resistance in this control however, should be altered continuously in order to comply with the charging specifications of the battery manufacturer such as the voltage and maximum charge current of the battery.

This control employs two converter voltage control loops namely, i.e. Charge Controller (CC) and Voltage Droop Controller (VDC) [102]. The CC is responsible for the battery charging and the power flow between microgrid buses and the ESU is regulated by the VDC. The VDC undertakes microgrid DC bus voltage regulation $V_{o,i}$ in (2.10) to a level defined in (2.11), where k_d denotes compensation factor for SoC balancing. As the loads and other sources are the determinants of the actual bus voltage, the flow direction of the converter output current $i_{o,i}$ is determined by the VDC. The objective of the CC is to regulate the battery terminal voltage to V_{bref} . The current reference for the inner current control loop

Figure 2.19: Control for ESU in DBS power management

is defined in (2.11) and is the difference between the output of VDC i.e. i_{droop} and that of CC i.e. i_{charge} .

There is a competition between both the aforementioned voltage control loops for the boost inductor current control. To provide a predictable behavior for the given control strategy, such competition must be controlled. Such control is possible by limiting the influence range of individual loops. The saturation levels of PI controllers are useful in this condition where i_{droop} and i_{charge} can be limited from a range of zero to maximum level. The maximum value for CC output is given by I_{Cmax} as shown in Fig. 2.19 [102]. I_{Dsat} is the maximum output of the VDC and represents the maximum discharge current of the battery bank.

$$V_{o,i}^* = V_{ref} - r_{d,i} i_{o,i} \quad (2.10)$$

$$V_{o,i}^* = V_{ref} - r_{d,i} K_d i_{o,i} \quad (2.11)$$

$$i_{Lref} = i_{droop} - i_{charge} \quad (2.12)$$

B. SoC equalization

The arrangement of ESU in microgrids is done to supply more power by the unit with higher charge and this unit should absorb less power compared to other units in ESS. It is attained by modification of the droop resistance of VDC by the compensating factor k_d [102]. The compensation factor must only occur in case of imbalance of SoC between the ESUs to avoid its interference with the DBS operation. The compensation factor k_d converges to 1 during post SoC equalization between ESUs which changes the droop resistance to the initial value thus restoring the normal operation of DBS. The secondary controller collects the SoC information from every ESU and computes the average SoC value. The average

SoC is then resent to each of the ESUs via Low Bandwidth Communication (LBC) link. The compensation factor is estimated by the local droop controller where a positive integer is defined as convergence factor to adjust the speed of SoC equalization. The mathematical expression for the SoC equalization process is explained in [102].

C. Surge current compensation

The power variations in the DC microgrid can be decomposed into high and low frequency components [103]. High frequency variations are the transient variations in power from milliseconds to minutes. Energy storages with high ramp rate like supercapacitors deal with the high frequency oscillations of system net power [47]. On the other hand, low frequency components are based on an hourly average and are dealt by controlling the energy storages such as batteries with high energy capacity. Regular sharp changes in the output current during the microgrid operation rises the temperature of batteries like Li-ion that deteriorate the efficiency of the battery and decrease its lifetime [104]. A novel EMS where the SC is integrated to a droop-controlled DC microgrid is proposed in [104] that operate as an independent SC energy storage system.

Figure 2.20: Mode switcher for surge current compensation

The virtual impedance loops with series connected virtual resistor and capacitor are adjusted in Supercapacitor Energy Storage System (SCESS) such that the adaptive surge current compensation can be achieved for various load and source transients in DC microgrid. The proposed EMS also contains SoC regulation loop as shown in Fig 2.20 [104]. Conventionally, to avoid interaction among

SoC regulation and surge current compensation, SoC regulation used to be slow. The functions mentioned above perform simultaneous operation with efficient implementation in [104]. In order to mitigate the issue of dynamic performance, i.e. during sudden and frequent load changes, a mode switcher between virtual impedance loop and SoC regulation loop is used to manage transitions such that the over-stress and safety concerns due to deterioration of compensation capacity and low/high SoC conditions are mitigated. The surge current compensation mode is terminated when the SoC level reaches low/high limit prioritizing safe range of SoC.

Power line signaling

Another decentralized method for deploying coordinated control is PLS [77]. In particular, DC bus is injected with sinusoidal signals of specific frequency, granting each device to receive and send information regarding its internal operational mode, performance, status or history. Despite PLS relying upon digital communication, here it is classified as decentralized since the only communication medium is the power network which is also termed as power line communication in literatures of power system [77]. PLS is used as a primary communication carrier by REbus that is an open standard in distributing DC electricity to various sectors including business enterprises, homes, campuses [105]. Reference [61] and [106] propose other methods for exchanging information among devices unaccompanied by the use of dedicated amplifiers where Pulse Width Modulation (PWM) of DC-DC converters generate signals. Signal injection in [106] is carried out in open-loop whereas in [61] it is carried out by means of Proportional Resonant (PR) controllers avoiding steady-state error in DC bus. PLS in comparison to DBS and adaptive droop is complicated to implement. In addition, an appropriate power sharing is not achieved since it is commonly used to shut corrupted components of the system or to change the operating modes. However, the injection of periodic sinusoidal signals into the system improve the quality of voltage waveform in comparison with DBS and adaptive droop methods in which common DC bus voltage deviation is inherent.

2.4 Summary

In this chapter, different aspects of DC microgrids have been reviewed. Along with the review of constituents of DC microgrids such as PV and energy storages, the

local converter control for these sources have been discussed. The importance of hybridization of energy storages has been elaborated and the existing topologies of converters for HESS have been summarized along with the recommendation of active topology for HESS application.

Various hardware topologies play a vital role in the formation of DC microgrids depending upon the application they have been used for. This chapter classifies the DC microgrid topologies into single-bus topology, multibus topology and reconfigurable topology. The importance and the application of these topologies have been summarized. The reconfigurable topology consists of ringbus topology, mesh type topology and zonal type DC microgrid system. This thesis will highlight the single bus topology consisting of unipolar and bipolar-type DC microgrids along with the multibus topology formed by interconnecting two DC microgrids in the following chapters.

Since DC microgrid consists of various parallel interfaced converters, the coordinated control among converters along with the local converter control plays a vital role in forming a stable, reliable and flexible DC microgrid. The last section of this chapter reviews the coordinated control of DC microgrids namely centralized, distributed and decentralized control depending upon the communication links used in the system. The advantages, importance and drawbacks of these coordinated control approaches have been highlighted and the state of the art in each approach have been reviewed. This thesis will focus on the communication free decentralized control of DC microgrids to achieve a simple, flexible and reliable DC microgrid in following chapters.

Chapter 3

Decentralized Control of DC Microgrids

Storage is the pathway to a truly
smart and clean energy future.

—*eco-business.com*, 2000

The DC microgrid control can be sub divided into local control and coordinated control levels [77]. The local interface converter control plays a vital role in efficient and reliable operation of DC microgrids. A review of PV and battery converter control as well as coordinated decentralized control for multiple converters in DC microgrid such as DBS, adaptive adjustment of droop coefficient and PLS have been discussed in Chapter 2. To ensure the proper local control and the coordinated control for different modules interconnected in DC microgrids, the local voltage and current control should be flexible along with the implementation of power sharing among multiple converters involved in DC microgrids.

Decentralized autonomous control of DC microgrids is gaining attention due to the drawbacks of centralized control discussed in section 2.3.1. The objective of implementation of decentralized control in DC microgrids is to construct an independent, communication link free system. Such control should be tunable to any modifications due to the expansion in the system. One of the ways to realize decentralized control in DC microgrids is to apply droop based control for autonomous operation of its constituents and microgrid as a whole. The advantages and drawbacks of droop based control are discussed, as follows.

3.1 Autonomous Droop Control

The concept of droop control evolved due to its wide application in controlling multiple synchronous generators in traditional power systems [107]. The droop method is based upon the concept of drooping the frequency of the AC generator when there is an escalation in the output power [108]. The concept has been further applied to microgrids to achieve proportional power sharing among the DGs [109]. Since the droop method uses local power measurements, it achieves higher flexibility and reliability in the physical location of the converter modules [108]. Improvement in the reliability takes place in the absence of critical communications amidst the modules without limiting the physical location of the modules.

In a DC microgrid, the power sharing by DERs is inversely proportional to their line resistances. The stochastic nature of equivalent line resistances from each DER to the distributed loads cause unbalanced power sharing among DERs. From the power management perspective, the droop control has been widely applied in DC microgrids to ensure the proportional power sharing among the DERs. The Thevenin equivalent circuit in Fig 3.1 illustrates such control [86].

Figure 3.1: Thevenin equivalent circuit for one DER

V_{ref} represents voltage source reference and r_{di} represents the droop gain in Fig 3.1. r_{linei} and L_{linei} signify the line resistance and inductance from source to the load

bus for i^{th} DER taken in consideration. Z_{linei} and V_{bus} indicate the line impedance and DC bus voltage respectively in Fig 3.1.

The droop gain r_{di} is the virtual value that can be manipulated in order to control the flow of current from the DER, which is why it is also termed as virtual resistance. This phenomenon of desired current sharing can be explained by Fig 3.1 and (3.1). From (3.1), the converter voltage reference for droop control as in (3.2) can be derived. This expression has been indicated in (2.10) in section 2.3.3 to realize decentralized coordinated control of converters. Such conventional droop control can be elaborated as in Fig 3.2. The new voltage reference for DC output voltage generated by the power electronic converter (DC/DC converter) is obtained by multiplying the output current flowing into the DC bus with the droop gain to achieve desired power sharing. It can be deduced from (3.2), when the virtual output impedance causes increment in the output current, output voltage reference reduces linearly because of the droop control. V_{oi} adjusts the output voltage of individual sources in DC microgrid for stable operation and is provided to outer voltage and inner current control loops of the i^{th} converter shown in Fig 3.2.

Figure 3.2: Conventional droop control for DC microgrids

$$i_{oi} = \frac{V_{ref} - V_{bus}}{r_{di} + r_{linei}} \quad (3.1)$$

$$V_{oi} = V_{ref} - r_{di}i_{oi} \quad (3.2)$$

Fig 3.3 [62, 95, 110] shows the equivalent circuit for two parallel connected DC sources through converter sharing common load to highlight the extended problem of droop control. All source converters should contribute to balance total power consumed by the loads and the losses in droop control without any com-

Figure 3.3: Equivalent circuit of two source single load DC microgrid

munication between converters. Measurement of DC bus voltage is done at each source converter [86]. Droop based control has some inherent limitations which are discussed, as follows.

A. DC bus voltage deviation

Droop control is realized in DC microgrids by the linear reduction in DC output voltage as the output current delivered by the converters increases. The DC bus suffers from the definite voltage deviation under loaded condition. The maximum allowable DC bus voltage deviation in droop control during full load can be expressed as (3.3) [62]:

$$r_{dmax} = \frac{\varepsilon_v}{i_{fl}} \quad (3.3)$$

Where, r_{dmax} , ε_v and i_{fl} signify maximum allowable droop gain, maximum allowable DC bus voltage deviation and full load current of the i^{th} converter of a DC microgrid, respectively.

B. Current sharing degradation

For the two source microgrid shown in Fig 3.3, the remotely controlled DC bus voltage can be expressed from (3.3) for $i = 1, 2$ as (3.4) and (3.5).

$$V_{load} = V_{ref} - r_{d1}i_{o1} - r_{line1}i_{o1} \quad (3.4)$$

$$V_{load} = V_{ref} - r_{d2}i_{o2} - r_{line2}i_{o2} \quad (3.5)$$

The following equation in (3.6) can be derived from (3.4) and (3.5).

$$\frac{i_{o1}}{i_{o2}} = \frac{r_{d2}}{r_{d1}} + \frac{r_{line2} - \frac{r_{d2}r_{line1}}{r_{d1}}}{r_{d1} + r_{line1}} \quad (3.6)$$

According to the conventional droop control in DC microgrids, the output current of converter is inversely proportional to its virtual resistance. Therefore, it can be deduced from (3.6) that the expression in (3.7) should be valid to eliminate the current sharing error. The graphical representation of current sharing and virtual resistance is depicted in Fig 3.4 by lines $r_{d1} + r_{line1}$ and $r_{d2} + r_{line2}$.

$$\frac{r_{d1}}{r_{d2}} = \frac{r_{line1}}{r_{line2}} \quad (3.7)$$

Assuming that the system is not so large such that the line resistance is small, the larger virtual resistance r_{di} can be selected for DC microgrids. Since, $r_{di} \gg r_{linei}$, the following expression in (3.8) can be derived:

$$\frac{i_{o1}}{i_{o2}} = \frac{r_{d2} + r_{line2}}{r_{d1} + r_{line1}} \approx \frac{r_{d2}}{r_{d1}} \quad (3.8)$$

The expression in (3.8) is valid only for small microgrids. Since larger r_{di} leads

Figure 3.4: Relationship between current sharing and virtual resistance

to the consequence of higher voltage deviation at individual converter output and might jeopardize the system stability [62], the necessity of satisfying the condition at (3.8) arises in order to invalidate current sharing error and maintain DC bus voltage.

To mitigate the aforementioned limitations of conventional droop control, a novel control based upon P-controller in [34] modifies the effective droop gain for effective voltage regulation and power sharing simultaneously. The novelty of this concept claimed by authors is the absence of communication links between sources in a single area. The droop gain is adjusted to its original position by nullifying the effect of line resistance with virtual negative resistance using active signal. As a result, the voltage is well regulated with current sharing accuracy. The proportional feedback control proposed is known as “line drop compensator” [34]. The advantage of the proposed control is the independent operation of converters without any communication links. The simplicity of the control implemented leads to system cost reduction. The proposed controller improves the voltage regulation and power sharing in two interconnected DC microgrids. Nevertheless, lack of experimental verification does not validate the system.

The co-ordinated control among distributed units in DC microgrids plays a vital role to nurture system stability and power quality enhancement [90]. One of the ways to realize decentralized control of DC microgrids consisting of HESS is frequency co-ordinating virtual impedance concept [111] which is elaborated, as follows.

3.2 Frequency Co-ordinated Virtual Impedances

The classical droop control used for power sharing in DC microgrids assures only static power regulation and do not target the frequency based power management [111]. The frequency based power management plays a vital role in microgrids because various type of DGs and ESS have dynamic behaviour under different time scales [111]. For instance, wind turbine is comprised of mechanical parts and hence the response of wind turbine is slower than that of PV. Similarly, due to the chemical limitations, chemical batteries respond slowly in comparison to SC [111]. Control strategies presented in [54] show the distribution of power demand between battery and SC. Such control strategies employ filters at certain frequency ranges such that battery supplies low frequency components and SC supplies high frequency components. The necessity to monitor the net power exchange through a high bandwidth communication link among different energy storages may reduce system reliability. The SoC balancing based droop control proposed in [60] and [100] only deals with the distributed batteries. Dynamic power sharing between

battery and SC is realized in [111] employing frequency-shaped virtual impedance. Despite achieving autonomous power sharing of distributed energy storage, the output impedance characteristics can be problematic at high frequency ranges especially for noisy output voltage of power converters. This Chapter investigates the frequency co-ordinating virtual impedance concept in DC microgrids proposed in [111] and proposes the insertion of high order low pass filter for battery and high order high pass filter for SC converters instead of low order low and high pass filters for battery and SC converters implemented in [111].

Frequency coordinating virtual impedance can be the solution for the mitigation of dynamic control problem as discussed above. The idea is to shape converters for the hybrid energy storages; such that the high frequency power oscillation is minimized by the SC and the low frequency oscillation is catered by the battery converter. The principle and implementation of such control are discussed as follows.

The conventional droop control expressed in (3.2) can be written as (3.9) where, term R_{droop} characterizes the equivalent resistance for converters in HESS and is produced by the droop controller.

$$V_{oi} = V_{ref} - R_{droop} i_{oi} \quad (3.9)$$

$$V_{oi}(s) = V_{ref}(s) - Z_{droop}(s) i_{oi}(s) \quad (3.10)$$

$$Z_{droop}(s) = R_{droop}(s) F(s) \quad (3.11)$$

However, (3.9) does not expedite transient power regulation since it only describes the static power sharing among the individual sources. Conversion of R_{droop} to Z_{droop} in (3.10) provides effective frequency domain shaping of the virtual output impedance. Equation (3.11) signifies power scale parameters in the form of R_{droop} to determine steady state power flow and $F(s)$ determines transient behaviors. The control loop of the converter in DC microgrid with an implementation of virtual impedance is shown in Fig 3.5. Reference current (i_{ref}) for the current control loop of the converter can be written as in (3.12) and $G_{conv}(s)$ represents the transfer function for inner closed loop current control. The real converter output impedance ($Z_{conv}(s)$) is slightly different from the desired $Z_{droop}(s)$ because of the actuation delay of $G_{conv}(s)$. Because of the fast dynamics of $G_{conv}(s)$, it can be expressed as unit gain at low frequency. Hence, converter output characteristics can be fully determined by $Z_{droop}(s)$ within the bandwidth of $G_{conv}(s)$. These

Figure 3.6: Inner current control loop

Figure 3.7: Bode plots for open loop current control

The open loop Bode plots for d to i_L is shown in Fig 3.7. Bode plots show that the PM of 60° is achieved at gain crossover $1kHz$ ($6.28 * 10^3 rad/s$). The controller designed has following parameters: $K_p = 2.87$ and $K_i = 1.02 * 10^4$ and the converter parameters are listed in Table 3.1.

The control loop for the designed converter for battery and SC is shown in Fig 3.8 [111]. The low pass and high pass filters inserted in series with the R_{droop} differentiate the frequency response characteristics of the individual converter.

Figure 3.8: Control loops for Hybrid ESS (a) for battery converter (b) for super-capacitor converter

The purpose of such configuration on one hand is to let battery respond only to slow and long term power demand avoiding surplus charge/discharge cycles, and allow SC to absorb fast and short term fluctuations, reducing capacitor size from economy point of view on the other hand.

$$Z_{bat}(s) = \frac{R_{droop}(\omega_c + s)}{G_{conv}(s)\omega_c} \quad (3.18)$$

$$Z_{sup}(s) = \frac{R_{droop}(\omega_c + s)}{G_{conv}(s)s} \quad (3.19)$$

$$Z_{ESS}(s) = Z_{bat} \parallel Z_{sup} = \frac{R_{droop}}{G_{conv}(s)} \quad (3.20)$$

The equivalent impedances of battery converter ($Z_{bat}(s)$) and SC converter ($Z_{sup}(s)$) are expressed in (3.18) and (3.19) respectively [111]. The equivalent impedance (Z_{ESS}) for the entire HESS is given by (3.20) [111].

Table 3.1: Boost converter parameters

Parameters	Value
Input voltage (V)	190
Output voltage (V)	380
Capacitance (μF)	470
Inductance (mH)	5
Switching frequency (kHz)	20

Higher order filters can be inserted to the above mentioned control loops for better

Figure 3.9: Impedance vs frequency for converters with lower order filters

Figure 3.10: Impedance vs frequency for converters with higher order filters

attenuation of ripple power. Frequencies outside its passband can be attenuated faster by a high order filter compared to a low order filter. Comparison of attenuation of ripple power by the use of first order and second order filters will be discussed in section 3.2.3. The modified equations using second order LPF and HPF for the control loops in Fig 3.8 are given by (3.21) and (3.22). The impedance versus frequency plots are shown in Fig 3.9 [111] and Fig 3.10 for the control loops with first order and second order filters respectively. Z_{bat} and Z_{sup} intersect at the cut-off frequency (ω_c). The response time scales for the battery and the SC converter are explained by the two frequencies ω_c and the converter frequency ω_{conv} . SC responds to the power fluctuations at higher frequency range between ω_c and ω_{conv} , while battery supplies energy below the frequency ω_c since Z_{ESS} is domi-

nated by the battery. Thus, the HESS realizes complementary benefits of SC and battery. Attenuation of a higher order filter outside the passband is sharper than a lower order filter which is equivalent to sharp increase in system impedance and can be seen from the plot of $(Z(dB))$ vs frequency comparing Fig 3.10 and Fig 3.9. The corresponding values for cut-off and converter frequencies are $\omega_c = 6.28\text{rad/s}$ and $\omega_{conv} = 6.28 * 10^3\text{rad/s}$ respectively and the converter parameters are listed in Table 3.1.

$$Z'_{bat}(s) = \frac{R_{droop}(\omega_c^2 + 2\xi\omega_c s + s^2)}{G_{conv}(s)\omega_c^2} \quad (3.21)$$

$$Z'_{sup}(s) = \frac{R_{droop}(\omega_c^2 + 2\xi\omega_c s + s^2)}{G_{conv}(s)s^2} \quad (3.22)$$

Where, $\xi = 0.7$ is the damping ratio.

3.2.2 Supercapacitor Voltage Restoration

Other significant issue of concern is the SC voltage restoration in the virtual impedance configuration for the proposed HESS. After the transient charging/discharging process the SC voltage will deviate from its nominal value. In such condition, further power fluctuations in the system may not be handled by SC. An additional SC voltage control loop is needed in the HESS control system to address this problem as shown in Fig 3.11. The PI coefficient can be set such that the bandwidth of $Z_{sup}(s)$ is greater than the frequency response of the voltage restoration loop.

Figure 3.11: Supercapacitor voltage restoration loop

The law of power conservation ignoring power losses in the converter is expressed by (3.23). The linearized form of (3.23) with normal values of v_{dc} and v_{sup} can

be expressed as in (3.24). i_{sup} and v_{sup} can be expressed as in (3.24) and (3.25) respectively and the modified converter control loop in accordance to them is obtained in Fig 3.12. The converter impedance is expressed in (3.26).

$$i_{dc}V_{dc} = i_{sup}v_{sup} \quad (3.23)$$

$$i_{sup} = i_{dc} \frac{V_{dc0}}{v_{sup0}} \quad (3.24)$$

$$v_{sup} = \frac{-1}{C_{sup}} \int i_{sup}(t) dt \quad (3.25)$$

$$\begin{aligned} Z_{sup} &= \frac{V_{ref}(s) - V_{dc}(s)}{i_{dc}(s)} \\ &= \frac{R_{droop}(\omega_c + s)}{G_{conv}(s)s} \left(1 + \frac{G_{conv}(s)}{sC_{sup}} \frac{v_{dc0}}{v_{sup0}} \frac{K_p s + K_i}{s} \right) \end{aligned} \quad (3.26)$$

Where,

i_{dc} : current injected into the DC network;

i_{sup} : supercapacitor output current;

V_{dc} : DC bus voltage for HESS application;

v_{sup} : supercapacitor output voltage;

C_{sup} : supercapacitor value;

C_{dc} : DC network capacitor ;

Figure 3.12: Converter model for modified supercapacitor voltage restoration loop

Increase in $Z_{sup}(s)$ at frequencies below ω_{sup} is seen upon adding this voltage restoration control loop determined by PI controller parameters. ω_{sup} should be lesser than ω_c for control agreement. Total impedance of HESS is not altered by

Table 3.2: Simulation and experimental parameters

Parameters	Simulation value	Experimental value
Nominal bus voltage (V)	380	100
Battery terminal voltage (V)	190	48
Battery capacity (Ah)	150	150
SC terminal voltage (V)	190	50
SC capacity (μF)	2200	2200
Load1/ Load2 (Ω)	150/150	50/50

Figure 3.13: Simulation and experimental setup (a) Schematic layout (b) Experimental platform

the SC voltage restoration since the battery dominates the lower frequency range.

3.2.3 Simulation and Experimental Verification

A. Simulation results

A 380V DC microgrid was built in Piecewise Linear Electrical Circuit Simulation (PLECS) software. The control strategies analyzed above are realized through simulations. The schematic layout of simulation and experimental platform are shown in Fig 3.13(a). The PV, battery and SC converter parameters for controller design discussed in sections above are listed in Table 3.1. The nominal system parameters used during simulation and experiment are listed in Table 3.2. The use of first and second order LPF/HPF are tested for two operating conditions: a) step load change and b) sinusoidal disturbance on PV generation.

For the time scale co-ordination of HESS based on the concept of frequency coordinating virtual impedance, a step load increase at $t = 1.5s$ is introduced in the system and the corresponding voltage and power waveform are shown in Fig 3.14(a). The step load decrease at $t = 1.5s$ is depicted in Fig 3.14(b). It can be said

Figure 3.14: Waveforms for existing control loop during step load change (a) Step load increase (b) Step load decrease

from the waveforms that during step load increase, the battery power increases slowly, whereas, the SC almost spontaneously responds to the power fluctuations. Similarly, during step load decrease, the SC power decreases instantaneously in response to the power fluctuations in the system, but the battery power decreases gradually. When the battery power decreases completely to respond to the load decrease in the system, the SC goes through voltage restoration process and the SC power rests at zero until the next transient condition takes place in the system. This is because of the fact that the battery converter consists of first order LPF and responds to the low frequency variations in bus voltage whereas SC utilizes first order HPF to respond to the high frequency variations in the system.

Fig 3.15(a) and Fig 3.15(b) show the system performance during the same step load variation at $t = 1.5s$, however the virtual impedances are implemented with second order filters. The advantages of implementation of virtual impedances with second order LPF for battery converter and second order HPF for SC converter are discussed in section 3.2.1. The use of second order filters may induce voltage

Figure 3.15: Waveforms for proposed control loop during step load change (a) Step load increase (b) Step load decrease

and current oscillations during step load change in the system. By increasing the cut-off frequency of battery converter in comparison with the control loops implemented for first order filters and by the increment in widely used value for damping ratio of 0.707, the oscillation duration can be minimized.

The waveforms for sinusoidal disturbance on PV generation are shown in Fig 3.16. The generation demand mismatch is supplied by the HESS and the DC bus voltage (380V) is regulated. Fig 3.17 shows the performance during the same sinusoidal disturbance as that in Fig 3.16, but the virtual impedances are implemented with second order filters.

Since the attenuation of higher order filter outside the passband is sharper than the lower order, the ripple power has been diminished. It is proved by the comparison of frequency spectrum in Fig 3.18 for two control strategies using first order and second order filters. The Fast Fourier Transform (FFT) diagram shows that the magnitude of ripple power in battery is decreased from 65VA in Fig 3.18(a) to 11VA in Fig 3.18(b) by the use of second order filters. The decrease in ripple

Figure 3.16: Waveforms for existing control loop during change in PV generation

power decreases the stress on battery to increase its life time. In other words, the essence of showing FFT is to prove the better performance of second order filters over first order filters in attenuating different frequency components in time-domain caused by changing PV generation in the system. The corresponding time-domain results are shown in Fig 3.16 and Fig 3.17. The role of SC is to co-ordinate with battery for providing high frequency oscillations caused by the disturbance due to PV generation and hence the magnitude of SC power has also been decreased in Fig 3.18(b).

B. Experimental results

A scaled down experimental setup for a 100V DC bus voltage to validate the control strategies discussed above was constructed as shown in Fig 3.13(a). The experimental setup in Fig 3.13(b) shows the interfacing converters for PV, lead-

Figure 3.17: Change in PV generation for proposed control loop

Figure 3.18: FFT of the system (a) using first order filter (b) using second order filter

Figure 3.19: Experimental waveforms for existing control loop during step load change

Figure 3.20: Experimental waveforms with lower-order filters during transient process

acid battery and SC to the DC bus. The system was controlled by a dSPACE DS1103 PPC controller board. When step load is applied to the system at $t = 500ms$ in Fig 3.19, the bus voltage is well regulated at $V_{dc} = 100V$. It can be seen that the battery current slowly increases to provide the load demand whereas the SC current caters to the power fluctuation in the system during dynamic response due to load current step change. The sinusoidal fluctuation in PV generation and

Figure 3.21: Experimental waveforms with higher-order filters during transient process

the system response for it is depicted in Fig 3.20 utilizing lower order filters in the control loop. It can be seen that the SC current responds to the PV fluctuation and maintains constant DC bus voltage and smoothen the load current, reducing the stress on the battery. The DC bus and SC voltage in Fig 3.21 are controlled using the control algorithm proposed which attenuates ripple power and noisy output better than that of the lower order filters.

3.3 Summary

In this chapter, the decentralized coordination control based upon frequency coordinated virtual impedance concept has been introduced for the power management in DC microgrids. Such control strategy is superior to the conventional droop control because of the relationship between diverse time scales and dynamic nature of various ESS and DGs. However, the co-ordination of multiple converters need advanced power management in both steady-state and transient period. This decentralized control approach has been applied to HESS consisting of lead-acid battery and SC along with the PV in this thesis.

Bi-directional DC-DC converters act as a power electronic interface between the battery/SC and the DC bus. Solar PV is interfaced to the DC bus by the means of a DC-DC boost converter. The virtual output impedances are shaped into

frequency-domain so that the battery converter absorbs low frequency and the SC converter absorbs high frequency components of power variations in DC microgrids. Furthermore, a higher order LPF and HPF in battery and SC converter respectively has been inserted and the effectiveness of the proposed control has been examined. It shows that the power fluctuations in battery during system operation is reduced which increases the battery lifetime.

Chapter 4

Interconnection of DC Microgrids

There will be embedded energy storage (at every layer of the grid). It will be a collection of microgrids.

—*John Hewa, ARPA-E Energy Summit 2014*

The application of DC microgrid for supplying power to DC loads along with sensitive loads ranging from electric vehicles, naval ships, space crafts, submarines, and industrial power systems to consumer electronics, telecommunication systems and rural areas has risen due to its efficient nature and benefits of increased power supply and higher reliability. Recent advancement includes the role of DC microgrid as a facilitator to integrate modernized electronic loads and alternative energy sources that produce DC output power such as photovoltaic (PV) system, energy storages (e.g. chemical battery and supercapacitor) and fuel cell [59, 62, 98, 112, 113]. In **Chapter 3**, the decentralized control of DC microgrid consisting of HESS has been proposed and elaborated. This chapter will discuss about the interconnection of multiple microgrids to improve reliability of the system as discussed in section 2.2.2 and will propose a decentralized control for two interconnected DC microgrids.

Although there is significant research for implementation of DC microgrids, limited studies are done regarding modelling, stability analysis, and control of these systems, especially in the case that they are connected to the other microgrids to create DC microgrid clusters. Hierarchical model for interconnection of multiple DC microgrids based on the introduced hierarchical control loops in [95] are yet

to be studied thoroughly. A hierarchical control strategy is recommended for DC microgrids with the control levels divided into: primary, secondary, and tertiary control [114]. The primary control deals with the inner control loops and droop control of the DC sources, which is strictly local. The droop control in this level is a resistive virtual loop and provides the voltage reference to the inner control loops. Nevertheless, for ESSs and RES, droop control is not always the preferred control strategy where specified power is injected/absorbed to/from them [67]. The droop control created deviations are removed with the secondary control by setting the reference of primary control to maintain the bus voltage of DC microgrids to acceptable levels. The tertiary control manages the current flow to/from an external DC source, which can be DC or AC microgrid, or a DC distribution system or a DC/AC converter connected to the main grid [67].

In the primary level, the ratings of the power converters give the measure of droop coefficient. Recently, various adaptive droop methods have been presented in this issue [60, 100, 101, 115]. For load sharing in multiterminal DC grids among the converters, an adaptive droop control scheme has been presented in [115]. A control strategy with fuzzy logic for low voltage DC microgrid has been presented in [116] to ensure low voltage deviation achieved by the modification of droop coefficients with respect to state of charge (SoC) of every energy storage unit. A SoC-dependent function with discharging mode specifically for ESSs inside a microgrid has been proposed in [100]. On the other hand, [60] has proposed two separate functions for both charging and discharging mode of the battery as per its SoC and capacity. Similarly, a double quadrant SoC based droop control method has been presented in [101] that ensures SoC balancing and output power adjustment in both charging and discharging modes.

An ESS can address the renewable intermittency in an islanded DC microgrid enhancing the reliability and making the system more stable. In addition, the interconnection of neighboring DC microgrids for exchange of power can further enhance the reliability [117, 118]. A control strategy for two interconnected DC microgrids operating at different voltage levels for rural grid has been proposed in [117]. A bidirectional DC-DC converter has been implemented in this control to make the system reliable and energy efficient. Forming multiple DC microgrid clusters by connecting multiple identical DC buses via tie-line also aids in making the system more efficient and reliable. The primary challenge in interconnecting DC microgrids is keeping the system stable, since the involvement of multiple parallel converters in a DC microgrid cluster make the system unstable. Despite

DC microgrid being one of the most widely researched technologies in recent times, DC microgrid cluster is still a new concept yet to be explored. The interconnection of DC microgrids still requires research regarding its operation and control.

This chapter proposes a decentralized control approach for controlling the bus voltage of geographically dispersed microgrids in an allowable range that can manage the power flow via tie-line across the microgrid. Such approach being decentralized, is void of communication stress. The decentralized control is accompanied by mode change based operation. Thus, the distributed units can cope up with power flow control and BVR providing autonomy to the interconnected microgrids. In case of power deficit, power is injected/generated into/from the microgrid caused by demand-supply mismatch in a particular microgrid.

4.1 Interconnection of DC Microgrids Through Tie-line

Tie-line bias control is the mode of automatic generation control for interconnected AC power systems. The functions of tie-line bias control can be classified as [119]:

- a) It allows each area to respond to its local load changes.
- b) It motivates each area in the cluster to respond to the system frequency change.
- c) When an area is unable to supply its demand, unscheduled sharing occurs in the interconnected system. In power systems, areas (microgrids) are interconnected in order to share the generation and load.

Load frequency control (LFC) is employed in AC systems to respond to the frequency change of each area, in an interconnected system. In abnormal conditions, it also allows power flow through tie-line as inter-area support [120]. The terms “obligation” and “contribution” clarified by [119] for the tie-line bias control refer to the functions (a), (b) and (c) listed above respectively. Various control strategies have been proposed for LFC in AC systems [121, 122]. Initially, centralized control strategy was used to address LFC. The limitation of such a control strategy was the computational burden due to communication links [121, 122] in geographically dispersed control areas leading to the evolution in the idea of decentralized control. Decentralization of each cluster control plays a vital role in saving the cost for data communication and reducing the stress for network monitoring to achieve

the dynamic operation of power systems [121]. The scope of this thesis does not cover the review of control strategies in AC systems.

Figure 4.1: Schematic layout of two DC microgrids interconnected with tie-line

The interconnection of DC microgrid clusters have been discussed in literature references [11, 34, 67, 118, 123]. Hierarchical control has been proposed in [67, 118, 123] to regulate the DC bus voltage and the efficiency of parallel connected batteries in each microgrid is improved by the use of adaptive droop based upon the SoC information. Despite low bandwidth communication between neighboring network for the estimated average voltage and SoC of batteries of cluster being examined using hardware in the loop simulation in this distributed approach, the issue of addressing geographically dispersed cluster still prevails. Tertiary control for power sharing among microgrids in a cluster has been proposed by reference [11] where each microgrid has communication network communion to the secondary control. Decentralized control approach in individual DC microgrid that modifies effective droop gain for good voltage regulation and load sharing has been proposed by reference [34]. It exhibits better performance compared to conventional droop control and hierarchical secondary control. However, the examination of this control approach for interconnected microgrids focuses only on steady state performance and the tie-line power flow control is still centralized. Examination of source sharing has not been conducted. Though all these literature have significant contribution within the scope of the papers, the interconnection of DC microgrids along with voltage regulation and power flow is still an open research. In DC microgrids, tie-line bias control is achieved by regulating the DC bus voltage to a specific level and provision of power flow between the control areas when an area is unable to respond to its demand during disturbance such that the “obligation” function (b) and “contribution” function of tie-line bias control is achieved. The construction of an autonomous DC microgrid makes it able to

respond to its local load change. Section 4.2 further explains these functions of two DC microgrids interconnected with tie-line.

Fig. 4.1 demonstrates the general configuration of using tie-line for interconnection of two DC microgrids. Two neighboring DC microgrids, Microgrid 1 (MG1) and Microgrid 2 (MG2) in remote areas operating at the same voltage level have been considered in this thesis for the reliable power supply to the load. The interconnected microgrids consist of PV interfaced to each DC bus by means of a DC/DC boost converter. ESS in each microgrid is formed by a battery and a bi-directional DC/DC converter. The circuit diagrams for interfacing converters for PV and ESS are depicted in Fig. 2.3(a) and Fig. 2.4(a) respectively.

The output voltage for conventional V-I droop control in terms of virtual output impedance can be expressed as (3.2) [95]. The term r_{di} characterizes the equivalent resistance of the converter, affiliated to the droop rate [111]. All the buses in the DC microgrid cluster obey the droop control in (3.2). Assuming there are n buses in the DC microgrid cluster and applying Kirchhoff's current law, the current flowing from i^{th} bus to $(n - 1)$ buses can be expressed as (4.1) [124]. The power injected through the tie-line from the i^{th} bus can be represented by (4.2). Power loss in the tie-line is expressed as (4.3). The power balance of the i^{th} microgrid during tie-line power flow is represented by (4.4).

$$I_{dc,i(tie)} = \sum_{\substack{j=1 \\ j \neq i}}^n Y_{tie,ij} (V_{dc,i} - V_{dc,j}) \quad (4.1)$$

$$P_{tie,i} = V_{dc,i} I_{dc,i(tie)} \quad (4.2)$$

$$\Delta P_{tie} = I_{dc,i(tie)}^2 Z_{tie,ij} \quad (4.3)$$

$$P_{G,i} - P_{D,i} - P_{tie,i} = 0 \quad (4.4)$$

Where, $V_{dc,i}$ and $V_{dc,j}$ are the respective DC bus voltages of i^{th} and j^{th} bus. $Y_{tie,ij}$, $Z_{tie,ij}$ and $P_{tie,i}$ represent the tie-line admittance, impedance and tie-line power flow respectively. $P_{G,i}$ and $P_{D,i}$ denote total generation and demand on i^{th} microgrid respectively. Only two microgrids (MG1 and MG2) have been considered for the study in this thesis. MG1 and MG2 shown in Fig. 4.1 operate autonomously unless there is power deficit in one of the microgrids.

4.2 Decentralized Control Strategies

4.2.1 Autonomous Decentralized Control

Most converters act as inherent current source converters [79]. Reference current (i_{ref}) for the current control loop of the converter can be generated from (3.2). The transfer function ($G_{conv,i}(s)$) for the inner closed loop current control in the i^{th} converter of both microgrids has low pass characteristic with high bandwidth due to fast switching [79] and is expressed as in (4.5), where τ_i represents time constant. This transfer function yields the bus current (i_{busi}) at the output [79].

Figure 4.2: Model of two interconnected microgrids with decentralized control loop for bus voltage error minimization

$$G_{conv,i}(s) = 1/(\tau_i s + 1) \quad (4.5)$$

$$V_{dc1} + V_{dc2} = 2v_{MG}^* \quad (4.6)$$

$$2V_{dc1} + v_{tie} = 2v_{MG}^* \quad (4.7)$$

$$2V_{dc2} - v_{tie} = 2v_{MG}^* \quad (4.8)$$

$$V_{dc1} = v_{MG}^* - R_{dp1}i_{o1} + (k_{p1} + k_{i1}/s) \times (2v_{MG}^* - \{2V_{dc1} + v_{tie}\}) \quad (4.9)$$

$$V_{dc2} = v_{MG}^* - R_{dp2}i_{o2} + (k_{p2} + k_{i2}/s) \times (2v_{MG}^* - \{2V_{dc2} - v_{tie}\}) \quad (4.10)$$

$$v_{tie} = I_{tie}Z_{tie} \quad (4.11)$$

The power flow of local terminal and the voltage deviation of the system are regulated by the converters involved in a DC microgrid. Converters are termed as terminal and bus regulating unit for power flow control as per their objective in order to avoid control conflict.

Terminal regulating units are the renewable DGs performing on MPPT. Their role is to supply the power demand of the system and the power production is independent of DC bus voltage variation. Unlike the PV converter, the battery converter in DC microgrid regulates the system voltage and nurtures power balance of the system. Because of such an objective, it is termed as bus regulating unit and can be expressed as a Thevenin equivalent circuit with series impedance. The Thevenin voltage source refers to the voltage reference, the series impedance refers to virtual impedance and the unit control operates in droop control mode [77]. Fig. 4.2 shows the control loops for battery converter in two interconnected microgrids [125]. The control loop for voltage error signal generation of MG1 and MG2 buses is shown by the red dotted indication. These error signals represent voltage correction term V_{err_1} and V_{err_2} that restore the voltages at MG1 and MG2 buses, which are added to the droop control unit of each microgrid. The principle behind the bus voltage error minimization indicated in Fig. 4.2 is expressed as in (4.6) and can be elaborated as (4.7) and (4.8) for MG1 and MG2 respectively, where V_{dc1} , V_{dc2} represent the DC bus voltages of MG1 and MG2 respectively and v_{MG}^* signifies the microgrid reference voltage. R_{dp1} and R_{dp2} represent droop gains of battery converters in MG1 and MG2 respectively. I_{tie} and Z_{tie} stand for tie-line current and impedance, respectively. C_{bus1} , C_{bus2} and R_{L1} , R_{L2} in Fig. 4.2 represent bus capacitors and load resistances for MG1 and MG2 respectively [118]. The generalized expressions for the battery converter output voltages for MG1 and MG2 can be simplified as in (4.9) and (4.10). The tie-line voltage drop v_{tie} is expressed as (4.11).

The tie-line power flow as calculated based upon (4.2) is dependent on the voltage difference between two buses. The amount of tie-line power flow depends upon $\pm 5\%$ change in the DC bus voltages of interconnected microgrids. The maximum temperature of the conductor at which the line is designed to operate determines the rating of tie-line. There is always a time delay between a sudden change in thermal heating of conductors to the following temperature rise as the conductors have significant thermal mass. A tie-line can withstand 115% overload for 10 minutes without exceeding design temperature [126].

The DC current is uniformly distributed over the cross sectional area when passed

through a round cylindrical conductor and its resistance is given by (4.12) [127]. The conductive material's cross-sectional area (A_c), its resistivity (ρ) and length (l) determine the resistance of Z_{tie} . The resistivity of a conductor and temperature coefficient depend upon the conductor material. No change in effective resistance due to the skin effect and frequency change takes place in DC systems.

$$Z_{tie} = \rho l / A_c \quad (4.12)$$

The control strategy proposed above is based upon (4.6) and is only applicable to minimize the bus voltage errors of two microgrids. Due to this limitation, the topology for n bus microgrids connected with multiple tie-lines and the impact of Z_{tie} variation in the system have not been considered in this thesis.

4.2.2 Mode Adaptive Decentralized Control

As mentioned in section 4.2.1, the converters in DC microgrids are categorized into terminal regulating unit and bus regulating unit. Each converter is attributed to a particular function, either to regulate power flow or to regulate the bus voltage in the local terminal. This is done particularly to avoid control conflict in the system. The operation modes of renewable DGs and loads should be adjusted adaptively to counter their intermittent nature. For example, renewable generators like wind and PV operate at MPPT when there is an increase in load demand but this is not the case when the demand is low. To mitigate this issue, the operation modes of DGs and ESS involved in a microgrid are designated depending upon the voltage level.

The DC bus voltage level as shown in Fig. 4.3 is grouped under three regions: nominal voltage, V_{high} and V_{low} [79, 111]. V_{high} and V_{low} are designated as $\pm 5\%$ of the nominal DC bus voltage in order to indicate the operation modes designation. The droop operation indicated in Fig. 4.3 is the BVR mode while the red lines indicate constant power (CP) mode. The constant power mode for PV refers to the MPPT mode and that in battery refers to the charge/discharge in current control mode. For example, when power is interrupted in renewable DG like PV or there is a surge in local consumption in MG1, the DC bus voltage at MG1 decreases. In addition, deviation in the bus voltage among two microgrids leads to power flow from MG2 to MG1. ESS of both microgrids, in such a case, operate in BVR mode. On the other hand, when the local load demand at one

Table 4.1: Operation modes and corresponding values during different voltage levels

MG1	MG2	MG1/MG2 modes	$V_{bus} > V_{high}$	$V_{low} < V_{bus} < V_{high}$	$V_{bus} < V_{low}$	P_{tie}
$P_{G1} < P_{L1}$ $SoC_{ES1} \leq LL$	$P_{G2} < P_{L2}$ $SoC_{ES2} \leq LL$	MPPT/MPPT BRM/BRM	-	-	V_{bus1}, V_{bus2}	-
$P_{G1} > P_{L1}$ $SoC_{ES1} \geq UL$	$P_{G2} > P_{L2}$ $SoC_{ES2} \geq UL$	BRM/BRM Disch [†] /Disch [†]	V_{bus1}, V_{bus2}	-	-	-
$P_{G1} > P_{L1}$ $SoC_{ES1} \leq LL$	$P_{G2} > P_{L2}$ $SoC_{ES2} \leq LL$	MPPT/MPPT Ch/Ch	-	V_{bus1}, V_{bus2}	-	-
$P_{G1} < P_{L1}$ $SoC_{ES1} \geq UL$	$P_{G2} < P_{L2}$ $SoC_{ES2} \geq UL$	MPPT/MPPT Disch/Disch	-	V_{bus1}, V_{bus2}	-	-
$P_{G1} > P_{L1}$ $SoC_{ES1} \leq LL$	$P_{G2} > P_{L2}$ $SoC_{ES2} \geq UL$	MPPT/MPPT ch/Disch	-	V_{bus1}, V_{bus2}	-	-
$P_{G1} < P_{L1}$ $SoC_{ES1} \geq UL$	$P_{G2} < P_{L2}$ $SoC_{ES2} \leq LL$	MPPT/MPPT Disch/ch	-	V_{bus1}, V_{bus2}	-	-
$P_{G1} > P_{L1}$ $SoC_{ES1} \geq UL$	$P_{G2} < P_{L2}$ $SoC_{ES2} \leq LL$	BRM/MPPT Disch [†] /ch	V_{bus1}	-	V_{bus2}	(4.1) & (4.2)
$P_{G1} < P_{L1}$ $SoC_{ES1} \leq LL$	$P_{G2} > P_{L2}$ $SoC_{ES2} \geq UL$	MPPT/BRM ch/Disch [†]	V_{bus2}	-	V_{bus1}	(4.1) & (4.2)

[†] denotes discharge at manufacturer's specification in current control mode

LL and UL denote SoC lower and upper limit of ES respectively

Figure 4.3: Graphical representation of mode adaptive control

microgrid or both microgrids is less than the total generation in each microgrid, the DC bus voltage increases. The terminal regulating unit such as PV should change its operation from MPPT to BVR mode to retain this increment to the nominal value. Likewise, the battery converter shifts to current control mode and its charge/discharge is determined by the reference current provided to the battery converter (i.e. rated charging current provided by the manufacturer). When the local demand is sufficiently met by the local generation, no mode change is observed. The terminal regulating unit operates on MPPT mode and bus regulating unit on BVR mode in this case. Thus, in order to maintain the DC bus voltage, the distributed generation units in two microgrids switch their operation modes, as per the change in demand-supply.

If the capacity of an energy storage and the generation units in both microgrids are not able to cater local load demand, load curtailment must be opted. The first row of Table 4.1 provides the details on the generation and energy storage status of such a case. As the bus voltage of the DC microgrid decreases during excessive demand, the flow of power takes place via tie-line caused by the difference in the bus voltages of two microgrids within the capacity of the tie-line.

The decentralized control proposed in this thesis is preferred to the centralized and distributed control for interconnecting DC microgrids since it nullifies the

Table 4.2: Simulation and experimental parameters

Parameters	Simulation value	Experimental value
Nominal bus voltage (V)	380	48
Battery terminal voltage (V)	190	24
Battery capacity (Ah)	150	7
Load1/ Load2 (Ω)	30/30	120/120

communication stress of geographically distant areas. Moreover, this approach to control is feasible and simple in nature. In addition, the decentralized mode adaptive control for the power management of DC microgrids adjusts the operation modes of RES and ESS as discussed earlier. Such self-disciplined regulations of converters in microgrids without communication links make the system more reliable and flexible.

4.2.3 Simulation and Experimental Verification

A. Simulation results

To verify the aforementioned control strategies, two microgrids consisting of PV and battery are built in PLECS environment. The DC bus voltage is set to be 380V. The use of decentralized control is tested for two types of load: a) constant power load (CPL) and b) a step load change in each microgrid to examine whether the load change is self-sustained by the respective microgrid.

The control loop proposed in Fig. 4.2 is implemented to examine the essence of the control loop as shown in Fig. 4.4. The voltage difference (ΔV) of MG1 and MG2 is 0.724V before $t = 4s$ and due to the CPL of 1000W and 1500W connected to MG1 and MG2 respectively, there is a flow of power ($P_{tie} = 249.8W$). I_{tie} signifies the corresponding tie-line current in Fig. 4.4. This phenomenon proves the necessity of control loop for bus voltage error minimization in Fig. 4.2 for the autonomous operation of each microgrid when the local supply is sufficient to cater the local demand. After the activation of control loop at $t = 4s$ for minimizing the error in bus voltage, bus voltages are maintained at 380V to reduce the tie-line power flow to zero, thus, achieving the function b) discussed in section 4.1.

A step load is introduced in the system with the proposed decentralized control at $t = 5s$ and $10s$ in MG1 and MG2 respectively in Fig. 4.5. From the waveforms, it can be seen that at steady state, both the DC bus voltages of MG1 (V_{dc1}) and MG2 (V_{dc2}) are 380V and hence the tie-line current is zero. At $t = 5s$, there is a

Figure 4.4: Performance of proposed decentralized control method

step load change in MG1 which causes the power demand to increase. Since PV at both microgrids is in MPPT mode, the battery responds to the power deficit caused by load change. The response of battery to the load change regulates the bus voltage fluctuation and it is maintained to be 380V, making tie-line current flow to zero. Similarly, at $t = 10s$, a step load is applied to MG2 and it is able to regulate the bus voltage fluctuation and supply power to maintain generation-demand balance. This shows that the microgrid is able to cater its local demand and hence the “obligation” function a) of tie-line bias control discussed in section 4.1 is achieved.

The logic behind the relationship between bus voltage increment/decrement due to the change in generation/demand is provided in section 4.2.2. For the sake of brevity, CPL of 200W that is less than MPPT generation of PV is provided in both microgrids. The changes in MG1 have been observed to validate mode change based operation setting V_{high} as 390V and V_{low} as 370V and the bus voltages of MG1 and MG2 along with tie-line current flow are shown in Fig. 4.6. A DC bus signal of 395V is provided at $t = 0s$ in the control logic, PV at this moment operates at BVR (Fig. 4.7) and battery is charged with manufacturer’s charging current reference. At 5s, the DC bus voltage is ramped from 395V $\rightarrow$ 380V (slope -5 per second). When the control logic finds the moment of 390V at $t = 6s$ in Fig. 4.6, the PV and battery converters are changed to MPPT (Fig. 4.7) and BVR mode respectively. Similarly, a ramped DC signal from 380V $\rightarrow$ 365V has been

Figure 4.5: Waveforms for DC bus voltages and battery power in MG1 and MG2

observed in simulation. The power generation, state of ESS and mode changes in both microgrids has been tabulated in Table 4.1. The first two rows in Table 4.1 indicate two extreme scenarios of operation when load and generation curtailment respectively should be executed. The subscripts G, L and ES denote generation, load and energy storage (battery) for the respective microgrid. The tie-line current which is the “contribution” discussed in previous section, can be calculated using (4.1) and its maximum value can be obtained by substituting V_{high} and V_{low} in place of bus voltages of i^{th} and j^{th} microgrid in (4.1). The nominal system parameters used during simulation and experiment are listed in Table 4.2.

B. Experimental results

Figure 4.6: DC bus voltages and tie-line current during mode change

Figure 4.7: PV power at MG1 and MG2 during mode change

In this section, a prototype of a droop controlled two interconnected DC microgrids with implementation of control strategy discussed in section 4.2 is established. The schematic layout of experimental platform is shown in Fig. 4.8 and the nominal system parameters are listed in Table 4.2. The DC bus voltages of the two mi-

crogrids are set at 48V, which is generally implemented in telecommunication applications. Each microgrid consists of PV and lead acid battery interfaced to the DC bus by means of a DC-DC boost converter and a bi-directional DC-DC converter respectively. The system was controlled by a dSPACE DS1103 PPC controller board. Four experimental cases have been carried out to validate the interconnection of DC microgrids through tie-line.

Figure 4.8: Schematic layout of experimental platform

Figure 4.9: Step load change in MG2

Voltage stability test by step load change in the system

This test demonstrates the self-sustained operation of DC microgrids connected through tie-line when the generation of a microgrid is sufficient to supply the demand. The battery currents and DC bus voltages of both microgrids during step load change at $t = 80ms$ in MG2 are shown in Fig. 4.9. The corresponding

battery of MG2 (I_{bat2}) responds to the demand while the battery current at MG1 (I_{bat1}) remains unchanged. It can be seen from Fig. 4.9 that the battery is charging before step load change in the system since the generation is sufficient to supply the system demand. After step load change, the load power demand of 38.4W has been catered by the battery in MG2. Generation curtailment by mode change based operation has not been examined in this section and is explained in "Mode transition test" below in this Chapter. Fig. 4.10 shows the tie-line current flow during step load change in MG2 at $t = 80ms$. The zero tie-line current proves that both microgrids are able to cater to the local demand autonomously. The DC bus voltages of 48V for both microgrids are shown in both Fig. 4.9 and Fig. 4.10 and are well regulated.

Figure 4.10: Tie-line current during step load change in MG2

Voltage stability test by generation fluctuation

This experiment aims to verify the voltage stability under proposed control scheme. To emulate the generation fluctuation, an oscillating current is injected by the PV converter in MG1. The bus voltages and PV converter currents for MG1 and MG2 are demonstrated in Fig. 4.11 and the corresponding battery currents for MG1 and MG2 along with bus voltages are displayed in Fig. 4.12. It can be seen from the waveforms that the bus voltage in MG1 is well regulated since the power fluctuation from PV is compensated by the battery in MG1. The PV and battery waveforms in MG2 are unaffected by this variation. The generation from PV supplies the load power of 19.2W in MG2, while the battery charges with excess

Figure 4.11: Sinusoidal fluctuation in PV generation in MG1

Figure 4.12: Bus voltages and battery current during sinusoidal fluctuation in PV generation in MG1

generation maintaining constant DC bus voltage of 48V.

Mode transition test

In this case, MG1 initially operates in generation dominating mode PV being at MPPT mode of operation. The battery is being charged at this time since the renewable generation is sufficient to cater to the load demand. When the battery reaches the saturation point, the bus voltage rises. In such a case, the

Figure 4.13: Test for mode change based operation in MG1

Figure 4.14: Examination of tie-line current flow from MG1 to MG2

PV generation working on MPPT is supposed to switch to bus regulation mode in order to curtail the generation. A mode change logic is provided in MG1 at $t = 100ms$ and is demonstrated in Fig. 4.13. The waveforms show that the PV unit goes to bus regulation mode while the battery discharges for the system losses. The control strategy is effective to regulate the bus voltages.

Tie-line power flow test

The change in the bus voltage is realized at MG1, leading to tie-line current flow

Figure 4.15: Bus voltages and battery current during tie-line current flow in MG2

to MG2 as expressed in (4.1). Both MG1 and MG2 have a load of 60Ω . It can be seen from Fig. 4.14 that the tie-line current of $800mA$ flows from the higher voltage (MG1) to the lower voltage level (MG2). MG1 provides tie-line current while supplying local demand whereas MG2 supplies local demand only. The bus voltages and battery currents of both microgrids are shown in Fig. 4.15.

4.3 Summary

In this chapter, the interconnection of two DC microgrids through tie-line is implemented for enhancing the reliability and source sharing during power surplus/deficit in a microgrid. A decentralized control has been proposed focusing on geographically dispersed clusters to provide resilience to the system. The control strategy acknowledges the BVR in each DC microgrid. The proposed control strategy has been facilitated by mode adaptive control that designates the operation modes of different DG units to venture autonomous operation in microgrids. As a result, both the system reliability and flexibility could be enhanced. System performance is verified through simulation and experimental results. The objective of proposed control strategy can be summarized as follows:

- The use of decentralized control approach eliminates the communication stress when the microgrid control areas are geographically dispersed.

- The interconnection of microgrids with tie-line facilitates the generation sharing when one of the microgrids has supply-demand mismatch.
- Each microgrid can operate autonomously when there is no deficit in supply and has the provision of generation curtailment during supply surplus.
- The dynamic operation during load/source variation in microgrids has been examined to maintain the bus voltage.

Chapter 5

Bipolar-Type DC Microgrids

People are beginning to understand that they need their own onsite capabilities to island themselves from the grid. That's because the grid's external vulnerabilities will continue to be a problem until we do have substantial amounts of distributed generation.

—Jon Wellinghoff, 2015

After a century long repression of DC power by its AC opponent, DC power delivery has regained popularity in recent times, the key reason being the development of HVDC transmission systems. The controllability and power capacity of DC power delivery has made it advantageous over the AC transmission lines [128–130]. This trend has now found its scope from transmission to the distribution system, which is the bottom part of the electrical supply chains [79]. It might be widely used to increase the power quality and capacity by providing a greater resilience against irregular loads and power surge, and to facilitate the penetration of renewable DGs [33, 79, 111, 131]. In **Chapter 3** and **Chapter 4**, the decentralized control of DC microgrids with unipolar DC bus has been proposed. One of the disadvantages of DC microgrids with unipolar DC bus as discussed in section 2.2.1 is the necessity of higher precision in circuit and control parameter design. On the other hand, consumers have no redundancy on supply voltage level since they have to be powered with only one bus at a specific voltage level. This chapter will discuss about the bipolar-type DC microgrids to provide DGs and loads with

different voltage levels and serve as an option for alternative voltage levels [130].

The DC distribution technologies can accommodate the lowest voltage level due to their relative maturity of Low-Voltage DC (LVDC) electric apparatuses that include DC circuit breakers and power electronic converters. Initially, primary DC distribution systems with a rated voltage of 48V are deployed for communication power supplies [132] followed by the transportation power systems alike in ships and electric aircrafts. The DC voltage level is scaled up to several hundred volts to handle the extended power range [76,133]. The latest initiatives in DC distribution are reaching for electric vehicle charging stations and residential applications in green buildings [134]. The advantages of DC distribution are highlighted in section 1.1.

On the flip side, the practical application of DC microgrids adheres to the following limitations [64]:

- a) DC microgrid requires private DC distribution lines.
- b) The absence of zero cross point of voltage makes the protection in DC systems complicated in comparison to the AC system.

Efficient and high-quality power is essential for the customers in commercial as well as industrial sectors like semiconductor factories, banks and hospitals since the downtime related to voltage sag banks, hospitals or blackout is a matter of great concern [64].

To make the power supply efficient as well as to increase its quality, “a low-voltage bipolar-type DC microgrid” has been proposed in [135]. This system distributes the DC power through three-wire lines, which is then converted to the required AC or DC voltages by the help of load-side converters. In case of voltage sag or blackout in the utility grid, the DC microgrid can provide high-quality power in a stable manner, whereas in the case of AC microgrids, inverters of the DGs should be tripped unless they have the fault-ride-through capability [64].

Higher reliability, ability of power transfer in case of line failure, reduced losses during decreased levels of current and increased energy transmission capacity make the bipolar transmission lines applied in HVDC advantageous over the unipolar systems [136].

A typical low voltage bipolar-type DC grid is shown in Fig 5.1 [130]. The Medium Voltage AC (MVAC) and LVDC grid are interfaced by a distribution transformer and a distribution AC/DC converter. To provide two alternative voltage levels

Figure 5.1: A typical low voltage bipolar-type DC grid

for DGs and loads with different voltage or power scales, a bipolar configuration can be adopted for the DC grid similar to the three-phase structure in AC power systems [64, 136]. Each pole, positive or negative, is treated as a single-phase AC system. In addition, the voltage across the positive and negative terminals is analogous to the line-line voltage in AC systems. The three-wire bipolar DC microgrid consists of local loads on the upper/positive and the lower/negative terminals connected to the neutral terminal respectively as shown in Fig. 5.1. The flexibility lies in the connection of heavy loads to the upper and lower terminals achieving twice the voltage of positive/negative half [137]. In case of failure of one wire, the system continues to supply power through the remaining two wires.

The bipolar-type DC microgrids bring some challenges along with the above mentioned advantages. Because of different loadings in the upper and lower terminals, the terminal voltage fluctuates from the nominal value resulting in an unbalanced bipolar-type DC microgrid. To mitigate such a problem of power quality and system stability due to the asymmetrical power distribution in the bipolar-type DC microgrid, a comprehensive investigation is required for both the converter topology and the operation control strategy [130].

Distribution converter topologies for bipolar-type DC microgrids

The distribution converter plays a key role in the formation of bipolar-type LVDC

distribution [130]. One of the ways to obtain the bipolar DC output is the utilization of two cascaded Voltage Source Converter (VSC) as depicted in Fig 5.2 [130]. The disadvantage of such a topology is the requirement of two separated converters along with the two isolated windings for the distribution transformer that increases the size and cost of the system. Another way to achieve the bipolar DC

Figure 5.2: Two cascaded VSC for bipolar output

Figure 5.3: Single VSC with neutral line current regulation for bipolar output

output using single VSC is to connect the neutral line of distribution transformer

to the midpoint of DC output capacitors as shown in Fig 5.3 [130]. The DC voltage is balanced by regulating the current in the neutral line. However, the DC component of the neutral line current might cause transformer saturation.

The neutral line DC current can be prevented by using an extra half-bridge circuit for voltage balancing as shown in Fig 5.4 by redistributing the currents [130]. It has a more simplified structure than the topology shown in Fig 5.2 and is more tolerant to unbalanced load currents than the topology shown in Fig 5.3 [130]. Such a voltage balancer has been reported in [65, 130].

Figure 5.4: Extra half-bridge circuit for achieving bipolar output

5.1 Decentralized Control of Bipolar-Type DC Microgrids

The asymmetric distribution of loads at the upper and lower terminals is a major challenge of a bipolar type DC microgrid. It results in the fluctuation of terminal voltage from the nominal value making the DC microgrid unbalanced. In order to mitigate the issue of voltage imbalance, [64] and [138] have proposed a centralized voltage balancer. The disadvantage of such a solution is that the failure of

the central voltage balancer deteriorates the system functionality. A decentralized control for voltage balancing in a bidirectional DC/DC boost converter is proposed in reference [137], however, the topology proposed consists of extra diodes that account for the additional system losses. Moreover, it does not discuss the power contribution to the positive and negative halves by the use of multiple bus regulating units in the system. A topology integrating a Single-Ended Primary Converter (SEPIC) and a Cuk converter is proposed in reference [139]. Such an integration increases the number of passive elements in the circuit in the presence of multiple DERs interconnected to the microgrid, which may increase the system losses. Therefore, the control of parallel converters which interface the DERs and the topology of the converters along with the voltage balancer plays a vital role in the formation of an efficient bipolar-type DC microgrid.

Several types of droop control which supplant the centralized master slave control have been proposed in different literature [62,77,78,94,95] for the parallel operation of converters that are applied in the unipolar DC microgrids and can be implemented in the bipolar-type DC microgrids. Since the droop control is decentralized, it has many advantages such as plug and play capability; no communication link is required between the converters, simplicity and easy maintenance.

An improved bipolar-type DC microgrid is proposed in this chapter where decentralized control for parallel converters interfacing the DERs is implemented. The proposed decentralized voltage balancing control supersedes the centralized voltage balancer in terms of the utilization of communication links and enhances the system reliability. The decentralized control for boost converter control and the widely implemented centralized control for voltage balancing circuit is explained in this section. Such a control can be adopted in the bipolar-type DC microgrid consisting of multiple energy storages. One of the challenges of control conflict in the implementation of decentralized voltage balancer concept is mitigated by the means of droop control and will be discussed in section 5.2. An experimental prototype of the two-source bipolar-type DC microgrid has been built to validate its performance and is discussed in section 5.3.

System configuration and droop scheme

The topology and control scheme for two ESSs parallelly interfaced to the common bipolar DC bus are shown in Fig. 5.5. The circuit consists of two control loops, namely, *boost converter control* and *voltage balancing control*. The basic droop scheme mentioned in literature for the interfacing boost converters of two energy

storages in Fig. 5.5 is expressed in (3.2) [95]. The droop coefficient or the virtual resistance R_{droopi} is designed as expressed in (3.3). The implementation of virtual resistance will ensure proportional power sharing between the ESSs as long as the virtual resistances are tuned well according to (3.3). The limitations associated with the droop control implemented in the DC microgrid due to the tuning of virtual resistance are DC bus voltage deviation and current sharing accuracy. Several literature have proposed/reviewed valid solutions to these problems in [34, 62, 77, 78, 81, 92, 94, 95, 102]. The expression for droop control implemented in the *boost converter control* for the bipolar configuration as shown in Fig. 5.5 is given by (5.1).

Figure 5.5: Power circuit for a bipolar DC microgrid with control block diagram

$$V_{ref} - I_{oi} R_{droopi} = V_i^+ + V_i^- \quad (5.1)$$

Where, V_i^+ and V_i^- are the capacitor voltages of upper half and lower half of the

bipolar configuration of i^{th} converter shown in Fig. 5.5. R_{droopi} denotes the virtual resistance of i^{th} converter in a bipolar-type DC microgrid for the decentralized boost converter control loop as shown in Fig. 5.5.

The interfacing converters for the DERs involved in DC microgrids are classified as terminal and bus regulating units in order to avoid control conflict. DGs serving as the constant power source working at MPPT such as solar PV and wind are categorized as terminal regulating unit while others like ESS are classified as bus regulating units [77, 81]. The terminal and bus regulating units in a microgrid are discussed in section 2.3.3 and section 4.2.1. In this section, two bus regulating units implementing droop control for power sharing are analyzed to achieve decentralized voltage balancing control for the bipolar-type DC microgrid.

5.2 Decentralized Voltage Balancing Control

Essence of voltage balancing and control

The challenge in the bipolar-type DC microgrids lies on the asymmetrical operation due to the load distribution on its positive and negative halves. Such an operation might cause voltage imbalance in the system and lead to poor power quality and system instability. To mitigate such a problem, voltage balancing control should be implemented with thorough investigation of the converter topology and its operation control. Several literature have proposed a central voltage balancer for voltage balancing control in DC microgrids as shown in Fig. 5.5 and its disadvantages have been indicated in previous section. The focus of this chapter is to propose a bipolar-type DC microgrid with a decentralized control which has the capability of preserving the functionality of microgrid by ride through the (even if there is) malfunction in a central voltage balancer.

A simple way to implement decentralized control is to generate the inductor current reference from the differences in V_i^+ and V_i^- using conventional minimization of error signal based upon a proportional-integral (PI) controller between the upper and lower half of the bipolar configuration of ESS. The inner current control loop generates the duty cycle for switches $Si3$ and $Si4$ tracking the reference inductor current.

The problem with such decentralized control implementation arises when there are two bus regulating units such as two ESSs in Fig. 5.5 due to control conflict. This

Figure 5.6: Voltage and current waveforms to show control conflict

is because of the fact that multiple sources and storages with same priority within the system may not operate in the same voltage band to share load according to their ratings [78]. For instance, the decentralized voltage balancing achieved by the PI-based control may have different voltage offsets in practice and the inductor current references generated for the two ESSs increase/decrease infinitely as shown in Fig. 5.6. This is due to the integral part of PI-based voltage controller used to generate the current reference. ΔV denotes the voltage difference between upper and lower terminals of the DC bus and I_{L_ba1} and I_{L_ba2} are the inductor currents of ESS1 and ESS2 in the voltage balancing circuit in Fig. 5.5. Different voltage offsets are added to V_1^- and V_2^- respectively in the simulation result of Fig. 5.6 to highlight the problem which exists in practical scenarios.

Proposed control strategy

The circuit diagram for a half-bridge voltage balancer, consisting of two IGBTs, two capacitors and a reactor is shown in Fig. 5.7 taking ESS1 in Fig. 5.5 as an example. Inductor L_bai in the diagram performs the voltage balancing role only. The DC bus is segregated into a three-wire system consisting of positive, neutral and negative lines. If the upper and lower halves are equally loaded, there will be no current flowing through the inductor L_bai . The voltage fluctuation in the circuit occurs when there is an unbalanced load in the positive and negative halves of the balancing circuit. The advantage of implementing such a topology reduces the ohmic power loss by half in comparison to a two-wire DC bus based system. However, the power sharing achieved does not show good result and the problem shown in Fig. 5.6 and discussed above exists.

Figure 5.7: Proposed control (a) Voltage balancing circuit (b) V-I droop curve for voltage balancing circuit

In order to mitigate the issue of control conflict between more than one voltage balancing circuit, a droop based control as shown in Fig. 5.7(a) is proposed and is expressed by (5.2). A droop control achieved by multiplication of the inductor current I_{L_bai} with a droop gain is subtracted from the difference of V_i^+ and V_i^- . This generates an error signal, which is passed through the PI controller to generate the inductor current reference. The inner current control loop generates the reference signal for PWM switching. The gains for balancing circuits R_{bai} of ESS1 and ESS2 introduced in this thesis that are similar to the droop gain in droop control are calculated using (5.3), where i_{L_baimax} denotes the maximum inductor current of voltage balancing circuit of i^{th} converter. This expression can be explained by the V-I relationship of Fig. 5.7(b). When the balancing inductor current is not equal to zero, the bus voltage deviation between the positive and negative halves of the bipolar configuration exists and its value varies with the load current. Furthermore, assuming that all the line resistances (r_{line}) of three lines are equal, the impact of line resistances in the system is mathematically analyzed. Combining (5.1) and (5.2), the upper half and lower half capacitor voltages can be obtained as in (5.3) and (5.4).

$$V_i^+ - V_i^- = i_{L_bai} R_{bai} \quad (5.2)$$

$$R_{bai} = \frac{V_i^+ - V_i^-}{i_{L_baimax}} \quad (5.3)$$

$$V_i^+ = \frac{1}{2} V_{ref} + \frac{1}{2} I_{L_bai} R_{bai} - \frac{1}{2} I_{oi} R_{droopi} \quad (5.4)$$

$$V_i^- = \frac{1}{2}V_{ref} - \frac{1}{2}I_{L_bai}R_{bai} - \frac{1}{2}I_{oi}R_{droopi} \quad (5.5)$$

According to Kirchhoff's Current Law (KCL),

$$I_{L_bai} = I_{oi}^- - I_{oi} \quad (5.6)$$

The upper half bus voltage V^+ for the two converters can be expressed as (5.7), where $i = 1, 2$.

$$\begin{aligned} V^+ &= V_i^+ - I_{oi}r_{line} + I_{L_bai}r_{line} \\ &= \frac{1}{2}V_{ref} - I_{oi}\left(\frac{1}{2}R_{droopi} + \frac{1}{2}R_{bai} + 2r_{line}\right) + I_{oi}^-\left(\frac{1}{2}R_{bai} + r_{line}\right) \end{aligned} \quad (5.7)$$

Putting the value of i which indicates the converter number and equating the terms in (5.7), (5.8) is obtained.

$$\begin{aligned} I_{o1} \left(\frac{1}{2}R_{droop1} + \frac{1}{2}R_{ba1} + 2r_{line} \right) - I_{o1}^- \left(\frac{1}{2}R_{ba1} + r_{line} \right) \\ = I_{o2} \left(\frac{1}{2}R_{droop2} + \frac{1}{2}R_{ba2} + 2r_{line} \right) - I_{o2}^- \left(\frac{1}{2}R_{ba2} + r_{line} \right) \end{aligned} \quad (5.8)$$

Similarly, equating the lower half bus voltages (V^-) for two converters as in (5.7), (5.9) can be obtained.

$$\begin{aligned} I_{o1} \left(\frac{1}{2}R_{ba1} - \frac{1}{2}R_{droop1} + r_{line} \right) - I_{o1}^- \left(\frac{1}{2}R_{ba1} + 2r_{line} \right) \\ = I_{o2} \left(\frac{1}{2}R_{ba2} - \frac{1}{2}R_{droop2} + r_{line} \right) - I_{o2}^- \left(\frac{1}{2}R_{ba2} + 2r_{line} \right) \end{aligned} \quad (5.9)$$

Where,

I_{o1} : positive-half current of the ESS1 in a bipolar-type DC microgrid;

I_{o2} : positive-half current of the ESS2 in a bipolar-type DC microgrid;

I_{o1}^- : negative-half current of the ESS1 in a bipolar-type DC microgrid;

I_{o2}^- : negative-half current of the ESS2 in a bipolar-type DC microgrid;

Usually in DC MGs, for high power applications and small systems where transmission line is short, the line resistance has only small value in comparison with larger R_{droopi} that is selected for the system [94]. The inverse proportional relationship between the output currents and virtual resistances for power sharing can

be achieved only when $R_{droopi} \gg r_{line}$. So, ignoring r_{line} in (5.8) and (5.9) will yield,

$$\begin{aligned} I_{o1} \left(\frac{1}{2} R_{droop1} + \frac{1}{2} R_{ba1} \right) - I_{o1}^- \left(\frac{1}{2} R_{ba1} \right) \\ = I_{o2} \left(\frac{1}{2} R_{droop2} + \frac{1}{2} R_{ba2} \right) - I_{o2}^- \left(\frac{1}{2} R_{ba2} \right) \end{aligned} \quad (5.10)$$

$$\begin{aligned} I_{o1} \left(\frac{1}{2} R_{ba1} - \frac{1}{2} R_{droop1} \right) - I_{o1}^- \left(\frac{1}{2} R_{ba1} \right) \\ = I_{o2} \left(\frac{1}{2} R_{ba2} - \frac{1}{2} R_{droop2} \right) - I_{o2}^- \left(\frac{1}{2} R_{ba2} \right) \end{aligned} \quad (5.11)$$

Subtracting and adding (5.10) and (5.11) respectively, (5.12) and (5.13) can be obtained.

$$I_{o1} R_{droop1} = I_{o2} R_{droop2} \quad (5.12)$$

$$R_{ba1} (I_{o1} - I_{o1}^-) = R_{ba2} (I_{o2} - I_{o2}^-) \quad (5.13)$$

Substitution of (5.6) in (5.13) will yield (5.14),

$$I_{L_ba1} R_{ba1} = I_{L_ba2} R_{ba2} \quad (5.14)$$

From (5.12) and (5.14), it can be said that the loads at positive and negative halves are shared according to the designated droop gains even though the loads at each halves are different, provided that $R_{droopi} \gg r_{line}$.

Table 5.1: Simulation and experimental parameters

Parameters	Simulation value	Experimental value
Nominal bus voltage (V)	760	100
$L_boost1, L_boost2, L_ba1, L_ba2$ (mH)	2	5
$C11, C12, C21, C22$ (μF)	4700	470
Load1/Load2[positive half] (Ω)	50/100	50/25
Load1/Load2[negative half] (Ω)	100/100	50/50
Switching frequency (kHz)	10	20

5.3 Simulation and Experimental Verification

Simulation results

Figure 5.8: Voltage and current waveforms for same droop gain

A bipolar-type DC microgrid is constructed in PLECS with two bus regulating units i.e. ESS1 and ESS2 as shown in Fig. 2.7 with the terminal voltage of 380V on each half and the power sharing is observed for same droop gain and different droop

Figure 5.9: Voltage and current waveforms for different droop gains

gains. The simulation and experimental parameters are tabulated in Table 5.1. In order to observe dynamic operation, a step load is applied at positive half i.e. R_1 is changed. It can be seen from Fig. 5.8, that the DC bus voltages at positive

and negative halves are well regulated and the load power at the positive half (P_{load}^+) is changed to supply the power deficit when the droop gains of both the ESS are same. The inductor current for boost converters (I_{L_boost1}) and (I_{L_boost2}) for ESS1 and ESS2 show the contribution for step load change at $t = 6s$. This also applies to the inductor currents (I_{L_ba1}) and (I_{L_ba2}) in voltage balancing circuits. There is no change in load power at the negative half (P_{load}^-). The slight change in V^+ and V^- in Fig. 5.8 is due to an inherent load-dependent voltage deviation obtained due to the expense of accurate current sharing discussed in limitations of droop control in section 3.1. The corresponding equation for the control strategy applied are given by (5.2) and (5.3).

Fig. 5.9 shows the case when the ratio of droop gains for ESS1 and ESS2 is 1:2. It can be seen from the boost inductor currents and balancing inductor currents that the power sharing by ESS1 is two times that of ESS2. A step load is applied at $t = 6s$ on the positive half to observe the dynamics due to the unbalanced load in the system. (I_{L_boost1}) and (I_{L_boost2}) show the power contribution at designated ratio and is also applicable for (I_{L_ba1}) and (I_{L_ba2}). There is no change in the negative half power and the DC bus voltage is well regulated.

Experimental results

A scaled down experimental prototype of a bipolar-type DC microgrid with 100V DC bus voltage was developed to show the effectiveness of proposed control loops through the system level operation results. The experimental cases are listed, as follows.

A. Application of same droop gain

The droop gains for *boost converter control* and *voltage balancing control* are designed to be the same. It can be seen from Fig. 5.10 that the bus voltages are well regulated and the load current at positive half responds to the power deficit due to the step load change. The positive bus voltage deviation is caused by the larger droop gain to achieve better power sharing. The inductor currents for boost converters and voltage balancing circuits are shown in Fig. 5.11. The power sharing is similar for both the converters and balancing circuits. For example, before $t = 6s$, the current supplied by ESS1 (I_{L_boost1}) and that of ESS2 (I_{L_boost2}) is approximately 1A. The inductor currents in balancing circuits for ESS1 (I_{L_ba1}) and ESS2 (I_{L_ba2}) at steady state is zero and 360mA after step load change.

B. Application of different droop gains

Figure 5.10: Bus voltages and load current waveforms for same droop gain

Figure 5.11: Inductor currents for boost converters and balancing circuits for same droop gain

The droop gains of ESS1 and ESS2 are set to be in 1:2 ratio and the results are depicted in Fig. 5.12 and Fig. 5.13. The bus voltages are well regulated and the load current at the positive half contributes power according to the load demand, which can be seen from the step load change in the system in Fig. 5.12. The inductor current for both the boost converters share power according to the designated droop ratio before and after load change, for example before $t = 6s$, $I_{L_boost1} = 1.3A$ and $I_{L_boost2} = 666mA$ approximately as shown in Fig. 5.13.

Figure 5.12: Bus voltages and load current waveforms for different droop gain

Figure 5.13: Inductor currents for boost converters and balancing circuits for different droop gain

The inductor current in balancing circuits for ESS1 (I_{L_ba1}) and ESS2 (I_{L_ba2}) at steady state are zero and 400mA and 200mA after step load change, respectively. A step load is applied to investigate the system stability and it can be seen that the system performs well. Hence, the control loop is effective to mitigate the problem of control conflict discussed in Fig. 5.6.

5.4 Summary

The bipolar-type DC microgrid is advantageous over the single bus topology because the consumers have an option to choose the supply voltage level and is resilient to the faults. The distribution converters play a vital role in formation of bipolar-type DC microgrids. Various converter topologies to obtain DC output have been summarized in this chapter.

The bipolar configuration of converters in DC microgrid can be formed by utilizing a converter to boost the input voltage and adopting a three-wire system by the means of a voltage balancing circuit. Replacement of a centralized proportional-integral controller with multiple decentralized voltage balancers in a microgrid enhances the system reliability by removal of the communication links. The decentralized voltage balancing control for the bipolar-type DC microgrids is proposed in this chapter to improve the system reliability. The problem associated with the implementation of such a decentralized control strategy in the bipolar-type DC microgrid consisting of two bus regulating units has been highlighted. Droop based control is implemented in the voltage balancing circuits to avoid control conflict in the presence of two bus regulating units. The controller designed is effective to mitigate the issue of control conflict through the system level results during steady and dynamic operations.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The utilization of DC microgrids in power industry has seen an upsurge due to their advantages over the AC systems that have unfolded in the recent years. A DC microgrid reduces the power conversion stages, does not require frequency, phase and reactive power control in its operation making it advantageous over the AC microgrids. Popularity of the DC microgrids is attributed to the increasing use of DC inherent loads in industrial, commercial as well as residential applications. The increased penetration of renewable resources like solar PV, chemical batteries that are inherently DC type sources also have a major contribution to the rising demand of DC microgrids. However, the intermittent nature of RES has obstructed the implementation of DC microgrid projects. The cost-effective solution to renewable intermittency, system topology and standards for reliable, stable and efficient power supply still needs examinations through research. The review of constituents of DC microgrids such as PV and energy storages, the local converter control for these sources have been elaborated in this thesis. Moreover, the importance of hybridization of energy storages has been discussed and the existing topologies of converters for HESS have been summarized along with the recommendation of active topology for HESS application. Since DC microgrid consists of various parallel interfaced converters, the co-ordinated control among converters along with the local converter control plays a vital role in forming a stable, reliable, and flexible DC microgrid. The coordinated control of DC microgrids namely centralized, distributed, and decentralized control depending upon the communication links have been reviewed. This thesis has proposed decentral-

ized control approaches for unipolar DC microgrids with HESS, interconnection of two DC microgrids with tie-line and bipolar-type DC microgrids. The decentralized control has an advantage of simplicity in control and is free of communication stress.

Lead-acid battery and SC are used to form an HESS and are connected to a common DC bus through bi-directional DC-DC converters. The decentralized coordination control strategy based on frequency-based power management is proposed in this thesis. This eliminates the necessity to monitor net power exchange through a high bandwidth communication link among different energy storages, thus, increasing the system reliability. Such frequency coordinating virtual impedance concept proposed shapes converters in the hybrid energy storage, such that battery converter can absorb low frequency power variations while SC converter can absorb the high frequency power variations. Thus, the battery supplies long-term power demand and the SC responds to short-term power fluctuations during the transient process. Insertion of high order low pass filter in battery converter and high order high pass filter for SC converter instead of lower order low/high pass filters helps in the reduction of ripple power in battery decreasing the stress on battery and increasing its lifetime. Another prominent issue to be addressed in the virtual impedance configuration for the proposed HESS is the SC voltage restoration. After the transient charging/discharging process, the SC voltage will deviate from its nominal value. In this case, the SC might not be able to cater further power fluctuations in the system. To address this problem, an additional SC voltage control loop is imparted in the control system for HESS. However, the SC voltage restoration does not change the total impedance of HESS. This is because the battery dominates the lower frequency range.

The interconnection of identical DC buses through tie-line and formation of DC microgrid clusters improves the reliability of the system, which is particularly important in rural areas where utility grid is not available. A prototype of a droop controlled two DC microgrids interconnected with tie-line with the implementation of decentralized control strategy has been established. Contrary to the centralized control implemented for the interconnection of DC microgrids with tie-line, the decentralized control proposed in this thesis is preferable because it eliminates the communication stress for geographically dispersed control areas. The control implemented qualitatively proves to be simple and feasible with the provision of generation sharing. Moreover, the decentralized mode adaptive control for the power management of DC microgrids adjusts the operation modes of RES and

ESS depending upon the designated voltage level. The decentralized control is accompanied by the mode change based operation so that the distributed units like PV and ESS in microgrids can adaptively adjust their operation modes depending upon the designated voltage level. By doing so, each microgrid can operate autonomously when there is no deficit in supply and has the provision of generation curtailment during supply surplus. Tie-line power flow takes place in a microgrid from another microgrid, due to the bus voltage decrement beyond the designated level caused by the increment in local consumption, which could not be satisfied by the local generation and storages. The effectiveness of proposed decentralized control has been verified experimentally in the two interconnected microgrids. Such self-disciplined regulation of converters in the microgrids without communication links enhances the flexibility and reliability of the system.

Efforts are being made to elevate the level of quality, reliability and efficient power supply of the conventional DC microgrids. One of the approaches being made to achieve reliable power supply is using bipolar-type DC microgrids. However, different loading in the upper and lower terminals and voltage fluctuation from the nominal value at these terminals make the system unbalanced. Therefore, the control of parallel converters that interface the DERs and the topology of the converter along with the voltage balancer play a vital role in formation of an efficient bipolar-type DC microgrid. An improved bipolar-type DC microgrid where decentralized control for parallel converters interfacing the DERs has been implemented in this thesis. The proposed decentralized voltage balancing control supersedes the centralized voltage balancer in terms of utilization of the communication links and enhances the system reliability. Such a control can be adopted in the bipolar-type DC microgrid consisting of multiple energy storages. One of the challenges of control conflict in the implementation of decentralized voltage balancer concept is mitigated with the droop control as proposed in this thesis, which has the capability of preserving the functionality of a DC microgrid by ride through the malfunction that is prone in a central voltage balancer concept.

6.2 Future Work

Research work presented in this thesis for unipolar, interconnected and bipolar-type DC microgrids have shown potential benefits to implement the decentralized control over classical centralized control. Yet, there are some motivations for

conducting further research in the DC microgrid implementation. For that, the following topics are recommended for possible future investigation.

1. The research work presented in this thesis for the interconnection of DC microgrids with tie-line has focused on formulating the control strategy for interconnection of two microgrids hence; the power flow from one microgrid to the other is straightforward. For the case of ' n ' microgrids, the power flow will be complicated because the topology of interconnection and tie-line impedance vary. The energy transaction between multiple microgrids when a microgrid in a cluster is unable to supply its demand is surely an interesting topic for investigation from the cost and control perspective.
2. Protection of the DC system is a challenging task because the DC current does not have natural zero crossing like in the AC current. The major areas that could be investigated are identification of fault types, choice of protective devices and the protection system design.
3. AC standards are matured enough in comparison with the DC systems since it has the history of century long implementation. The global adoption of DC systems lack standards for generating, transmitting and distributing along with the end use of DC power. For the ease of unified design and installation and trustworthy to entrepreneurs, there is the necessity for guidelines and standards to implement the DC systems.
4. The significance of reliability in power converter systems can never be understated. From technical point of view, the power converter system with lower reliability would not only experience more frequent failures at any given period of time, but is also more susceptible to any unexpected faults. On the other hand, from economic perspective, the cost of unreliability could rise exponentially which depends on the stage at which the problem is identified. The financial loss induced by the late detection of system unreliability can sometimes bankrupt the entire organization. Finally, higher system reliability is also driven by the advancing paradigm in this industry, where some notable shifts in the customer expectations, reliability targets and R & D approaches of organizations are becoming more urgent than ever.

Appendix A

Energy Storage Parameters

In this Appendix, different values and specifications for the major attributes of chemical batteries and supercapacitor are tabulated with the corresponding references.

A.1 Vanadium Redox Flow Battery

Table A.1: VRB battery parameters

VRB	Source				
	[140]	[141]	[142]	[143]	[144]
Efficiency	60..75	70	67..81		75..85
Lifetime [cycles]	14000				12k+
Energy density [Wh/l]					16..33
Power density [W/l]					
Specific energy [Wh/kg]					10..30
Specific power [W/kg]					
Energy cost [\$/kWh]		710	200..220	350	150..1000
Power cost [\$/kW]		210		175	600..1500
Operating temperature [$^{\circ}C$]					

A.2 Lead-acid Battery

Table A.2: Lead-acid battery parameters

Lead-acid	Source						
	[144]	[145]	[146]	[147]	[148]	[149]	
Efficiency	70..90			70..80		85..90	
Lifetime [cycles]	500..1000	> 700	200..300	500..1000		1200..1800	
Energy density [Wh/l]	50..80				55 – 80		
Power density [W/l]	100..400						
Specific energy [Wh/kg]	30..50	30..45	30..50	30..50	15 – 40		
Specific power [W/kg]	75..300	50..100	180	75..300	75 – 415		
Energy cost [\$ /kWh]	200..400	54..100		650..670			
Power cost [\$ /kW]	300..600			2660			
Operating temperature [°C]			–20.. + 60		+15.. + 25	25	

A.3 NiCd battery

Table A.3: NiCd battery parameters

NiCd	Source					
	[144]	[145]	[146]	[147]	[148]	[149]
Efficiency	60..70			65..75		60..83
Lifetime [cycles]	2000..2500	2000	1500	2500..3000		1500..3000
Energy density [Wh/l]	60..150				30 – 150	
Power density [W/l]						
Specific energy [Wh/kg]	50..75	35..55	45..80	50..75	35 – 55	15..50
Specific power [W/kg]	150..300	400	150	150..300	50 – 150	50..100
Energy cost [\$ /kWh]	800..1500	> 300		3590..3725		400..2400
Power cost [\$ /kW]	500..1500			890..930		
Operating temperature [°C]			−40.. + 60		−20.. + 60	

A.4 NiMH battery

Table A.4: NiMH battery parameters

NiCd	Source					
	[150]	[151]	[145]	[146]	[148]	[149]
Efficiency	65..75					65..70
Lifetime [cycles]	1500		500..600	300..500		1500
Energy density [Wh/l]	200..350	130			83 – 170	
Power density [W/l]						
Specific energy [Wh/kg]	50..60	70	60..85	60..120	35 – 55	80
Specific power [W/kg]	250		> 200	250..1000	50 – 150	
Energy cost [\$ /kWh]	250		> 400			
Power cost [\$ /kW]						
Operating temperature [°C]		–10.. + 55		–20.. + 60	–20.. + 60	

A.5 Li-ion battery

Table A.5: Li-ion battery parameters

Li-ion	Source					
	[144]	[150]	[146]	[147]	[148]	[149]
Efficiency	> 90	95		85..95		> 90
Lifetime [cycles]	1000 – 10000	2500	500..1000	1000..1000		> 1500
Energy density [Wh/l]	200..500	400..600			230 – 500	
Power density [W/l]						
Specific energy [Wh/kg]	75..200	150..200	110..200	75..200	90 – 200	80 – 150
Specific power [W/kg]	150..315	540	1800	150..315	750 – 1250	50 – 2000
Energy cost [\$/kWh]	600 – 2500	450		4790..5060		900 – 1300
Power cost [\$/kW]	1200 – 4000			1220..1265		
Operating temperature [°C]			–20.. + 60	–30.. + 60	–40.. + 60	

A.6 Supercapacitor

Table A.6: Supercapacitor parameters

SC	Source					
	[144]	[152]	[147]	[148]	[149]	[153]
Efficiency	> 90	88	95		85..98	98
Lifetime [cycles]	> 100000	> 1000000	1000000	< 1000000	> 500000	> 100000
Energy density [Wh/l]	10..30			< 20		
Power density [W/l]	> 100000					
Specific energy [Wh/kg]	2..15	1..10	2..15		5	< 5
Specific power [W/kg]	500..5000	1000..5000	500..5000		10000	> 1000
Energy cost [\$/kWh]	300 – 2000		99750..106400		20000	
Power cost [\$/kW]	100 – 300		811..840	wide range		
Operating temperature [°C]		–45.. + 60				

Appendix B

Small Signal Modeling of Boost Converter

The power circuit of the i^{th} boost converter, with transistor S_i as switch and output filter capacitor C_i is shown in Fig. B.1. The operating principle of the converter is based on the periodic accumulation of energy and transferring it through inductor L_i in the circuit with filter C_i and load R_i . The modes of operation of boost

Figure B.1: Power circuit of DC-DC boost converter

converter can be divided into two i.e. during switch-ON and during switch-OFF as shown in Fig. B.2(a) and Fig. B.2(b), respectively. The duration of S_i -ON and S_i -OFF are $t_{on} = dT_s$ and $t_{off} = dT_s$ respectively. Based upon Fig. B.2 (a) and Fig. B.2 (b), the state equations for each interval of operation can be derived as follows:

When switch S_i is ON:

$$L_i \frac{di_{L_i}}{dt} = E \quad (\text{B.1})$$

Figure B.2: Modes of operation in boost converter (a) when switch S_i is ON (b)when switch S_i is OFF

$$C_i \frac{dv_{oi}}{dt} = -\frac{v_{oi}}{R_i} \quad (\text{B.2})$$

When switch S_i is OFF:

$$L_i \frac{di_{Li}}{dt} = E - v_{oi} \quad (\text{B.3})$$

$$C_i \frac{dv_{oi}}{dt} = i_{Li} - \frac{v_{oi}}{R_i} \quad (\text{B.4})$$

Where,

e : input voltage of boost converter;

L_i : inductor current for i^{th} boost converter;

S_i : switch for i^{th} boost converter;

C_i :bus capacitor for i^{th} boost converter;

R_i : resistive load for i^{th} boost converter;

D_i : diode for i^{th} boost converter;

v_{oi} : output voltage of i^{th} boost converter;

v_{ci} : capacitor voltage of i^{th} boost converter;

i_{oi} : output current of i^{th} boost converter;

i_{ci} : capacitor current of i^{th} boost converter;

i_{Li} : inductor current of i^{th} boost converter;

Averaging state equations over a switching cycle, the following equations are obtained.

$$L_i \frac{di_{Li}}{dt} = E - (1 - d)v_{oi} \quad (\text{B.5})$$

$$C_i \frac{dv_{oi}}{dt} = (1 - d)i_{Li} - \frac{v_{oi}}{R_i} \quad (\text{B.6})$$

Introducing perturbation in state variables, the following expressions are achieved.

$$\begin{aligned} i_{Li} &= I_{Li} + \hat{i}_{Li} \\ e &= E + \hat{e} \\ v_{oi} &= V_{oi} + \hat{v}_{oi} \\ d &= D + \hat{d} \end{aligned} \quad (\text{B.7})$$

Inclusion of above perturbations in (B.5) and (B.6) yields,

$$L_i \frac{d(i_{Li} + \hat{i}_{Li})}{dt} = (E + \hat{e}) - (1 - D - \hat{d})(V_{oi} + \hat{v}_{oi}) \quad (\text{B.8})$$

$$C_i \frac{d(V_{oi} + \hat{v}_{oi})}{dt} = (1 - D - \hat{d})(i_{Li} + \hat{i}_{Li}) - \frac{(V_{oi} + \hat{v}_{oi})}{R_i} \quad (\text{B.9})$$

Equating AC and DC quantities and proceeding with AC equations, the following can be obtained.

$$L_i \frac{d\hat{i}_{Li}}{dt} = \hat{e} - (1 - D)\hat{v}_{oi} + V_{oi}\hat{d} \quad (\text{B.10})$$

$$C_i \frac{d\hat{v}_{oi}}{dt} = (1 - D)\hat{i}_{Li} - I_{Li}\hat{d} - \frac{\hat{v}_{oi}}{R_i} \quad (\text{B.11})$$

Taking Laplace transform and arranging in symmetrical sequence, the following

expressions can be obtained.

$$\begin{bmatrix} sL_i & 1-D \\ 1-D & -\left(sC_{oi} + \frac{1}{R_i}\right) \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_{Li}(s) \\ \hat{v}_{oi}(s) \end{bmatrix} = \begin{bmatrix} V_{oi} \\ I_{Li} \end{bmatrix} \cdot \hat{d}(s) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot \hat{e}(s) \quad (\text{B.12})$$

$$\begin{aligned} \begin{bmatrix} \hat{i}_{Li}(s) \\ \hat{v}_{oi}(s) \end{bmatrix} &= \begin{bmatrix} sL_i & 1-D \\ 1-D & -\left(sC_{oi} + \frac{1}{R_i}\right) \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{oi} \\ I_{Li} \end{bmatrix} \cdot \hat{d}(s) \\ &+ \begin{bmatrix} sL_i & 1-D \\ 1-D & -\left(sC_{oi} + \frac{1}{R_i}\right) \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot \hat{e}(s) \end{aligned} \quad (\text{B.13})$$

Calculating inverse matrix, converter transfer function will be obtained as follows:

Control to output voltage transfer function

$$\frac{\hat{v}_{oi}(s)}{\hat{d}(s)} = \frac{(1-D)V_{oi} - (L_i I_{Li})(s)}{(LC)s^2 + \frac{L}{R}s + (1-D)^2} \quad (\text{B.14})$$

Control to input current transfer function

$$\frac{\hat{i}_L(s)}{\hat{d}(s)} = \frac{(CV_o)s + 2(1-D)I_L}{(LC)s^2 + \frac{L}{R}s + (1-D)^2} \quad (\text{B.15})$$

Current to output transfer function

$$\frac{\hat{v}_{oi}(s)}{\hat{i}_{Li}(s)} = \frac{(1-D)V_{oi} - (L_i I_{Li})s}{C_i V_{oi} s + (1-D)I_{Li}} \quad (\text{B.16})$$

Author's Publications

Journal Papers

1. Sujan Adhikari, Qianwen Xu, Yi Tang, Peng Wang, and Xiaoqiang Li. Decentralized control of two DC microgrids interconnected with tie-line. *Journal of Modern Power Systems and Clean Energy*, 5(4):599–608, 2017.
2. Sujan Adhikari, Zhe Zhang, Yi Tang, Peng Wang, and Yang Qi. Decentralized Voltage Balancing Control of Bipolar-Type DC Microgrids. *IEEE trans. on Energy Conversion (submitted, under review)*, pages 1–7, 2017.

Conference Papers

1. Sujan Adhikari, Zhang Lei, Wang Peng, and Yi Tang. A Battery/Supercapacitor Hybrid Energy Storage System for DC Microgrids. In *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, pages 1747–1753, 2016.
2. Sujan Adhikari, Yi Tang, and Peng Wang. Secondary Control for DC Microgrids: A Review. In *Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, number October, pages 1–6. IEEE, 2016.
3. Sujan Adhikari, Qianwen Xu, Yi Tang, and Peng Wang. Decentralized Control of DC Microgrid Clusters. In *2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia)*, pages 567–572, 2017.

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