Coordinated power management for islanded microgrids

Lin, Pengfeng

2019

Lin, P. (2019). Coordinated power management for islanded microgrids. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/136787>

<https://doi.org/10.32657/10356/136787>

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SINGAPORE

**COORDINATED POWER MANAGEMENT FOR
ISLANDED MICROGRIDS**

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Energy Research Institute @ NTU**

2019

COORDINATED POWER MANAGEMENT FOR ISLANDED MICROGRIDS

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

2019

Statement of Originality

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

20 June, 2019

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

20 June, 2019

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WANG Peng

Authorship Attribution Statement

This thesis contains material from 4 papers published in the following peer-reviewed journals where I was the first author.

Chapter 2 is published as P. Lin, P. Wang, J. Xiao, J. Wang, C. Jin and Y. Tang, "An Integral Droop for Transient Power Allocation and Output Impedance Shaping of Hybrid Energy Storage System in DC Microgrid," *IEEE Transactions on Power Electronics*, vol. 33, no. 7, pp. 6262-6277, 2018. DOI: 10.1109/TPEL.2017.2741262.

The contributions of the co-authors are as follows:

I prepared the manuscript drafts, designed the case studies and analyzed the algorithms.

Prof. P. Wang, Dr. J. Xiao, Mr. J. Wang, Dr. C. Jin and Dr. Y. Tang revised and proofread the manuscript.

Chapter 3 is published as P. Lin, C. Zhang, P. Wang and J. Xiao, "A Decentralized Composite Controller for Unified Voltage Control with Global System Large-Signal Stability in DC Microgrids," *IEEE Transactions on Smart Grid*. DOI: 10.1109/TSG.2018.2875165.

The contributions of the co-authors are as follows:

I prepared the manuscript drafts, designed the case studies and analyzed the algorithms.

Dr. C. Zhang, Prof. P. Wang and Dr. J. Xiao revised and proofread the manuscript.

Chapter 4 is published as P. Lin et al., "A Distributed Power Management Strategy for Multi-Paralleled Bidirectional Interlinking Converters in Hybrid AC/DC Microgrids," *IEEE Transactions on Smart Grid*. DOI: 10.1109/TSG.2018.2890420.

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algorithms.

Prof. P. Wang, Dr. C. Jin, Dr. J. Xiao, Dr. X. Li, Dr. F. Guo and Dr. C. Zhang revised and proofread the manuscript.

Chapter 5 is published as P. Lin et al., “A Distributed Control Architecture for Global System Economic Operation in Autonomous Hybrid AC/DC Microgrids,” *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2603-2617, 2019. DOI: 10.1109/TSG.2018.2805839.

The contributions of the co-authors are as follows:

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Abstract

This thesis enriches the power sharing concepts in four aspects, i.e., transient power sharing, stable power sharing, bidirectional interlinking converters (BICs) distributed power sharing and economic power sharing. These newly extended power sharing schemes are applied to different system applications and have inherent logical relations, which can be detailed as follows.

To mitigate the generation intermittency of RES and load uncertainties, hybrid energy storage systems (HESSs) are constructed. In a particular HESS, those storages with high ramp rate but limited energy capacities are denoted as ES_{HS} , whereas the storages with restrained dynamic responses are referred as ES_{LS} . To coordinate ES_{HS} and ES_{LS} , this thesis proposes an integral droop (ID), inspired by the electrical characteristics of capacitor charging/discharging process, and apply the droop to ES_{HS} . ES_{LS} are with ordinary V-P droops. Through the coordination of the ID and conventional V-P droop, the transient power allocation in HESSs can be autonomously realized in a decentralized manner. The high frequency components of power demand can be compensated by ES_{HS} , whereas ES_{LS} respond to the smooth change of load power, thus achieving transient power sharing in energy storages. Additionally, by means of small signal analyses, it is revealed that the proposed ID can shape the output impedance of the HESS and stabilize the entire HESS system. The effectiveness of ID is verified by both simulations and experimental results.

In a DC microgrid (MG), apart from HESSs, there also exist other power sources such as fuel cells and DC generators. The complex interactions between plenty of sources, HESSs, resistive loads and electronic loads, would unavoidably cause instabilities. For all that the proposed ID exhibits stabilizing effects to HESSs, however, small signal analyses are only tenable at certain equilibriums, which would not hold in full operation range. To guarantee HESS correct functions and overall DC MG stability, a decentralized composite controller (DCC) is proposed to attain global system large signal stabilization. The main idea of the DCC is to partition the DC MG into dispatchable unit (DU) subsystems and the lumped load. A well-devised high gain observer is adopted to estimate the electrical coupling of a particular DU subsystem with other DUs and the

load. Then, rather than coping with the MG as a whole, the DCC is locally designed to offset the estimated coupling and stabilize the internal states of the DU subsystem. By doing so, each subsystem can be virtually decoupled from the MG and functions in an isolated fashion. When DU subsystems are interlinked, large signal stabilization of the entire MG would be obtained by only guaranteeing the localized stability of individual subsystems. This stabilizing strategy has not been reported in the literature so far. Relevant theoretical analyses are rigorously conducted by employing Lyapunov stability theorem. The feasibilities of the DCC and the intended stable power sharing among DUs, have been verified by both simulations and experimental tests.

Notice that both the transient power sharing and stable power sharing are addressed in DC MGs. Although many DC compatible sources and loads are emerging in modern power system, AC conversion techniques portray predominant roles in power generation, transmission and distribution networks. To merge the advantages of AC and DC systems, hybrid AC/DC MGs should be built up where AC and DC subgrids are bridged by a bidirectional interlinking converter (BIC). The increasing number of sources installed into the hybrid system would definitely result in the capacity increase of either AC or DC subgrid. This would bring about larger power interactions between the two subgrids, and more power may flow through the BIC. To meet the requirements of growing subgrid capacities, instead of frequently upgrading a single BIC, a more likely way is to deploy multiple BICs connected in parallel to stack up the power exchange capacity between AC and DC subgrids. In this context, this thesis proposes a distributed power management strategy (DPMS) for multi-paralleled BICs to avoid the overstress of a single BIC. Each BIC is assigned with a localized distributed controller (LDC) which generates the respective power reference for the BIC. By using the LDC, BICs are allowed to exchange information with one another in the distributed communication graph. The power interactions between AC and DC subgrids can be proportionally allocated to BICs based on their different power ratings in a fully distributed manner, which gives BICs distributed power sharing. The validity of DPMS is then verified by a RT-LAB hardware-in-loop (HIL) experimental platform.

For a hybrid AC/DC MG running for the long term, economic operations would

be critically significant. As a continuous work of BICs distributed power sharing, the thesis also proposes a distributed control architecture for realizing economic power sharing among distributed generators (DGs). It is widely accepted that the entire power system operating cost can be minimized when DGs have the same incremental costs (ICs). The proposed architecture consists of two levels. In the first level, the AC frequency-IC (f_{ac} -IC) droop and the DC bus voltage-IC (V_{dc} -IC) droop are employed in the AC and DC subgrids respectively. With the synchronization of f_{ac} and V_{dc} , DG ICs in each subgrid will be equalized. However, the droops will inevitably cause deviations of f_{ac} and V_{dc} . Then a distributed control canonical form (DCCF), which provides a generalized method for f_{ac} and V_{dc} recoveries, is proposed in the second level. The DCCF allows DGs to communicate only with their neighbors, thus alleviating the communication burdens and enhancing the system scalability. Due to the presence of DCCF, f_{ac} and V_{dc} fluctuations, which naturally indicate subgrid loading conditions, are invisible. An original relative loading index (RLI) is proposed to extract the hidden loading condition of each subgrid even though f_{ac} and V_{dc} are clamped as constants. By using RLI, the power reference of the BIC can be easily defined. All DG ICs the hybrid MG converge to the same value in the steady state, therefore obtaining the wanted economic power sharing. The viabilities of the proposed control architecture and the economic power sharing are verified by simulations and HIL tests.

Acknowledgements

First and foremost, I would like to extend my earnest gratitude and appreciation to my supervisor, Professor Wang Peng for his continuous guidance, invaluable supports and enthusiastic encouragements through all phases of my Ph.D. journey. What I learned from him is not only the knowledge of electrical engineering, but also to maintain a positive attitude toward life and academic activities.

I sincerely acknowledge Associate Professor Wan Man Pun, Assistant Professor Tang Yi and Dr. Koh Leong Hai. As Thesis Advisory Committee members, they provided helpful suggestions on improving the quality of this thesis.

Special thanks go to my colleagues and friends in Energy Research Institute @ NTU (ERI@N), Dr. Jin Chi, Dr. Zhang Chuanlin, Mr. Wang Junjun, Mr. Zhang Zhe, Mr. Shi Donghan, Dr. Tu Pengfei, Dr. Jiang Wentao, Mr. Dong Chaoyu, etc. I would also thank my officemates, Dr. Xiao Jianfang, Dr. Zhao Tianyang, Dr. Fang Jingyang, Dr. Xu Qianwen, Mr. Yao Shuhan, Mrs. Zhang Huajun, Mr. Liu Xiaochuan, Mr. Qi Yang, Mr. Guo Ke, Mr. Chen Shuxin, Mr. Qiu Huang, Mr. Lu Nanjun, etc., for their kind helps and persistent patience.

My sincere thanks are then given to the technicians in Water and Energy Research Lab (WERL), Mr. Tan Peng Chye and Mr. Lee Chew Siong, for their helpful technical supports.

Last but not least, I wish to express my deepest appreciations to my parents, grandparents and Mr. Sun Yin who have always been supporting me along with the Ph.D. journey. Their kind understanding and endless love make me a more sincere, honest, and stronger man than I ever thought was possible.

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List of Abbreviations

ACwC	AC loads with converters
BIC	Bidirectional Interlinking converter
CSP	Concentrated Solar Power
CERTS	Consortium for Electric Reliability Technology Solutions
CEC	California Energy Commission
CPL	Constant Power Load
CPS	Constant Power Source
CA	Consensus Algorithm
CVM	Constant Voltage Mode
CCs	Circulating Currents
3C	Circular Chain Control
DOE	Department of Energy
DG	Distributed Generator
DCC	Decentralized Composite Controller
DU	Dispatchable Unit
DPMS	Distributed Power Management Strategy
DCCF	Distributed Control Canonical Form
DM	Droop Mode
DSP	Digital Signal Processor
ESSs	Energy Storage Systems
ESs	Energy Storages
ES_H	ESs with High Ramp Rates
ES_L	ESs with Low Ramp Rates
ESR	Equivalent Series Resistor
GML	Generalized Minor Loop
GPS	Global Power Sharing
HESS	Hybrid Energy Storage System
HPF	High Pass Filter
HIL	Hardware in Loop
ID	Integral Droop
ICs	Incremental Costs

List of Abbreviations

LPF	Low Pass Filter
LDC	Localized Distributed Controller
LSA	Large Signal Analyses
LC	Loading Condition
MG	Microgrid
MRIC	Minimum Relative Impedance Criterion
MPC	Model Predictive Control
NDC	Nationally Determined Contribution
NTUA	National Technical University of Athens
PV	Photo-Voltaic
PnP	Plug-and-Play
PCC	point of Common Power Coupling
PI	Proportional-Integral
RES	Renewable Energy Source
RLI	Relative Loading Index
SC	Supercapacitor
SSA	Small Signal Analyses

Chapter 1

Introduction

This chapter starts with the backgrounds of the related research work, detailing the developments of renewable energy sources (RESs) and microgrids (MGs). Three typical MG configurations, i.e., AC, DC and hybrid AC/DC MGs are respectively elucidated. The control strategies of hybrid energy storage systems and MGs are also expounded. Then, the motivations and the corresponding contributions of this thesis are presented. Finally, detailed thesis organizations are minutely elaborated.

1.1 Background

1.1.1 Renewable Energy Boosting and Microgrids

Conventional fossil fuels such as coal and oil have been contributing to global climate deterioration as well as air contamination. The worldwide environmental issues and depleting fossil reserves encourage the progressive advancements of renewable related technologies. As reported in [1], Wind, solar, hydropower, geothermal, biomass and other renewable energy sources (RESs) are deemed as the Energy Choices of 21st Century. Nowadays, many countries and regions are actively investigating the potential of renewable energy to bolster their economic growths and social developments [2]–[6].

China, the world largest developing country, takes renewable energy as a crucial pillar in the government's strategy to mitigate the impacts of power industry on the national environment. As a country making effort to the wide deployments of renewable technologies, China has launched ambitious programs: in its official Nationally Determined Contribution (NDC), the country committed to increasing non-fossil fuels, including renewable sources and nuclear energy, to 20% by 2030 [7]. Referring to China's 13th Five Year Plan, hydropower installed capacity is envisioned to go beyond 350 GW, with the wind and solar reaching at 200 GW and 100 GW, respectively.

In the United States, wind power capacity was 61.1 GW in 2013, an increase of 26.5% from the previous year [8]. For the following year, wind generations contribute to the electricity of 181.1 TWh, amounting to approximately 4.33% of entire electricity produced nationwide [9]. It is predicted by the US Department of Energy (DOE) that wind power would account for 20% of US electricity by 2030 including a 4% share from offshore high-quality wind resources [10]. As the most abundant RES in the US, it is documented in [2] that, by 2030, utility-scale photo-voltaic (PV) and concentrated solar power (CSP) 80000 GW and 37000 GW, respectively, and rooftop PV power is comparatively low of around 700 GW. In addition, according to the estimation of DOE, biomass power, geothermal power, hydropower and ocean technology enabling power would be 100 GW, 500 GW, 290 GW and 289.3 GW separately.

Figure 1.1: Worldwide RES capacities, EU-28 and top 6 countries in 2017.

From the worldwide perspective, Europe, Japan and India, etc., are also experiencing considerable boosting in RES technologies. Note that in Figure 1.1, BRICS refers to Brazil, the Russian Federation, India, China and South Africa [11]. It is illustrated that China is the top country who has the highest RES capacity at the end of 2017, followed distantly by the US, Germany, India, the United Kingdom and Japan. China alone takes for about 30% of the renewable installation through the whole world, totaling 647 GW.

The deployments of RESs can substantially reduce greenhouse gas emissions, hence decreasing carbon footprints. The continuously increasing penetration of RESs into existing power system may bring about challenges to the safe and reliable operations in the system [12]. Fortunately, these challenges can be potentially addressed by microgrid (MG) techniques. As electrical entities working in a more flexible fashion, MGs enable to incorporate heterogeneous RESs, energy storage systems (ESSs) and other distributed generators (DGs), and realize efficient power management [13], [14]. Moreover, the computational burdens of distribution/transmission network operators can also be remarkably mitigated, since MGs can be seen as energy sources or loads whose controls are locally achieved and independent from the utility.

There are numerous real MG systems that have been established for both demonstrations and commercial uses. In the European Union (EU), MGs are

deemed as key building blocks in active distribution networks. Two research programs were initiated for MG developments, i.e., the *Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids* (1998-2002) launched by National Technical University of Athens (NTUA) with funding of €4.5 million. The project investigated basic RES integration into an electrical system whose control algorithms are based on decentralized, hierarchical and distributed schemes. During 2002-2006, a follow-up project *More Microgrids: Advanced Architectures and Control Concepts for More Microgrids* with €8.5 million was set up and again led by NTUA. The project concentrated more on commercially incorporating multiple MGs, protocol standardization and hardware capability of plug-and-play (PnP) functions.

In the United States (US), the expansion of MGs would be comparatively slower than the EU. Led by the US DOE and the California Energy Commission (CEC), MGs applications in the US are supposed to match the diverse end-use requirements of enhancing system power quality and reliability. The most renowned US MG program is exercised by the Consortium for Electric Reliability Technology Solutions (CERTS). The CERTS MG was developed to identify how emerging technologies influence the reliability of existing power system, economy, government regulation and environments. The MG was also adopted to modeling the seamless transition between the separation from the utility with faulty condition and the reconnection to the restored utility grid. After the justification of CERTS MG through simulations and laboratory tests at the University of Wisconsin, Madison, the MG concept was further substantiated by the on-site full scale tests at the Dolan Technology Center in Ohio state, which was run by American Electric Power. Based on the well built hardware platforms, there came two products for analyzing the MG behavior, i.e., the μ Grid Analysis Tool (μ Grid) and the Distributed Energy Resources Customer Adoption Model (DER-CAM). Co-funded by DOE, General Electric (GE) also initiated a two-year MG program to demonstrate a unified energy management hierarchy for a wide set of MG utilization.

In Singapore, Energy Research Institute @ NTU (Eri@N), Nanyang Technological University, is leading a flagship project titled Renewable Energy Integration Demonstrate - Singapore (REIDS). The project manages to build an islanded

and self-sustained MG system in Semakau Island (sited south of the Singapore main island) for including PV, wind power, energy storages, diesel generators and hydrogen gas. The MG paradigm would encourage progressive deployments of RES technologies in Southeast Asia and the concept is particularly promising for the Indonesian archipelago where around one thousand islands having populations do not access conventional power plants. Energy Market Authority (EMA) in Singapore is also piloting a MG testing bed at the jetty area of Pulau Ubin, an island north-east of Singapore [15]. This testing platform aims to evaluate electricity supply reliability with a MG infrastructure using intermittent RESs techniques. Since October 2013, about 30 participants from around the jetty area have signed up to voluntarily take part in this testing bed. They include various businesses, telecommunications base stations, residential premises and government agencies. Thanks to the MG, they have been enjoying a cheaper, cleaner and more reliable electricity supply from RES generations.

Technically, MGs can work in both grid-connected mode and islanded mode, as explained in [16]. For the former mode, a MG would be linked to the utility grid by switching on an isolation switch at the point of common power coupling (PCC). Compared with the utility, the power capacity of the MG is much smaller, and the grid would dominate the frequency as well as voltage of the MG. Moreover, any power mismatch induced in the MG system could be instantly compensated by the grid. In this mode, DGs are normally scheduled at power/current control mode so that they would not participate in system dynamic regulations and inject the scheduled power into the utility [17]. In contrast, in the case that the utility is in disruption and even collapse, the MG could disconnect from the grid and work in the islanded manner [18]. Without the support of the utility, the MG has to stabilize and regulate its internal frequency and voltage by itself. The isolated system would suffer from low inertia and stability issues, and this thesis will focus on islanded MG operations which are more challenging than the grid-connected mode.

Figure 1.2: A typical AC MG configuration.

Figure 1.3: A typical DC MG configuration.

1.1.2 AC, DC and Hybrid AC/DC Microgrids

According to different types of MG buses, MGs could be classified into AC MGs, DC MGs and hybrid AC/DC MGs. The salient features of these three types of MGs are respectively detailed in the following context.

A: AC MGs

Figure 1.2 shows a typical AC MG system configuration where all power devices are linked to a common AC bus. The microturbine is interfaced with an AC/AC converter. Wind turbine is operated under maximum power point tracking (MPPT) mode to fully harness the clean energy. A resistive load is straightly connected the bus, whereas motor drive consumes power through an AC/AC interfacing converter. Electronic load refers to the entity comprising an AC/DC rectifier and a resistive load. Energy storages enable to compensate the

Figure 1.4: A typical hybrid AC/DC MG configuration.

power mismatch between power generations and loads.

Many academical and industrial efforts have been devoted to AC MGs due to the fact that AC system are widely utilized in generation, transmission and distribution networks [19]–[22]. AC power systems take precedence over DC ones for multiple reasons. Firstly, before power electronics are broadly employed, the voltage levels in AC systems are more easily converted into higher or lower ones than in DC systems. Secondly, AC generators are more flexible than DC generators and AC motors are cheaper than DC motors. Given the dominant role of AC systems, AC MGs can better integrate RESs into traditional power systems to alleviate fossil fuel shortages. Thirdly, without upgrading conventional loads, AC MGs can be expanded to rural areas where power distribution is hard to be constructed and reliable power electricity is unavailable.

B: DC MGs

A typical DC MG has been displayed in Figure 1.3 where loads are fed by sources via a DC bus. A diesel generator is with an AC/DC rectifier injecting power to the bus. Similar to the wind turbine in Figure 1.2, PV array is under MPPT mode to maximize the clean energy harvesting. Energy storages help to store the surplus power induced in the MG and regulate DC bus voltage when power deficiency is detected.

It should be mentioned that the controversy over the DC candidates has been lasting for decades. In recent years, however, DC MGs are revealed to be increasingly popular in the applications of onboard power system, commercial

complex and residential premises [23]–[26]. The benefits of DC MGs can be summarized as follows. Firstly, DC systems give better compatibility. Clean energy sources such as fuel cells and PV arrays are of DC voltage, and nearly all energy storages are DC by nature. In this sense, DC MGs are exhibiting captivating potential by accommodating increasing shares of modern electrical units. Secondly, DC MGs allow for higher efficiency. For regular AC power systems, most of loads need a front-end AC-DC conversion for generating a stable DC link. Similar requirements can also be found in the installation of PV and energy storages to AC MGs. The existence of multistage power conversion in both supply and demand ends definitely cause power losses. It is reported in [27] that power conversion efficiency in DC MGs is estimated 15% higher than that in AC MGs. Thirdly, DC architectures render better controllability. In AC networks, frequency and voltage harmonics coexist, which require accurate synchronizations and engender more complicated power quality controls. Differently, these problems can be perfectly avoided in DC MGs where only voltage magnitude should be properly regulated. Therefore, it is much easier to control DC MGs working in designated operations.

C: Hybrid AC/DC MGs

Despite that DC MGs are shown bearing several merits, only having DC MGs, however, would not be acceptable because AC power delivery still takes an important role in modern power system and is expected to be so even for the subsequent decades. In this regard, it is more practical to bridge AC and DC networks together, and then formulate hybrid AC/DC MGs. A typical system configuration of hybrid AC/DC MG has been illustrated in Figure 1.4. A bidirectional interlinking converter (BIC) and a transformer are connected in series to interlink the AC bus and DC bus. The intention of using hybrid AC/DC structure is to reduce the power loss occurred in the intricate conversion stages of power converters. Detailed explanations are planned below.

Provided that the hybrid architecture is not adopted, in an AC MG, a DC source have to be transformed into AC by a DC/AC inverter before it can be coupled to AC bus. If the source is scheduled to feed a DC load, then an additional AC/DC rectifier is needed. Regarding the AC load with converter (ACwC), they absorb power from AC bus through an AC/DC rectifier and a DC/AC inverter, and the

power conversion flow from the DC source to ACwC can be determined as DC-AC-DC-AC. Considering an AC source, it can be directly used to supply AC loads without any interfacing converter. However, for a DC load, an AC/DC rectifier is required. For ACwC, the power conversion flow from the AC source can be identified as AC-DC-AC, where there must be an AC/DC rectifier and a DC/AC inverter.

In a DC MG, an AC source needs an AC/DC rectifier to convert AC voltage into DC before linking to DC bus. A DC load can be directly coupled to the bus. In contrast, an ACwC needs a DC/AC inverter to transform the DC bus voltage into the AC one with particular magnitude, and the power conversion flow from the AC source to the ACwC is AC-DC-AC. For a DC source, if its end-use consumer is an AC load or an ACwC, then the conversion flow from the source to the load is DC-AC, which suggests that a DC/AC inverter is necessitated.

To avoid unnecessary power conversion from AC to DC or vice versa, it is recommended in [28] that hybrid AC/DC MGs should be constructed in which AC-compatible sources/loads and DC-compatible sources/loads are respectively placed in AC subgrids and DC subgrids, so that the power loss in conversion stages could be reduced. The advantages of hybrid AC/DC MGs can be summarized as follows.

- Circumventing excessive power conversion stages and endowing higher system efficiency of the hybrid MG.
- Eliminating front-end rectifiers for DC loads or ACwCs in the AC subgrid, thus simplifying the electric equipment and realizing overall cost reductions.
- Dispersing harmonic currents and voltages of the AC subgrid into the DC subgrid by properly controlling BIC, thereby improving the AC system power quality.
- Balancing loading conditions in both AC and DC subgrids, to avoid possible overstress of a particular subgrid and enhance MG operational reliability.

Figure 1.5: Passive coordination topology.

1.1.3 Hybrid Energy Storage System

Normally, RESs are characterized by power fluctuation and intermittency, which challenge the reliable operation of the entire MG system. For a MG without fossil fuel powered DGs, the difference between the power generated by RESs and consumption of loads can be defined as power mismatch. To cover this power unbalance, ESSs are assumed as a desirable solution serving as the energy buffer of MGs. This means that the excess power from RESs can be stored in ESSs, whereas power is released by ESSs in the case of overstressed loads. Unfortunately, no single energy storage (ES) is capable of meeting the expectations of both energy density and power density. Concretely, a cluster of ESs with high ramp rates (ES_H s) such as supercapacitors (SCs) are featured by high power density but restrained energy density. In contrast, electrochemistry-based ESs (ES_L s) such as lead acid battery have high energy density but limit dynamic performances. In view of this, hybrid energy storage systems (HESSs) provide feasible options and are broadly implemented in MGs to harvest all the advantages of distinguished ESs, meanwhile, cost-effective system design can also be achieved.

To optimize the energy management system (EMS) for HESSs, plenty of coordinated control methods are comprehensively explored in the literature, and they can be classified into passive, semi-active and active types, respectively [29]. Detailed control diagrams are explicated in the following.

A: Passive Coordination

Taking DC system as an example, the power circuit topology of passive coordination in HESS is shown in Figure 1.5. Passive coordination topology, where a battery and a SC are connected in parallel and directly power the load without any power electronic interfaces. This topology is one of the most common

Figure 1.6: (a) Battery semi-active coordination topology; (b) Supercapacitor semi-active coordination topology; (c) Parallel semi-active coordination topology.

configurations in practice and has been studied by many researchers. The obvious drawback is that the current fed by battery and SC is completely uncontrollable and fully determined by the equivalent series resistor (ESR). Hence, the system controllability and flexibility could be compromised due to the limited control degree of freedom.

B: Semi-Active Coordination

The philosophy of semi-active coordination is to adopt bidirectional DC/DC converters as the interfaces with energy storages. These coordination topologies can be categorized into three types: battery semi-active, SC semi-active and parallel semi-active, respectively.

For battery semi-active coordination, as in Figure 1.6 (a), a DC/DC converter is placed between battery and load to regulate the output voltage of the battery to a near ideal constant value. The utilization of this topology allows significant performance enhancements including prolonged lifetime and higher efficiency, etc. Moreover, the matching between battery and SC terminal voltages is no

Figure 1.7: (a) Battery active coordination topology; (b) Supercapacitor active coordination topology; (c) Parallel active coordination topology.

longer required. The disadvantage of this topology is that the load voltage is vulnerable to the charging/discharging process of SC. The voltage rating of SC should match the nominal voltage of the load. Additionally, the capacitance value must be designed such that the maximum/minimum voltage of SC remains in the allowable range, which could result in the bulky volume of SC in practice.

By comparison to the battery semi-active coordination as depicted in the previous paragraph, the SC one locates a DC/DC converter between SC and load, as in Figure 1.6 (b). This topology is like the active power filter in a three-phase power system to supply high order harmonics and reactive power. The SC is known with high power density; the utilization of SC-interfaced converter helps to schedule SC to only compensate the dynamic power demand and stay idle in steady state. This coordination method also applies to those loads with plenty of regenerative energy which drives the SC to be charged despite the voltage fluctuation of the load. It should be mentioned that even the voltage of SC is independent of load, the battery should be designed to match the voltage rating of load and the output current remains as a static value because SC handles the fast

changes of the power consumed.

The diagram of HESS with parallel semi-active coordination is displayed in Figure 1.6 (c) where a DC/DC converter is installed between the parallel branch of battery/SC and load. This topology is the straightforward improvement of passive coordination topology. The terminal voltage can be conveniently changed according to the different requirements of load. However, it also suffers from the difficulty that the battery still responses to part of the dynamic power and SC fails to be flexibly charged/discharged because its voltage is determined by the battery terminal voltage. Another shortcoming is that the circulating current between battery and SC cannot be controlled, which may cause detrimental effects on overall HESS performances.

C: Active Coordination

The central idea of active coordination for HESS is to employ two DC/DC converters in the configuration as shown in Figure 1.5. The battery/SC active coordination diagram is displayed in Figures 1.7 (a) and (b) where, apart from the interfacing converter of load, the battery or SC is also equipped with an individual converter. Therefore, these active coordination methods can be viewed as the enhancement of semi-active coordinations in Figures 1.6. Conceding that these two topologies permit more flexible in terminal voltage matching, nevertheless, they are put forward at the price of placing additional DC/DC converter in the HESS.

The parallel active coordination, as shown in Figures 1.7 (c), is so far the most effective hybridization method for HESS. This structure completely decouples the voltage connection between battery and SC, although two DC/DC converters are used. The voltage matching issue can be actively solved through tuning the terminal voltage of interfacing converters. On the other hand, the output power delivered by the two ESs can be fully controlled such that battery and SC enable to provide high and low frequencies of power demand.

Figure 1.8: Decentralized control scheme of MG.

Figure 1.9: Centralized control scheme of MG.

1.1.4 Microgrid Control Techniques

By investigating whether there are communication networks, the control techniques for MGs can be categorized into decentralized, centralized and distributed, respectively.

As illustrated in Figure 1.8, decentralized control scheme features that, given certain physical connections, all local systems have their own local controllers. These controllers do not exchange data with communication links. Each controller samples necessary data from the local system and generates local control signal by not perceiving the operating status of other systems. In the decentralized scheme, local systems could flexibly plug in or plug out from the MG. System scalability and reliability can both be significantly escalated.

It is worth mentioning that the decentralized scheme may not be competent to realize advance control objectives and optimal system operations, which, however, can be perfectly addressed by the centralized scheme, see Figure 1.9. Under the centralized scheme, there is a central controller collecting data from all local controllers across the whole system. By processing the collected information, economic decisions and optimized control commands could be figured out and

Figure 1.10: Distributed control scheme of MG.

broadcast to local systems. However, as criticized in [30], the centralized diagram would suffer from single point of failures, which means the failure of a single part of system will cause the entire system malfunctions. The centralized method would induce intensive communications between the central controller and local controllers and heavy computational burdens in the central controller, which make the communication system more vulnerable to malicious cyber attacks. Moreover, the MG system extension or reconfiguration would be relatively difficult for the centralized scheme, because new communication links have to be built up when there are newly integrated electric devices and the central controller has also to be reprogrammed for adapting the updated system configuration.

To overcome the difficulties caused by single point of failures while not to compromise favorable functionalities of the central controller, a distributed communication scheme is proposed in the literature [30], as depicted in Figure 1.10. Consensus algorithms are normally utilized to accomplish comparable system performances to the centralized one. By decomposing centralized communication to peer-to-peer communication, the distributed scheme allows local controllers to exchange data among each other. Even when there is a communication link failure, the original system functions can still be realized, thus remarkably strengthening MG operation reliability. Besides, due to the fact that a new power unit can be incorporated into the existing system by only establishing a communication link with any in-service unit, the MG system expansion would hence be executed with the distributed scheme in a more convenient way.

1.2 Motivations

For an MG working in the islanded mode, effective power sharing controls should be implemented for managing DGs, ESSs, RESs and various loads. However, conventional power sharing concepts only focus on proportional load power distribution among sources in AC MGs or DC MGs. The concepts rarely take into account of energy storage dynamics, system stability, BICs power sharing as well as economic operations. Detailed explanations are provided as follows.

(1) *Energy storage dynamics*: RESs highly depend on weather conditions and give inevitable intermittency in power generations. Furthermore, the power consumption by a large number of end-users would also cause loading uncertainties. It is hence crucial to ensure the demand-supply power balance in MGs, which de facto can be achieved by HESSs. As mentioned previously, the high frequency components in the power imbalance should be handled by ES_H , whereas the low frequency components should be covered by ES_L . However, traditional power sharing approaches, although functioning in a decentralized way, fail to dynamically allocate the power imbalance to ES_H s and ES_L s respectively.

(2) *System stability*: In DC MGs, power electronic loads and motor drives, when tightly regulated, would behave as constant power loads (CPLs). From the small signal point of view, CPLs have incremental negative impedances that can interact with source power converters and cause system MG instability. Additionally, decentralized droop controllers implemented in source converters superpose virtual output impedances which further aggregate the dynamic interactions between sources and CPLs. Existing decentralized stabilizers, however, can only stabilize MGs in the small signal sense. Although there are large signal stabilization methods reported in the literature, those methods need central controllers to collect data throughout the entire system, which results in intensive communication and heavy computational burden. So far, achieving global system large signal stability in MGs in a decentralized fashion has not been well addressed.

(3) *BICs power sharing*: For a hybrid AC/DC MG, with the increasing penetrations of RESs and end-users, the AC subgrid and DC subgrid would have growing capacities, and it is expected that the power interactions between the subgrids will also be escalated. In this sense, a single BIC, which bridges the

two subgrids, may not satisfy the power flow requirement between AC and DC networks, which encourages the multi-paralleled BIC configuration. Due to the existence of multiple BICs, the power flow should be proportionally allocated to these BICs according to their respective ratings. Besides, all electrical sources in the whole hybrid MG should proportionally share entire load powers. However, simultaneous realizations of accurate power sharing among BICs and global power sharing among all sources in the hybrid MG have not been accomplished yet.

(4) *Economic operations*: A hybrid AC/DC MG would incorporate heterogeneous DGs that have their own generation costs. To minimize the holistic operating cost of the entire MG, both centralized optimizations and decentralized optimizations are studied in published works. For the former, a central controller is required which can be used for predicting power profiles of loads and RESs. Then centralized computations have to be executed to attain commands for dispatching DG power generations. Although centralized optimizations could be easy, the methods are susceptible to single point of failures. To tackle this problem, decentralized optimal system operations are examined to elude communication links. Nevertheless, DC bus voltage and AC frequency in the respective subgrids will deviate from the nominal values. An appropriate power management strategy for saving MG operating costs while ensuring power qualities and mitigating communication intensity, has not been put forward.

1.3 Major Contributions of the Thesis

This thesis enriches the connotation of power sharing concepts in terms of transient power sharing, stable power sharing, BICs distributed power sharing and economic power sharing, to address the preceding four issues. It is these extended power sharing mechanisms that make up the major contributions of the thesis.

A: Transient power sharing

In an islanded DC MG, there would be intermittency in power generation of RESs because RESs substantially reply on ambient environmental factors. Moreover, versatile end-user behaviors would also cause uncertainties to the DC MG. To compensate for the power imbalance between generations and consump-

tions, a HESS that consists of ES_H s and ES_L s should be utilized. Considering the dissimilar dynamic characteristics of ESs, it is desired that ES_H s supply the high frequency components of the power imbalance, whereas ES_L s cover the low frequencies. For this purpose, an integral droop (ID), inspired by the electrical characteristics of capacitor charging/discharging process, is proposed and applied to ES_H s. ES_L s are with conventional V-P droop. Through the coordination of ID and V-P droop, the transient power allocation in the HESS can be intrinsically realized in a decentralized way. The high frequency parts of the mismatched power can be autonomously addressed by the ESs with ID, while the ESs with V-P droop respond to the smooth change of power imbalance. Additionally, ID coefficient can be designed according to the nominal ramp rate of the ESs with slow responses, which helps to extend the lifespan of the HESS. On the other hand, to easily assess the HESS stability feeding CPLs, a minimum relative impedance criterion (MRIC) is developed. Based on MRIC, it is revealed that the proposed ID can shape the output impedance of the HESS and stabilize the entire system in the small signal sense. The feasibility and effectiveness of ID are verified by both simulations and experimental results.

B: Stable power sharing

Apart from HESS, there also exist DGs such as fuel cells and DC generators. The aforementioned ID, however, does not ensure the global system stability of the entire DC MG, although it is vindicated contributing to HESS stabilization in the small signal sense. To realize the large signal stabilization of the DC MG, a decentralized composite controller (DCC) is proposed to unify two types of voltage controls, i.e., constant voltage mode (CVM) and droop mode (DM). The main idea of the DCC is to partition the MG into dispatchable unit (DU) subsystems and the lumped load. A well-devised high gain observer is adopted to estimate the electrical coupling of a particular DU subsystem with other DUs and the load. Then, rather than coping with the MG as a whole, the DCC is locally designed to offset the estimated coupling and stabilize the internal states of the DU subsystem. By doing so, each subsystem can be virtually decoupled from the MG and functions in an isolated fashion. When DU subsystems are interlinked, large signal stabilization of the entire MG would be obtained by only guaranteeing the localized stability of individual subsystems. This stabilizing strategy has not

been reported in the literature so far. Relevant theoretical analyses are rigorously conducted by employing Lyapunov stability theorem. The effectiveness of the DCC has been verified by simulations. Experimentations show that the DCC enables faster system performance recovery and provides wider stability margin than the conventional PI controller.

C: BICs distributed power sharing

Notice that the ID in HESS and the decentralized composite large signal controller are both examined in a DC MG. However, owing to the dominant role of AC power conversion, the DC MG should be interlinked with an AC system, then constituting a hybrid AC/DC MG. It should be emphasized that the hybrid system merges the advantages of both AC and DC networks, which allows for easier power management of all electrical devices. As mentioned earlier, multi-paralleled BICs configuration should be employed to satisfy the requirements of the rising power interactions between AC and DC subgrids. To better coordinate multiple BICs, the power sharing concepts in individual subgrids can be generalized to BIC applications. As such, a distributed power management strategy (DPMS) is proposed for multi-paralleled BICs to avoid the overstress of a single BIC. In this strategy, each BIC is assigned with a well-devised localized distributed controller (LDC) which generates the respective power reference for the BIC. By using the LDC, BICs are allowed to exchange information with one another in the distributed communication graph. The power interactions between AC and DC subgrids can be proportionally allocated to BICs based on their different power ratings in a fully distributed manner. Then the system reliability and scalability are significantly improved. Meanwhile, accurate global power sharing among all AC and DC sources in the MG would be accordingly attained. The validities of the proposed DPMS are verified by a controller hardware-in-loop (HIL) experimental platform.

D: Economic power sharing

For a hybrid AC/DC MG working in the long run, the economic operation is a critical issue. It is renowned that the entire power system operation cost can be minimized when DGs have the same incremental costs (ICs). To this end, a distributed control architecture is proposed for the hybrid MG to realize

global system economic operation. The architecture consists of two levels. In the first level, the AC frequency-IC (f_{ac} -IC) droop and the DC bus voltage-IC (V_{dc} -IC) droop are employed in the AC and DC subgrids respectively. With the synchronization of f_{ac} and V_{dc} , DG ICs in each subgrid will be equalized. However, the droops will inevitably cause deviations of f_{ac} and V_{dc} . Then a distributed control canonical form (DCCF), which provides a generalized method for f_{ac} and V_{dc} recoveries, is proposed in the second level. The DCCF allows DGs to communicate only with their neighbors, thus alleviating the communication burdens and enhancing the system extendability. Due to the presence of DCCF, f_{ac} and V_{dc} fluctuations, which naturally indicate subgrid loading conditions, are invisible. An original relative loading index (RLI) is proposed to extract the hidden loading condition of each subgrid even though f_{ac} and V_{dc} are clamped as constants. By using RLI, the power reference of the BIC can be easily defined. All DG ICs the hybrid MG converge to the same value in the steady state. The feasibility and effectiveness of the proposed control architecture are verified by simulations and RT-LAB HIL tests.

1.4 Thesis Organization

This thesis enriches the connotation of power sharing concepts in terms of transient power sharing, stable power sharing, BICs distributed power sharing and economic power sharing in MG applications. Chapters 2-5 respectively correspond to the four extended power sharing mechanisms.

Following Chapter 1 wherein brief introductions of RES developments, MGs techniques, MG control strategies and HESSs are presented, Chapter 2 addresses the transient power sharing and elaborates the proposition of ID. By the cooperation of ID and V-P droop, high pass filter (HPF) and low pass filter (LPF) can be autonomously formulated. The HPF and LPF would dynamic allocate high frequency and low frequency components of power imbalance in the MG system to ES_{HS} and ES_{LS} respectively, thus realizing transient power sharing in HESSs. It is also proved that ID helps to improve the small signal stability margin in the HESS loaded by CPLs.

Noting that a DC MG may have numerous sources and loads whose interactions

with one another may cause stability issues. Furthermore, the continuously variant system equilibrium stands as an ginormous barrier for small signal stability analyses. As such, Chapter 3 proposes a DCC to obtain the stable power sharing. For a given DU, the DCC uses a high gain observer to perceive the electrical coupling of the DU with surrounding circuits. The estimated values are subsequently offset by the high gain controller which also vouches for the DU large signal stability. When it comes the system level, without any communication, global system large signal stabilization can be spontaneously achieved, and the results are theoretically justified by Lyapunov theorems.

In Chapter 4, the DC MG studied in the previous two chapters is interlinked with an AC MG through BICs, given the constitution of a hybrid AC/DC MG. To meet the expectations of increasing capacity in both AC and DC subgrids, Chapter 4 touches the third extended power sharing scheme, BICs distributed power sharing, and a DPMS is proposed. The DPMS assigns LDCs to all BICs so that LDCs can convey respective power transferring references to BICs. LDCs can communicate with each other via the distributed communication. In this way, the power interactions between AC and DC networks can be proportionally shared by BICs, which is similar to the power sharing among DGs in AC or DC MGs. Meanwhile, all sources throughout the hybrid system will also share the entire loads in proportion to their individual ratings.

Chapter 5 manages to accomplish the economic power sharing for minimizing the overall operating costs of the hybrid AC/DC MG, and a distributed control architecture is superposed to a typical hybrid system. In the first level of the architecture, f_{ac} -IC and V_{dc} -IC droops are separately applied to AC and DC DGs with generation costs. To recover f_{ac} and V_{dc} to their nominal values, in the second level, a DCCF is proposed. Due to the fact that the restored f_{ac} and V_{dc} no longer give indications of AC and DC subgrids, the RLI is further formulated to extract the hidden subgrid loading conditions. Then all DG ICs in the hybrid MG are equalized in the steady state, which means the MG system is in economic operation.

Finally, Chapter 6 gives relevant conclusions and future works.

Chapter 2

An Integral Droop for Transient Power Allocation and Output Impedance Shaping of Hybrid Energy Storage System in DC Microgrid

As stressed in Chapter 1, this thesis addresses fourfold power sharing mechanisms, i.e., transient power sharing, stable power sharing, BICs distributed power sharing and economic power sharing. In this chapter, the first type of power sharing will be explicated. To compensate the power imbalance induced by RES intermittency and load uncertainties, the HESS containing ES_H s and ES_L s would be utilized. An ID controller is proposed for ES_H s and ES_L s are with V-P droops. By coordination of ID and V-P droops, ES_H s and ES_L s could spontaneously respond to high frequency and low frequency parts of power imbalance, thus achieving the intended transient power sharing.

2.1 Introduction

In DC MGs, RESs are usually characterized by power fluctuation and intermittency, which challenge the reliable operation of the entire system. The difference between the power generated by RESs and consumption of loads is normally defined as power imbalance. To compensate this power unbalance, ESSs, serving as the power buffer of MGs, are considered to be a desirable solution. The surplus power produced by RESs can be stored in ESSs, whereas power will be released by ESSs in the case of overstressed loads. Unfortunately, no single ES is capable of meeting the expectations of both high energy density and high power density. A cluster of ESs with high ramp rate such as supercapacitors (SCs) are featured by high power density but restrained energy density. In contrast, electrochemistry-based ESs such as lithium ion batteries, have high energy density but limited power density. Instead of simply increasing the capacity of ESs to meet high power and energy demand, HESSs, taking the advantages of different ESs, can provide a more feasible option, and has been broadly implemented in DC MGs.

To optimize the energy management system for DC MGs, the hardware configurations regarding HESSs has been comprehensively explored in the literature. As in Chapter 1, they can be classified as passive, semi-active and active types. Passive coordination directly connects the battery and SC in parallel to power the loads without any controllers [31], [32]. Conceding that the passive coordination is simple and effective, however, the controllability and flexibility of the entire HESSs are inevitably compromised. System scalabilities are also adversely constrained due to the limited control degree of freedom. The semi-active coordination only integrates a DC/DC converter to the battery whereas SC is directly interfaced with the output port of the converter without any interlinking devices. This method takes the advantages of regulating the battery current to a near constant [33]–[35]. However, the semi-active coordination is challenged by the fact that capacitor values would be excessively large because of voltage matching problems. The active coordination is by far universally considered to prevail over the passive and semi-active ones. Through the active coordination, all ESs possess their own local converters to fully achieve power dispatch. Besides, the dynamic responses of ESs with different ramp rates can also be regulated by

properly designing the controllers for interfacing converters. In order to flexibly schedule the ESs, active coordination is utilized for HESSs in this chapter.

The control algorithms for HESSs based on active coordination can further be categorized as decentralized, centralized, and distributed ones. Model predictive control (MPC) is utilized in a central controller to generate low/high frequency power references for batteries and SCs respectively, as in [36]. In this way, the coordination of HESS is achieved. The similar idea can also be found in [37] where the coordinated operation of diversified ESs is realized in a centralized way. Distributed control requires information exchange between neighboring ESs for evaluating consensus algorithms (CAs) [38]–[40]. However, it should be mentioned that in the case of single-point failures, the operation of centralized and distributed control schemes will be undesirably influenced, and the whole system would even collapse. Additionally, MPC and CAs will absolutely complicate the controllers because the mathematical operations are computationally demanding. For decentralized control, multiple participating converters are integrated close to the DC bus, the output voltage of each converter, also referred as local bus signal, almost equals to the DC bus voltage. The converters have the perception of the common bus voltage and further know the status of the others, and consequently, no information exchange among converters is required [41], [42]. In this sense, the system under decentralized control is conceived to be the most reliable one among three methods. The ID, which is proposed for HESSs in this chapter, will also be shown to have the benefits of decentralized control.

To dynamically schedule the power among ESs characterized by different ramp rates, HPFs and LPFs are normally utilized to decouple power demand into high/low frequency components. In [43], the HPF and LPF are integrated into local controllers as virtual impedances for DC/DC converters. While in [44], a LPF is applied to the converter voltage feedback loop of ESs with slow dynamics aiming to allocate low frequency power to them. Regardless of the adoption of HPF and LPF, to further simplify the power decoupling mechanism and retain transient power allocations in HESSs, this chapter proposes the ID which is inspired by investigating the charging/discharging procedures of the capacitors. The ID control is then applied to the ESs with quick responses and high power density, and the conventional V-P droop is assigned to the ESs with relatively slow

responses. Through the coordinated operations of ID and V-P droop, the HPF/LPF for power decomposition can be inherently formulated. When load step-up/down is enabled, the ESs regulated by ID can handle the high-frequency power change, whereas ESs with V-P droop would respond to low-frequency power demand. In [45] and [46], a virtual capacitor and an adaptive virtual capacitor controls are proposed. However, when these current based droops are interacting with CPL, it is easy for the system to reach a situation where no mathematic solution exists for the system model.

Apart from the transient power allocation issues in HESSs, sufficient system stability margin in the steady state should also be ensured for all possible operating conditions. The DC MG stability is normally challenged by those converters with tightly regulated constant power, such as speed regulated motor drive and electronic loads. Within control bandwidth, these types of converters can be simulated as CPLs which exhibit negative impedances in low frequency range and threaten system stability, as already explicated in Chapter 1. Differently, an ideal CPL has infinite control bandwidth and its input impedance always has phase of -180° at all frequencies. With no generality lost and considering the worst case, in this chapter, the ideal CPL is adopted for all the relevant analyses. The MRIC, which is the simplified version of Nyquist criterion, is derived in this chapter especially for a class of energy storage systems integrated with CPLs. The output impedances of a system including the ID and the V-P droop is compared with the one with only V-P droop controllers. Using MRIC, it is shown that the proposed ID controller helps to shape the impedance of HESS and increase the stability margin of the whole system.

The remainder of this chapter is organized as follows. First, the derivation of the ID controller is provided. The transient power allocation scheme in HESSs is analyzed and the ID coefficient design is also explicated. Second, an effective method of PI (proportional-integral) controller design for localized DC/DC converters by means of pole placement is presented. The functionality of output impedance shaping of HESSs and the system stabilization effect of the proposed ID are also studied. Finally, simulations and experiments attest to the effectiveness of ID and the transient power sharing.

Figure 2.1: A generic schematic of an autonomous DC microgrid.

Figure 2.2: Simplified schematic of a DC MG integrated with HESS.

2.2 Integral Droop and Transient Power Allocation

2.2.1 DC MG with HESS

A generic schematic of an autonomous DC microgrid including a HESS is shown in Figure 2.1. A wind turbine and a number of solar PV panels, serving as clean power suppliers, are operated under MPPT mode. A diesel generator is employed as the backup generation and linked to the DC bus through an AC/DC power converter. DC resistive loads are directly connected to DC bus, whereas energy conversion devices are needed for AC loads. A motor drive is generally regarded as a type of CPL due to its tightly regulated load power. The HESS consisting of various energy storages is explicitly highlighted in Figure 2.1 and they are connected to the common DC bus through bidirectional DC/DC converters to realize either charging or discharging functionality.

As this chapter focuses on the overall performances of the HESS, those RESs

Figure 2.3: Illustrative circuits for discharging/charging process of a capacitor.

can be emulated as a lumped constant power source (CPS), and by the same token, the motor drive, as well as other power electronic loads, are modeled as a lumped CPL [47]. Moreover, for convenient explanation, ESs are classified as a cluster of ES_L and a cluster of ES_H , respectively. The layout of the entire DC MG can be accordingly simplified as in Figure 2.2 which contains HESS, CPS, CPL and resistive load, respectively.

The power demand P_d is defined as the difference between total power consumption and CPS, as described below

$$P_d = P_{CPL}(t) + P_R(t) - P_{CPS}(t) \quad (2.1)$$

where $P_R(t)$ is the power consumed by the resistive load. $P_{CPL}(t)$ and $P_{CPS}(t)$ are the power of CPL and CPS along with time.

It is important to emphasize that the HESS will be discharged if P_d is positive and charged if it is negative. Under both cases, the fast change of P_d should be ideally allocated to ES_H while ES_L only responds to the slow P_d change. This helps to prolong the lifetime of HESS. As mentioned earlier, a simple way to realize power allocation is to add HPF/LPF into the control loops of interfacing converters. To further simplify the local controllers and enhance the system reliability, a novel ID for ES_H to achieve dynamic power sharing will be derived in the subsequent context.

2.2.2 Integral Droop

It is well known that increasing the capacitance of DC bus will mitigate the bus voltage deviation and contribute the enlarged stability margin to the whole system

Figure 2.4: Profiles of voltage and current of the capacitor during discharging/charging process.

[48]. A capacitor straightly connected to the DC bus will naturally inject/absorb power to/from the bus in the case of load changes. Based on this fact, the electrical characteristics of the capacitor during both charging and discharging processes should be carefully reviewed in order to provide the theoretical basis of the proposed ID control. The illustrative circuit comprising a capacitor in series with a resistor is shown in Figure 2.3.

Performing Kirchhoff's voltage law for the discharging case as described by Figure 2.3 (a), the differential equation of the capacitor is given as

$$RC\dot{v}_C + v_C = 0 \quad (2.2)$$

where R , C and v_C represent the series resistance, capacitance and capacitor voltage, respectively. Solving the dynamic equation (2.1) obtains the time domain descriptions of the capacitor voltage and current,

$$\begin{cases} v_C = V_0 e^{-t/RC} \\ i_C = \frac{V_0}{R} e^{-t/RC} \end{cases} \quad (2.3)$$

where V_0 denotes the initial voltage on the capacitor. Accordingly, the mathematical solution for the charging case can also be presented in (2.4),

$$\begin{cases} v_C = E + (V_0 - E)e^{-t/RC} \\ i_C = \frac{V_0 - E}{R} e^{-t/RC} \end{cases} \quad (2.4)$$

where E is the external DC source. V_0 is assumed to be smaller than E , which means that the capacitor can be charged after switching on and its voltage will

eventually increase to E in steady state. Combining (2.3) and (2.4), the generalized relation between v_C and i_C can be summarized by (2.5),

$$v_C = V_0 - k \int i_C dt \quad (2.5)$$

where $k = 1/C$ is a constant indicating the discharging/charging rate. For the both cases discussed above, the corresponding voltage and current profiles depicted by (2.3) and (2.4) are also shown in Figure 2.4. It is easily observed that the capacitor tends to supply the burst power at the instant when the switch is on and the power exponentially decreases to zero at the end of discharging/charging process.

The features of capacitor currents illustrated in Figure 2.4 give the inspiration to design a new droop controller which bears the identical format to (2.5) by replacing current with power value. The new controller is called integral droop (ID) and given as below,

$$V = V_n - n \int P_H dt \quad (2.6)$$

where V_n is the nominal voltage reference as in conventional V-P droop controller, n is the integral droop coefficient which should be carefully tuned in order to obtain desirable transient power performances. P_H denotes the high frequency component of power demand, and the subscript H , which has the same meaning to that in ES_H , implies that the corresponding power should be balanced by the ES_H .

2.2.3 Transient Power Allocation

Combining (2.5) and (2.6), it is reasonable to infer that if the localized power converters are regulated by the ID controller, the power profiles of the converter will certainly resemble the current profiles as displayed in Figure 2.4. Hence, the ID is highly suitable for the HESS consisting of energy storages with high power density but limited energy density. It should be mentioned that the ID only compensates the transient power, and the coordination with the traditional linear V-P droop as described by (2.7) is needed to conveniently implement the energy management for HESS,

$$V = V_n - m \times P_L \quad (2.7)$$

where P_L denotes the slow change of power demand. m is the droop coefficient determined by the ratio of the maximum allowed DC bus voltage deviation δV_{max} and the nominal power rating P_{rating} of a given ES_L , as computed in (2.8),

$$m = \frac{\Delta V_{max}}{P_{rating}}. \quad (2.8)$$

It should be noted that the ID is assigned to the ES_H and the V-P droop is used to regulate the output voltage of converters integrated with ES_L . Hence, the sum of P_H and P_L equals to the lumped power demand P_d written by (2.9),

$$P_H + P_L = P_d. \quad (2.9)$$

By virtue of (2.6), (2.7) and (2.9), expressing P_H and P_L in term of P_d gives (2.10) and (2.11),

$$P_H = \frac{s}{s + n/m} P_d, \quad (2.10)$$

$$P_L = \frac{n/m}{s + n/m} P_d, \quad (2.11)$$

where s is Laplace operator. As can be seen from (2.10) and (2.11), the coordination of ID and V-P intrinsically formulate the HPF and LPF in the HESS without any additional power allocation measures. The power demand is spontaneously decomposed into high/low frequency components and transient power allocation among ESs is consequently achieved. The ratio of droop coefficients (n/m) is the cut-off angular frequency of HPF/LPF, it can be designed to satisfy the specified transient power allocation requirements. A smaller n/m drives the ES_H to compensate more transient power demand, which hence mitigates the stress of ES_L .

It is worth noting that (2.10) and (2.11) only reveal the power dynamics of the simplest system comprising an ES_H and an ES_L . However, when considering multiple ES_H s with different power capacities, the transient power sharing among ES_H s should also be carefully explored. Assuming there are total j ES_H modules in the HESS, each of them is regulated by (2.6) which can be written in s domain as in (2.12),

$$V_i = V_n - \frac{n_i}{s} P_{Hi} \quad (2.12)$$

where $i \in [1, j]$. It is easy to show that P_{Hi} is inversely proportional to n_i , as described below,

$$P_{H1} : P_{H2} : \dots : P_{Hj} = \frac{1}{n_1} : \frac{1}{n_2} : \dots : \frac{1}{n_j}. \quad (2.13)$$

In this way, the transient power sharing among multiple different ES_H s can be conveniently achieved by appropriately tuning their respective ID coefficients, which is identical to the power sharing in the conventional V-P droops. Combining (2.12) and (2.13), the equivalent ID equation is obtained as below,

$$V = V_n - \frac{n_{eq}}{s} P_H \quad (2.14)$$

where $n_{eq} = \left(\sum_{i=1}^j \frac{1}{n_i} \right)^{-1}$ and $P_H = \sum_{i=1}^j P_{Hi}$.

Observing (2.14), the multiple ES_H s can be simplified to an equivalent one, and the analysis from (2.9) to (2.11) also applies to the coordinated operation between ES_L and the equivalent ES_H . A scenario that transient power is shared by two ES_H s will be discussed later. For easy interpretation, the subsequent context regarding parameters design and system analysis will focus on the case only including one ES_H and one ES_L . It should be mentioned that the underlying assumption of derivation of (2.13) is that the HESS is integrated near the DC bus; the line impedance between converter output and DC bus can be neglected. However, if the line impedance is intolerable, the revised droop reported in [49] can be employed to compensate the voltage drop, and the analyses presented above still hold. To obtain better power management and even long term economic operation, the decentralized control in this chapter is also open to work with higher level controllers, such hierarchical control [44] and distributed control [41].

2.2.4 ID Coefficient Design

To better understand the power allocation, the expressions of P_H and P_L in the time domain can be obtained by evaluating the step response of (2.10) and (2.11), which are written by (2.15) and (2.16),

$$P_H = P_d e^{-\frac{n}{m}t}, \quad (2.15)$$

Figure 2.5: Step responses of P_H and P_L with respect to the variation of n/m .

$$P_L = P_d \left(1 - e^{-\frac{n}{m}t} \right). \quad (2.16)$$

The cut-off angular frequency n/m is a constant denoting the decay rate of the exponential term. The power dynamics of ES_H and ES_L are mainly determined by the value of n/m . P_H and P_L with respect to the variation of n/m are also displayed in Figure 2.5.

Different from the V-P droop coefficient m , the ID coefficient n can be designed according to the ramp rate of ES_L . Three assumptions are made: 1) The response time of ES_H is far smaller than that of ES_L , which means that the ramp rate of ES_H could be viewed to be infinite when compared to ES_L ; 2) The bandwidth of converter controllers are high enough to track the voltage references generated by ID/V-P controllers; 3) The power demand P_d in MG subjects to (2.17),

$$P_d^* = \sup_{t \geq 0} |P_d(t)| \quad (2.17)$$

where $\sup|\cdot|$ is the supremum of P_d along with time, and P_d^* is a positive constant. Equation (2.17) implies that P_d is a finite value for all operational conditions, which is feasible in real cases.

Taking the derivative of (2.16), the power changing rate for a given n/m can be calculated as in (2.18),

$$\frac{dP_L}{dt} = P_d \cdot \frac{n}{m} \cdot e^{-\frac{n}{m}t}. \quad (2.18)$$

To ensure the safe operation of the HESS, the value of (2.18) should be less than or equal to the ramp rate r_{ramp} of ES_L . As P_d^* is defined as the maximum

possible power demand, the worst case that the HESS feeds a load of P_d^* should also be taken into account when designing the ID coefficient n . The calculation of n can be found in (2.19) and (2.20),

$$\max \left(\frac{dP_L}{dt} \right) = P_d \cdot \frac{n}{m} \leq P_d^* \cdot \frac{n}{m} \leq r_{ramp}, \quad (2.19)$$

$$n \leq \frac{r_{ramp} \cdot m}{P_d^*}. \quad (2.20)$$

2.2.5 Discussions

Firstly, from a holistic perspective, power allocation problem has three different parts, power allocation among ES_H s, power allocation among ES_L s, and power allocation between ES_H s group and ES_L s group. For ES_H s, the high frequency P_d is allocated to each member of ES_H s according to their respective power capacity. For ES_L s, conventional V-P droop schemes are utilized to ensure the power shared by each ES_L is inversely proportional to their droop coefficients. Moreover, it is worth noting that multiple V-P droop controllers can be merged into an equivalent one which is similar to (2.14). By virtual of the amalgamated ID and V-P droops, power allocation analysis detailed in (2.10) and (2.11) still holds.

Secondly, it should be mentioned that the proposed ID controller and V-P droop are interdependent. On the one hand, as an ES_H regulated by ID only provides high frequency power, it must coordinate with ES_L under V-P droop which would handle the low frequency power. On the other hand, the existence of ID allows ES_L to refrain from providing/absorbing burst power, thus alleviating the stress of ES_L and considerably prolonging its lifespan. Hence, they have close pertinence to each other.

Thirdly, to obtain the desirable performances of HESS, V-P droop coefficient and ID coefficient can be determined by (2.8) and (2.20) respectively. The design procedures are generalized methods which theoretically maintain free from the constraints like converter volume, ES quantity, etc. The possible limitation is that the inner control loop response of the converter is overlooked. To avoid this concern, the PI design guidelines should be adopted to ensure the converter

Figure 2.6: Layout of parallel-connected bidirectional DC/DC converters for ID and V-P droop.

Figure 2.7: Double PI controllers diagram for the localized DC/DC converter.

stability and desirable responding capability. Considering the scenario that numerous ES_L s and ES_H s simultaneously exist, they are fully controllable as all of them have their own interfacing converters. Then multiple ID controllers and V-P droop controllers can be consolidated into equivalent ones. The transient power allocation scheme can be analyzed by (2.10) and (2.11), and the design of n_{eq} in (2.14) is also subjected to (2.20).

2.3 Output Impedance Shaping of HESS by ID

In the last section, it has been shown that the most attractive advantage of the ID controller is that, by correctly tuning the coefficient n , the output power changing rate of the interfacing converter can be flexibly designed to be less than the ramp rate of ES_L , which lengthen the lifetime of ES_L . It should be also noted that the ID not only helps to achieve these desirable transient performances, it can also stabilize the system feeding CPL by shaping the output impedance of the HESS.

Figure 2.8: Simplified current and voltage regulation loops.

2.3.1 PI Controller Design

The realizations of both ID and V-P controllers are to generate respective voltage references for localized DC/DC bidirectional power converters. Only with the stable localized converter system can the aforesaid power decomposition mechanism be effectively achieved. Besides, the response speed of ES_L converter inner control loops should be adequately slow to mitigate the stress of ES_L , whereas the ES_H converter controller has to be sufficiently fast so that the burst power can be released by ES_H in the case of sudden load increase. The layout of the two boost converters connected in parallel is shown in Figure 2.6, where the parameters accompanied by subscripts “ H ” and “ L ” correspond to the ES_H and ES_L respectively. i_{LH} and i_{LL} denote the inductor current of converters and are operated in continuous current mode (CCM). i_{oH} and i_{oL} are the output current of the two converters delivered to the loads. V_{oH} and V_{oL} are the terminal voltages which represent the dynamics of the output capacitors. d_H and d_L are the averaged duty cycle in a switching period. Dual loop PI control is adopted for both converters to track the voltage references V_{ref} produced by ID and V-P, and the control diagram is presented in Figure 2.7. PI_c and PI_v are the compensators of the current and voltage regulation loops respectively, which can be written as below,

$$PI_c = \frac{k_{pc}s + k_{ic}}{s}, \quad PI_v = \frac{k_{pv}s + k_{iv}}{s} \quad (2.21)$$

where k_{pc} , k_{ic} , k_{pv} and k_{iv} are the constants to be tuned. The V_{in} is the input voltage of ESSs. The average duty cycle D is calculated by 2.22,

$$D = 1 - \frac{V_{in}}{V_{ref}}. \quad (2.22)$$

As shown in Figure 2.7, the complete control diagram consists of two segments: controller and converter. System disturbances, including constant value 1, V_{in} and i_o , are shown in the forward path of the converter. These disturbances can be counteracted by the feedforward terms in the controller so that PI compensators can function more precisely.

The main considerations of the compensators design can be concisely described as follows: 1) The response speed of current regulation should be slower than that of PWM modulator and much faster than that of voltage loop; 2) Sufficient robustness of control loops should be guaranteed so that, in the case of large disturbances, the dominant poles of the system would not pass through imaginary axis and enter the right half complex plane; 3) The PI parameters should be flexibly tuned according to versatile requirements of pole positions in practice. Based on the above presumptions, the current and voltage regulation loops are individually illustrated in Figure 2.8. When designing the voltage controller, the current loop is approximated as a unity gain due to its much faster response. In the following context, the PI compensators are designed by using pole placement method. The parameters with subscripts “c” and “v” are associated with the current and voltage regulation loops respectively.

The close loop transfer function of the current control diagram as in Figure 2.8 (a) can be written below,

$$G_c = \frac{T_c}{1 + T_c} = \frac{(k_{pc}V_{ref}/L)s + (k_{ic}V_{ref}/L)}{s^2 + (k_{pc}V_{ref}/L)s + (k_{ic}V_{ref}/L)} \quad (2.23)$$

which exhibits a typical second order system form with two poles and one zero. The main idea of pole placement is to compute proper k_{pc} and k_{ic} such that the characteristic polynomial has the expected roots $-\sigma_c \pm j\omega_c$. Then the desired polynomial is given as

$$[s - (-\sigma_c + j\omega_c)][s - (-\sigma_c - j\omega_c)] = s^2 + 2\sigma_c s + \omega_{nc}^2 \quad (2.24)$$

where $\omega_{nc}^2 = \sigma_c^2 + \omega_c^2$. Through matching the coefficients of (2.24) and denominator of (2.23), the PI parameters for current regulation loop are easily determined by (2.25),

$$\begin{cases} \frac{k_{pc} V_{ref}}{L} = 2\sigma_c \\ \frac{k_{ic} V_{ref}}{L} = \omega_{nc}^2 \end{cases} \Rightarrow \begin{cases} k_{pc} = \frac{2\sigma_c L}{V_{ref}} \\ k_{ic} = \frac{\omega_{nc}^2 L}{V_{ref}} \end{cases}. \quad (2.25)$$

Substituting (2.25) into (2.23), the step response of (2.23) in time domain can be written as (2.26),

$$G_c(t) = 1 + \frac{\omega_{nc}}{\omega_c} e^{-\sigma_c t} \sin(\omega_c t - \beta_c), \quad (2.26)$$

where $\beta_c = \cos^{-1}(\sigma_c/\omega_{nc})$ is the lagging angle which belongs to $(0, \pi/2)$. The peak time t_{pc} can be computed by setting the first order derivative of (2.26) to 0, which is written by (2.27),

$$G_c^{(1)}(t) \Big|_{t=t_{pc}} = 0 \Rightarrow t_{pc} = \frac{2\beta_c}{\omega_c}. \quad (2.27)$$

Furthermore, substituting (2.27) into (2.26) yields the peak value of (2.26), and the percent overshoot (*P.O.c*) of the step response of the second order system can be found in (2.28),

$$P.O._c = (G_c(t_{pc}) - 1) \cdot 100\% = e^{-\frac{2\beta_c}{\tan(\beta_c)}} \cdot 100\% \quad (2.28)$$

As observed from (2.26), the *P.O.c* is only related to the ratio of σ_c and ω_{nc} , and its minimum value can be found as $e^{-2} \cdot 100\%$ (13.53%) by computing the limit of *P.O.c* as β_c approaches zero. It is inferred that β_c is the stability indicator of the system (2.23), and a smaller β_c allows larger stability margin. In this section, the *P.O.c* is restrained under 15% to ensure the stable system operation. β_c can be consequently determined by (29),

$$13.53\% < P.O._c \leq 15\% \Rightarrow 0 < \beta_c \leq 0.1\pi. \quad (2.29)$$

Taking into account of the worst case, β_c is set as 0.1π , and referring to (2.26), the relation of σ_c and ω_c is computed by (2.30),

$$\omega_c = \sigma_c \tan(\beta_c). \quad (2.30)$$

In addition to the stability issues dominated by β_c , the response speed matching of control loops is another important problem. The settling time t_{sc} is usually defined as the time elapsed from the exertion of a step input to the time when the system output has entered and remained within a specified error band. In this sense, t_{sc} can be viewed as the indicator of response speed of (2.23), which can be computed by (2.31),

$$\begin{aligned} \left| \frac{\omega_{nc}}{\omega_c} e^{-\sigma_c t} \right|_{t=t_{sc}} &= \left| \frac{e^{-\sigma_c t}}{\sin \beta_c} \right|_{t=t_{sc}} = \Delta_c, \quad 0 < \Delta_c \leq 5\% \\ \Rightarrow t_{sc} &= \frac{\ln(\sin \beta_c \cdot \Delta_c)^{-1}}{\sigma_c} \end{aligned} \quad (2.31)$$

It is observed from (2.31) that once β_c is determined, a larger ω_c leads to shortened response time. Since the output signal of the current control loop is transferred to the modulator for PWM generation, t_{sc} should be at least 10 times longer than the switching period T_{sw} of the carrier signal. Hence, the real part of the desired roots ω_c can be evaluated by (2.32)

$$\sigma_c = \frac{\ln(\sin \beta_c \cdot \Delta_c)^{-1}}{k_c T_{sw}} \quad (2.32)$$

where $k_c \geq 10$ is a constant. Combining (2.28) and (2.31), it can be concluded that the stability margin of (2.23) is mainly dominated by the angle β_c , and the response time is determined by both β_c and σ_c . To meet the different requirements of system stability and response time in practices, the expected poles can be easily calculated by (2.30) and (2.32). Then k_{pc} and k_{ic} are further identified by (2.25).

For the voltage regulation diagram shown in Figure 2.8 (b), the close loop transfer function is written by (2.33),

$$G_v = \frac{T_v}{1 + T_v} = \frac{(k_{pv}(1-D)/C)s + k_{iv}(1-D)/C}{s^2 + (k_{pv}(1-D)/C)s + k_{iv}(1-D)/C}. \quad (2.33)$$

Similar to (2.30) and (2.32), the imaginary and real parts of the designated poles for (2.33) can be given as the following,

$$\omega_v = \sigma_v \tan(\beta_v) \quad (2.34)$$

$$\sigma_v = \frac{\ln(\sin \beta_v \Delta_v)^{-1}}{k_v k_c T_{sw}} \quad (2.35)$$

Figure 2.9: Equivalent Thevenin circuit of the cascaded system consisting of ES_L , ES_H and load.

where $\beta_v = \beta_c = 0.1\pi$ is the measurement of $P.O.v$. $\Delta_v = \Delta_c = 5\%$ is the percent error band for determining the settling time. $k_v \geq 10$ is a positive constant which means that the response time of the voltage regulation loop is at least 10 times longer than that of the current loop. The corresponding k_{pv} and k_{iv} in (2.33) can also be evaluated by (2.36),

$$\begin{cases} \frac{k_{pc}(1-D)}{C} = 2\sigma_v \\ \frac{k_{ic}(1-D)}{C} = \omega_{nv}^2 \end{cases} \Rightarrow \begin{cases} k_{pv} = \frac{2\sigma_v C}{1-D} \\ k_{iv} = \frac{\omega_{nv}^2 C}{1-D} \end{cases} \quad (2.36)$$

where $\omega_{nv}^2 = \sigma_v^2 + \omega_v^2$.

The salient advantage of the compensator design using pole placement over those design approaches using bode plot is that the PI parameters are directly and intuitively related to the required response time and the allowed maximum overshoot of system step response in time domain. This is highly useful for HESS because the controllers of converters should strictly work in coordination. Especially for that ES_H , the settling time of voltage and current regulation loops should be smaller enough in order for releasing sufficient power to load in system transition.

2.3.2 Minimum Relative Impedance Criterion (MRIC)

As discussed earlier, the presence of CPLs, unfortunately, pose threats to the stable operation of the entire MG. To examine the stability of the studied system, a common way is to establish state space equations of the complete system based on a small signal model by linearizing the plant around an equilibrium operating point. However, it is worth mentioning that MGs are complicated by numerous

Figure 2.10: The Nyquist contour of $-Z_{LL}$ and $-Z_{HL}$ and stability margin comparisons with the increase of CPL: (a) CPL=2kW; (b) CPL=3kW; (c) CPL=4kW.

energy sources and energy conversion devices. The RESs and distributed loads are highly intermittent and uncertain. Therefore, it is very difficult to obtain a fixed MG model and further use it to access the stability of the system.

Impedance matching method provides a flexible way to explore the stability of MG containing multiple cascaded devices [50], [51]. The central idea of this method is to establish an equivalent Thevenin model comprising the voltage source and the output impedance. The ratio of the source output impedance and load input impedance is regarded as the generalized minor loop (GML) of the cascaded system [50]. On this basis, several stability criteria have been reported, such as Middlebrook criterion, Gain Margin Phase Margin criterion, Passivity-based Stability Criterion, etc [51]. Yet these criteria are normally criticized for conservativeness and they ultimately originate from Nyquist criterion. In fact, for a close loop control system, system stability can be ensured as long as the minor loop abides by Nyquist criterion, and this principle also applies to the HESS studied in this chapter. If Nyquist contour of GML does not anticlockwise encircle the critical point $(-1, j0)$, then the cascaded system is stable. The equivalent circuit corresponding to the layout shown in Fig. 6 is illustrated in Figure 2.9. V_{eqH} and V_{eqL} are the equivalent voltage sources. Z_H and Z_L denote the output impedances and Z_{load} represents the linearized lumped impedance of P_d . It has been proved that CPS and resistive load help to stabilize the DC bus [47]. To examine the system stability under the worst case, CPL is considered in this section as the only power consumer. Therefore, the power of CPL should be equal to P_d and the impedance of CPL can be computed in (2.37),

$$Z_{load} = Z_{CPL} = -\frac{V_b^2}{P_d} \quad (2.37)$$

where V_b is the DC bus voltage.

It should be noted that the boost converters are inherently the nonlinear systems which contain bilinear terms coupling the control input and state variables together [52]. To derive the equivalent output impedance of converters integrated with ES_H and ES_L , the small signal model is established by linearizing the individual converter system. The linearized state space equations of the ES_H and ES_L subsystems are written by (2.38) and (2.39),

$$\Delta \dot{X}_H = A_H \Delta X_H + B_H \Delta i_{oH}, \quad (2.38)$$

$$\Delta \dot{X}_L = A_L \Delta X_L + B_L \Delta i_{oL} \quad (2.39)$$

where A_H and A_L are the state matrices; B_H and B_L are the input matrices. The detailed derivations of (2.38) and (2.39) are provided in Appendix A. ΔX_H and ΔX_L represent the state vectors, which are expressed by (2.40) and (2.41),

$$\Delta X_H = [\Delta v_{oH} \ \Delta i_{LH} \ \Delta \xi_{1H} \ \Delta \xi_{2H} \ \Delta \xi_{3H}]^T \quad (2.40)$$

$$\Delta X_L = [\Delta v_{oL} \ \Delta i_{LL} \ \Delta \xi_{1L} \ \Delta \xi_{2L}]^T. \quad (2.41)$$

In (2.40), $\Delta \xi_{1H}$, $\Delta \xi_{2H}$, and $\Delta \xi_{3H}$ denote the state variables in ID, voltage PI controller and current PI controller of ES_H subsystem. Similarly, in (2.41), $\Delta \xi_{1L}$ and $\Delta \xi_{2L}$ are the state variables in voltage and current PI controllers of ES_L subsystem. Based on (2.38) and (2.39), the output impedances of the two subsystems are given as below,

$$Z_H = -\frac{\Delta v_{oH}}{\Delta i_{oH}} = C_H(sI - A_H)^{-1} B_H, \quad (2.42)$$

$$Z_L = -\frac{\Delta v_{oL}}{\Delta i_{oL}} = C_L(sI - A_L)^{-1} B_L, \quad (2.43)$$

where $C_H = [-1 \ 0 \ 0 \ 0 \ 0]$ and $C_L = [-1 \ 0 \ 0 \ 0]$ are constant matrices. The total output impedance Z_{HL} of HESS is the equivalent impedance of the parallel-connected Z_H and Z_L , which is computed by (2.44),

$$Z_{HL} = Z_H // Z_L = \frac{Z_H Z_L}{Z_H + Z_L}. \quad (2.44)$$

Combining (2.37) and (2.44) yields the GML of the cascaded system as below,

$$GML = \frac{Z_{HL}}{Z_{CPL}}. \quad (2.45)$$

The stability of HESS can be then studied by investigating if GML adheres to the Nyquist criterion. It is easy to know from (2.37) that Z_{CPL} is a negative constant when the CPL power and bus voltage are given. Therefore, MRIC, which is a new extension of Nyquist criterion, is specially derived for a cluster of systems

Table 2.1: System parameters for HESS.

Parameters	Description	Value
V_n	Nominal bus reference	170 V
ΔV_{max}	Maximum allowed voltage deviation	± 10 V
L_H, L_L	Converter inductors	2 mH
C_H, C_L	Converter capacitors	470 μ F
β_v, β_c	Phase lags	0.1π
Δ_v, Δ_c	Specified error band	5 %
f_{sw}	Switching frequency	20 kHz

integrated with CPLs, in order to realize convenient stability analysis, as presented by (2.46),

$$\begin{aligned}
& \text{real} \left(\frac{Z_{HL}}{Z_{CPL}} \right) > -1 \\
& \Rightarrow \text{real}(-Z_{HL}) - Z_{CPL} > 0 \\
& \Rightarrow \min[\text{real}(-Z_{HL})] - Z_{CPL} > 0
\end{aligned} \tag{2.46}$$

where $\text{real}(\cdot)$ denotes the real part of a complex value. Accordingly, the MRIC stability margin γ_{ZHL} of HESS feeding CPL is defined as

$$\gamma_{ZHL} = \min[\text{real}(-Z_{HL})] - Z_{CPL}. \tag{2.47}$$

γ_{ZHL} actually measures how far the $-Z_{HL}$ Nyquist contour is from that of Z_{CPL} , which also equivalently indicate the gain margin in the Z_{HL}/Z_{CPL} Nyquist plot. Hence, $(Z_{CPL}, j0)$ serves as the critical point under MRIC as $(-1, j0)$ does in the conventional Nyquist criterion.

2.3.3 HESS Output Impedance Shaping by ID

The converter parameters in Figure 2.6 and the controllers in Figure 2.7 are provided in Table 2.1. To expound the impedance shaping and stabilization effect of the proposed ID controller, two different types of HESS with the same total V-P droop characteristics are adopted in this part. The HESS consisting of ES_L ($m_I = 0.01$) and ES_H ($n = 0.01 \cdot 2\pi$) is referred as type I, denoted as HESS_I, whereas another type of HESS, expressed as HESS_{II}, is assumed to have two ES_L

Table 2.2: Parameters for HESS_I and HESS_{II}.

HESS Type	CPL (kW)	V-P droop coefficient m	ID droop coefficient n
I	2/3/4	$m_I = 0.01$	$0.01 \cdot 2\pi$
II	2/3/4	$m_{II} = 0.02$	Null

Table 2.3: Parameters for stability testing.

CPL (kW)	V-P droop coefficient m	ID droop coefficient n
4	0.01	$0.01 \cdot \pi$
4	0.01	$0.01 \cdot 2\pi$
4	0.01	$0.01 \cdot 3\pi$

whose interfacing converters are connected in parallel with V-P droop coefficients twice of m_I ($m_{II}=0.02$). The parameters of these two comparative HESS types are listed in Table 2.2. For HESS_I, the steady DC bus voltage is dominated by ES_L because ES_H only compensates high frequency transient power. While for HESS_{II}, the equivalent droop coefficient m_{eq} of the whole HESS_{II} can be calculated as $m_{eq} = m_{II}/2$ which equals to m_I . Therefore, given that HESS_I and HESS_{II} are loaded by the same CPL, the bus voltage of the two system are also identical in steady state.

Following the previous reasoning, the output impedance of HESS_I is signified by Z_{HL} as in (2.44), and accordingly, the output impedance Z_{LL} of HESS_{II} can be also written as below,

$$Z_{LL} = \frac{Z_L}{2} |_{m_{II}=0.02}. \quad (2.48)$$

By means of the definition of (2.47), the stability margin tests of HESS_I and HESS_{II} under three different load conditions (CPL=2kW/3kW/4kW) are shown in Figure 2.10. $\gamma_{ZHL}/\gamma_{ZLL}$ represent the relative distance between the minimum real part of $-Z_{HL}/-Z_{LL}$ and Z_{CPL} . It can be observed from Figure 2.10 (a) that when CPL is scheduled as 2kW, the critical point is (-11.25, $j0$). γ_{ZHL} and γ_{ZLL} are estimated as 10.34 and 6.6 respectively, which reveals that HESS_I is more stable than HESS_{II}.

Figure 2.11: The Nyquist contour of $-Z_{HL}$ and stability margin comparisons with the variation of ID droop coefficient: $n_1 = 0.01 \cdot 1\pi$; $n_2 = 0.01 \cdot 2\pi$; $n_3 = 0.01 \cdot 3\pi$.

Similar results can also be found in Figure 2.10 (b) where CPL increases to 3kW, and the corresponding critical point moves to $(-6.53, j0)$. For this scenario, $\gamma_{ZHL}=3.23$ is still larger than $\gamma_{ZLL}=1.43$, which verifies the effectiveness of output impedance shaping mechanism and stabilization functionality of the proposed ID controller. By comparing MRIC stability margin in the cases of 2kW and 3kW CPLs, it is obvious that the growth of CPL decreases the stability margin of both systems.

Figure 2.10 (c) shows an extreme situation where CPL rises to 4kW and the steady DC bus voltage drops to 130V, which is rigorously not allowed in practice. Fortunately, it can be seen that, even in this atrocious condition, the stability margin γ_{ZHL} of HESS_I still remains around 0.995. However, the Nyquist contour of $-Z_{LL}$ of HESS_{II} has encircled the critical point $(-4.23, j0)$, and system instability will be induced.

Another interesting finding is that, despite the changes of CPL, the minimum real part of $-Z_{HL}$ almost maintains at about 3.32, and the stability margin changes mainly caused by the motion of the critical point. This characteristic is greatly favored by the HESS designers to determine the maximum permitted load for ensuring system stable operations.

To further examine the impact of ID coefficient n on the impedance shaping, three different values of n implemented on HESS_I are listed in Table 2.3, where CPL 4kW is considered. The comparative stability margin test is conducted in

Figure 2.12: Transient power allocation among ES_H and ES_L .

Figure 2.11. It is recognized that the decrease of n tends to enlarge the stability margin. This is fairly comprehensible from the perspective of transient power allocation pattern that n/m acts as the cut-off angular frequency of HPF/LPF and a smaller n/m drives ES_H to compensate more high frequency power demand. By the analogy between (2.5) and (2.5), n can be viewed as the indicator of the capacitive effect that ID can provide for the DC bus. If a small value of n is assigned to ID, then ES_H is much stronger to smooth the DC bus voltage, and in this way, the bus can be stabilized.

Figure 2.13: Transient power oscillations caused by the improper design of PI controller.

Figure 2.14: Power profiles of HESS_I and HESS_{II} with consecutive CPL step-up.

2.4 Simulations

To verify the effectiveness of the proposed ID controller, the HESS shown in Figure 2.6 was modeled in Matlab/Simulink environment, and simulation results are presented. System parameters are listed in Table 2.1. It is known that, from the impedance perspective, the existence of resistive loads and CPS would not jeopardize the overall system stability. The most intractable scenario is that the lumped load of HESS is only dominated by CPL. Hence, in this section, HESS loaded by only CPL is considered, and neither resistive load nor CPS is involved. The subsequent context will investigate the power allocation performances under ID coefficient variation. It will also show that improper PI controller design will unfavorably cause transient power oscillations in system transition. Additionally, the output impedance shaping for HESS by ID will be validated to stabilize the whole system through time domain simulations of HESS_I and HESS_{II}.

A: Case 1

As mentioned earlier, the coordinated operation with ID and V-P droop naturally decompose the power demand into high frequency and low frequency ones which are further allocated to ES_H and ES_L respectively. The power dynamics of the HESS feeding 300W CPL are visible in Figure 2.12. When the load step-up and step-down are triggered at 0.5s and 8s, the ES_H immediately responds to compensate the load power of fast change and gradually decrease to zero in a short time, while the power of ES_L smoothly rise from 0 to 300W and consistently handle the whole load power in the steady state.

According to power dynamics depicted by (2.15) and (2.16), the ratio of n and m would remarkably affect the transient power allocation performances. The V-P coefficient m , which is in principle computed by (2.8), is assumed to be a constant 0.01 in this chapter. Observing the different power profiles displayed in Figure 2.12, the transient durations of the scenarios with n set as $0.01 \cdot 1\pi$, $0.01 \cdot 2\pi$, and $0.01 \cdot 3\pi$ are around 6s, 4s, and 2s, respectively. The simulation results are in good agreement with the previous analysis. Therefore, it can be concluded that the lowered ID coefficient drives the ES_H to compensate more transient power and the stress of ES_L is mitigated.

B: Case 2

Parameters $\beta_c = \beta_v$ dominate the stability margin of (2.23) and (2.33), while $\Delta_c = \Delta_v$ are mostly related to the response speed of the close loop systems. The ideal ranges of these parameters design have been given in (2.29) and (2.31). In case 2, m and n are selected as 0.01 and $0.01 \cdot 2\pi$ respectively. The scenarios, in which the $\beta_c, \beta_v, \Delta_c$ and Δ_v are chosen beyond the constraints of (2.29) and (2.31), are examined. Simulation results under different parameter settings are shown in Figure 2.13. Comparing the Figures 2.13 (a) and (b), when Δ_c and Δ_v are selected as 15%, more severe power oscillation is observed in the case of $\beta_c = \beta_v = 0.4\pi$. The same result can also be found through the comparison of Figures 2.13 (c) and (d). The reason for these findings is that, as indicated by (2.28), the increased values of β_c and β_v may result in over large $P.O.$ and hence the instability would be induced.

On the other hand, by scrutinizing Figures 2.13 (a) and (c), both β_c and β_v are assigned as 0.35π , and power oscillation is less damped when Δ_c and Δ_v equal 30%. This fact is supported by the previous analysis in (2.31) that the rising Δ_c and Δ_v weaken the constraint on final value convergence of step response. Consequently, as suggested by (2.32) and (2.35), the absolute value of the designated pole real part would be lowered, which challenges the stability of the converter system. Figures 2.13 (d) gives the worst transient power performance that the four parameters go far beyond the predefined ranges, which is rigorously not permitted in real applications.

C: Case 3

It has been proved in the small signal sense that the adoption of ID helps to shape the output impedance of HESS by keeping the minimum real part of $-Z_{HL}$ far away from MRIC critical point. As a result, through the comparative studies of HESS_I and HESS_{II}, the ID allows augmented stability margin upon MRIC. The time domain simulations of the two type of HESSs under consecutive step-up of CPL are demonstrated in Figure 2.14. From Figure 2.14 (a), the transient power allocation in HESS_I continuously functions well and the system stability is also ensured even though the CPL rises to 4kW. While proceeding to Figure 2.14 (b), the instability of HESS_{II} unexceptionally occurs when CPL of 4kW is exerted at

Figure 2.15: Experimental setup.

Table 2.4: Cases for experimental verifications.

	Converter #1	Converter #2	Converter #3
Case 4	V-P	ID	Idle
Case 5	V-P	ID	CPS
Case 6	V-P	ID	ID

18s. These results validate the stability analysis in Figure 2.10 (c) that the MRIC criterion is violated because the critical point is enclosed by the Nyquist contour of $-Z_{LL}$.

2.5 Experimental Verifications

For experimental verifications, an in-house platform was established as shown in Figure 2.15. System parameters are the same as in simulations and have been already listed in Table 2.1. For convenience, both resistive load and CPL are incorporated in the DC system which has three converters. The electronic load is always configured as the CPL. The operation modes of converters in the following three different cases are summarized in Table 2.4.

A: Case 4

In this case, the HESS is assumed to operate under discharging mode, and the

Figure 2.16: Transient power allocation among ESs when HESS is discharged.

Figure 2.17: Transient power allocation among ESs when HESS is charged.

Figure 2.18: Transient power allocation among one ES_L and two ES_H s.

converter #1 (ES_L) is assigned with conventional V-P droop, while converter #2 (ES_H) is regulated under ID control. Converter #3 is in idle mode and CPS is not involved. The transient power allocation between the ES_H and ES_L considering ID coefficient variations can be seen in Figure 2.16. To start with, the HESS is operating in steady state, and the ES_L continuously delivers power to the resistive load while the power of ES_H maintains at zero. When the CPL is enabled and disabled in sequence, it is clear that ES_H tends to compensate the demand load of high frequency and the ES_L responds to the load change much slower than ES_H . Meanwhile, the individual output voltage of both ESs slightly drops.

Another finding is that a larger ID coefficient gives rise to a faster response of the whole HESS, and the total power supplied by ES_H accordingly decreases to zero after system transition. The experimental results of this case are fully consistent with the simulations as in case 1, which again validate the effectiveness of the proposed ID.

B: Case 5

Apart from the fact that the HESS release power when power deficiency is detected, on the other hand, in the case that the surplus power is induced, the HESS should also correctly function in the charging mode. Case 5 investigates the transient power performances of ES_H and ES_L when they are both charged. As indicated by Table 2.4, different from case 4, converter #3, in this case, is simulated as a CPS which directly inject 2A current into the system regardless of DC bus deviation. As the resistive load is deliberately regulated to be light, CPS entirely compensates the resistive power and then the remaining CPS power has to be absorbed by HESS. The corresponding experimental results are illustrated in Figure 2.17.

It is visible that when converter #3 is activated, ES_H and ES_L will concurrently absorb power from the DC bus, while the power allocation mechanism formulated by coordination of V-P droop and ID still functions effectively. This means that the proposed ID controller retains the bi-directional power flow of HESS, which makes it flexible to realize power management in HESS.

C: Case 6

It is known that multiple converters connected in parallel are quite common in

the MG system. The paralleled operations and the equivalent pattern of traditional V-P droop controllers have been extensively studied in the literature [53]. Hence, case 6 assumes that converter #1 is with V-P droop while converter #2 (ES_{H1}) and converter #3 (ES_{H2}) are under ID controllers with different droop coefficients (n_1 and n_2). This case focuses on the transient power sharing among two ES_H s. The HESS is also working in discharging mode and CPS is neglected. The relevant experimental results are plotted in Figure 2.18. It can be seen that the V-P droop coefficient m and the overall equivalent ID coefficient n_{eq} in all three scenarios remain identical to that in previous cases. As a result, when CPL step-up and step-down are exerted, the system transient duration keep invariant, which are 2s, 4s, and 6s, respectively. Moreover, based on (2.10), (2.11) and (2.14), it is straightforward to recognize that the total power P_H and P_L supplied by ES_H s and ES_L also remain unchanged.

As detailed in Figure 2.18, it is worth noting that the fast-changing power demand is simultaneously shared by ES_{H1} and ES_{H2} respectively. Despite the alteration of n_{eq} , on the condition that n_1 is set two times of n_2 , the corresponding power delivered by ES_{H1} is half of that by ES_{H2} , which is perfectly in line with the analysis by (2.13). This transient power sharing scheme among ID controllers elegantly allows the convenient HESS extension and provides efficacious assistance for EMS design.

2.6 Summary

This chapter introduces the ID for a class of ESs with fast response to obtain transient power allocation in HESS. By cooperation of ID and V-P droop, the high frequency components of power demand and the low frequency ones are respectively assigned to the ES_H and ES_L . The ID coefficient n is carefully designed according to the nominal ramp rate of ES_L , intending to prolong the lifespan of HESS. The practical PI controllers design method for DC/DC converters using pole placement is also provided. The prominent advantage of this method is directly relating the PI parameters to the controller response in the time domain, which facilitates the design of HESS. To further evaluate the stability of the whole system, the MRIC is derived based on Nyquist criterion

especially for a class of systems feeding CPLs. According to MRIC, the proposed ID exhibits the stabilization effect on HESS by shaping the output impedance of the system. Simulations and experimental results have validated the feasibility and effectiveness of the ID. Proceeding to apply the proposed ID controller in the real systems, the power fluctuation of RESs can be modeled as the superposition of repeated power increase/decrease. The expected result is that the transient power allocation dynamics shown in the experiments would consecutively appear with time lapse, thus giving rise to the desired transient power sharing.

Chapter 3

A Decentralized Composite Controller for Unified Voltage Control with Global System Large Signal Stability in DC Microgrids

This chapter is the continuance of Chapter 2, which studies the DC system from the perspective of overall MG stability and obtains the intended stable power sharing. In Chapter 2, although ID controller applied to the ES_H is shown contributing to HESS stability. However, the stability is analyzed in the small signal sense which is only valid in the vicinity of particular static points, and those other power generations in the DC MG are not considered. To achieve a more reliable stabilization for the DC power system, a decentralized composite controller (DCC) is proposed. The DCC enables to unify two types of voltage controls, i.e., constant voltage mode (CVM) and droop mode (DM), which can also serve as the inner controller for the ID in HESS. The main idea is to partition the MG into dispatchable unit (DU) subsystems and the lumped load. DUs include ESs, fuel cells and DC generators, etc. A well-devised high gain observer is adopted to estimate the electrical coupling of a particular DU subsystem with other DUs and the load. Then, rather than coping with the MG as a whole, the DCC is locally designed to offset the estimated coupling and stabilize the internal states of the DU subsystem. By doing so, each subsystem can be virtually decoupled from the MG and functions in an isolated fashion. When DU subsystems are interlinked, large signal stabilization of the entire MG would autonomously be obtained by only guaranteeing the localized stability of individual subsystems, therefore accomplishing the desired stable power sharing.

3.1 Introduction

In a given DC MG, the bus voltage is a natural indicator of power quality and overall system stability. Hence, appropriate DC bus control is an essential issue and could be realized by those dispatchable units (DUs) such as ESs, fuel cells and DC generators, etc. [54]. Normally, the bus control includes constant voltage mode (CVM) and droop mode (DM). The former can be configured to supply power to voltage-sensitive loads with high power quality requirements. A DU source regulated by CVM should bear sufficient power rating to accommodate all the possible loading conditions [55]. However, in the case that the demanded load power substantially grows, to avoid the overstress of a particular DU, DM should be utilized and implemented for multiple DUs. Then the load can be proportionally shared by different DUs in accordance with their respective ratings. By means of DM, the DC bus voltage will float along with load variations, which means that the heavier loads give the larger voltage drops, and vice versa [53].

For DC DUs, the realizations of CVM and DM significantly rely on their properly controlled interfacing converters. These converters help to feed resistive loads and constant power loads (CPLs). The former ones are known as passive components which contribute damping effects to the MG. Dissimilarly, CPLs are commonly referred to those power electronic loads and motors with tightly regulated speed, etc. They present negative impedances to the DC bus within their control bandwidths, and unfavorably interact with source converters, thus threatening the stable operations of the MG [56]. Furthermore, droop controllers virtually increase the converter output impedances, which further escalates the source-load interactions and entails the bus voltage being more vulnerable to load variations [57]. To address these problems, abundant stabilization studies have been conducted using either small signal analyses (SSA) or large signal analyses (LSA).

The philosophy of SSA is to establish the linearized mathematical model of the MG, such as the state space model and the transfer function, at an equilibrium under a small perturbation. For examples, in [58], [59], the eigenvalue loci of a linearized aircraft power system model are analyzed to predict the maximum allowable loads. Note that the eigenvalue method can only be executed off-line,

Table 3.1: Comparisons between DCC and existing stabilization methods.

References	SSA	LSA	Only DU model needed	Complete MG model needed	Self- disciplined stabilization
[58], [59]	✓	×	×	✓	×
[56], [60], [61]	✓	×	✓	×	✓
[62], [63]	✓	×	×	✓	×
[64], [65]	✓	×	✓	×	✓
[48], [66]	×	✓	✓	×	×
[67]	×	✓	✓	×	×
[68], [69]	×	✓	×	✓	×
[70]	×	✓	×	✓	×
Proposed DCC	×	✓	✓	×	✓

and the entire MG system accurate model is necessitated. A low pass filter based droop controller is proposed in [60] to form virtual impedances for source converters, intending to widen the stability margin of the MG in the small signal sense. Similarly, a virtual inductor is presented in [61] to damp the potential DC power oscillations by modifying the system transfer function. Since these virtual impedance method enabled controls are only evaluated in each individual DU converter, the controls certainly take the advantages of high scalability and PnP functionalities. A cubature Kalman filter (CKF) approach is proposed in [62] to improve the small signal stabilization of nonlinear DC loads. Yet this approach can only be implemented in a central controller which needs intensive communications across the whole MG, and the convergence of CKF necessitates MG models with high accuracy. A small signal model of a DC MG feeding CPLs is obtained in [63]. The model is utilized to examine the equilibrium existence of the DC system and predict the MG qualitative behavior around a given equilibrium. However, the method in [63] requires complete information of a system with known configurations, and it may not adapt to those MGs with high variable structures. To stabilize the DC MG under changing structures, a better choice is to decompose the MG stabilization target into the DU level; as long as each DU is stabilized properly, the entire DC MG could be stable. This concept

is termed as “self-disciplined stabilization” by [64], wherein a passivity based control (PBC) is studied with SSA to reshape converter output impedance, thus increasing the MG damping in the small signal sense. Similar efforts can also be found in [65] where the impacts of DU output current, input voltage and voltage reference on system passivity are all considered. Conceding that SSA is simple and viable, nevertheless, the locally linearized model is only true in the small vicinity of a steady point. However, the DC MG may have changing equilibriums as it incorporates numerous RESs featured by intermittencies and DUs with PnP properties. The above stabilization controllers would not be valid in full operation ranges.

On the contrary, LSA attempts to study the nonlinear system adopting Lyapunov techniques without localized linearization. With this benefit, a MG equipped with the stabilizer designed by LSA can resist large external disturbances such as unexpected faults, hardware protection and load connection/ disconnection, etc. [71]. A Kalman filter (KF) based network impedance estimation method is proposed in [66] to identify the large signal operating region in real time. But this process may increase online computational burdens, and the KF algorithm is also sensitive to system parameters. A LSA stabilizer enabled by a virtual capacitor is reported in [48] to stabilize a DC link. The stabilizer is actually based on fuzzy modeling approaches. It is worth noting that the controllers mentioned in [66] and [48] only consider a single converter model, and they may not be suitable for MG applications since analysis intricacies exponentially increase when the MG constantly scales up. To suppress the underlying resonance of a LCL-type voltage source converter (VSC), an auxiliary large signal stabilizer is employed to ameliorate the VSC control diagram [67]. Nevertheless, only parts of the model states are involved in solving Lyapunov function, and hence, the stabilization of the entire system is not realized. In [68], a virtual impedance control is proposed, and the control method makes a trade-off between the CPL dynamic performances and the output voltage controls of DU systems. Although it helps to alleviate the destabilizing effects of CPL, the nonlinearities of source converters are neglected, which is not feasible in practice. In [69], fuzzy logic is employed to revise current control loop for inverter-dominated AC MG. Despite that fuzzy control law enables inverters to tolerate large disturbance, however,

similar to [68], the controller only considers the linear parts of MG system and converter nonlinearities are unluckily neglected. Moreover, the necessary proof of the system large signal stability is not provided. In [70], a robust voltage control scheme is stated to function in a decentralized way, and the scheme can decently control the bus voltage by rejecting large disturbances. Yet the controller designs substantially hinge on global data collection of the complete MG model through communications. This weakness unfavorably compromises the system scalability, and the centralized controller design process is possibly undermined by single point communication failures. Some other LSA tools such as Brayton-Moser's Mixed Potential and Reverse Trajectory Tracking, can also be found in [71], [72], etc. These tools merely give the attraction domain of a dynamic system in a specified steady state. In addition, a common characteristic of the above LSA methods is that they would be confined to simple model analyses. The complete model of a large-scale system has to be greatly reduced if the LSA is a necessity. For the DC MG with a growing number of sources/loads, these approaches cannot keep pace with the MG evolutions and may suffer from severe difficulties.

To avoid unnecessary compromises to model completeness and make LSA more applicable to the DC MG with amounting complexities, a decentralized composite controller (DCC) is proposed in this chapter to unify both CVM and DM. Each DU, as well as its interfacing converter, constitute a subsystem. For easy explanations, similar to [73], [74]. RESs are emulated as CPSs. These CPSs together with resistive loads and CPLs are merged into the equivalent lumped load which would be fed by DUs. In this context, the electrical coupling of a particular DU subsystem with other subsystems/ loads is firstly estimated by a well-devised high gain observer [75]. Then, instead of directly dealing with the DC MG as a whole, the DCC is individually designed to counteract the observed coupling and simultaneously stabilize the internal states of each subsystem in the large signal sense. By doing so, each DU subsystem is decoupled from one another and operates in an isolated way from the perspectives of control and stability. When those subsystems are interconnected, the global system large signal stability of the entire MG can be achieved by simply ensuring the local stabilities of individual subsystems. Hence, the DCC based stabilization scheme is fully decentralized,

Figure 3.1: Electrical device grouping in a DC MG.

which remarkably enhances the flexibility and scalability of the MG. Besides, the proposed DCC makes a breakthrough that the tradeoff between dynamic model integrity and LSA could be subtly circumvented. Comprehensive comparisons between the DCC and those existing methods have been summarized in Table 3.1, which helps to better illustrate the contribution of DCC.

The remainder of this chapter is organized as follows. First, electrical coupling concepts are elaborated, and the DCC for the unified controls of CVM and DM is presented. Second, the global system large signal stability of the entire MG is theoretically analyzed through Lyapunov techniques. Then the effectiveness of the DCC is vindicated by simulations. Finally, experimental comparisons show the DCC outperforms the traditional PI controller. The results also reveal that the proposed control law can withstand large system disturbances and expand the MG stability margin.

3.2 Device Grouping in DC MG and Coupling Elaboration

3.2.1 Device Grouping

Figure 3.1 plots a generic schematic of an autonomous DC MG wherein all electrical devices are classified into four groups, resistive loads (Rs), CPSs, CPLs and DUs. As explained in Chapter 2, Rs can be directly linked to the DC bus without any interlinking converters. CPSs are referred to RESs, such as solar PV and wind turbines, which are operated MPPT modes to harvest clean energy.

Figure 3.2: Detailed DU configurations feeding the lumped load.

Power electronic loads and motor drives can be viewed as CPLs which absorb power from the DC bus regardless of voltage deviations. It should be noted that CPSs and CPLs stem from power control schemes; their correct operations highly necessitate a stable and reliable DC bus. For this purpose, DUs should be configured to realize the designated bus controls, i.e., CVM and DM, respectively. Proceeding to Figure 3.2, to facilitate the system modeling, CPSs, CPLs and resistors can be amalgamated and expressed as the lumped load P_L which has the same definition to (2.1).

From the small signal point of view, the linearized form of a CPS consists of a positive resistor and a current source. Therefore, as reported in [47], CPSs help to widen the MG stability margin and may also counterbalance the destabilization effects incurred by CPLs. In a practical MG, the power requested by the lumped load should be completely compensated by a single DU or several DUs. This means that, in the case of CPS generations exceeding the total consumption of CPLs and R_s , P_L would be a negative value. The surplus power induced in the system, in principle, should be stored by the ES-based DUs so that unnecessary power losses could be avoided. However, this favorable scenario will be purposely excluded from this chapter as CPSs would not undermine the system stability.

Instead, the subsequent context mainly concentrates on designing the large signal stabilizer for the MG, and hence, worse situations, like P_L being dominated by CPLs, will be considered.

3.2.2 Coupling Elaboration

As emphasized earlier, a DU which has enough capacity for picking up all the loads should be controlled by CVM to minimize bus voltage deviations and improve the overall power quality. For this situation, no additional DU is needed. Taking the first DU in Figure 3.2 as an example, the DU helps to construct a slack DC bus for the MG. This means that the power delivered by the DU subsystem completely depends on P_L variations. The increased/decreased P_L will draw more/less power from the source, which consequently causes the inductor current i_{L1} to rise/fall. In this sense, it is reasonable to conceive that the output power P_{o1} represents the electrical coupling between the DU subsystem and the lumped load.

On the other hand, when a single DU with limited capacity cannot supply the load, multiple DUs should be scheduled and work in DMs (see Figure 3.2). By using droops, all DUs are allowed to participate in bus voltage controls according to their respective power ratings. Similar to the scenario in CVM, for the i th DU subsystem, its electrical coupling with other subsystems and loads, should be quantified as its contributed power based on proportional power sharing rules.

Regarding a particular subsystem with either CVM or DM, if the coupling mentioned above could be precisely estimated and then neutralized in a certain way, the DU subsystem can be virtually segregated from the MG. Thanks to this scheme, system level stabilization task can be decomposed into the stabilization of each subsystem. Concretely, as long as the internal states residing in DU subsystems are individually stabilized in the large signal sense, the global system stability of the whole MG can thus be guaranteed. These original concepts highly feature the proposed DCC, and it will be meticulously explicated from the next section onward.

3.3 Proposed Decentralized Composite Controller

3.3.1 Canonical DU Modeling

As detailed in Figure 3.2, the averaged model of the i th boost converter can be expressed as,

$$\dot{i}_{Li} = \frac{E_i}{L_i} - \frac{1-d_i}{L_i}v_{Ci}, \quad \dot{v}_{Ci} = \frac{1-d_i}{C_i}i_{Li} - \frac{P_{oi}}{C_i v_{Ci}}, \quad (3.1)$$

where i_{Li} and v_{Ci} are the instantaneous inductor current and capacitor voltage. d_i is the duty cycle generated by the controller. E_i denotes the input voltage. Variables accompanied by the subscript “ i ” mean that they are associating with the i th DU subsystem. The average model describes the converter dynamics in the switching period while the high frequency impacts are neglected [76]. The model hence is tenable regardless of different switching frequencies, and this assumption is widely accepted by a plethora of studies.

Observing from (3.1), it is easy to find bilinear terms that couple the control input d_i and the states i_{Li} , v_{Ci} . To cope with this tricky nonlinearity, as indicated by [77], the exact feedback linearization should be performed. With a coordinate transformation, equation (3.1) could be represented by the two new states which are the total energy stored by the converter and the converter input power, respectively. The first state z_{i1} can be constructed as below,

$$z_{i1} = 0.5L_i i_{Li}^2 + 0.5C_i v_{Ci}^2. \quad (3.2)$$

Computing the derivative of z_{i1} yields,

$$\dot{z}_{i1} = L_i i_{Li} \dot{i}_{Li} + C_i v_{Ci} \dot{v}_{Ci} = E_i i_{Li} - P_{oi}. \quad (3.3)$$

Taking $E_i i_{Li}$ as the second state z_{i2} , its dynamic is given as,

$$\dot{z}_{i2} = u_i = E_i \dot{i}_{Li} = \frac{E_i^2}{L_i} - \frac{1-d_i}{L_i} E_i v_{Ci}. \quad (3.4)$$

Combining (3.3) and (3.4), new dynamics can be obtained,

$$\dot{z}_{i1} = z_{i2} + S_i, \quad \dot{z}_{i2} = u_i, \quad (3.5)$$

where $\varsigma_i = -P_{oi}$ denotes the aforementioned coupling imposed by outside electrical components to the i th DU subsystem. u_i is the equivalent control signal, from which the duty cycle d_i in (3.1) can be accordingly derived as,

$$d_i = 1 - \frac{E_i}{v_{Ci}} + \frac{L_i u_i}{E_i v_{Ci}}. \quad (3.6)$$

To realize unified voltage control, the objective of d_i is to drive v_{Ci} stably tracking the voltage reference. However, the scenario would be different with the new state variables. For (3.5), the intention is to design a control input u_i such that z_{i1} enables to practically approach its reference z_{i1r} which is

$$z_{i1r} = 0.5L_i i_{Lir}^2 + 0.5C_i v_{Cir}^2 = 0.5L_i \left(\frac{-S_i}{E_i}\right)^2 + 0.5C_i v_{Cir}^2. \quad (3.7)$$

In (3.7), v_{Cir} represents the output voltage reference. It could be a constant in CVM, or determined by a droop controller in DM. For the latter, v_{Cir} can be written below,

$$v_{Cir} = V_n - m_i P_{oi} = V^* + m_i \varsigma_i, \quad (3.8)$$

where V_n is the nominal DC bus voltage, and m_i is the droop coefficient of the i th DU subsystem. It is essential to emphasize that the input voltage E_i is a measured value given by a voltage transducer. Assuming that the transducer can reflect E_i dynamic with high fidelity, the real-time variation of E_i could be fully materialized in the canonical modeling. Thus, E_i dynamic would not vitiate the subsequent conclusions concerning the MG stabilization made by DCC.

3.3.2 High Gain Observer Design

Comparing (3.1) and (3.5) shows that the inborn nonlinear model of the boost converter has been converted into a linear one, which substantially facilitates the large signal stabilizer design. Unfortunately, dynamics described by (3.7) are affected by ς_i that is exactly the additive inverse of the output power. The presence of ς_i may severely threaten the tracking performances and even impair the system stability. In addition, it is visible from (3.7) that the calculation of reference z_{i1r} also involves the coupling. On these bases, it is imperative to know the precise

value of ς_i and further process it appropriately in the control law. To this end, a high gain observer is devised as the following [75],

$$\begin{cases} \dot{\hat{z}}_{i11} = z_{i2} + \hat{z}_{i12} + l_{i1}\sigma_i(z_{i1} - \hat{z}_{i11}) \\ \dot{\hat{z}}_{i12} = \hat{z}_{i13} + l_{i2}\sigma_i^2(z_{i1} - \hat{z}_{i11}) \\ \dot{\hat{z}}_{i13} = l_{i3}\sigma_i^3(z_{i1} - \hat{z}_{i11}) \end{cases}, \quad (3.9)$$

where $\hat{z}_{i11}$, $\hat{z}_{i12}$, $\hat{z}_{i13}$ are the estimates of z_{i1} , ς_i , $\dot{\varsigma}_i$. $\sigma_i > 1$ is a positive scaling gain which will be identified later. $H_i = \text{Col}(l_{i1} \ l_{i2} \ l_{i3})$ is an observer gain vector with its components being corresponding to the coefficients of a Hurwitz polynomial,

$$p_i(s) = s^3 + l_{i1}s^2 + l_{i2}s + l_{i3}. \quad (3.10)$$

From a practical point of view, P_{oi} has its physical meaning, and it would not go to infinity in the real engineering. Therefore, the derivatives of ς_i should be limited in bounded ranges, which can be mathematically delineated below,

$$\max_{i \leq n, j=1, 2} \left\{ \sup \left| \frac{\partial \varsigma_i^j}{\partial t^j} \right| \right\} \leq D, \quad D \in R_+. \quad (3.11)$$

Combining (3.5) and (3.9) with the denotations $e_{i1} = z_{i1} - \hat{z}_{i11}$, $e_{i2} = (\varsigma_i - \hat{z}_{i12})/\sigma_i$, $e_{i3} = (\dot{\varsigma}_i - \hat{z}_{i13})/\sigma_i^2$, error dynamics can be acquired as,

$$\dot{e}_i = \sigma_i A_i e_i + B_i \ddot{\varsigma}_i, \quad (3.12)$$

where $e_i = [e_{i1} \ e_{i2} \ e_{i3}]^T$ is the error vector. $A_i = [-l_{i1} \ 1 \ 0; -l_{i2} \ 0 \ 1; -l_{i3} \ 0 \ 0]$ and $B_i = [0 \ 0 \ \sigma_i^{-2}]^T$ represent the system matrices. Referring to (3.10), A_i is a Hurwitz matrix. Hence, there must exist a symmetrical and positive definite matrix Q_i satisfying $Q_i^T A_i + A_i Q_i + I = 0$. Next, it will be shown that error dynamics can be stabilized at the origin if σ_i is properly tuned, which suggests that, $\hat{z}_{i11}$, $\hat{z}_{i12}$, $\hat{z}_{i13}$ enable to practically track z_{i1} , ς_i , $\dot{\varsigma}_i$. To this end, constructing a Lyapunov function $V_{ei} = e_i^T Q_i e_i$ whose time derivative along its trajectory is given by,

$$\dot{e}_i = \sigma_i A_i e_i + B_i \ddot{\varsigma}_i, \quad (3.13)$$

where $\varsigma_i = \sigma_i^{-2} \lambda_{\max}(Q_i) D$ and $\lambda_{\max}(Q_i)$ denotes the maximum eigenvalue of Q_i .

With the completion of squares, the following inequality holds,

$$2\gamma_i \|e_i\| \leq \|e_i\|^2 + \gamma_i^2. \quad (3.14)$$

Substituting (3.14) into (3.13) yields

$$\begin{aligned}\dot{V}_{ei} &\leq -(\sigma_i - 1)\|e_i\|^2 + \gamma_i^2 \\ &\leq -(\sigma_i - 1)\lambda_{\max}^{-1}(Q_i)V_{ei} + \gamma_i^2.\end{aligned}\quad (3.15)$$

Defining $\Omega_{\varepsilon i} = \{e_i \in R^3 | V_{ei} \leq \varepsilon_i\}$ where $\varepsilon_i > 0$ is a constant which can be arbitrarily small, it is apparent that $\Omega_{\varepsilon i} \subset R^3$. Noting that σ_i is independent of γ_i , a sufficiently large γ_i can be selected to satisfy

$$\gamma_i^2 \leq 0.5(\sigma_i - 1)\lambda_{\max}^{-1}(Q_i)\varepsilon_i \quad (3.16)$$

Then, for any $e_i \in (R^3 \setminus \Omega_{\varepsilon i})$ and thereby $V_{ei} \geq \varepsilon_i$, (3.15) can be rearranged as

$$\dot{V}_{ei} \leq -(\sigma_i - 1)\lambda_{\max}^{-1}(Q_i)\varepsilon_i + \gamma_i^2. \quad (3.17)$$

With the substitution of (3.16) into (3.17), slightly manipulating (3.17) gives the following

$$\dot{V}_{ei} \leq -0.5(\sigma_i - 1)\lambda_{\max}^{-1}(Q_i)\varepsilon_i < 0. \quad (3.18)$$

As implied by (3.18), the derivative of Lyapunov function for the errors can be rigorously negative in the case of $V_{ei} \geq \varepsilon_i$. Moreover, by scrutinizing (3.16), σ_i and ε_i are inversely correlated. When γ_i keeps unchanged, the increased σ_i leads to the decreased ε_i . Hence, it is possible to adequately magnify σ_i so that ε_i almost equals zero, which means $\Omega_{\varepsilon i}$ can be infinitesimal and consequently e_i can be regulated as small as possible. In this sense, based on (3.9), it is rational to replace ς_i in (3.7) and (3.8) with the estimated value $\hat{z}_{i12}$, which can be expressed as

$$z_{i1r} = 0.5L_i\left(\frac{-\hat{z}_{i12}}{E_i}\right)^2 + 0.5C_i v_{Cir}^2, \quad (3.19)$$

$$v_{Cir} = V_n + m_i \hat{z}_{i12}. \quad (3.20)$$

3.3.3 Decentralized Composite Controller Design

The above context has presented a well-devised observer to estimate the electrical coupling between the i th DU system and the externals. The estimated quantity

can now be employed to accomplish the proposed composite controller design. For that, intermediate states should be introduced first. These states are defined as,

$$\xi_{i1} = z_{i1} - z_{i1r}, \quad \xi_{i2} = (z_{i2} - z_{i2r}) / \beta_i, \quad v_i = (u_i - u_{ir}) / \beta_i^2, \quad (3.21)$$

where $\beta_i > 1$ is a positive scaling factor which will be made precisely later. v_i is an auxiliary control input. z_{i1r} has been given by (3.19). z_{i2r} and u_{ir} are the reference signals for z_{i2} and u_i , which are given below,

$$z_{i2r} = \dot{z}_{i1r} - \hat{z}_{i12}, \quad u_{ir} = \ddot{z}_{i1r} - \hat{z}_{i13}. \quad (3.22)$$

Regarding the first two equations in (3.21), it is evident that z_{i1} and z_{i2} are equal to their references z_{i1r} and z_{i2r} in the case that the intermediate states reduce to zero. Accordingly, the boost converter output voltage v_{Ci} can also be forced to track v_{cir} , which is the ultimate objective of this chapter. For better understanding this scheme, the derivatives of ξ_{i1} and ξ_{i2} can be computed as

$$\dot{\xi}_{i1} = \beta_i \xi_{i2} + \sigma_i e_{i2}, \quad \dot{\xi}_{i2} = \beta_i v_i + l_{i2} \sigma_i^2 e_{i1} / \beta_i. \quad (3.23)$$

To stabilize the above dynamics, v_i could be designed as the linear combination of ξ_{i1} and ξ_{i2} , i.e., $-k_{i1}\xi_{i1} - k_{i2}\xi_{i2}$. k_{i1} and k_{i2} are positive constants. Then the equivalent control u_i as in (3.5) can be expressed as,

$$u_i = -\beta_i^2(k_{i1}\xi_{i1} + k_{i2}\xi_{i2}) + u_{ir}, \quad (3.24)$$

For (3.23), the compact form of the close loop system can be described as

$$\dot{\xi}_i = \beta_i \Lambda_i \xi_i + \Phi_i \quad (3.25)$$

where $\xi_i = [\xi_{i1} \ \xi_{i2}]^T$. $\Lambda_i = [0 \ 1; -k_{i1} - k_{i2}]$ and $\Phi_i = [\sigma_i e_{i2} \ l_{i2} \sigma_i^2 e_{i1} / \beta_i]^T$ are the system matrices. It should be mentioned that all the derivations of z_{i1r} , z_{i2r} and u_{ir} involve the estimated values $\hat{z}_{i11}$, $\hat{z}_{i12}$ and $\hat{z}_{i13}$. These values will eventually appear in the duty cycle expression with the substitution of u_i in (3.24) into (3.6), which gives rise to the formation of “composite controller”. With this controller, the impacts of coupling ς_i on tracking performances of the system (3.5) can be nearly eliminated. Moreover, the proposed controller is completely decentralized which only contains the local state information of the

Figure 3.3: Control diagram of the proposed DCC for unified voltage control.

i th DU subsystem. Hence, the flexibility, reliability and PnP functionality of the whole system can be considerably fortified. The detailed control diagram of the DCC are illustrated in Figure 3.3.

3.3.4 Global System Stability in the large signal Sense

It has been outlined that the DCC allows large signal stabilization for the entire DC MG. The main feature of the proposed controller is that the global system stability in the large signal sense can be ensured if all subsystems are individually stabilized. To justify these discussions, relevant theoretical analyses will be provided in this subsection, which could be divided into two steps.

Step 1: In the entire DC MG system, any trajectory of all the intermediate states will be uniformly bounded.

For the i th close loop subsystem (3.25), choosing a Lyapunov function $W_i = \xi_i^T P_i \xi_i$ where P_i is a positive definite and symmetrical matrix subjected to $P_i^T \Lambda_i + \Lambda_i P_i + I = 0$, the derivative of W_i is computed as,

$$\begin{aligned} \dot{W}_i &= \beta_i \frac{\partial W_i}{\partial \xi_i^T} \Lambda_i \xi_i + \frac{\partial W_i}{\partial \xi_i^T} \Phi_i = -\beta_i \|\xi_i\|^2 + 2\xi_i^T P_i \Phi_i \\ &\leq -\beta_i \|\xi_i\|^2 + 2\sqrt{\Delta_i} \|\xi_i\|, \end{aligned} \quad (3.26)$$

where $\sqrt{\Delta_i} = \lambda_{\max}(P_i) \|\Phi_i\|$ and $\lambda_{\max} P_i$ is the maximum eigenvalue of P_i . Similar to (3.14), manipulating (3.26) yields,

$$\dot{W}_i \leq -(\beta_i - 1) \|\xi_i\|^2 + \Delta_i. \quad (3.27)$$

With regard to the MG in Figure 3.2, a Lyapunov function for the whole system can be written as

$$W = \xi_\Gamma^T P \xi_\Gamma = \sum_{i=1}^n W_i \quad (3.28)$$

where $\xi_\Gamma = [\xi_1^T \cdots \xi_i^T \cdots \xi_n^T]^T$ and $P = \text{diag}\{P_1 \cdots P_i \cdots P_n\}$.

The derivative of W is calculated below,

$$\begin{aligned} \dot{W} &\leq - \sum_{i=1}^n \{(\beta_i - 1)\|\xi_i\|^2\} + \sum_{i=1}^n \Delta_i \leq -(\beta - 1)\|\xi_\Gamma\|^2 + \Delta \\ &\leq -(\beta - 1)\lambda_{\max}^{-1}(P)W + \Delta \end{aligned} \quad (3.29)$$

where $\beta = \min\{\beta_i\}$, $\Delta = n \cdot \max\{\Delta_i\}$. $\lambda_{\max}(P)$ is the maximum eigenvalue of P . By analogy with (3.15) (3.16), for any constant $\delta > 0$, formulating a set $\Omega_\delta = \{\xi_\Gamma \in R^{2n} | W \leq \delta\}$, it is undoubtable that $\Omega_\delta \subset R^{2n}$. A sufficiently large β can be chosen to satisfy

$$\Delta \leq 0.5(\beta - 1)\lambda_{\max}^{-1}(P)\delta. \quad (3.30)$$

Then substituting (3.30) into (3.29) results in

$$\dot{W} \leq -(\beta - 1)\lambda_{\max}^{-1}(P)(W - 0.5\delta). \quad (3.31)$$

In what follows, it will be certified that, for any initial state $\xi_\Gamma|_{t=0}$ confined in $\Omega = R^{2n} \setminus \Omega_\delta$, i.e., $W \geq \delta$, the trajectory of ξ_Γ will be unexceptionally captured by Ω_δ .

If this statement is not true, there must exist a finite time instant $t_f > 0$ such that $W|_{t=0} < W|_{t=t_f}$ and $\dot{W}|_{t=t_f} \geq 0$. But in the duration of $t \in [0, t_f)$, all components in ξ_Γ are well defined. $\dot{W}$ in (3.31) will always be a negative value, which results in the contradiction of $0 \leq \dot{W}|_{t=t_f} < 0$. Therefore, finite-time escaping phenomena would not occur, and ξ_Γ is uniformly bounded.

Step 2: All the intermediate states can be practically regulated at the origin, and therefore, the global system large signal stability is guaranteed.

For $\xi_\Gamma \in \Omega$ and $W \geq \delta$, (3.31) can be further modified as

$$\dot{W} \leq -0.5(\beta - 1)\lambda_{\max}^{-1}(P)\delta < 0. \quad (3.32)$$

It can be seen from (3.32) that, the DC MG which comprises DU subsystems has a Lyapunov function with a negative derivative, and hence, the MG is a stable system. Moreover, note that β is inversely related to δ , as suggested by (3.30). Given an invariant Δ , it is feasible to deliberately enlarge β such that δ nearly converges to zero. Hence, Ω_δ could be regulated to be arbitrarily small, and ξ_Γ is almost stabilized at the origin. As for the i th DU subsystems, z_{i1} , z_{i2} and v_{Ci} will practically track the references z_{i1r} , z_{i2r} and v_{Cir} . In this sense, the output voltage controls of those subsystems have been realized. It is worth mentioning that, as observed from (3.21), reference values (v_{Cir} and z_{ir}) are only incorporated in the intermediate state calculations, and they do not involve the analyses from (3.26) to (3.32). Therefore, in theory, the large signal stability of the overall system would not be affected no matter whether MG is in CVM or DM. It should be noted that the proposed large signal stabilizer can be extended to other types of DC/DC converters, such as buck converters and buck-boost converters. As long as the converter systems are expressed into the canonical forms, the high gain observers and high gain controller can be directly utilized, and stability analyses resemble the process in this section.

3.4 Simulations for Parameters Tuning

Unlike the PI controllers that could be tuned in the frequency domain, the proposed DCC formulates the control law for DU converters straightly in the time domain. To select the relevant parameters of the high gain observer (3.9) and the composite controller (3.24), corresponding parameter tuning procedures will be provided in this section. Focusing on the i th DU in Figure 3.2, no matter whether the DU works in CVM and DM, the output voltage reference is unexceptionally conveyed to the DCC who further forces v_{Ci} to track the desired value. For this reason, only CVM would be utilized for the parameter tuning, and the well-tuned quantities can be extended to DM without any change.

For the Hurwitz polynomial in (3.10), a characteristic function with multiple poles assigned as -1 can be formed below

$$(s + 1)^3 = s^3 + 3s^2 + 3s + 1. \quad (3.33)$$

Matching the coefficients in (3.10) and (3.33) results in

$$l_{i1} = 3, l_{i2} = 3, l_{i3} = 1. \quad (3.34)$$

For the composite control law, k_{i1} , k_{i2} in equation (3.24) also subject to a Hurwitz polynomial

$$p_i(s) = s^2 + k_{i2}s + k_{i1}. \quad (3.35)$$

Similar to (3.33), a second-order characteristic function with repeated poles of -1 can be given as

$$(s + 1)^2 = s^2 + 2s + 1. \quad (3.36)$$

By means of coefficient matching, k_{i1} and k_{i2} could be easily determined as 1 and 2 separately.

Then output power observing performances with different observer gains ($\sigma_i=1000, 2000, 3000, 4000, 5000$) under dissimilar control gains ($\beta_i=500, 750, 1000$), are shown in Figure 3.4 (a)-(c). It is apparent from Figure 3.4 (a) that the decreased σ_i leads to the slow observer dynamic. The tracking duration can be estimated as 1 ms with σ_i of 5000, whereas the convergence time rises to 12 ms when σ_i reduces to 1000. Comparing Figure 3.4 (a)-(c) reveals that performances of the high gain observer are little affected when β_i is differently set, which means the tuning of σ_i is almost decoupled from β_i variations. Proceeding to Figure 3.4 (d), output voltage transients are recorded under heterogeneous β_i settings (450, 550, 650, 850, 1000) while σ_i is fixed at 3000. The larger β_i causes the shorter voltage transition period. A long duration of about 15 ms can be observed with β_i being selected as 450, whereas the voltage transient state accounts for only 6ms when $\beta_i=1000$. Note that the high gain observer offers output power estimations for the state feedback control law, as in (3.21) (3.24). The observer is supposed to bear faster dynamics than the control law. For instance, the settling times of the state feedback control law and the observer could be identified as 10 ms and 2 ms. The requirement, according to Figure 3.4, can be satisfied by choosing σ_i and β_i as 3000 and 650 respectively. This set of parameters would be further utilized in the subsequent simulations and experimental verifications.

Figure 3.4: Parameter tuning of σ_i and β_i .

Figure 3.5: Experimental setup.

Figure 3.6: Two boost converters feeding the lumped load P_L .

Table 3.2: System parameters for DC MG.

Parameter	Description	Value
V_n	Nominal bus voltage	170 V
L_1, L_2	Converter inductors	2 mH
E_1, E_2	Input voltage	100 V
C_1, C_2	Converter capacitors	470 μ F
f_{sw}	Switching frequency	20 kHz
l_{11}, l_{12}, l_{13}	Observer gains for converter #1	3, 3, 1
l_{21}, l_{22}, l_{23}	Observer gains for converter #2	3, 3, 1
σ_1, σ_2	Observer scaling gains	3000
k_{11}, k_{12}	DCC parameters for converter #1	1, 2
k_{21}, k_{22}	DCC parameters for converter #2	1, 2
β_1, β_2	DCC scaling gains	650

Table 3.3: CVM Tests. (only converter #1 used)

	Voltage reference	Load
Case 1	v_{C1r} : 170 V	CPL: 50 W $\rightarrow$ 350 W
Case 2	v_{C1r} : 170 V $\rightarrow$ 160 V v_{C1r} : 170 V $\rightarrow$ 150 V	CPL: 550W
Case 3	v_{C1r} : 170 V	CPL: 550W $\rightarrow$ 650W

Table 3.4: DM Tests. (both two converters used)

	Droop coefficient	Load
Case 4	$m_1 = m_2 = 0.01$	CPL: 100 W $\rightarrow$ 700 W
Case 5	$m_1 = m_2 = 0.02$ $m_1 = m_2 = 0.04$	CPL: 100 W $\rightarrow$ 700 W
Case 6	$m_1 = m_2 = 0.01$	CPL: 100 W $\rightarrow$ 1000 W

Figure 3.7: Case 1: CVM with CPL from 50W to 350W.

3.5 Experimental Verifications

3.5.1 CVM (Constant Voltage Mode)

Based on the established hardware platform, CVM by only using converter #1 is tested.

To corroborate the effectiveness and feasibility of the DCC, an in-house experimental platform is built up, as displayed in Figure 3.5. The one-line diagram has been given in Figure 3.6. The platform consists of a Dspace 1006 controller, two boost converters, the lumped load (a resistive load and an electronic load). Related parameters are summarized in Table 3.2. The inductances and capacitances are chosen as 2 mH and 470 μ F, according to the design guideline in [76]. There are two small resistors of 0.2 Ω installed between converter terminals and DC bus to avoid the rush current induced by the difference of terminal capacitors. As mentioned earlier, resistive loads and CPSs would not deteriorate the MG stability. The most challenging case is that the lumped load is a pure CPL. In the experiment phase, the electronic load acting as a CPL is integrated to the DC bus, and for operating safety, the resistive load is also incorporated into the system. It should be noted that the damping effect devoted by the resistor is minor because the resistance is purposely tuned to be excessively large, i.e. 1698 Ω . Hence, the CPL still overwhelmingly dominates the lumped load. On these bases, as in Table 3.3 and Table 3.4, 6 cases are arranged to compare the voltage control performances of the converters under the DCC and the PI. Experimental results will show that the former method helps to stabilize the DC MG and contributes larger operation range than the latter one in both CVM and DM.

A: Case 1 This case investigates regular system operations in CVM. The key parameters in the DCC have been provided in Table 3.2. PI parameters (voltage loop: $k_p=0.1$, $k_i=15.75$; current loop: $k_p=0.775$, $k_i=24.35$;) are selected complying to the design standards reported in [77]. The parameters are further adjusted slightly so that voltage deviations resulted from load changes are identical to that with the DCC. Hence, it is fair to conduct the necessary comparisons of DCC and PI controllers.

Figure 3.8: Case 2: CVM with v_{C1r} from 170V to 160V.

As shown in Figure 3.7, DC bus is rigorously regulated at 170 V at the beginning. When a sudden CPL step-up from 50 W to 350 W is activated, identical voltage drops (5 V) are observed for both PI and DCC controls. It is conspicuous that the DCC is competent to restore the bus voltage to its nominal value (170 V) within about 10 ms, whereas the voltage recovery time of PI is estimated as 70 ms. A slight overshoot on the inductor current i_{L1} (see Figure 3.7 (a)) is due to the fact that the DCC endeavors to transfer more power from the source to the load for shortening the transient duration. Hence, the load-changing effects on the bus voltage can be minimized.

B: Case 2

As understood from [78], a DC system integrated with an invariant CPL and a resistor may suffer from more serious stability problems when the bus voltage is lowered. Motivated by this assertion, different from case 1 where MG voltage is maintained strictly at 170 V, case 2 examines the system stability given that the voltage reference declines while the CPL maintains at a comparatively high level

Figure 3.9: Case 2: CVM with v_{C1r} from 170V to 150V.

(550 W). As shown in Figure 3.8, when v_{C1r} steps down from 170 V to 160 V, the MG is stable under both DCC and PI controls. However, transient oscillations of the bus voltage and the inductor current are found in the PI regulated system. In the situation that v_{C1r} reduces from 170 V to 150 V, as recorded in Figure 3.9, the system with the PI unfortunately collapses, whereas the DCC stabilizes the DC bus voltage at the targeted value.

C: Case 3

Following case 1, case 3 studies a scenario that the CPL abruptly surges from 50 W to 650 W, and experimental results have been shown in Figure 3.10. For this atrocious case, with the proposed DCC, although a voltage drop of 10V occurs at the instant of a load change, the bus voltage quickly recovers to 170 V in a short time, which means voltage regulation has been realized. In contrast, the PI controller fails to survive this huge CPL increase, and the entire MG system is destabilized.

Summarily, the results in case 2 and case 3 experimentally consolidates the

Figure 3.10: Case 3: CVM with CPL from 50W to 650W.

theoretical analyses that, the DCC can extend the system operating margin and attain the large signal stability. By using DCC, considerable equilibrium changes are permitted by the MG, and thus, operation flexibility can be markedly raised. Besides, for the lab setup, the nominal power of the DU boost converter is 560 W with the design margin of 20%. In case 3, the CPL with 650W has already exceeded the nominal value, which means the DCC still works elegantly even in overloading condition.

3.5.2 DM (Droop Mode)

Subsequent to CVM tests, MG operations involving two converters working in DMs are studied in this part.

A: Case 4

Figure 3.11 shows experimental results with the droop coefficients of two converters set as 0.01 when the CPL steps up from 100 W to 700 W. In this

Figure 3.11: Case 4: DM with $m_1 = m_2 = 0.01$ and CPL from 100W to 700W.

case, DU would evenly share CPL variations. For DCC and PI controls, they respond to the identical droop controller. The same voltage drops of around 7 V are observed when the load increase is triggered. The DC bus reaches a new level which is 166.5 V. Differences lie in that the DCC spends 10 ms on the bus voltage transition, whereas the PI controller takes estimated 50 ms. Similar to case 1, inductor overshoots are found during system transitions by employing the DCC. These phenomena could be well explained by exigent power transfer enforced by the DCC from the source to the load. As a result, more rapid system dynamics can be acquired.

B: Case 5

It is important to reiterate that droop controllers intentionally enlarge the output impedances of the converters, which is a compromised solution to sidestep the voltage conflicts of multiple sources. The increased droop gains may induce more power interactions between CPL and sources, thus possibly aggravating the MG stability. For this reason, different from ordinary operations shown by

Figure 3.12: Case 5: DM with $m_1 = m_2 = 0.02$ and CPL 100W to 700W.

case 4, case 5 would explore the impacts of droop gain fluctuations on the MG performances.

With reference to Table 3.4, droop gains are chosen as 0.02 for the two converters at first. The bus voltage fixes at 169 V when the CPL is scheduled as 100 W (see Figure 3.12). When the CPL unexpectedly rises to 700 W, both DCC and PI controls can stably regulate the bus voltage at around 163 V. It should be noted that the PI controller causes transient voltage and current oscillations, while the proposed DCC allows a smoother system transition. Continuing to increase the droop gains to 0.04, relevant results have been shown in Figure 3.13. The PI controller based MG is unstable under the CPL step-up, whereas the DCC regulates the bus voltage stabilized at a new value that is 156 V.

C: Case 6

Subsequent to case 4, in this case, droop gains are maintained invariant as 0.01. The overall system stabilities regulated by both DCC and PI controllers are compared when the CPL brutally grows to 1000 W. As plotted in Figure 3.14 (a),

Figure 3.13: Case 5: DM with $m_1 = m_2 = 0.04$ and CPL 100W to 700W.

although voltage drop of 8 V is inspected in the transient state, the DCC stabilizes the DC bus at 165 V after the CPL step-up is enabled. Unluckily, this cruel load increase cannot be tolerated under the PI control case, and thus, the whole MG is unstable, as depicted in Figure 3.14 (b).

Conclusively, the observations reported by case 5 and case 6 again validate that the DCC proposed in this chapter is a large signal stabilizer. It can weather large system disturbances and ensures stable operations in a wider range.

From the six cases in the experimentation, the DCC prevails over the PI control in terms of faster bus voltage transition and wider system operating range. Although the PI may engender the overshoot/drop of current/voltage being within allowable limit, the PI control has its inherent disadvantages such as neglecting parts of dynamics when establishing DU models and failing to address the fiendish coupling effects among DUs. Differently, the observer synthesized in the DCC helps to rapidly and accurately estimate the couplings which are further involved in the composite control law. This maneuver decouples a particular DU from

neighboring devices, from the perspective of control and stability. Moreover, the DCC ensures the negative derivative of each DU Lyapunov function, thus resulting in the large signal stability. By adopting DCC, no system dynamics are overlooked, and the large signal stability holds no matter how far the initial values of the DU internal state are away from the expected ones.

Figure 3.14: Case 6: DM with $m_1 = m_2 = 0.01$ and CPL 100W to 1000W.

3.6 Summary

In this Chapter, a novel DCC is proposed to serve as a large signal stabilizer for a DC MG system. For a certain subsystem, the electrical coupling imposed by the externals in the DC MG can be estimated by a properly designed high gain observer. Then the coupling can be counteracted by the DCC, which enables the DU subsystem to virtually work in a separated manner. On these bases, the stabilization task of the whole MG system could be dissembled into the stabilizations of single subsystems. Specifically, the global system large signal

stability would be attained as long as the internal states inside each DU subsystems are appositely stabilized. Therefore, the proposed controller is decentralized, which escalates the MG flexibility, reliability and PnP functionality to a large measure. Besides, by using the DCC, the compromises between system model completeness and LSA can be elegantly shunned. Related theoretical analyses based on Lyapunov functions are also provided. Comparative studies performed on a hardware platform demonstrate that the DCC takes advantages over the traditional PI by shortening the MG transition duration and broadening the system stability margin.

Chapter 4

A Distributed Power Management Strategy for Multi-Paralleled Bidirectional Interlinking Converters in Hybrid AC/DC Microgrids

In spite of the wide adoptions of DC enabling techniques, an undeniable fact is that AC power conversion still plays a dominant role in modern electrical systems. In this context, Chapter 4 further integrates the DC MG examined in Chapter 2 and Chapter 3 with an AC MG, thus giving rise to a hybrid AC/DC MG. The hybrid system has been proven a promising solution to merge the advantages of both AC and DC power conversions. For a given hybrid MG, BICs enable flexible power interactions between AC and DC subgrids. In each subgrid, power sharing among diversified sources has been effectively realized by droop controllers. These power sharing concepts can also be extended to BIC applications. To this end, a distributed power management strategy (DPMS) is proposed for multi-paralleled BICs in the hybrid MG to avoid the overstress of a single BIC. In this strategy, each BIC is assigned with a well-devised localized distributed controller (LDC) which generates the respective power reference for the BIC. By using the LDC, BICs are allowed to exchange information with one another in the distributed communication graph. The power interactions between AC and DC subgrids can be proportionally allocated to BICs based on their different power ratings in a fully distributed manner, which achieves the intended BICs distributed power sharing in this thesis. Then the system reliability and scalability are significantly improved. Meanwhile, accurate global power sharing among all AC and DC sources in the MG would also be attained.

4.1 Introduction

Hybrid AC/DC MGs have become increasingly popular since they consolidate the advantages of both AC and DC MGs. AC and DC sources/loads can be coupled to the corresponding buses for reducing the power conversion stages and minimizing system costs, as already explained in Chapter 1. Around the world, several projects on hybrid AC/DC systems have been demonstrated, such as Hachinohe microgrid in Japan [79], Bronsbergen Holiday Park Netherland [80], Kythnos Greece [81] and European Supergrid [82], etc. For a certain hybrid MG, its BIC works as a critical unit bridging AC and DC buses. Nonetheless, it is worth mentioning that the rising number of distributed energy resources integrated into the MG will unavoidably result in the capacity increase of each subgrid. This would bring about larger power interactions between the two subgrids, and more power may flow through the BIC. To meet the requirements of growing subgrid capacities, instead of frequently upgrading a single BIC, a more likely way is to deploy multiple BICs connected in parallel to stack up the power exchange capacity between AC and DC subgrids. By doing so, the power flowing from the AC subgrid to the DC one or vice versa can be cooperatively shared by these BICs. Hence, the MG scalability and redundancy can be improved.

Unlike the control schemes for the single BIC in a hybrid system, power management strategies of the multi-paralleled BICs involves more challenges. In the published literature, most studies endeavor to mitigate circulating currents (CCs) among BICs since the CCs may cause extra power loss and even damage power devices. Many effective control algorithms have been proposed. For example, a common inductor is employed to form a high zero sequence impedance which significantly reduces the CCs [83]. Generation schemes of the CCs are exhaustively investigated in [84], and the CCs can be almost eliminated by adding a PI controller in the zero channel. In [85], high frequency transformers are integrated into a modular inverter system. With well-designed current controllers, the system CCs can be successfully suppressed. From the perspective of modulation, some other methods based on the space vector modulation can also be found in [86], [87] for desirable CCs mitigations.

Apart from the CCs problem that has been commendably resolved in early

studies, power sharing among interfacing converters is also an important issue in the hybrid MG. In the DC subgrid, voltage-power ($V_{dc} - P_{dc}$) droop controllers ensure that the load power can be proportionally shared by distinctive sources with different power ratings [53]. Notice that V_{dc} , for easy explanations in the hybrid system, represents the DC bus voltage, which has the same definition to V_b in Chapter 2 and Chapter 3. In the AC network, regulated by the frequency-active power ($f_{ac} - P_{ac}$) droops, AC sources pick up loads and release active power in proportion to their ratings with the synchronization of f_{ac} . The same principle also applies to the reactive power (Q_{ac}) sharing by simply choosing the drooped quantity as voltage magnitude (V_{ac}) [88]. However, these control methods are parochially confined to the pure AC or DC subgrid. They cannot be directly applied to the power allocation among BICs without any modification.

To smoothly extend the power sharing concepts into the parallel BICs configuration, diverse control schemes have been analyzed. These schemes can be generally classified into centralized control and decentralized control. The former requires a central controller to communicate with all in-service BICs and broadcast power references to them. In [89], a current sharing diagram for a parallel DC-DC converter system is referred as the master-slave control. But the diagram de facto belongs the centralized control since the master controller serves as a central controller in the system. In [90], a circular chain control (3C) method is proposed for an AC MG. Yet 3C does not consider the bidirectional power flow. The control may also experience cascaded faults when an inverter is down or a commutation link fails. In [91], an advance secondary control is scrutinized for recovering the frequency and voltage in both AC and DC subgrids, whereas proportional power sharing among all sources is reserved. Taking into account of different operating modes in the MG, a hierarchical framework in [92] intends to achieve the optimal operation of the parallel converter interfaces. However, the centralized control is widely criticized to be vulnerable to single point of failures. It may not be suitable for systems that have high reliability requirements.

In contrast, the decentralized control is much preferred since the power management of BICs is independent of communication networks. In [93], although it is claimed that no communication is used, the control approach needs to know in advance the total power capacity of the whole hybrid MG. The approach

Figure 4.1: An autonomous hybrid AC/DC MG with multi-paralleled BICs.

may not be applicable to the system with real-time PnP operations. In [94], a DC MG is integrated into the utility grid via several BICs. But the droop controls are assigned to the BICs of the hybrid MG to regulate the DC subgrid bus voltage. These BICs are only allowed to transfer power from the AC subgrid to the DC one, which unnecessarily deprives the BICs of bidirectional power flow functionalities. A distributed scheme in [95] is applied to adaptively modify the droop gains in a DC MG. Yet the scheme may not fit the BIC structures since it needs the information of AC current around 50 Hz being propagated in communication infrastructures. This maneuver would scarify the signal fidelity and result in imprecise current sharing, especially when low-bandwidth communication is employed. A unified control documented in [96] asserts that it can realize proportional power allocations for BICs. However, this unified control requires the total equivalent droop gains of AC and DC subgrids, which would not be realistic since the overall droop gains may vary with the integrations of new distributed sources. Additionally, the unified method fails to obtain accurate global power sharing (GPS) among AC and DC sources due to the mismatched line impedances between BICs and the DC bus. The autonomous operation scheme proposed in [97] introduces novel droop controls for BICs. But the accurate GPS may not be ensured since no scheme enforces the loading situations in two subgrids to be the same in steady state.

In fact, for a MG functioning for the long run, its BICs, which may be distributed far away from each other, would not be identical in terms of manufac-

Figure 4.2: Simplified schematics of the AC subgrid and the DC subgrid.

turers, power ratings, and component parameters, etc. Yet all centralized controls discussed above overlook the discrepancies of the BIC power ratings, and simply focus on the equal power sharing among BICs. Moreover, a central controller has to be re-programmed if a new BIC needs to be installed, which compromises the system efficiencies and PnP properties. It is conceded that decentralized controls allow BICs to coordinately share the power flow. However, as in [94], [97], droop controllers only define the power direction references only from AC to DC or from DC to AC. Bidirectional power flows are not considered and will thus not happen in real operations. Single-way power flow caused by droops stands as a barrier for the MG system expansion. The power sharing exactness can also be impaired by variant system parameters such as output impedances of the BIC DC ports.

To address above the ticklish problems, a distributed power management strategy (DPMS) is proposed in this chapter for multi-paralleled BICs operation in a hybrid AC/DC MG. In the proposed strategy, all BICs are equipped with localized distributed controllers (LDCs). By using the LDCs, each BIC is allowed to exchange information with one another in a more flexible communication graph. It is worth noting that the deviations of f_{ac} and V_{dc} help to determine the loading conditions of both subgrids. All BICs can detect a common f_{ac} prevailing over the AC network, but the exact V_{dc} would be imperceptible because of various line impedances between BICs and the DC bus. To balance power generations in the two subgrids and reduce communication burdens, only one BIC (defined as the leader) is allowed to receive the V_{dc} information sent by a sensor mounted on the DC bus. The remaining BICs (referred to as the followers) autonomously reach consensus with the leader BIC such that global load balancing between AC and DC subgrids can be exactly achieved. Meanwhile, the bidirectional power flow

would be precisely shared by all BICs in accordance with their different capacities, and the overstress of a particular BIC could be avoided. Furthermore, the proposed LDCs facilitate the modularized system design. Once the controller of a newly-installed BIC is locally tuned, without reporting to a central controller, the BIC can directly join the BICs community and contribute to the power transmission. This merit is substantially favored in practical engineering with the ease of automatic PnP.

The remainder of this chapter is organized as follows. First, the droop controls in AC and DC subgrids are shortly illustrated and the bidirectional power flow on BICs is analyzed. Second, the novel LDC is proposed for multi-paralleled BICs power sharing. An efficient design guideline for the flexible implementation of LDCs is also presented. Third, the convergence of DPMS under distributed control framework is vindicated. Finally, controller hardware-in-loop (HIL) tests validate the effectiveness of the DPMS.

4.2 Individual Operations of AC and DC Subgrids

Figure 4.1 shows a generic schematic of an autonomous hybrid AD/DC MG. There are RESs, ESs and diverse loads. Diesel generators work as the power generations for both AC and DC subgrids. Resistive loads (R_s) can be directly linked to AC and DC buses without any interfacing devices, as already expounded in previous chapters. Motor drives and those power electronic loads can be CPLs because of their tightly-regulated consumed power. Multiple BICs connected in parallel form a BICs community which interlinks the two subgrids. The simplified layouts of individual subgrids are demonstrated in Figure 4.2. In each subgrid, the energy resources except RESs are referred as DUs and operate under droop controls. RESs, CPLs, and R_s are combined as the lumped load, as defined in (2.1). P_{Lac} and P_{Ldc} are respectively the lumped load in AC and DC subgrids.

4.2.1 AC Subgrid Control

Borrowed from classical power systems, $f_{ac} - P_{ac}$ and $V_{ac} - Q_{ac}$ droop controllers are applied in the AC subgrid to regulate the AC bus. These droops can be

expressed as follows

$$f_{ac} = f_{ac \max} - a_{Pi} P_{aci}^M, \quad i \in [1, m], \quad (4.1)$$

$$V_{ac} = V_{ac \max} - a_{Qi} Q_{aci}^M, \quad i \in [1, m], \quad (4.2)$$

where $f_{ac \max}$ and $V_{ac \max}$ are the allowable maximum AC frequency and maximum voltage amplitude. m represents the total number of AC DUs. a_{Pi} and a_{Qi} are the droop coefficients,

$$a_{Pi} = \frac{f_{ac \max} - f_{ac \min}}{P_{ac \max}}, \quad a_{Qi} = \frac{V_{ac \max} - V_{ac \min}}{Q_{ac \max}}. \quad (4.3)$$

In (4.1) and (4.2), P_{Maci} and Q_{Maci} are the measured power processed by LPFs. Their dynamics are

$$\dot{P}_{aci}^M = \omega_{LPF} (P_{acj} - P_{aci}^M), \quad \dot{Q}_{aci}^M = \omega_{LPF} (Q_{acj} - Q_{aci}^M) \quad (4.4)$$

where ω_{LPF} is the cutoff angular frequency of LPFs. P_{aci} and Q_{aci} are the real active and reactive powers.

In an AC system with complex line impedance, the controls of active and reactive powers may not be fully decoupled. However, the virtual impedance techniques in [98] are recommended to tune the AC DU output impedances being mainly inductive, so that droop controls governed by (4.1) and (4.2) are still tenable. For the implementation of virtual impedance, it is highly suggested to only counteract the resistive component of AC line impedance while remaining the inductive part being the original value. By doing so, the MG stability margin would not be markedly affected. Moreover, there is only one prevailing frequency throughout the AC network. Each AC DU proportionally contributes to the load according to its power rating. However, the error of the reactive power sharing will always exist because different terminal impedances between DUs and AC bus may cause different voltage drops. Control methods regarding the reactive power sharing improvements are documented in the literature [99], [100]. Yet these methods will not be discussed here since reactive power is only confined in the AC subgrid and would not exist in the DC part. Instead, this chapter focuses more on the power flow coordination between AC and DC subgrids.

4.2.2 DC Subgrid Control

Due to the absence of f_{ac} and Q_{ac} , the DC subgrid has a simpler droop scheme

$$V_{dc} = V_{dc \max} - d_j P_{dcj}^M, \quad j \in [1, n], \quad (4.5)$$

where $V_{dc \max}$ represents the maximum output voltage of the j th DU. d_j is the DC droop coefficient as described below

$$d_j = (V_{dc \max} - V_{dc \min}) / P_{dcj \max}, \quad (4.6)$$

The dynamic of ΔP_{dcj}^M is written in (4.7) with P_{dcj} being the real DC power,

$$\dot{P}_{dcj}^M = \omega_{LPF} (P_{dcj} - P_{dcj}^M). \quad (4.7)$$

Similar to the reactive power sharing in the AC subgrid, the power allocation among the DC DUs could also differ from the designated proportional distribution. This is caused by the terminal impedance disparities between DUs and DC bus. However, the intention of this chapter is to realize the distributed power management of multi-paralleled BICs and GPS in the hybrid MG. The effects of terminal impedances on system performances are assumed to be minor and can be ignored. It is worth noting that, not only do LPFs inbuilt in droop controllers help to filter the measured powers, they also contribute emulated inertia to both AC and DC subgrids for smoothing f_{ac} and V_{dc} variations. When a DU is controlled with a LPF, it tends to burst large power to smooth the variations of f_{ac} and V_{dc} , thus helping to improve power quality in AC and DC subgrids.

4.3 Distributed Power Management Strategy

4.3.1 Analysis of Power Flow on BICs Community

For both AC and DC networks, droop schemes give rise to the floating f_{ac} and V_{dc} which can be used to determine AC and DC loading conditions (LCs). Referring to (4.1) and (4.5), the large drop of f_{ac} (or V_{dc}) indicates that the AC (or DC) network is heavily loaded, whereas f_{ac} (or V_{dc}) would increase in the case of light

load. In the hybrid MG, AC and DC subgrids coexist. They are interconnected by the BICs community which aims to coordinate the power generations between the two subgrids. Concretely, if the AC LC is detected being higher than the DC LC, then BICs will extract the power from the AC subgrid and inject it into the DC one. Conversely, the power will be channeled from the DC subgrid to the AC one when the DC LC exceeds the AC LC. By doing so, the AC and DC LCs will be equalized in steady state. All DUs in the hybrid MG proportionally supply the power to the lumped load, which means GPS has been accomplished [49].

The combined droop equations in the separated AC and DC subgrids can be written below,

$$f_{ac} = f_{ac \max} - aP_{ac}^M, P_{ac}^M = \sum_{i=1}^m P_{aci}^M, P_{ac} = \sum_{i=1}^m P_{aci}, \quad (4.8)$$

$$V_{dc} = V_{dc \max} - dP_{dc}^M, P_{dc}^M = \sum_{j=1}^n P_{dcj}^M, P_{dc} = \sum_{j=1}^n P_{dcj}, \quad (4.9)$$

It is worth mentioning that a and d in (4.8) and (4.9) are the equivalent droop coefficients which are expressed as follows

$$a = \left(\sum_{i=1}^m a_{Pi}^{-1} \right)^{-1} = \frac{f_{ac \max} - f_{ac \min}}{P_{ac \max}}, P_{ac \max} = \sum_{i=1}^m P_{aci \max}, \quad (4.10)$$

$$d = \left(\sum_{j=1}^n d_j^{-1} \right)^{-1} = \frac{V_{dc \max} - V_{dc \min}}{P_{dc \max}}, P_{dc \max} = \sum_{j=1}^n P_{dcj \max}, \quad (4.11)$$

where $P_{ac \max}$ and $P_{dc \max}$ are the maximum active powers of the two subgrids. AC and DC LCs are defined below

$$LC(f_{ac}) = \frac{f_{ac} - f_{ac \max}}{f_{ac \max} - f_{ac \min}}, LC(V_{dc}) = \frac{V_{dc} - V_{dc \max}}{V_{dc \max} - V_{dc \min}}. \quad (4.12)$$

Taking the scenario of $LC(V_{dc}) > LC(f_{ac})$ for example, to achieve the GPS, the difference of $LC(V_{dc})$ and $LC(f_{ac})$ will be processed to generate the active power reference (ΔP_{BICs}) for the BICs community. It should be stressed that, no matter whether the two subgrids are heavily or lightly loaded, as long as $LC(V_{dc})$ and $LC(f_{ac})$ are different, BICs would drive power flowing from the subgrid with

relatively light load to another one. Once BICs are activated, the hybrid MG reaches a new operating point such that $LC(V_{dc})=LC(f_{ac})$. At this point, droop equations given in (4.8) and (4.9) have to be refined considering the involvement of ΔP_{BICs} ,

$$f_{ac} = f_{ac \max} - a \left(P_{ac}^M - \Delta P_{BICs}^M \right) \quad (4.13)$$

$$V_{dc} = V_{dc \max} - d \left(P_{dc}^M + \Delta P_{BICs}^M \right), \quad (4.14)$$

where ΔP_{BICs}^M is the measured value, and the instantaneous BICs power is denoted as ΔP_{BICs} .

Applying LC calculation rules to (4.13) and (4.14) yields,

$$LC(f_{ac}) = \frac{-P_{ac}^M + \Delta P_{BICs}^M}{P_{ac \max}}, \quad LC(V_{dc}) = \frac{-P_{dc}^M - \Delta P_{BICs}^M}{P_{dc \max}}. \quad (4.15)$$

By equating $LC(f_{ac})$ and $LC(V_{dc})$, the power flow on the BICs community can be obtained,

$$\Delta P_{BICs}^M = \frac{P_{ac}^M P_{dc \max} - P_{dc}^M P_{ac \max}}{P_{dc \max} + P_{ac \max}}. \quad (4.16)$$

For the scenario discussed above, the AC subgrid can be emulated as one of DC loads with an AC/DC interface (BICs community). The DC subgrid can be viewed as one of power sources in the AC subgrid. In this regard, ΔP_{BICs}^M should be contributed by all DC DUs and assigned to all AC DUs based on their respective ratings. Similar to (4.13) and (4.14), droops in (4.1) and (4.5) should be modified below

$$f_{ac} = f_{ac \max} - a_{Pi} \left(P_{aci}^M - \Delta P_{BICsi}^M \right), \quad i \in [1, m], \quad (4.17)$$

$$V_{dc} = V_{dc \max} - d_j \left(P_{dcj}^M + \Delta P_{BICsj}^M \right), \quad j \in [1, n], \quad (4.18)$$

where ΔP_{BICsi}^M is the supplementary power received by the i th AC DU. ΔP_{BICsj}^M is the additional power generated by the j th DC DU. To have an explicit view of how power allocation occurs in each subgrid, deviations of f_{ac} and V_{dc} from their maximum values before and after BIC operation can be written as follows,

Before BIC operation:

$$\begin{cases} \Delta f_{ac} = f_{ac \max} - f_{ac} = a_{Pi} P_{aci}^M = a P_{ac}^M \\ \Delta V_{dc} = V_{dc \max} - V_{dc} = d_j P_{dcj}^M = d P_{dc}^M \end{cases}, \quad (4.19)$$

After BIC operation:

$$\begin{cases} \Delta f_{ac} = f_{ac \max} - f_{ac} = a_{Pi} (P_{aci}^M - \Delta P_{BICsi}^M) = a (P_{ac} - \Delta P_{BICs}^M) \\ \Delta V_{dc} = V_{dc \max} - V_{dc} = d_j (P_{dcj}^M + \Delta P_{BICsj}^M) = d (P_{dc} + \Delta P_{BICs}^M) \end{cases}. \quad (4.20)$$

Manipulating (4.19) and (4.20), ΔP_{BICsi}^M and ΔP_{BICsj}^M are given as,

$$\Delta P_{BICsi}^M = \frac{a}{a_{Pi}} \Delta P_{BICs}^M = \frac{P_{aci \max}}{P_{ac \max}} \Delta P_{BICs}^M, \quad \sum_{i=1}^m \Delta P_{BICsi}^M = \Delta P_{BICs}^M, \quad (4.21)$$

$$\Delta P_{BICsj}^M = \frac{d}{d_j} \Delta P_{BICs}^M = \frac{P_{dcj \max}}{P_{dc \max}} \Delta P_{BICs}^M, \quad \sum_{j=1}^n \Delta P_{BICsj}^M = \Delta P_{BICs}^M. \quad (4.22)$$

Substituting (4.10) and (4.11) into (4.20), and further conducting LC calculations, relations among all DUs generation across the overall MG system can be identified below,

$$\begin{aligned} \frac{P_{aci}'}{P_{aci \max}} &= \frac{P_{aci}^M - \Delta P_{BICsi}^M}{P_{aci \max}} = \frac{P_{ac}^M - \Delta P_{BICs}^M}{P_{ac \max}} \\ &= \frac{P_{dcj}'}{P_{dcj \max}} = \frac{P_{dcj}^M + \Delta P_{BICsj}^M}{P_{dcj \max}} = \frac{P_{dc}^M + \Delta P_{BICs}^M}{P_{dc \max}} \end{aligned} \quad (4.23)$$

In steady state, the measured quantities equal the real power values. P_{aci}' and P_{dcj}' are the real active power provided by the i th AC DU and the j th DC DU after BICs community is configured. All DUs in the hybrid MG produce the power proportional to their ratings, which means the GPS is perfectly realized.

4.3.2 Proposed LDC

Given that the multi-paralleled BICs may have different power ratings, the concepts of power sharing in AC and DC subgrids should also be extended to the

Figure 4.3: Multi-paralleled BICs under the proposed DPMS.

BICs community. As analyzed before, to obtain GPS, the power flow on BICs can be computed as ΔP_{BICs} . The follow-up objective is to schedule BICs to proportionally share ΔP_{BICs} . As in Figure 4.3, each BIC is regulated by the proposed LDC which separately gives the respective active power reference. By using LDC, the power sharing among BICs can be realized in a fully distributed way. A particular BIC only needs to know the operation status of its nearest neighbors, which substantially improves the system PnP capability. Before proceeding to illustrate the LDC, some preliminaries pertaining to graph theory have to be introduced to better understand the related reasoning.

A: Graph Theory

For a network graph, there are totally N nodes $\mathcal{V} = \{v_1, v_2, \dots, v_N\}$, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ represents the set of edges linking two different nodes. This graph is assumed to be undirected if $(v_k, v_l) \subseteq \mathcal{E}$ and $(v_l, v_k) \subseteq \mathcal{E}$, otherwise, it is directed [101]. For MG applications, communication networks are normally modeled as undirected graph [102]. Furthermore, the set formed by the neighbors of the k th vertex can be expressed as $\mathcal{N}_k \triangleq \{v_k \subseteq \mathcal{V} (k, l) \subseteq \mathcal{E}\}$. The symmetrical adjacent matrix $\mathcal{A} \subseteq \mathbb{R}^{N \times N}$ possesses components $a_{kl} = a_{lk} = 1$ if $v_l \subseteq \mathcal{N}_k$, otherwise, $a_{kl} = a_{lk} = 0$. The adjacent matrix means that node l is capable

Figure 4.4: Control diagram of the proposed LDC.

of receiving information from node k if node l is one of its neighbors, and vice versa. Laplacian matrix $L \subseteq R^{N \times N}$ equals $\mathcal{A} - \mathcal{D}$, where $\mathcal{D}$ is the in-degree matrix denoted as $\mathcal{D} = \text{diag}\{\mathcal{d}_k\} \subseteq R^{N \times N}$, and $\mathcal{d}_k = \sum a_{kl}$ if $v_l \subseteq \mathcal{N}_k$. As reported in [103], BICs can cooperatively function if the communication graph maintains at least a spanning tree. Concretely, there exists at least one BIC working as the root node such that the necessary information can be propagated to all other BICs. This BIC is defined as the leader in this chapter, and other BICs are referred as the followers.

B: LDC

In the last few parts, it has been shown that the power interaction between the two subgrids can be theoretically computed as ΔP_{BICs} which has to be transferred by the BICs community. To avoid an overstressed BIC in the MG, as in Figure 4.3, the first control objective is that the sum of all BIC power references equals ΔP_{BICs} , and these references should be proportional to the respective BIC ratings,

$$\sum_{k=1}^x P_{kref} = \Delta P_{BICs}, \quad \frac{P_{1ref}}{P_{1\max}} = \dots = \frac{P_{kref}}{P_{k\max}} = \dots = \frac{P_{xref}}{P_{x\max}}. \quad (4.24)$$

As emphasized earlier, GPS realizations necessitate f_{ac} of AC bus and V_{dc} of DC bus. All BICs can easily perceive f_{ac} and know the AC loading condition as there is only one dominating frequency in the AC subgrid. Unfortunately, V_{dc} cannot be locally sensed by BICs due to the existence of line impedance between BICs and DC bus. To measure V_{dc} , an excessive sensor deployed on DC bus must be used. Moreover, communication processes incurred in the BICs community should not be over complicated. High system scalabilities have to be guaranteed for the ease of modularized BIC design. In this context, apart from the constraint

Figure 4.5: Schematic of the k th BIC.

given in (4.24), the second objective is that the exact value of V_{dc} transmitted by the DC bus sensor could only be known by the leader BIC. The follower BICs are scheduled to achieve consensus with the leader by collecting information from their neighbors. Provided that the leader BIC is down, its leading role can be randomly assigned to the rest BICs, thus ensuring normal operations of the BICs community and fortifying PnP capabilities.

In response to the two objectives formulated above, an original LDC is devised for the k th BIC, as detailed below,

$$\begin{cases} P_{kref} = k_{kp}e_k + k_{ki} \int e_k dt \\ e_k = \alpha_k \sum_l \left(\frac{P_{lref}}{P_{lmax}} - \frac{P_{kref}}{P_{kmax}} \right) + g_k \beta_k e_{LC} \\ e_{LC} = LC(V_{dc}) - LC(f_{ac}) \end{cases} \quad (4.25)$$

In (4.25), $\alpha_k, \beta_k \in R_+$ are the proportional gains. g_k is the pinning control gain, and it is a nonzero constant for the leader BIC. e_k is the summed error processed by a PI_k controller. Due to the presence of PI_k , e_k will be forced to be zero in steady state. It is easily observed that e_k comprises two kinds of errors, $P_{lref}/P_{lmax} - P_{kref}/P_{kmax}$ and $LC(V_{dc}) - LC(f_{ac})$ respectively. For the former, P_{lref}/P_{lmax} ($v_l \subseteq \mathcal{N}_k$) would be the information received from the neighbors of the k th BIC, and P_{kref}/P_{kmax} denotes the localized information of the k th BIC. Upon the MG system reaching an equilibrium point, $P_{lref}/P_{lmax} - P_{kref}/P_{kmax}$ is regulated to be zero. This means the first objective given in (4.24) has been achieved. As for the latter, $LC(V_{dc}) - LC(f_{ac})$ only presents in the LDC of the leader BIC. This term will also converge to zero at the end of system transition, which makes sure that the GPS of the whole MG can be realized. The control diagram of the proposed LDC is displayed in Figure 4.4.

Figure 4.6: Schematic of the k th BIC and its control diagram.

4.3.3 Implementation of LDC

As indicated in Figure 4.3, the realization of the LDC is to send power references to current regulation loops. Corresponding gate signals will be generated and drive the switches of BICs. Besides, sampling frequencies of BICs are normally the same as switching frequencies (f_{sw}) [104]. A BIC that has larger capacity may have lower f_{sw} for the reduction of switching losses. These facts result in different control delays in different BICs. Moreover, the low f_{sw} requires the large filtering inductances to suppress high order harmonics [105]. Therefore, multiple BICs may have different f_{sw} s, control delays, and filtering inductances, etc. These dissimilarities will hinder the PnP operations, and even engender stability issues if current compensators are improperly designed. To overcome these difficulties, a flexible and efficient current compensator design guideline is developed.

For a particular BIC working as either a leader or a follower, the corresponding LDC unexceptionally gives power reference to the current compensator. The compensator further generates gate signals to drive three phase bridges so that the real power flow on the BIC could track the power reference. Figure 4.5 shows the circuit schematic of the k th BIC. L_k is the filtering inductance. v_{abc} is the AC bus voltage and i_{kabc} is the inductor current. e_{abc} is the averaged output voltage of the BIC bridges. In the control diagrams (see Figure 4.6), v_{abc} , i_{kabc} and e_{kabc} are transformed into v_{dq0} , i_{kdq0} and e_{kdq0} respectively. τ_k denotes the control delay and usually computed as $\tau_k = 1.5T_{ksw} = 1.5/f_{ksw}$, where T_{ksw} is the switching period. As proved in [104], resistors would help to stabilize the control system. To consider the worst case, equivalent resistances are not drawn in Figure 4.5 and

Figure 4.7: The full schematic diagram of HIL tests.

Figure 4.8: Dominant eigenvalue loci of A_{sys} with PI parameter variations in LDC. (a) k_p increases from 2 to 22 with step of 2. (b) k_i increases from 400 to 900 with step of 50.

Figure 4.9: Physical setup of HIL tests.

will not be embodied in the following design guideline. PI_{kd} , PI_{kq} , and PI_{k0} are current compensators which are supposed to provide sufficient response speeds and phase margins (PMs). PI_{k0} in 0 channel is to eliminate zero sequence CCs in the BICs community, as understood from [84]. $d_{kd} = -v_d + L_k 2\pi f_{ac} i_{kq}$ and $d_{kq} = -v_q - L_k 2\pi f_{ac} i_{kd}$ are disturbances in the forward path.

PI_{kd} , PI_{kq} , and PI_{k0} can be written as the following,

$$PI_{kd} = \frac{k_{kdp}s + k_{kdi}}{s}, \quad PI_{kq} = \frac{k_{kqp}s + k_{kqi}}{s}, \quad PI_{k0} = \frac{k_{k0p}s + k_{k0i}}{s}. \quad (4.26)$$

To begin with, as seen from Figure 4.6, the open loop transfer function in d channel can be written below,

$$T_{kd} = (k_{kdp}s + k_{kdi}) / (L_k s^2 (\tau_k s + 1)). \quad (4.27)$$

Replacing s in (4.27) with $j\omega$ and doing manipulations yields

$$T_{kd}(j\omega) = (j\omega k_{kdp} + k_{kdi}) / (j(-\omega^3 L_k \tau_k + j\omega^2 L_k)). \quad (4.28)$$

The control bandwidth ω_k can be determined as $2\pi f_{ksw}/\varepsilon$, where ε is a constant set as 20. At ω_k , the magnitude of $T_{kd}(j\omega)$ should be 0 dB, which can be expressed as

$$\begin{aligned} |T_{kd}(j\omega)| &= \frac{(\omega_k k_{kdp})^2 + k_{kdi}^2}{(\omega_k^3 L_k \tau_k)^2 + (\omega_k^2 L_k)^2} = 1 \\ \Rightarrow k_{kdp} &= \frac{(\omega_k^3 L_k \tau_k)^2 + (\omega_k^2 L_k)^2}{\omega_k^2 + (k_{kdi}/k_{kdp})^2}. \end{aligned} \quad (4.29)$$

Table 4.1: System parameters for hybrid AC/DC MG.

Parameter	Description	Value
$f_{ac \max}$	Maximum AC frequency	51 Hz
$V_{dc \max}$	Maximum DC bus voltage	710 V
$f_{ac \min}$	Minimum AC frequency	49 Hz
$V_{dc \min}$	Minimum DC bus voltage	690 V
$P_{ac \max}, P_{dc \max}$	AC power rating, DC power rating	40 kW
$P_{1 \max}$	Power rating of BIC ₁	6 kW
$P_{2 \max}$	Power rating of BIC ₂	4 kW
$P_{3 \max}$	Power rating of BIC ₃	2 kW
ω_{LPF}	Cutoff angular frequency of LPF	500π
k_p	Proportional gain in LDC	2
k_i	Integral gain in LDC	800
$\alpha_1, \alpha_2, \alpha_3, \beta_3$	Proportional gain in LDC	2
g_1, g_2, g_3	Pining control gains in LDC	1, 0, 0
L_1, L_2, L_3	BIC inductances	8 mH
$f_{1sw}, f_{2sw}, f_{3sw}$	Switching frequencies of BICs	10 kHz, 15 kHz, 20 kHz

Additionally, the angle of $T_{kd}(j\omega)$ can be written below,

$$\begin{aligned} \angle T_{kd}(j\omega) &= \tan^{-1} \left(\frac{\omega_k^2 \tau_k k_{kdp} + k_{kdi}}{\omega_k \tau_k k_{kdi} - \omega_k k_{kdp}} \right) - 90^\circ \\ \Rightarrow \frac{\omega_k^2 \tau_k k_{kdp} + k_{kdi}}{\omega_k \tau_k k_{kdi} - \omega_k k_{kdp}} &= -\xi, \quad \xi = \tan(90^\circ - PM) \end{aligned} \quad (4.30)$$

where $PM \in (0, 90^\circ)$ and $\xi \in (0, \infty)$. The decreased PM gives the larger ξ . To exactly compute k_{kdp} and k_{kdi} , besides (4.29), an auxiliary equation can be obtained by rearranging (4.30),

$$\frac{k_{kdi}}{k_{kdp}} = \frac{\omega_k (\xi - \omega_k \tau_k)}{1 + \xi \omega_k \tau_k}. \quad (4.31)$$

Combining (4.29) and (4.31), k_{kdp} and k_{kdi} are determined below,

$$k_{kdp} = \frac{L_k^2 \omega_k^2 (\tau_k \xi \omega_k + 1)^2}{\xi^2 + 1}, \quad k_{kdi} = k_{kdp} \frac{\omega_k (\xi - \omega_k \tau_k)}{1 + \xi \omega_k \tau_k}. \quad (4.32)$$

With the designated k_{kdp} and k_{kdi} given in (4.32), the PM of the control system can be conveniently attained by theoretical calculations. As for the compensator designs in q and 0 channels, k_{kqp} , k_{kqi} , k_{k0p} and k_{k0i} can also be easily identified by referring to the process from (4.29) to (4.32).

4.3.4 Convergence Analysis of DPMS

DPMS addresses the power coordination between AC and DC subgrids, and further controls power flows on BICs. By considering AC and DC droops, BIC power flows and LDCs, the convergence analysis for the proposed control strategy in the hybrid MG would be provided below.

Referring to (4.25), the error dynamic can be written as,

$$e = \alpha L P_{\max}^{-1} P_{ref} + G \beta 1_x e_{LC}, \quad (4.33)$$

where $e = [e_1 \cdots e_k \cdots e_x]^T$, $\alpha = \text{diag}(\alpha_1 \cdots \alpha_k \cdots \alpha_x)$, $P_{\max} = \text{diag}(P_{1\max} \cdots P_{k\max} \cdots P_{x\max})$, $P_{ref} = [P_{1ref} \cdots P_{kref} \cdots P_{xref}]^T$, $G = \text{diag}(g_1 \cdots g_k \cdots g_x)$, $\beta = \text{diag}(\beta_1 \cdots \beta_k \cdots \beta_x)$. 1_x is a column vector with all elements being 1.

The hybrid MG system has equilibriums as long as the error vector e could be regulated to zero. Taking the derivative of (4.33) yields

$$\begin{aligned} \dot{e} &= \alpha L P_{\max}^{-1} \dot{P}_{ref} + G \beta 1_x \dot{e}_{LC} \\ P_{ref} &= k_p e + k_i \int e dt \Rightarrow \dot{P}_{ref} = k_p \dot{e} + k_i e \end{aligned} \quad (4.34)$$

For simplicity, it is assumed that $k_p = k_{1p} = \cdots k_{kp} = \cdots k_{xp}$ and $k_i = k_{1i} = \cdots k_{ki} = \cdots k_{xi}$. In (4.34), substituting the second equation into the first one gives

$$\begin{aligned} \dot{e} &= \alpha L P_{\max}^{-1} (k_p \dot{e} + k_i e) + G \beta 1_x \Phi, \quad \dot{e}_{LC} = \Phi \Rightarrow \\ \dot{e} &= (I - \alpha L P_{\max}^{-1} k_p)^{-1} \alpha L P_{\max}^{-1} k_i e + (I - \alpha L P_{\max}^{-1} k_p)^{-1} G \beta 1_x \Phi \end{aligned} \quad (4.35)$$

The dynamic of e incorporates an auxiliary state Φ which is exactly the first order differentiation of e_{LC} , and e_{LC} dynamic can be derived as

$$\begin{aligned} \dot{e}_{LC} &= \frac{\dot{V}_{dc}}{\Delta v} - \frac{\dot{f}_{ac}}{\Delta f} \Rightarrow \\ \dot{e}_{LC} &= -\omega_{LPP} e_{LC} - \omega_{LPP} \left(\frac{dP_{dc}}{\Delta v} - \frac{aP_{ac}}{\Delta f} \right) - \omega_{LPP} \left(\frac{d}{\Delta v} + \frac{a}{\Delta f} \right) 1_x^T P_{ref} \end{aligned} \quad (4.36)$$

Taking the derivative of Φ results in

$$\begin{aligned}\dot{\Phi} &= \ddot{e}_{LC} = -\omega_{LPF}\dot{e}_{LC} - \omega_{LPF}\left(\frac{d}{\Delta v} + \frac{a}{\Delta f}\right)1_x^T \dot{P}_{ref} \Rightarrow \\ \dot{\Phi} &= -\omega_{LPF}\Phi - \omega_{LPF}\left(\frac{d}{\Delta v} + \frac{a}{\Delta f}\right)1_x^T (k_p \dot{e} + k_i e)\end{aligned}\quad (4.37)$$

Substituting (4.35) into (4.37) and performing manipulations, an autonomous error model representing the overall MG can be obtained,

$$\begin{bmatrix} \dot{e} \\ \dot{\Phi} \end{bmatrix} = \underbrace{\begin{bmatrix} a & b \\ c & d \end{bmatrix}}_{A_{sys}} \begin{bmatrix} e \\ \Phi \end{bmatrix}, \quad (4.38)$$

where A_{sys} is system matrix. a , b , c and d could be detailed as

$$\begin{aligned}a &= (I - \alpha LP_{\max}^{-1} k_p)^{-1} \alpha LP_{\max}^{-1} k_i, \quad a \in R^{x \times x} \\ b &= (I - \alpha LP_{\max}^{-1} k_p)^{-1} G \beta 1_x, \quad b \in R^{x \times 1} \\ c &= -\omega_{LPF} \left(\frac{d}{\Delta v} + \frac{a}{\Delta f} \right) 1_x^T \left[k_p (I - \alpha LP_{\max}^{-1} k_p)^{-1} \alpha LP_{\max}^{-1} k_i + k_i \right], \quad c \in R^{1 \times x} \\ d &= -\omega_{LPF} \left[1 + \left(\frac{d}{\Delta v} + \frac{a}{\Delta f} \right) 1_x^T k_p (I - \alpha LP_{\max}^{-1} k_p)^{-1} G \beta 1_x \right], \quad d \in R^{1 \times 1}\end{aligned}$$

As long as A_{sys} in (4.38) has all eigenvalues with negative real parts, the system is stable and the steady state operation point does exist. (4.38) is a generalized mathematical model which adapts to the MG with BICs connected in arbitrary communication graph. Concentrating on a specific hybrid MG as in Figure 4.7 where three BICs are included and BIC₁ is the leader, with the corresponding parameters tabularized in Table 4.1, the dominant eigenvalue loci of A_{sys} against LDC k_p and k_i variations are shown Figure 4.8.

It is apparent from Figure 4.8 that the increased k_p would drive the dominant pole moving toward imaginary axis, which narrows down the stability margin. In contrast, when k_i increases from 400 to 900 with step of 50, the dominant pole moves along with the negative horizontal axis. From the holistic perspective, smaller k_p and larger k_i would help to improve the system stability. With dominant pole having negative real part, the equilibrium of the hybrid MG exists, i.e.,

$$\lim_{t \rightarrow \infty} e = 0, \quad \lim_{t \rightarrow \infty} \Phi = 0. \quad (4.39)$$

The smaller real part of the dominant pole leads to the faster convergence speeds of e and Φ from their initial values to zero. However, $\Phi = 0$ does not necessarily imply that e_{LC} could be 0 in steady state. For this reason, solving (4.38) in Laplace domain, $e(s)$ and $\Phi(s)$ can be derived as

$$\begin{bmatrix} e(s) \\ \Phi(s) \end{bmatrix} = [sI_{(x+1) \times (x+1)} - A_{sys}]^{-1} \begin{bmatrix} e_0 \\ \Phi_0 \end{bmatrix}, \quad (4.40)$$

where e_0 and Φ_0 are the initial values. In accordance with modern control theory, the inversion of $sI - A_{sys}$ can be calculated as,

$$\begin{aligned} [sI_{(x+1) \times (x+1)} - B]^{-1} &= \begin{bmatrix} sI_{x \times x} - a & -b \\ -c & s - d \end{bmatrix}^{-1} \\ &= \begin{bmatrix} (sI_{x \times x} - a)^{-1} + (sI_{x \times x} - a)^{-1} b \Delta^{-1} c (sI_{x \times x} - a)^{-1} & (sI_{x \times x} - a)^{-1} b \Delta^{-1} \\ \Delta^{-1} c (sI_{x \times x} - a)^{-1} & \Delta^{-1} \end{bmatrix}. \end{aligned} \quad (4.41)$$

where $\Delta = (s - d) + c(sI_{x \times x} - a)^{-1} b$.

Based on (4.41), $\Phi(s)$ can be further computed as

$$\Phi(s) = \Delta^{-1} c (sI_{x \times x} - a)^{-1} e_0 + \Delta^{-1} \Phi_0. \quad (4.42)$$

Considering the MG in Figure 4.7 again and substituting relevant parameters in Table 4.1 into (4.42), it is true that $e_0 = [e_{LC0}, 0, 0]^T$ and $\Phi_0 = 0$. Then $\Phi(s)$ could be concretized as

$$\Phi(s) = \Delta^{-1} c (sI_{x \times x} - a)^{-1} e_0 + \Delta^{-1} \Phi_0. \quad (4.43)$$

Note that the Laplace domain expression of e_{LC} dynamic can be delineated by

$$\Phi(s) = \Delta^{-1} c (sI_{x \times x} - a)^{-1} e_0 + \Delta^{-1} \Phi_0. \quad (4.44)$$

As recorded in Table 4.1, β_1 equals 2. Evaluating final value theorem on (4.44) gives the steady state value of e_{LC} in the time domain, i.e.,

$$\lim_{t \rightarrow \infty} e_{LC} = \lim_{s \rightarrow 0} s e_{LC}(s) = \lim_{s \rightarrow 0} \left[e_{LC0} - \frac{200 \cdot 2 \cdot e_{LC0}}{10s^2 + 5001s + 400} \right] = 0. \quad (4.45)$$

Through above theoretical analyses, it can be summarized that by using the proposed LDC, the difference (e_{LC}) of AC and DC LCs can be enforced to zero in steady state. The smaller k_p and larger k_i in LDCs will drive the dominant pole moving into more stable region, thus ensuring the existences of equilibriums and speeding up the convergence rate of error dynamics. For the investigations of the impacts of communication time delay on system stability, overall system small signal modeling should be performed. Then by varying the delay value, the eigenvalue loci can be accordingly identified to know the maximum time delay that the hybrid system can tolerate. Detailed procedures could refer to Chapter 5.

4.4 Hardware in Loop (HIL) Verifications

To validate the proposed DPMS for multi-paralleled BICs, an in-house controller HIL experimental platform is established as in Figure 4.9. The corresponding schematic has been plotted in Figure 4.7. The switching models of DUs and their associated controls are firstly developed in OP5600 simulator to form up the two subgrids with droop features. Each DU model is allocated to a CPU core in OPAL-RT platform for the acceleration of computation speed. BIC power circuits are also modeled in the real-time simulator, whereas the current compensators and LDCs are realized in Digital Signal Processor (DSP) controller boards. The inputs of DSPs are voltage and current measurements, which are converted from digital signals in the simulation model to the analog signals by the D2A terminals of OPAL-RT system. The outputs of the DSP controller boards are PWM signals, which will be sent to the PWM channels of OPAL-RT system and then drive the power switches in the BIC models. DSPs communicate with one other by CANbus which supports baud rate up to 1Mbps.

The effectiveness and feasibility of DPMS are corroborated by the following three cases. Case 1 tests the PnP functionalities of BICs. Case 2 considers an aberrant situation that the leading role of BIC₁ is transferred to BIC₂ due to the BIC₁ outage. Case 3 scrutinizes the bidirectional power flow of the BICs community.

A: Case 1 PnP Function Tests

Figure 4.10: Experimental results of case 1: (a) BIC₁ is enabled; (b) BIC₂ is enabled; (c) BIC₃ is enabled.

Figure 4.11: Experimental results of case 2.

Figure 4.12: Experimental results of case 3. (a) Power flow from the AC subgrid to the DC subgrid. (b) Power flow from the DC subgrid to the AC subgrid.

Figure 4.10 demonstrates the scenario that three BICs in Figure 4.7 are enabled in sequence. As plotted in Figure 4.10 (a), before BICs operation, AC and DC subgrids are feeding loads of around 12.84 kW and 0.92 kW, respectively. Since the two subgrids have equal capacities, it is easily reasoned that the AC subgrid is heavily loaded and DC loads are light. To globally balance the loads in the entire hybrid MG, the BICs community should be dispatched to channel the power from the DC subgrid to the AC one. Once BIC₁ is enabled, the output power of the two subgrids could converge to the same value which is 6.86 kW, and BIC₁ power is read as 5.95 kW. Next, when BIC₂ is triggered to avoid the overstress of BIC₁, BIC₂ power immediately increases to 2.38 kW while BIC₁ power quickly drops to 3.57 kW, as shown in Figure 4.10 (b). It should be emphasized that the summed power flow of the two BICs equals 5.95 kW which is previously transferred by only BIC₁. The power interaction between AC and DC subgrids keeps unchanged even in the case of BIC₂ is involved. Moreover, f_{ac} and V_{dc} are also unaffected, and they are stabilized at 50.66 Hz and 706.56 V respectively. Similar results can also be found when BIC₃ is activated. As evident in Figure 4.10 (c), the total power flow on the BICs community is proportionally allocated to the three BICs whose power can be estimated as 2.98 kW, 1.98 kW, and 0.99 kW. The ratio of these three quantities is approximately 3:2:1, which is in good agreement with the desired power sharing pattern. GPS in hybrid MG has also been precisely realized.

Summarily, the proportional power sharing among BICs with different power ratings can be perfectly achieved by DPMS with distributed communication. This method also reinforces PnP functionalities of the MG and facilitates the modularized system design, which is highly preferred in engineering practitioners.

B: Case 2 Leading Role Transition

Upon the equilibrium point described in Figure 4.10 (c), case 2 further takes into account that both power circuit and the controller board of BIC₁ (leader) are faulty. All PWM signals are disabled, the relays installed on AC and DC sides of BIC₁ should be turned off. Note that BIC₂ and BIC₃ are still communicating with each other, and their communication network remains as a spanning tree. This means, as long as either BIC₂ or BIC₃ is scheduled as a leader, the global power balancing of the two subgrids and the power sharing of BIC₂ and BIC₃

can still be obtained. As an exemplification, leading role transition from BIC₁ to BIC₂ is demonstrated in Figure 4.11. At the instant that BIC₁ is down, its power sharply decreases to zero. Fortunately, the power of BIC₂ and BIC₃ would instantaneously rise to 3.97 kW and 1.98 kW. The power ratio is approximated as 2:1, which again shows that the proper power sharing of BICs can be effectively accomplished. The powers supplied DU_{ac} and DU_{dc} maintain invariant at 6.8 kW, which suggests that GPS keeps unaffected by the BIC₁ outage. As revealed by this case, the system fault tolerant capability can also be strengthened under the proposed distributed control strategy.

C: Case 3 Bidirectional Power Flow on BICs

Above two cases have explored the global power balancing such that the DC subgrid supplies the power to the AC subgrid. Without loss of generality, case 3 will perform the bidirectional power flow tests for the BICs community. Following the steady state point in Figure 4.10 (c) wherein three BICs are under normal operations, in Figure 4.12, DC loads and AC loads are increased sequentially. Specifically, as reported in Figure 4.12 (a), power flow inversion of BICs unsurprisingly happens when load power in the DC subgrid rises. This suggests that the AC subgrid has relatively lighter loads in comparison with its DC counterpart, and the AC network would deliver power to the DC one. As identified from Figure 4.12 (a), after the DC load step-up is exerted, the power flows on BICs are -3.04 kW, -2.03 kW, -1.01 kW, which adheres to the power sharing rules stipulated in the preceding context. The total loads distributed in the hybrid MG are equally shared by AC and DC subgrids, and their output power can be measured as 18.85 kW. Accordingly, f_{ac} and V_{dc} decline to 50.06 Hz and 700.6 V respectively.

When it comes to the AC load step-up (see Figure 4.12 (b)), the AC subgrid sustains the atrocious loading situation. f_{ac} reduces to around 49.46 Hz, almost reaching the allowable minimum AC frequency. V_{dc} can be read as 694.60 V. To mitigate the overstress of the AC network, the DC subgrid helps to share the AC loads, and the output power of the two subgrids is nearly 30.79 kW. BICs power flows return to be positive values which are recognized as 2.60 kW, 1.74 kW, and 0.87 kW. The power ratio can be computed as 3:2:1, which matches the anticipation in the last section.

4.5 Summary

In this chapter, the proposed DPMS smoothly extends the power sharing concepts to the multi-paralleled BICs configuration in the hybrid AC/DC MG, realizing BICs distributed power sharing. Each BIC is accompanied by a novel LDC which produces the respective power reference. By means of the LDC, bidirectional power flows between AC and DC subgrids would be precisely distributed into BICs in accordance with their various power rating. In this way, an overstressed BIC can be avoided, and GPS across the entire hybrid MG can also be accomplished. A flexible and efficient current compensator design guideline is presented for the enhancements of the system modularization. Then the control system convergence of DPMS is analyzed. In-house HIL experiments validate the effectiveness of the proposed distributed control strategy.

Chapter 5

A Distributed Control Architecture for Global System Economic Operation in Autonomous Hybrid AC/DC Microgrids

This chapter is the continuous work of Chapter 4. With the increasing number of sources and loads incorporated into the hybrid MG, system economic operations would become a critical issue. It is renowned that the entire power system operation cost can be minimized when DGs have the same incremental costs (ICs). As such, this chapter proposes a distributed control architecture for hybrid AC/DC MGs to realize global system economic operation. The architecture consists of two levels. In the first level, the AC frequency-IC (f_{ac} -IC) droop and the DC bus voltage-IC (V_{dc} -IC) droop are employed in the AC and DC subgrids respectively. With the synchronization of f_{ac} and V_{dc} , DG ICs in each subgrid will be equalized. However, the droops will inevitably cause deviations of f_{ac} and V_{dc} . Then a distributed control canonical form (DCCF), which provides a generalized method for f_{ac} and V_{dc} recoveries, is proposed in the second level. The DCCF allows DGs to communicate only with their neighbors, thus alleviating the communication burdens and enhancing the system scalability. Due to the presence of DCCF, f_{ac} and V_{dc} fluctuations, which naturally indicate subgrid loading conditions, are invisible. An original relative loading index (RLI) is proposed to extract the hidden loading condition of each subgrid even though f_{ac} and V_{dc} are clamped as constants. By using RLI, the power reference of the bidirectional interlinking converter (BIC) can be easily defined. All DG ICs converge to the same value in the steady state, thus entails global MG system economic power sharing.

5.1 Introduction

Normally, different DGs in a MG have distinctive generation costs. Proper DGs dispatch schemes should be adopted to minimize the entire operation cost. In general, system optimization can be realized in centralized and decentralized ways. For the former, decision making for power allocation among DGs is accomplished in a central controller where time-consuming algorithms, including Lagrangian relaxation, genetic algorithm [106], quadratic programming [107] and robust two-stage coordination [108], are employed. Some other centralized methods taking into account of droop controllers can also be found in [109]–[111]. Although these algorithms are viable and effective, it is worth noting that the plausible performances of the centralized optimization may be compromised by the potential inaccuracy of load forecasting and the improper prediction of RES generations. Moreover, the centralized approaches are also vulnerable to the intensive communication and single point of failures.

To overcome the above difficulties, decentralized economic dispatch mechanisms, which do not rely on communication networks, are widely studied. For instance, in [112], a decentralized self-optimizing control is proposed to regulate the DG powers according to their respective generation costs, but PnP properties are not expounded. In [113], the costlier DGs are simply turned off to reduce the operation cost in the case of light load. By extending conventional droop concepts, a cost-based droop scheme is proposed in [101] where the remarkable decrease of total generation cost can be achieved. However, the scheme fails to obtain the optimal cost saving in all possible operating situations. To address this issue, IC based droops are illustrated in [114], [115] to minimize the MG cost in a completely decentralized manner. Nonetheless, the common shortcoming of decentralized methods is that the frequency and voltage deviations cannot be properly eliminated.

In an autonomous hybrid AC/DC MG, floating AC frequency, f_{ac} , and DC bus voltage, V_{dc} , could cause damages to those frequency-/ voltage- sensitive loads, and even result in whole system collapse. Furthermore, when the AC and DC subgrids are integrated to the main grids, synchronization with the mains would also require f_{ac} and V_{dc} to stabilize at their nominal values. For restorations of

f_{ac} and V_{dc} , both hierarchical frameworks and distributed control strategies are extensively explored in the literature. The former ones are not recommended for those MGs with high reliability requirements since the implementation of energy management entirely depends on central controllers [116]–[118]. In contrast, distributed ones are much preferable due to less communication burden and higher system scalability. However, most of the distributed controllers are parochially customized for either DC MGs or AC MGs [101], [119], [120]. A distributed control canonical form (DCCF), which can provide a generalized way for f_{ac} and V_{dc} restorations in the hybrid AC/DC MG, has not been reported. The deviated f_{ac} and V_{dc} straightforwardly indicate the loading conditions of AC and DC subgrids. Large f_{ac} and V_{dc} drops imply the heavy load and vice versa. The difference between f_{ac} and V_{dc} deviations helps to decide the transferred power of BIC so that the total MG loads can be appropriately shared by AC DGs and DC DGs. However, if f_{ac} and V_{dc} are tightly regulated and keep unchanged, the loading conditions of two subgrids are imperceptible. The lost loading information in the MG seriously challenge the normal operation of BIC, and this problem has also not been discussed so far.

To fill the aforesaid gaps, as well as retain the global system economic operation, in this chapter, a distributed power control architecture is proposed for a hybrid AC/DC MG. The architecture consists of two levels. In the first level, the IC based droops are adopted in each subgrid to obtain the equalized ICs when the system reaches an equilibrium point. Nevertheless, only having droops will inevitably cause f_{ac} and V_{dc} fluctuations. Therefore, in the second level, a DCCF, which is uniformly applicable to both AC and DC subgrids, is proposed to concurrently restore f_{ac} and V_{dc} . Then, an original relative loading index (RLI) is proposed to uncover the hidden loading condition of each subgrid even if f_{ac} and V_{dc} are clamped as constants. By using RLI, the power reference of BIC can be conveniently defined, and the ICs of all DGs in the hybrid MG will converge to the same value in the steady state, which means the global system economic operation is accomplished. To examine the impacts of communication time delay on the system performances, a small signal model of the MG under the proposed architecture is derived. By analyzing the eigenvalue loci, it will be shown that the longer time delay results in larger transient oscillations and even destabilize MG.

Figure 5.1: The proposed distributed control architecture for a representative hybrid AC/DC MG.

Figure 5.2: System droop characteristics with f_{ac}/V_{dc} restoration.

Following the introduction, the remainder of this chapter is organized as follows. First, the IC based droop schemes utilized in the first level are explained. Second, the DCCF and the novel RLI are proposed. The control diagram of BIC is then meticulously illustrated based on RLI, and the effects of communication time delay on the MG stability are also explored. Finally, HIL tests validate the feasibility and effectiveness of the proposed control architecture.

5.2 IC Based Droops in The First Level

System configuration of a hybrid AC/DC MG has been carefully shown in Figure 4.1 where various DGs are deployed in the AC and DC subgrids. Different from Chapter 5, the economic operation investigated in this chapter would not take into account of the multi-paralleled connection of BICs as the power transfer by BICs cause few power losses that could be overlooked. Instead, only one BIC is used to interlink AC and DC subsystems and the corresponding hybrid MG diagram can be seen in Figure 5.1. The detailed modeling for individual AC and DC subgrids are the same as in Figure 4.2.

5.2.1 Economic Operation Problem

In the conventional power system, the cost (C_k) of a particular DG is usually related to its output power (P_k). This relation can be described by a quadratic function [121],

$$C_k = 0.5a_k P_k^2 + b_k P_k + c_k, \quad (5.1)$$

where a_k , b_k , and c_k are the cost coefficients of the k th DG.

The economic operation model can be formulated below

$$\min C_{total} = \sum_k C_k \quad s.t. \quad P_{k,min} \leq P_k \leq P_{k,max}, \quad P_{load} = \sum_k^n P_k. \quad (5.2)$$

If P_k is confined within the permitted range, the necessary condition for total cost minimization is that the incremental costs (ICs) of all DGs are equal to some undetermined value λ [121].

$$IC_k = \lambda = \frac{\partial C_k}{\partial P_k} = a_k P_k + b_k. \quad (5.3)$$

Moreover, it is worth mentioning that once P_k reaches the predefined $P_{k,min}$ or $P_{k,max}$, the output power of the k th DG is limited to the bounded value. The remaining DGs continue to operate according to the above economic dispatch rules.

5.2.2 IC Based Droop In AC and DC Subgrids

In traditional droop schemes, the active power supplied by the DGs in AC and DC subgrids are proportional to their respective power ratings when f_{ac} and V_{dc} are synchronized. The droop principle can also be applied to the reactive power sharing, but normally accompanied by errors. The errors are caused by mismatched line impedances and system parameters. Although some methods for improving reactive power sharing accuracy could be found in [122], [123], these amendments would not be discussed here as the reactive power only exists in AC subgrid [115], [124]. By properly relating the IC to f_{ac} and V_{dc} , the DG ICs can reach equality when f_{ac} and V_{dc} converge to certain values after system transition [115]. This fact gives the IC based droops,

$$f_{ac} = f_{ac \max} - d_{ac} IC_i, \quad IC_i = a_i P_i^M + b_i, \quad i \in [1, m], \quad (5.4)$$

$$V_{dc} = V_{dc \max} - d_{dc} IC_j, \quad IC_j = a_j P_j^M + b_j, \quad j \in [1, n], \quad (5.5)$$

where $f_{ac \max}$ and $V_{dc \max}$ are the maximum AC frequency and DC bus voltage. d_{ac} and d_{dc} are the droop coefficients written as,

$$d_{ac} = f_{ac \max} - f_{ac \min}, \quad d_{dc} = V_{dc \max} - V_{dc \min}. \quad (5.6)$$

It should be noted that the calculations of d_{ac} and d_{dc} are only related to the maximum deviations of f_{ac} and V_{dc} . A single droop controller does not need any information from others, which enhances the system applicability and scalability.

In (5.4) and (5.5), P_i^M and P_j^M are the measured power processed by LPFs. Their dynamics are

$$\dot{P}_i^M = \omega_{LPF}(P_i - P_i^M), \quad \dot{P}_j^M = \omega_{LPF}(P_j - P_j^M) \quad (5.7)$$

where ω_{LPF} is the cutoff angular frequency of LPFs, as in (4.4). P_i and P_j are the real-time active powers. For the AC subgrid, the ICs of all AC DGs are enforced to be identical with the synchronization of f_{ac}

$$IC_1 = \dots = IC_i = \dots = IC_m. \quad (5.8)$$

Similarly, in the DC subgrid, ICs are the same in steady stat

$$IC_1 = \dots = IC_j = \dots = IC_n. \quad (5.9)$$

From (5.4) to (5.9), it has been revealed that the IC based droops are naturally decentralized and the optimal operating point can be achieved with no communication. To reserve this advantage, the IC based droops are employed in the first level of the proposed control architecture. To eliminate the f_{ac} and V_{dc} deviations caused by droops, in the second level, a DCCF is proposed as a generalized method to concurrently restore f_{ac} and V_{dc} for the hybrid MG. The schematic of the proposed architecture is displayed in Figure 5.1. Comprehensive explanations and relevant analyses will be conducted in the next section.

5.3 Distributed Control In The Second Level

The distributed control in the second level requires several preliminaries regarding graph theory which has, fortunately, been explicated in Chapter 4. Similar to DPMS in Chapter 4, the correct functioning of the hybrid MG can be guaranteed only if the communication graph maintains at least a spanning tree. Concretely, in each subgrid, there exists at least one DG such that the information of that DG can be propagated to all other DGs. This DG, in this chapter, is defined as the leader, whereas the other DGs are defined as the followers.

5.3.1 The Proposed DCCF

A: Control Objectives

It has been shown that the output power of a particular DG is finally regulated to reach a level such that all DG ICs in a particular subgrid are the same. An exemplification is offered in Figure 5.2. For convenient explanation, f_{ac} and V_{dc} are uniformly represented as x . The rudimentary IC based droop curve is given by the red solid line 1. At the beginning, DG_a and DG_b have the common IC_1 with x_0 , and the corresponding powers are P_{a1} and P_{b1} . To regulate x to its nominal value x_n , the compensating variable Δx is generated and the newly obtained droop

Figure 5.3: Control diagram of the proposed DCCF.

curve could be described by the red solid line 2. As a result, the system functions at a new steady point where the DG ICs are equalized at IC_2 , and DG_a supplies P_{a2} and DG_b supplies P_{b2} .

It is essential to stress that in the first level, the economic operation can be accomplished only when all DGs utilize the identical droop equations. This mechanism should also be maintained even after f_{ac} and V_{dc} restorations. In other word, in each subgrid, the compensating variables used for revising the rudimentary droop functions have to be the same, which formulates the first control objective for the DCCF,

$$\Delta x_y = \Delta x_z, \forall y, z \in i \text{ or } j. \quad (5.10)$$

On the other hand, to largely reduce the communication complexity and enhance the system scalability, the proposed controller in the second level should be completely distributed. Hence, in addition to constraint (5.10), another requirement is that the information of f_{ac} or V_{dc} would only be known by the leader DG in a subgrid. The follower DGs are scheduled to achieve consensus with the leader one by merely using the information obtained from their neighbors. In the case that the leader DG are accidentally down, its leading role can be randomly assigned to any of the rest DGs for ensuring the system normal operation, and in this way, the PnP capability can also be reinforced.

B: DCCF

Responding to the above two goals, a DCCF is proposed for the DG numbered

Figure 5.4: Relative loading index calculation.

by “y” as in (5.11),

$$\begin{cases} \Delta x_y = G_d \left(k_{py} e_y + k_{iy} \int e_y dt \right) \\ e_y = \gamma_y \sum_z (\Delta x_z - \Delta x_y) + g_y \rho_y (x_n - x) \end{cases}, \quad (5.11)$$

where $\gamma_y, \rho_y \subseteq R_+$ are the proportional gains. g_y is the pinning gain which is nonzero for the leader DG. e_y is the summed error which is processed by PI controller. e_y will be finally forced to be zero at the end of system transition due to the PI regulation. As observed from (5.11), e_y consists of two types of errors, $\Delta x_z - \Delta x_y$ and $x_n - x$ respectively. The former represents the difference between the localized compensating signal and the signal produced by the neighbors of DG_y. This error is to ensure that the control objective (5.10) can be achieved. The latter error denotes the deviation of f_{ac} or V_{dc} . The presence of this term aims to enforce the real time AC frequency and DC bus voltage to track their respective nominal values.

The control diagram of the proposed DCCF and its cooperation with IC based droop are displayed in Figure 5.3. As the information exchange processes are involved in DCCF, the communication time delay will be inevitably induced. For precise modeling, the delay term $G_d = 1/(\tau_d s + 1)$ is embodied in the first equation of (5.11). τ_d is the time delay which will be shown to potentially impair system stability.

Figure 5.5: Modeling of BIC and its control diagram.

5.3.2 The Proposed RLI and Control Strategy of BIC

A: The Proposed RLI

In AC and DC subgrids, the fluctuated x directly indicates the loading conditions. With the adoption of normalization scheme, and properly scheduling the transferred power of BIC, the global load balancing of the entire hybrid MG can be achieved [49]. However, due to the existence of DCCF, f_{ac} and V_{dc} are strictly clamped at their nominal values. The consequent problem is that the loading situations of the two subgrids are no longer accessible. Existing control methods of BIC in [49], [88] will absolutely fail.

To tackle this issue, an original RLI is proposed in this chapter to extract the hidden loading information after f_{ac}/V_{dc} recovery,

$$RLI(x) = \frac{x - x'_n}{\delta_x}, \quad x'_n = x_n + \Delta x, \quad (5.12)$$

where $x_n = 0.5(x_{\max} + x_{\min})$ is the nominal value. $\delta_x = 0.5(x_{\max} - x_{\min})$ is a constant denoting the maximum deviation of x from x_n . As emphasized in Figure 5.2, the DCCF enables the droop curve to shift upward by Δx to simultaneously realize IC equalization and f_{ac}/V_{dc} restoration. The main idea of RLI is to obtain the superposed term Δx by the communication link and remove it from the numerator of (5.12). By doing this, as seen from Figure 5.4, x can be accordingly mapped into the range of $[-1, 1]$, which is similar to the normalization scheme documented in [49], [88]. By means of RLI, even though f_{ac} and V_{dc} are rigorously

regulated, the loading status of each subgrid can be accurately calculated, thus facilitating the proper control of BIC.

B: Control of BIC

For a given hybrid MG, BIC should be scheduled to make sure that the RLIs of AC and DC subgrids are the same. As a result, the ICs equalization of all DGs in the MG can be realized. Mathematical modeling of BIC in rotating frame and the control diagram are shown in Figure 5.5 where the reference direction of power flow is also clearly defined. The difference of $RLI(f_{ac})$ and $RLI(V_{dc})$ is processed by a PI controller which further generates the active power reference for BIC. If $RLI(f_{ac}) > RLI(V_{dc})$, which means the AC subgrid is lightly loaded while the DC subgrid suffers from heavy load, then BIC drives the power flowing from the AC subgrid to the DC one. Inversely, the power of the DC subgrid would be channeled to the AC one in the case of $RLI(f_{ac}) < RLI(V_{dc})$. Because of the PI regulation, the RLI discrepancy can be eliminated in system steady state. Additionally, the power reference in q axis is configured as zero as there is no reactive power in DC network.

Inserting compensating values generated by (5.11) into (5.4) and (5.5), droop equations should be revised accordingly,

$$f_{ac} = f_{ac \max} - d_{ac}IC_i + \Delta f_{ac}, \quad (5.13)$$

$$V_{dc} = V_{dc \max} - d_{dc}IC_j + \Delta V_{dc}. \quad (5.14)$$

Applying RLI calculation rule to (5.13) and (5.14) yields,

$$RLI(f_{ac}) = \frac{f_{ac \max} - d_{ac}IC_i + \Delta f_{ac} - (f_{acn} + \Delta f_{ac})}{0.5(f_{ac \max} - f_{ac \min})}, \quad (5.15)$$

$$RLI(V_{dc}) = \frac{V_{dc \max} - d_{dc}IC_j + \Delta V_{dc} - (V_{dcn} + \Delta V_{dc})}{0.5(V_{dc \max} - V_{dc \min})}. \quad (5.16)$$

Equating $RLI(f_{ac})$ and $RLI(V_{dc})$ gives the following,

$$RLI(f_{ac}) = RLI(V_{dc}) \Rightarrow IC_i = IC_j. \quad (5.17)$$

Since subscripts i and j represent arbitrary DGs in AC and DC subgrids, thus the complete form of (5.17) can be written below,

$$\begin{aligned} IC_1 &= \dots = IC_i = \dots = IC_m \\ &= IC_1 = \dots = IC_j = \dots = IC_n \end{aligned} \quad (5.18)$$

As seen from (5.18), by properly scheduling the BIC power to equalize the RLIs of the two subgrids, all DG ICs converge to the same value in steady state. This means the total operating cost can be minimized and the global system economic operation of the hybrid AC/DC MG is realized. When the output power of a certain DG reaches its predefined value, the compensating signals produced by the DCCFs will spontaneously achieve a new equilibrium such that the rest DGs are working in economic dispatch principle and f_{ac}/V_{dc} restorations can be realized. Observing from (5.12), it is worth noting that the RLI calculations only involve f_{ac} , V_{dc} , Δf_{ac} and ΔV_{dc} . The BIC does not necessarily know the exact DG ICs. Considering a saturated DG in AC or DC subgrid, the DG delivers the bounded power and stops short of responding to the compensation signal. Yet its distributed controller keeps staying in the subgrid communication network and maintains synchronization with other DGs. Once the power saturation terminates, the compensating signal is again imposed in the DG inner loop so that this DG can participate in the f_{ac} or V_{dc} regulations. Thus, the saturated DG would not influence RLI computations and the BIC control diagram consistently stands.

5.3.3 Communication Time Delay Stability Analysis

The above contexts comprehensively explain the equilibrium operating point of the hybrid MG under the proposed distributed control architecture. As mentioned earlier, the distributed control requires DGs to exchange information through communication networks, which unavoidably results in communication time delay. The large time delay in the MG may compromise the system convergence speed, and even cause system oscillations [125]. Therefore, it is necessary to analyze the impacts of communication time delay on overall performances of the hybrid AC/DC MG. To do that, two considerations have to be made. Firstly, as detailed in Figure 5.2, it is fairly possible for a particular DG to have the IC locating beyond the linear range of the droop curve. This means the output power

of the DG has reached the minimum or maximum value. In this situation, the DG keep delivering the bounded power and the other DGs still operate abiding by the economic dispatch rules. However, in this chapter, this exceptional scenario would be excluded from stability studies since those DGs working with the bounded power intrinsically act as constant power sources (CPSs) which contribute the widened stability margin to the MG [47]. Secondly, as understood from [126], only the IC based droop characteristics and the dynamics of the proposed DCCF are considered because they are the two major factors that may undermine the MG stability.

Substituting (5.7) into (5.13) and (5.14), the resulted compact forms can be written as below,

$$\begin{cases} \tau_{ac}\dot{f} = f_{acmax}1_m - f - d_{ac}a_{ac}P_{ac}1_m - d_{ac}b_{ac} + \Delta f \\ \tau_{dc}\dot{V} = V_{dcmax}1_n - V - d_{dc}a_{dc}P_{dc}1_n - d_{dc}b_{dc} + \Delta V \end{cases}, \quad (5.19)$$

where $f = [f_1 \cdots f_i \cdots f_m]^T$, $V = [V_1 \cdots V_j \cdots V_n]^T$,
 $\Delta f = [\Delta f_{ac1} \cdots \Delta f_{aci} \cdots \Delta f_{acm}]^T$, $\Delta V = [\Delta V_{dc1} \cdots \Delta V_{dcj} \cdots \Delta V_{dcn}]^T$,
 $b_{ac} = [b_1 \cdots b_i \cdots b_m]^T$, $b_{dc} = [b_1 \cdots b_j \cdots b_n]^T$,
 $a_{ac} = \text{diag}(a_1 \cdots a_i \cdots a_m)$, $a_{dc} = \text{diag}(a_1 \cdots a_j \cdots a_n)$,
 $P_{ac} = \text{diag}(P_1 \cdots P_i \cdots P_m)$, $P_{dc} = \text{diag}(P_1 \cdots P_j \cdots P_n)$,
 $\tau_{ac} = \omega_{LPP}^{-1} I_{m \times m}$, $\tau_{dc} = \omega_{LPP}^{-1} I_{n \times n}$. 1_m and 1_n are column vectors with all elements being 1.

Replacing x in (5.11) with f_{ac} and V_{dc} respectively, the compact forms of controllers can also be obtained,

$$\begin{cases} \tau_{dac}\Delta\dot{f} = k_{pac}e_{ac} + k_{iac}\psi_{ac} - \Delta f, \dot{\psi}_{ac} = e_{ac} \\ \tau_{ddc}\Delta\dot{V} = k_{pdc}e_{dc} + k_{idc}\psi_{dc} - \Delta V, \dot{\psi}_{dc} = e_{dc} \end{cases}, \quad (5.20)$$

where $k_{pac} = \text{diag}(k_{p1} \cdots k_{pi} \cdots k_{pm})$, $k_{pdc} = \text{diag}(k_{p1} \cdots k_{pj} \cdots k_{pn})$,
 $k_{iac} = \text{diag}(k_{i1} \cdots k_{ii} \cdots k_{im})$, $k_{idc} = \text{diag}(k_{i1} \cdots k_{ij} \cdots k_{in})$,
 $\tau_{dac} = \text{diag}(\tau_{d1} \cdots \tau_{di} \cdots \tau_{dm})$, $\tau_{ddc} = \text{diag}(\tau_{d1} \cdots \tau_{dj} \cdots \tau_{dn})$,
 ψ_{ac} and ψ_{dc} are the intermediate state variables induced by integrators in (5.11). e_{ac} and e_{dc} are the error vectors,

$$\begin{cases} e_{ac} = -\gamma_{ac}L_{ac}\Delta f + G_{ac}\rho_{ac}(f_{acn}1_m - f) \\ e_{dc} = -\gamma_{dc}L_{dc}\Delta V + G_{dc}\rho_{dc}(V_{dcn}1_n - V) \end{cases}, \quad (5.21)$$

Figure 5.6: The representative hybrid AC/DC MG.

where $\gamma_{ac} = \text{diag}(\gamma_1 \cdots \gamma_i \cdots \gamma_m)$, $\gamma_{dc} = \text{diag}(\gamma_1 \cdots \gamma_j \cdots \gamma_n)$,

$G_{ac} = \text{diag}(g_1 \cdots g_i \cdots g_m)$, $G_{dc} = \text{diag}(g_1 \cdots g_j \cdots g_n)$,

$\rho_{ac} = \text{diag}(\rho_1 \cdots \rho_i \cdots \rho_m)$, $\rho_{dc} = \text{diag}(\rho_1 \cdots \rho_j \cdots \rho_n)$,

L_{ac} and L_{dc} are the Laplacian matrices describing communication networks of AC and DC subgrids. f_{acn} and V_{dcn} are the nominal AC frequency and nominal DC bus voltage respectively.

Combining (5.19), (5.20) and (5.21), and performing small signal disturbances, the dynamic model can be derived below,

$$\Delta \dot{X} = \begin{bmatrix} -\tau_{ac}^{-1} & 0 & \tau_{ac}^{-1} & 0 & 0 & 0 \\ 0 & -\tau_{dc}^{-1} & 0 & \tau_{dc}^{-1} & 0 & 0 \\ a_1 A_1 & 0 & C_1 & 0 & b_1 & 0 \\ 0 & a_2 A_2 & 0 & C_2 & 0 & b_2 \\ A_1 & 0 & B_1 & 0 & 0 & 0 \\ 0 & A_2 & 0 & B_2 & 0 & 0 \end{bmatrix} \Delta X, \quad (5.22)$$

where $X = [f \ V \ \Delta f \ \Delta V \ \psi_{ac} \ \psi_{dc}]^T$ is for the representation of original state vector and ΔX stands for the small signal quantity. Other related parameters in (5.22) are listed as follows: $A_1 = -G_{ac}\rho_{ac}$, $B_1 = -\gamma_{ac}L_{ac}$, $A_2 = -G_{dc}\rho_{dc}$, $B_2 = -\gamma_{dc}L_{dc}$, $a_1 = \tau_{dac}^{-1}k_{pac}$, $b_1 = \tau_{dac}^{-1}k_{iac}$, $a_2 = \tau_{ddc}^{-1}k_{pdc}$, $b_2 = \tau_{ddc}^{-1}k_{idc}$, $C_1 = a_1 B_1 - \tau_{dac}^{-1}I_{m \times m}$, $C_2 = a_2 B_2 - \tau_{ddc}^{-1}I_{n \times n}$.

Noting that (5.22) gives a generalized form of the system model, for simplicity, a scenario that each subgrid has 2 DGs (i.e., $m=n=2$) is considered, as seen from Figure 5.6. It is further assumed that the capacities of the two subgrids are comparable, and the hybrid MG has the symmetrical structure [49]. This allows setting the PI parameters of DCCF in both subgrids to be identical, i.e., $k_{pac} = k_{pdc} = k_p I_{2 \times 2}$, $k_{iac} = k_{idc} = k_i I_{2 \times 2}$, where k_p and k_i are constants.

Figure 5.7: Root loci plot with τ_d variation.

Besides, AC and DC subgrids have the identical communication networks, hence, the delay matrices in (5.20) can also be equally set, i.e., $\tau_{dac} = \tau_{ddc} = \tau_d I_{2 \times 2}$.

Figure 5.7 shows that the dominant eigenvalue behaviors of the autonomous system described by (5.22) with τ_d increasing from 0.05 s to 1.15 s. The remaining eigenvalues that have the real parts less than -8 are neglected. In the case of $\tau_d = 0.5$ s, complex eigenvalues are $-2.1 \pm j31.2$ which are in left half plane and the MG system is stable. The oscillation frequency pertaining to these eigenvalues is estimated as 5 Hz. In contrast, the MG system is unstable when communication time delay increases to 1 s. The corresponding eigenvalues are $0.15 \pm j22.1$ which have the oscillation frequency of 3.5 Hz. Observed from Figure 5.7, for the hybridized system under study, the maximum communication time delay should be smaller than 0.9 s in order to attain the stable operation.

5.3.4 Discussions

A: Decoupling of The Two Control Levels

There are two ways to avoid the system instability caused by the interactions between the two control levels. Firstly, for a particular DG in either AC or DC subgrid, the dynamics of its inner control loops in the first level should be tuned much faster than that of DCCF in the second level. By doing so, the signals

generated by the DCCF can be viewed as a constant for the inner loops, and the two control levels can be completely decoupled. Secondly, when the hybrid MG system is started, it is highly recommended to enable the DCCF only after the first level controllers function stably. Therefore, the underlying stability incurred by the interactions of the two levels can be subtly circumvented from the perspective of operating procedures.

B: The Control of Energy Storages

Energy storages are important in the MG system. In this chapter, ESs would not be involved in economic dispatch problems. Due to the absence of the main grid, the autonomous hybrid MG may have low system inertial. It is reasonable to schedule ESs as the system energy buffers. In AC and DC subgrids, for the worst case that all DGs are down, ESs could be utilized to build up AC or DC bus, and supply the requested power to critical loads. For a less serious case that the system RLI goes beyond the predefined range, the storages should work in power control mode to limit RLI in $[-1, 1]$. For instance, when the RES generations exceed the power consumptions, RLI tends to exceed 1 due to the surplus power. Upon this loading condition, energy storages would absorb power from the MG and regulate RLI to be slightly less than 1 or clamped at 1. Conversely, assuming that the MG is heavily loaded, RLI may drop below -1. Energy storages would release power so that RLI can increase to a bit larger than -1 or bounded at -1, thus ensuring the safe MG operations.

C: The Impacts of Non-Inductive Or Complex Line Impedances

In high voltage power systems, the transmission lines can be considered to be inductive. However, the line impedances of low voltage MGs would be non-inductive or complex. The active power regulations may affect the reactive power variations and vice versa. To retrieve the decoupled features of active and reactive powers, virtual impedance techniques in [98] can be utilized to shape the DG output impedances to be purely inductive. The proposed method can thus be applied to the system of non-inductive or complex impedances without any revision. Furthermore, as indicated by (5.12), the active power distribution is only related to frequency fluctuations. There is only one common frequency prevailing in the AC subgrid in the steady state, which ensures the nearly exact

active load sharing among DGs. Hence, ICs equalization merely depends on the AC frequency. The impacts of line impedances on the ICs are minor and could be neglected.

D: The Motivations for Configuring Leading Leader DGs

In both AC and DC subgrids, it is true that the convergence speed of the DCCF could be faster provided that all DGs know x_n . However, this unnecessarily requires DGs to have more prior knowledge of a given system, which may sacrifice the MG flexibility and PnP property. In this chapter, the worst case that only leader DG knows the information of x_n is considered. Then a follower DG with the DCCF only need to establish the communications with its neighbors, and system consensus could be achieved autonomously. Besides, it is worth noting that there are two control levels in the proposed distributed control architecture, i.e., IC based droop in the first level and the DCCF in the second level. The dynamic of the second level should be strictly slower than that of the first level to avoid dynamic conflicts between the two levels. In this sense, the convergence of the DCCF should not be over rapid, and hence, the scenario that all DGs know x_n would not be encouraged.

E: Advantages of The Proposed Scheme Over Existing Methods

In the published studies, the central idea of distributed optimization is to choose DG ICs as consensus variables and drive them to be the same. A distributed consensus based approach in [127] assigns each DG in a grid with an agent which produces the power reference for the DG. Those agents have to locally estimate the mismatch between demands and total generations. However, the estimated mismatch may not equal the real one, which possibly undermines the ICs equalization. The similar challenge can also be found in [128] where highly accurate predictions of RES generations and load variations are compulsory. Considering the random wind power, the economic dispatch for smart grids is studied in [129]. An initialization scheme has to be repeatedly exerted at each instant of wind power change, which may not be practical in real applications. A distributed algorithm reported in [130] requires that the output powers of all DGs have to be collected and sent to a particular DG. Yet the requirements of this algorithm are identical to that in central controls, which inevitably compromises the system flexibility

and scalability. Although the method proposed in [131] achieves ICs consistence with avoiding load power forecasting, the method unnecessarily escalates the computational burdens by introducing a mode switching control and intentionally reducing the consensus speed when the output power of a DG reaches the bounded value.

Compared with the above distributed optimization methods, the proposed architecture has the following advantages. Firstly, f_{ac}/V_{dc} can be perfectly stabilized at their nominal values, which will certainly protect those f_{ac}/V_{dc} -sensitive loads and significantly improve system power qualities. Secondly, no prediction of RESs and loads would be needed. The power balancing between the generation and the consumption can be autonomously achieved in the studied hybrid MG. Thirdly, when the output power of a DG is saturated, without any mode transition or changing control schemes, the proposed architecture allows the rest DGs continuing to share the load based on economic dispatch principle. Fourthly, the existing distributed optimizations share the drawback that they are provincially tailored for AC MG or DC MG. But in the hybrid MG, AC and DC subgrids coexist. The power management may involve more challenges, which motivates the proposition of RLI. By configuring the BIC to equate subgrid RLIs, the ICs of all DGs in the MG can be equalized, and hence, the global system economic operation can be accomplished.

5.4 Simulations

5.4.1 Comparisons of Classical Droop And IC Based Droop

Meticulous comparisons of system dynamics with conventional droops and the IC based droops are performed on the representative hybrid MG in Figure 5.6. Relevant system parameters are summarized in Table 5.1 and Table 5.2. The Laplacian matrices depicting communication graphs of the two subgrids can be written as $L_{ac} = L_{dc} = [1 \ -1; 1 \ 1]$. For a subgrid, unlike the centralized control where a central controller has to send commands to all DGs, the proposed DCCF is fully distributed. As mentioned before, only the leader DG knows the information x_n . The follower DGs endeavor to achieve consensus with the

Figure 5.8: The representative hybrid MG under conventional droops.

Figure 5.9: The representative hybrid MG under IC based droops.

Table 5.1: System parameters for hybrid MG under economic operation.

Parameter	Description	Value
$f_{ac \max}$	Maximum AC frequency	51 Hz
$V_{dc \max}$	Maximum DC bus voltage	710 V
f_{acn}	Nominal AC frequency	50 Hz
V_{dcn}	Nominal DC bus voltage	700 V
ω_{LPF}	Cutoff angular frequency of LPF	$500/\pi$
k_p	Proportional gain in DCCF	7
k_i	Integral gain in DCCF	800

Table 5.2: Coefficients of cost functions in Figure 5.6

	a_k	b_k	c_k
DG _{d1}	9.4e-2	1.22e-2	0.25
DG _{d2}	7.8e-2	3.41e-2	0.35
DG _{a1}	13e-2	5.9e-2	0.25
DG _{a2}	9.5e-2	8.5e-3	0.35

leader one such that the distributed controllers of all DGs in the subgrid produce the identical compensating variables for first level controllers. For AC and DC subgrids in Figure 5.6, leading roles are assigned to DG_{d1} and DG_{a1} respectively, whereas DG_{d2} and DG_{a2} are configured as the followers. On this basis, the pinning matrices in (5.21) can be derived as $G_{ac} = G_{dc} = [1 \ 0; \ 0 \ 0;]$.

Assuming the power rating of each DG is 15kW, for AC DGs (DG_{a1} and DG_{a2}), their classical droop gains are computed as 2/15000. By the same token, the droop coefficients of DG_{d1} and DG_{d2} are derived as 20/15000. According to (5.6), d_{ac} and d_{dc} could be calculated as 2 and 20, respectively. Observing from Figure 5.8, for conventional droops, the summed load across the hybrid MG is around 24 kW at the beginning. Due to the f_{ac} and V_{dc} regulation mechanisms of the DCCF, the frequency in AC subgrid and the bus voltage in DC subgrid keep unchanged at 50 Hz and 700 V. On the condition that load power steps up to 49 kW, the total cost of the MG system increases from 18 \$/h to 68.2 \$/h. Then f_{ac} and

Figure 5.10: The representative hybrid MG with DG_{d2} and DG_{d2} failures.

V_{dc} are quickly recovered to their nominal values. For fair comparisons, the same loading profile is exerted in the MG when IC based droops are utilized. As shown in Figure 5.9, initially, DG ICs are equalized at about 0.65 \$/kWh. The frequency drop and the voltage drop are found at the instant of load step-up. Fortunately, the DG IC equalization maintains unaffected by the sudden load change, and all DG ICs rise to 1.35 \$/kWh in the steady state. Comparing Figure 5.8 (e) and Figure 5.9 (e) indicates that the entire cost of DGs controlled by IC based droops is always less than the classical droops no matter how the loading condition varies.

5.4.2 Hybrid MG with Unexpected DG Failures

Upon the hybrid MG system displayed in Figure 5.6, simulation results for a scenario that DG_{d2} and DG_{d2} fail in sequence are shown in Figure 5.10. Initially, AC frequency and DC bus voltage are perfectly stabilized at 50 Hz and 700 V

Figure 5.11: HIL test stage 1: DCCF is enabled.

under the proposed distributed control architecture. However, when DG_{a2} is unfortunately down at 1 s, a significant frequency drop of 1 Hz is observed, and a slight voltage deviation also occurs. For this situation, the DG_{a2} power immediately falls to zero. The ICs of DG_{d1} , DG_{d2} , DG_{a1} gradually rise to 1.1 \$/kWh from 0.8 \$/kWh. When DG_{d2} is unpredictably out of service at 4 s, a drastic voltage drop of around 10 V could be inspected, and a small frequency fluctuation takes place. Due to the mechanisms of the proposed control scheme, the ICs of DG_{a1} and DG_{d1} are still equalized at around 1.9 \$/kWh. Therefore, it is easy to understand that the global system economic operation of the hybrid MG could be effectively realized even in the case of DG failures.

5.5 Experimental Verifications

To experimentally validate the feasibility and effectiveness of the proposed distributed control architecture for global system economic operation in hybrid AC/DC MG, an in-house HIL testing platform that has been shown in Figure 4.9, is utilized in this chapter. For better explanations, HIL tests are divided into eight stages which are shown in Table 5.3. From stage 1 to stage 7, the economic operation is achieved with the communication time delay of 20 μ s. In stage 8, longer time delays are deliberately set to study the dynamic responses of the MG system.

As detailed in Figure 5.11, at the beginning, DG_{a1} and DG_{d1} are in operation, while the other DGs and BIC are in idle mode. The initial AC frequency and DC

Table 5.3: Hardware in loop test sequence.

	DG _{d1}	DG _{d2}	DG _{a1}	DG _{a2}	BIC	DCCF	P _{Ldc} step-up	P _{Lac} step-up
Stage 1	on	off	on	off	off	off → on	off	off
Stage 2	on	off	on	off	off → on	on	off	off
Stage 3	on	off → on	on	off	off	on	off	off
Stage 4	on	off	on	off → on	off	on	off	off
Stage 5	on	off	on	off	off	on	off → on	off
Stage 6	on	off	on	off	off	on	off	off → on
Stage 7	on	off	on	off	off	on → off	off	off
Stage 8	on	off	on	off	off	off → on	off	off

Figure 5.12: HIL test stage 2: BIC is enabled.

Figure 5.13: HIL test stage 3: DG_{d2} is enabled. Figure 5.14: HIL test stage 4: DG_{a2} is enabled.

Figure 5.15: (a) HIL test stage 5: P_{Ldc} steps up. (b) Zoomed view of ICs.

Figure 5.16: (a) HIL test stage 6: P_{Lac} steps up. (b) Zoomed view of ICs.

Figure 5.17: (a) HIL test stage 7: DCCF is disabled and all communications fail.
(b) Zoomed view of ICs.

Figure 5.18: HIL test stage 8: MG with communication delay of 0.5 s.

Figure 5.19: HIL test stage 8: MG with communication delay of 1 s.

bus voltage are 50.55 Hz and 708.67 V respectively. On the condition that the DCCF in the second level is activated, f_{ac} and V_{dc} are stably regulated at their nominal values, i.e., 50 Hz and 700 V. When BIC is enabled in stage 2, IC_{d1} and IC_{a1} immediately converge to 1.8 \$/kWh, which means the system operating cost is minimized even though the MG currently has only DG_{a1} and DG_{d1} , as plotted in Figure 5.12.

According to Figures 5.13-5.14, it is evident that the proposed distributed control architecture does allow PnP functionalities. In Figures 5.13, DG_{d2} is unexpectedly integrated into the hybrid MG. IC_{d1} , IC_{d2} and IC_{a1} quickly reach a level of ICs being around 0.8 \$/kWh. Once DG_{a2} is suddenly plugged into the MG, all DG ICs are equalized at about 0.6 \$/kWh after system transition. These results are consistent with the analyses in Section 5.3, and global system economic operation of the studied hybrid AC/DC MG can thus be attained. Besides, it should be noted that f_{ac} and V_{dc} maintain at their respective nominal values no matter how MG system configuration varies.

Proceeding to Figure 5.15 and Figure 5.16, variations of all DG ICs could be found in the case that DC load P_{Ldc} and AC load P_{Lac} increase in sequence. When P_{Ldc} steps up firstly, DG ICs almost concurrently rise to the new optimal value which is estimated as 0.7 \$/kWh. When P_{Lac} step-up is also triggered, DG ICs remain at the same value in the steady state, and the newly-obtained IC is around 1 \$/kWh. In this sense, the overall system operating cost has been minimized.

Practically, the normal operation of MG system is threatened by considerable atrocious conditions. The attempt of this chapter is to scrutinize the performances

of the MG in the worst case that all communications fail and the entire second level controls malfunction. In this context, f_{ac} and V_{dc} are unregulated and they would deviate from their nominal values. As plotted in Figure 5.17, f_{ac} and V_{dc} shift to 50.79 Hz and 708.7 V after losing communication. Fortunately, all DG ICs still keep the same, which helps to maintain the global system economic operation.

Stages 1-7 have shown the steady operation of the MG system with communication time delay set as 20 μ s. However, as mentioned early, the enlarged delay seriously poses a threat to the system stability. In stage 8, τ_d is configured as 0.5 s and 1 s respectively, and the system dynamic responses are accordingly displayed in Figure 5.18 and Figure 5.19. Initially, the loads step-up and the DCCF are all disabled, as expounded in Table 5.3. In the case of $\tau_d=0.5$ s, when the second level control algorithms are exerted, large transient oscillations of DG ICs are observed, although the ICs maintain unaffected after 2 s system transition. As seen from Figure 5.18, the oscillation frequency is approximated as 5 Hz, which is in good agreement with the stability analyses in Figure 5.19. Next, in the situation that $\tau_d=1$ s, the whole system is unstable and oscillates at 3.5 Hz. This result is also well supported by the related analyses in Section 5.3, and for the hybrid AC/DC MG under study, the communication time delay should be less than 0.9 s, as indicated by Figure 5.19.

5.6 Summary

In this chapter, a distributed control architecture is proposed for the global system economic operation of the hybrid AC/DC MG. The first level of the architecture implements IC based droop controllers in AC and DC subgrids. Although all DG ICs converge to the same value in the steady state, the adoption of droop schemes unavoidably causes f_{ac} and V_{dc} deviations. To benefit from the IC based droops and also achieve f_{ac} and V_{dc} recovery, in second control level, a DCCF, which can be uniformly applied to AC and DC subgrids, is proposed for regulating f_{ac} and V_{dc} to their nominal values. Due to the presence of DCCF, f_{ac} and V_{dc} maintain invariable. Hence, the loading conditions of AC and DC subgrids are invisible. To address this problem, an original RLI is proposed to extract the hidden loading status of each subgrid. With the RLI, the power reference of BIC

can be easily defined. By properly scheduling the BIC, all DGs in the hybrid MG system will have the identical ICs in steady state, and the global system economic operation can thus be realized. Then, the impacts of communication time delay on overall stability are meticulously studied through a small signal model of a representative hybrid MG. Simulations and in-house HIL tests verify the feasibility and effectiveness of the proposed control architecture.

Chapter 6

Conclusions and Future Works

This chapter concludes the major contributions made by this thesis, i.e., enriching the connotations of power sharing concepts in terms of transient power sharing, stable power sharing, BICs distributed power sharing and economic power sharing. Each type of power sharing scheme and the main outcomes in its proper applications are carefully summarized. Furthermore, possible future works are presented.

6.1 Conclusion

In this thesis, power sharing concepts are enriched in four aspects: dynamic power sharing, stable power sharing, BICs distributed power sharing and economic power sharing. These newly-extended power sharing mechanisms are appropriately tailored for addressing different challenges in MG systems. It should be emphasized that the mechanisms are logically related and they are explained as follows.

To address the power fluctuations in RESs and loading power uncertainties, diversified energy storages are hybridized to form HESSs. In a given HESS, ES_H s and ES_L s have different dynamic characteristics. ES_H s have high power density but limited energy density, and ES_L s have slow response speeds but sufficient energy capacities. For the better coordination between ES_H s and ES_L s, a novel integral droop (ID) controller is proposed in Chapter 2 for ES_H s, and conventional V-P droop is applied to ES_L s. By the coordination of ID and V-P droops, when there is a change in load demand, ES_H s would only supply the transient powers which gradually reduce to zero in steady state. ES_L s would be slowly releasing powers to the equivalent load and feeding all load powers in steady state. In this way, transient power sharing in HESS has been realized. Moreover, by using small signal analyses, it is demonstrated that the proposed ID helps to widen stability margin for the HESS loaded by CPLs. An in-house hardware experimental platform verifies the effectiveness of investigated transient power sharing.

In a DC MG, not only HESSs but also other sources such as fuel cells and DC generators would exist. The coexistence of numerous sources, HESSs, resistive loads and CPLs, may cause issues to system stabilization. Although the ID controller in Chapter 2 is proven to contribute damping effects to the HESS, the small signal analyses are only valid in particular equilibriums, which would not hold in full system operations. To ensure HESS correct functioning and DC MG stability even under large disturbances, as a continuous work of Chapter 2, Chapter 3 addresses the stable power sharing among dispatchable units (DUs) in the DC MG to guarantee MG large signal stability. Notice that DUs refer to the units that can be scheduled to regulate DC bus voltage, and DUs naturally include HESSs and other schedulable DC generations. A decentralized composite controller (DCC) is proposed in Chapter 3. The DCC is separately deployed to

each DU. The DCC employs a well designed high gain observer to estimate the coupling of a certain DU with surrounding devices. Then the coupling is offset by the controller which allows the DU subsystem to be virtually isolated from the DC MG. As such, the stabilization task of the whole MG system can be decomposed into the stabilization of DU subsystems. Concretely, global system large signal stability can be achieved as long as the internal states in each DU are properly stabilized in the large signal sense. Hence, the proposed DCC could work in a fully decentralized manner, which enhanced the flexibility and scalability of DC MG. Hardware experimentations attest to the feasibility and validity of the intended stable power sharing enabled by DCC.

Chapter 2 and Chapter 3 mainly focus on DC MGs. Although large amounts of DC compatible sources and loads emerge in modern power systems, AC power conversions take dominant roles in generation, transmission and distribution networks. To simultaneously harness the advantages of AC and DC systems, a hybrid AC/DC MG should be established. For this purpose, Chapter 4 touches the power management of the hybrid MG and smoothly extend the power sharing concepts to multi-paralleled BICs. BICs assume the bidirectional power flow between AC and DC subgrids. A distributed power management strategy (DPMS) is proposed to allocate the power flow to BICs in proportion to their respective ratings, thus avoiding any possible BIC overloading. Moreover, by using DPMS, all DGs in the hybrid MG can proportionally share all the loads, which leads to the global power sharing (GPS) among DGs. An in-house hardware-in-loop (HIL) experimental platform is built up to substantiate the viability of BICs distributed power sharing.

With the increasing number of sources and loads incorporated into the hybrid AC/DC MG, economic operations would be critically important. As a continuation of Chapter 4, Chapter 5 proposes a distributed control architecture to save the global system operating cost of the hybrid MG. There are two control levels in the architecture. The first level utilizes IC based droops for DGs in AC and DC subgrids. With the synchronization of f_{ac} and V_{dc} , in each subgrid, DG ICs would converge to the same value in steady state, giving the optimal operation. However, droop controllers inevitably cause f_{ac} and V_{dc} deviations. To restore f_{ac} and V_{dc} while reserve IC based droops, a distributed control canonical form (DCCF) is

proposed in the second level, which can be uniformly applied to AC and DC subgrids. Due to the existence of DCCF, floating f_{ac} and V_{dc} which inherently indicate the loading conditions of AC and DC subgrids, are no longer available. To overcome this difficulty, a novel RLI is proposed in Chapter 5 to retrieve the hidden subgrid loading status. With RLI, the power reference of BIC can be easily determined. By appositely dispatching the BIC, in steady state, all DGs in the hybrid AC/DC MG would be equalized, which means the global system economic operation is accomplished. Simulations and HIL tests both verify the effectiveness of the desired economic power sharing.

6.2 Recommendations for Further Research

In addition to the extended four power sharing schemes presented in this thesis, there are some other promising research topics that worth meticulous investigations in the near future. These topics are detailed as follows.

A: Large Signal Stability For Complex Power System

Chapter 3 has shown how to design DCC controllers to achieve large signal stability in DC MGs. However, the DCC only considers DC/DC boost converters. In fact, modern islanded electrical system, such as on-board vehicular power systems, high-speed railway power systems, more electric aircraft systems and all electric ships, are evolving into hybrid AC/DC constructions. There are a plethora of AC converters and other DC converters (e.g. buck-boost type) that inherently exhibit nonlinearities. Although some large signal analysis tools are reported in the literature, these tools cannot be effectively utilized in complicated power systems. In this sense, a possible future work is to develop the large signal stabilization approach documented in Chapter 3 to accommodate complex hybrid AC/DC systems with heterogeneous converters connected in parallel, and the decentralized stabilization merits can still be reserved.

B: System Level Reliability Analyses

It is reported that power switching devices and electrolytic capacitors are the most easily damaged units in power converter systems. Even in normal operations, MG would be experiencing transient oscillations if controllers are not

properly designed (see Figure 2.13). These oscillations will certainly compromise component life cycles and device reliability. As such, for future works, the reliability mechanisms of power semiconductors and DC link capacitors should be carefully studied. Furthermore, reliability modeling methodologies should also be developed for the complex hybrid AC/DC MGs so that system level reliability and lifetime can be clearly identified.

C: MG Community

To obtain more reliable and economic operations, multiple MGs can be interconnected to constitute a MG community wherein the MGs with superfluent power can sale power to those MGs suffering from power deficiencies. In this sense, as a promising future topic, power market operating patterns in the MG community should be delicately scrutinized. Additionally, considering the RES generation uncertainties and versatile end-user behaviors, apposite RES forecasting and load prediction could be executed by using advanced data techniques. Combining with intricate MG community modeling, power flow constraints and energy trading strategies, efficient MG management system should be explored and even commercialized, if possible.

Appendix

For Figure 2.6 in Chapter 2, the dynamic average model of the converters for ES_H and ES_L can be written as below

$$\begin{cases} C_H \dot{v}_{oH} = (1 - d_H) i_{LH} - i_{oH} \\ L_H \dot{i}_{LH} = v_{in} - (1 - d_H) v_{oH} \end{cases}, \quad (A1)$$

$$\begin{cases} C_L \dot{v}_{oL} = (1 - d_L) i_{LL} - i_{oL} \\ L_L \dot{i}_{LL} = v_{in} - (1 - d_L) v_{oL} \end{cases}. \quad (A2)$$

Performing the small signal disturbances on (A1) and (A2) yields the linearized model written as the following,

$$\Delta \dot{x}_{1H} = A_{1H} \Delta x_{1H} + B_{1H} \Delta d_H + C_{1H} \Delta i_{oH}, \quad (A3)$$

$$\Delta \dot{x}_{1L} = A_{1L} \Delta x_{1L} + B_{1L} \Delta d_L + C_{1L} \Delta i_{oL}, \quad (A4)$$

where $\Delta x_{1H} = \begin{bmatrix} \Delta v_{oH} & \Delta i_{LH} \end{bmatrix}^T$, $\Delta x_{1L} = \begin{bmatrix} \Delta v_{oL} & \Delta i_{LL} \end{bmatrix}^T$,
 $A_{1H} = \begin{bmatrix} 0 & \frac{1-D_H}{C_H} \\ \frac{D_H-1}{L_H} & 0 \end{bmatrix}$, $A_{1L} = \begin{bmatrix} 0 & \frac{1-D_L}{C_L} \\ \frac{D_L-1}{L_L} & 0 \end{bmatrix}$, $B_{1H} = \begin{bmatrix} -\frac{I_{LH}}{C_H} & \frac{V_{CH}}{L_H} \end{bmatrix}^T$,
 $B_{1L} = \begin{bmatrix} -\frac{I_{LL}}{C_L} & \frac{V_{CL}}{L_L} \end{bmatrix}^T$, $C_{1H} = \begin{bmatrix} -\frac{1}{C_H} & 0 \end{bmatrix}^T$, $C_{1L} = \begin{bmatrix} -\frac{1}{C_L} & 0 \end{bmatrix}^T$.

Figure A1: Controllers for ES_H and ES_L .

To derive the full model of each converter, based on Figure 2.7, the complete controllers for ES_H and ES_L are detailed in Figure A1, where d_H and d_L are the control input of the converters. It is observed that ξ_{1H} , ξ_{2H} , ξ_{3H} , ξ_{1L} and ξ_{2L} are the state variables inside the controllers, and their dynamic models can be written as in (A5) and (A6),

$$\begin{cases} \dot{\xi}_{1H} = nP_{oH} = ni_{oH}v_{oH} \\ \dot{\xi}_{2H} = V_n - \xi_{1H} - v_{oH} \\ \dot{\xi}_{3H} = k_{p1H}\frac{d\xi_{2H}}{dt} + k_{i1H}\xi_{2H} + \frac{i_{oH}}{1-D_H} - i_{LH} \end{cases}, \quad (A5)$$

$$\begin{cases} \dot{\xi}_{1L} = V_n - mP_{oL} - v_{oL} = V_n - mi_{oL}v_{oL} - v_{oL} \\ \dot{\xi}_{2L} = k_{p1L}\frac{d\xi_{1L}}{dt} + k_{i1L}\xi_{1L} + \frac{i_{oL}}{1-D_L} - i_{LL} \end{cases}. \quad (A6)$$

The small signal dynamic models of (A5) and (A6) can be calculated by (A7) and (A8) respectively,

$$\Delta\dot{x}_{2H} = A_{2H}\Delta x_{1H} + B_{2H}\Delta x_{2H} + C_{2H}\Delta i_{oH}, \quad (A7)$$

$$\Delta\dot{x}_{2L} = A_{2L}\Delta x_{1L} + B_{2L}\Delta x_{2L} + C_{2H}\Delta i_{oL}, \quad (A8)$$

where $\Delta x_{2H} = \begin{bmatrix} \Delta\xi_{1H} & \Delta\xi_{2H} & \Delta\xi_{3H} \end{bmatrix}^T$, $\Delta x_{2L} = \begin{bmatrix} \Delta\xi_{1L} & \Delta\xi_{2L} \end{bmatrix}^T$,

$$A_{2H} = \begin{bmatrix} nI_{oH} & 0 \\ -1 & 0 \\ -k_{p1H} & -1 \end{bmatrix}, A_{2L} = \begin{bmatrix} -(mI_{oL} + 1) & 0 \\ -(mI_{oL} + 1)k_{p1L} & -1 \end{bmatrix}, B_{2H} = \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & 0 \\ -k_{p1H} & k_{i1H} & 0 \end{bmatrix},$$

$$B_{2L} = \begin{bmatrix} 0 & 0 \\ k_{i1L} & 0 \end{bmatrix}, C_{2H} = \begin{bmatrix} nV_{oH} \\ 0 \\ 1/(1-D_H) \end{bmatrix}, C_{2L} = \begin{bmatrix} -mV_{oL} \\ -(mV_{oL}k_{p1L} - 1) \end{bmatrix}.$$

The duty cycle generated by controllers can be viewed as the input signals of the converter models, and determined by (A9) and (A10),

$$\Delta d_H = A_{21H}\Delta x_{1H} + B_{21H}\Delta x_{2H} + C_{21H}\Delta i_{oH}, \quad (A9)$$

$$\Delta d_L = A_{21L}\Delta x_{1L} + B_{21L}\Delta x_{2L} + C_{21L}\Delta i_{oL}, \quad (A10)$$

where $A_{21H} = \begin{bmatrix} -k_{p1H}k_{p2H} & -k_{p2H} \end{bmatrix}$, $A_{21L} = \begin{bmatrix} -(mI_{oL} + 1)k_{p1L}k_{p2L} & -k_{p2L} \end{bmatrix}$,
 $B_{21H} = \begin{bmatrix} -k_{p1H}k_{p2H} & k_{i1H}k_{p2H} & k_{i2H} \end{bmatrix}$, $B_{21L} = \begin{bmatrix} k_{i1L}k_{p2L} & k_{i2L} \end{bmatrix}$, $C_{21H} = \begin{bmatrix} k_{p2H}/(1-D_H) \end{bmatrix}$, $C_{21L} = \begin{bmatrix} -(mV_{oL}k_{p1L} - 1)k_{p2L}/(1-D_L) \end{bmatrix}$.

Substituting (A9) into (A3), and combined with (A7), the model of the converter interfaced with ES_H can be written by (A11),

$$\Delta \dot{X}_H = A_H \Delta X_H + B_H \Delta i_{oH}, \quad (A11)$$

$$\text{where } \Delta X_H = \begin{bmatrix} \Delta x_{1H} & \Delta x_{2H} \end{bmatrix}^T, A_H = \begin{bmatrix} A_{1H} + B_{1H}A_{21H} & B_{1H}B_{21H} \\ A_{2H} & B_{2H} \end{bmatrix}_{5 \times 5},$$

$$B_H = \begin{bmatrix} C_{1H} + B_{1H}C_{21H} \\ C_{2H} \end{bmatrix}_{5 \times 1}.$$

By the same token, the small signal model of ESL converter can be described by (A12),

$$\Delta \dot{X}_L = A_L \Delta X_L + B_L \Delta i_{oL} \quad (A12)$$

$$\text{where } \Delta X_L = \begin{bmatrix} \Delta x_{1L} & \Delta x_{2L} \end{bmatrix}^T, A_L = \begin{bmatrix} A_{1L} + B_{1L}A_{21L} & B_{1L}B_{21L} \\ A_{2L} & B_{2L} \end{bmatrix}_{4 \times 4},$$

$$B_L = \begin{bmatrix} C_{1L} + B_{1L}C_{21L} \\ C_{2L} \end{bmatrix}_{4 \times 1}.$$

List of Publications

Journal Publications

- [1] **P. Lin**, P. Wang, J. Xiao, J. Wang, C. Jin and Y. Tang, “An Integral Droop for Transient Power Allocation and Output Impedance Shaping of Hybrid Energy Storage System in DC Microgrid,” *IEEE Transactions on Power Electronics*, vol. 33, no. 7, pp. 6262-6277, 2018.
- [2] **P. Lin**, C. Zhang, P. Wang and J. Xiao, “ A Decentralized Composite Controller for Unified Voltage Control with Global System Large-Signal Stability in DC Microgrids,” *IEEE Transactions on Smart Grid*. (Accepted)
- [3] **P. Lin** et al., “ A Distributed Power Management Strategy for Multi-Paralleled Bidirectional Interlinking Converters in Hybrid AC/DC Microgrids,” *IEEE Transactions on Smart Grid*. (Accepted)
- [4] **P. Lin** et al., “ A Distributed Control Architecture for Global System Economic Operation in Autonomous Hybrid AC/DC Microgrids,” *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2603-2617, 2019.
- [5] **P. Lin** , C. Zhang, J. Wang, C. Jin and P. Wang, “On Autonomous Large Signal Stabilization for Islanded Multi-bus DC Microgrids: A Uniform Nonsmooth Control Scheme,” *IEEE Transactions on Industrial Electronics*. (Accepted)
- [6] **P. Lin** , T. Zhao, B. Wang, Y. Wang and P. Wang, “A Semi-Consensus Strategy Toward Multi-Functional Hybrid Energy Storage System in DC Microgrids,” *IEEE Transactions on Energy Conversion*. (Accepted)
- [7] Y. Qi, **P. Lin**, Y. Wang, and Y. Tang, “ Two-Dimensional Impedance-Shaping Control with Enhanced Harmonic Power Sharing for Inverter-Based Microgrids,” *IEEE Transactions on Power Electronics*. (Accepted)

- [8] X. Li, **P. Lin**, Y. Tang, and K. Wang, “Magnetic Integration of LTL Filter With Two LC-Traps for Grid-Connected Power Converters,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1434–1446, 2018.
- [9] J. Fang, **P. Lin**, Y. Tang, “Active Magnetic Decoupling for Improving the Performance of Integrated LCL-Filters in Grid-Connected Converters,” *IEEE Transactions on Power Electronics*, vol. 65, no. 2, pp. 1367–1376, 2018.

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- [1] **P. Lin**, Q. Xu, P. Wang, J. Xiao, and H. Li, “Improved virtual capacitive droop control for hybridization of energy storages in DC microgrid,” *IEEE 2nd Annual Southern Power Electronics Conference (SPEC)*, 2016.
- [2] **P. Lin** et al., “A global robust output regulation method for grid-connected inverter with LCL filter in weak grid condition,” *12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2017.
- [3] **P. Lin**, P. Wang, Q. Xu, J. Xiao, I. U. Nutkani, and C. F. Hoong, “An integral-droop based dynamic power sharing control for hybrid energy storage system in DC microgrid,” *IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia)*, 2017.
- [4] **P. Lin** et al., “Modified Strong Tracking Cubature Kalman Filter For LiFePO₄ Storage System,” *Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, 2017.
- [5] **P. Lin**, P. Wang, J. Xiao, C. Jin, and K. L. Hai, “A distributed control architecture for hybrid AC/DC microgrid economic operation,” *12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2018.
- [6] **P. Lin**, C. Zhang, P. Wang, J. Xiao, and C. Jin, “A Synthesized Control Scheme for Large Signal Stabilization of DC Microgrids,” *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018.

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- [9] **P. Lin**, P. Wang, J. Xiao, C. Jin, Z. Lian, K. L. Hai, “Comprehensive Stability Analyses for Hybrid AC/DC Microgrids With Multi-Paralleled Interlinking Converters Under Distributed Control” *Innovative Smart Grid Technologies Asia (ISGT Asia)*, 2019.

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