Analysis and Control for AC and DC Microgrids

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BY
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ANALYSIS AND CONTROL OF AC AND DC MICROGRIDS

PH.D. THESIS

by

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May, 2016

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ABSTRACT

Power system today is undergoing a green revolution toward smart grid, in which more renewable generations are increasingly penetrating into the grid dispersedly driven by both demonstrated economic and environmental benefits, which fundamentally changes the structure of paradigm system. At the same time, relying on advanced power electronics, energy storage, information and communication infrastructure and devices, other active elements such as demand response and transactive energy are emerging which again increase the heterogeneity and complicate the control of the system to achieve a desired performance. To facilitate the integration of the system, microgrid plays an important role in this process.

The role of microgrid is previously viewed as an effective autonomous system in the distribution system to integrate the renewable energy. With it unique structure and characteristics, it also has the potential to integrate the entire heterogeneous system as a constitutional element, upon which the future distribution system built. To fulfil this potential, both the centralized control and distributed control will be applied in the control system of microgrids, where in most of the centralized applications power flow analysis is required as a basis steady state analysis tool and multiagent system is increasingly adopted in the application based on distributed control.

Existing power flow analyses, which have not taken into account the ongoing changes of the system structure and specific characteristics of the control method for microgrid, are no longer suitable for the next generation distribution system composed of microgrids. To overcome their limitations and make them suitable for analysing the microgrid system, a new formulation is proposed to take into consideration the concepts of virtual impedance and droop control. New formulation is built and implemented for both AC and DC microgrids, with improved accuracy and controllability for microgrid. As a demonstration of it to the centralized control, the proposed power flow analysis is applied to the optimization of a DC community microgrid, where the purpose is to minimize the operation cost of the system considering both the fuel cost and demand response.

For the multiagent system based distributed control, the application of two different consensus algorithms is explored in this work, to fulfil different control objectives. The average consensus is firstly applied to a microgrid with energy storage system in order to make the state of charge balanced. This approach is proven to be effective and superior to the previous control methods in term of flexibility and fault tolerance. The other two applications of multiagent system are aiming to minimize the operation cost, but in a distributed way, for AC microgrid and DC microgrid, respectively. The incremental cost consensus algorithm designed by the author is applied to these two kinds of systems, and the total operation costs in both systems are successfully reduced. Regarding the specific control system implementation, the effects of communication condition and other related control parameters are analysed to give the guidance of the system design.

DANSK RESUME

Elsystemet i dag gennemgår en grøn revolution mod smart grid, hvor mere vedvarende generationer i stigende grad at blive en del af elnettet drevet af både påviste økonomiske og miljømæssige fordele, som fundamentalt ændrer strukturen af paradigme system. Samtidig, bygger på avancerede effektelektronik, energilagring, information og kommunikation infrastruktur og udstyr, andre aktive elementer såsom efterspørgsel respons og transactive energi dukker der igen øger heterogenitet og komplicere kontrollen med systemet for at opnå et ønsket ydeevne. For at lette integration af systemet, microgrid spiller en vigtig rolle i denne proces.
Microgrid er tidligere ses som et effektivt autonomt system i distributionssystemet at integrere vedvarende energi. Med den unikke struktur og egenskaber, det har også potentiale til at integrere hele heterogene systemet som et konstitutionelt element, som den fremtidige distributionssystem bygget på. For at opfylde dette potentiale, både den centraliserede kontrol og distribueret kontrol vil blive anvendt i kontrolsystemet med Microgrids, hvor i det meste af den centraliserede applikationer power flow analyse er påkrævet som grundlag steady state analyse værktøj og multiagent systemet er i stigende grad vedtaget i ansøgningen baseret på fordelt styring.

Eksisterende power flow analyser, som ikke har taget den igangværende ændring af systemet struktur og særlige karakteristika kontrol metode til microgrid, ikke længere er egnet til den næste generation distributionssystem bestod af Microgrids. For at overvinde deres begrænsninger og gøre dem egnede til at analysere microgrid systemet, er en ny formulering foreslået at tage hensyn til begreberne virtuelle impedans og hænge kontrol. Ny formulering er bygget og implementeret for både AC og DC Microgrids, med forbedret præcision og styrbarhed for microgrid. Som en demonstration af det til den centraliserede kontrol, er den foreslåede effekt flow analyse anvendes til optimering af en DC samfund microgrid, hvor formålet er at minimere driftsomkostninger for systemet overvejer både omkostningerne brændstof og efterspørgsel respons.

For det multiagent system baseret distribueret kontrol, er anvendelsen af to forskellige konsensus algoritmer udforsket i dette arbejde, for at opfylde forskellige mål kontrol. Den gennemsnitlige konsensus først påføres en microgrid med energilagringssystem for at gøre ladningstilstanden afbalanceret. Denne fremgangsmåde har vist sig at være effektiv og overlegen i forhold til de tidligere kontrolmetoder i sigt af fleksibilitet og fejltolerance. De to andre anvendelser af multiagent systemet søger at minimere driftsomkostninger, men i et distribueret måde, for både AC microgrid og DC microgrid. Den ekstraomkostning konsensus algoritme designet af forfatteren påføres disse to former for systemer, og de samlede driftsomkostninger i begge systemer er lykkedes reduceres. For den

specifikke styresystem implementering, er virkningerne af kommunikation tilstand og andre parametre relateret kontrol analyseres for at give vejledning af systemets design

THESIS DETAILS AND PUBLICATIONS

Thesis Title: Analysis and Control for AC and DC Microgrids

Ph.D. Student: Chendan Li

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- Chendan Li, Sanjay K. Chaudhary, Mehdi Savaghebi, Juan C. Vasquez, and Josep M. Guerrero, " Power Flow Analysis for Low-Voltage AC and DC Microgrids Considering Droop Control and Virtual Impedance", *Smart Grid, IEEE Transactions on*, accepted.
- C. Li, F. de Bosio, F. Chen S. K. Chaudhary, J. C. Vasquez and J. M. Guerrero, "Operation Cost Minimization of Droop-Controlled DC Microgrids Based on Real-Time Pricing and Optimal Power Flow", has been submitted to *IEEE Journal of Emerging and Selected Topics in Power Electronics.*
- Chendan Li, Ernane A. A. Coelho, Tomislav Dragicevic, Juan C. Vasquez, and Josep M. Guerrero, "Multiagent Based Distributed State of Charge Balancing Control for Distributed Energy Storage Units in AC Microgrids," has been submitted to *Industry Applications, IEEE Transactions on*.
- Chendan Li, Mehdi Savaghebi, Juan C. Vasquez, and Josep M. Guerrero, "Multiagent-based Distributed Control for Operation Cost Minimization of Droop-Controlled AC Microgrids," has been submitted to *Energis*.
- Chendan Li, Juan C. Vasquez, and Josep M. Guerrero "Convergence Analysis of Distributed Control for Operation Cost Minimization of Droop Controlled DC Microgrid Based on Multiagent*", 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long beach, CA, 2016, in press.*

Other peer viewed Publications:

- C. Li, S. K. Chaudhary, J. C. Vasquez and J. M. Guerrero, "Power flow analysis for droop controlled LV hybrid AC-DC microgrids with virtual impedance," 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1-4. doi: 10.1109/PESGM.2014.6939887
- C. Li, T. Dragicevic, M. G. Plaza, F. Andrade, J. C. Vasquez and J. M. Guerrero, "Multiagent based distributed control for state-of-charge balance

of distributed energy storage in DC microgrids," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 2180-2184. doi: 10.1109/IECON.2014.7048804

- C. Li, F. de Bosio, S. K. Chaudhary, M. Graells, J. C. Vasquez and J. M. Guerrero, "Operation cost minimization of droop-controlled DC microgrids based on real-time pricing and optimal power flow," Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE, Yokohama, 2015, pp. 003905-003909. doi: 10.1109/IECON.2015.7392709
- C. Li, S. K. Chaudhary, J. C. Vasquez and J. M. Guerrero, "Power flow analysis algorithm for islanded LV microgrids including distributed generator units with droop control and virtual impedance loop," 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, Fort Worth, TX, 2014, pp. 3181-3185. doi:10.1109/APEC.2014.6803760
- Chendan Li, S. K. Chaudhary, T. Dragicevic, J. C. Vasquez and J. M. Guerrero, "Power flow analysis for DC voltage droop controlled DC microgrids," Systems, Signals & Devices (SSD), 2014 11th International Multi-Conference on, Barcelona, 2014, pp. 1-5.
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  doi: 10.1109/ENERGYCON.2014.6850592
- N. N. Quang, E. R. Sanseverino, M. L. Di Silvestre, A. Madonia, C. Li and J. M. Guerrero, "Optimal power flow based on glow worm-swarm optimization for three-phase islanded microgrids," AEIT Annual

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doi: 10.1109/DEMPED.2015.7303732
- Eleonora Riva Sanseverino, Ninh Nguyen Quang, Maria Luisa Di Silvestre, Josep M. Guerrero, Chendan Li, Optimal power flow in three-phase islanded microgrids with inverter interfaced units, Electric Power Systems Research, Volume 123, June 2015, Pages 48-56, ISSN 0378-7796, http://dx.doi.org/10.1016/j.epsr.2015.01.020.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensure.

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Chendan Li

March 2016

Aalborg

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CHAPTER 1. INTRODUCTION

1.1. MICROGRID IN THE CONTEXT OF SMART GRID

Increasing awareness of energy crisis, global warming and severer impact of the power outage ignites the ongoing revolution of the power system [1]. The revolution in the grid is featured by the continuing expansion of renewable generation, energy storage, and other emerging advanced technologies and new components to improve the reliability, sustainability and efficiency of the system [2][3]. With Distributed Energy Resources (DER), the grid is no longer a one-way power flow grid, in which the large power plants serve the consumers far away via a transmission and distribution system. Rather, it is becoming a networked system where a number of small and distributed resources will also serve the entire grid along with large plants and at the same time past consumers will become prosumer, both importing and exporting power from/to the grid. This transition toward a future smart grid can be illustrated as in Fig. 1.1.

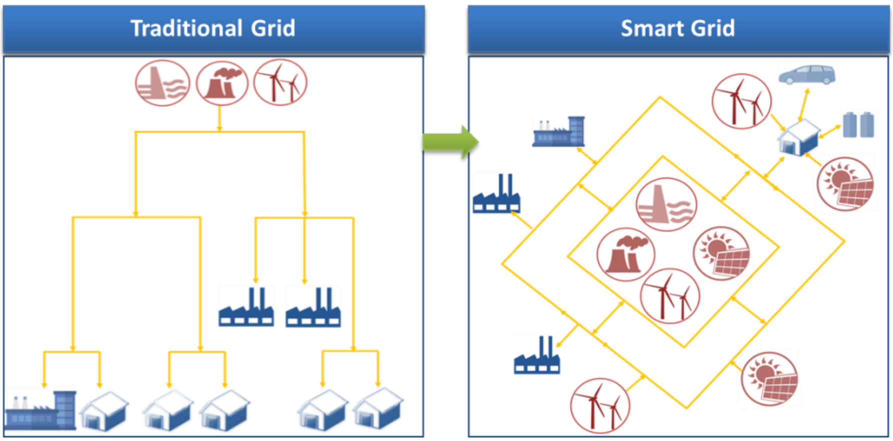


Figure 1.1. Transition from traditional grid to smart grid

Where the revolution will happen most is the distribution part, where a feeder is traditionally taken as passive lumped load referred to the upper grid or the substation and with considerably limited visibility and controllability [4]. To effectively tackle the emerging new devices and increasing DER on the customer side, an aggregator is an essential part needed to synthesize the heterogeneous components through the distribution system. As is initially proposed to integrate various generators, especially the renewables in a small autonomous grid, microgrid is appealing to extend its definition into a constitutional unit/aggregator of the distribution system to facilitate the revolution of smart grid [1], [5] and [6].

The following parts describe the physical structure of the microgrid which suitable for this extension and the corresponding system architecture for the management of the whole distribution system.

1.1.1. PHYSICAL STRUCTURE OF MICROGRID IN SMART GRID

Apart from other forms of the autonomous power systems like that in vessels or in airplanes, the microgrid in the distribution system can be defined according to U.S. Department of Energy (DOE) as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid; A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and islanded-mode [7]–[10].

Microgrids in the distribution system can be classified into several different groups in terms of different categorical methods. Fig. 1.2 shows the classification of them in terms of transmission type, ownership, and number of Point of Common Couplings (PCCs).

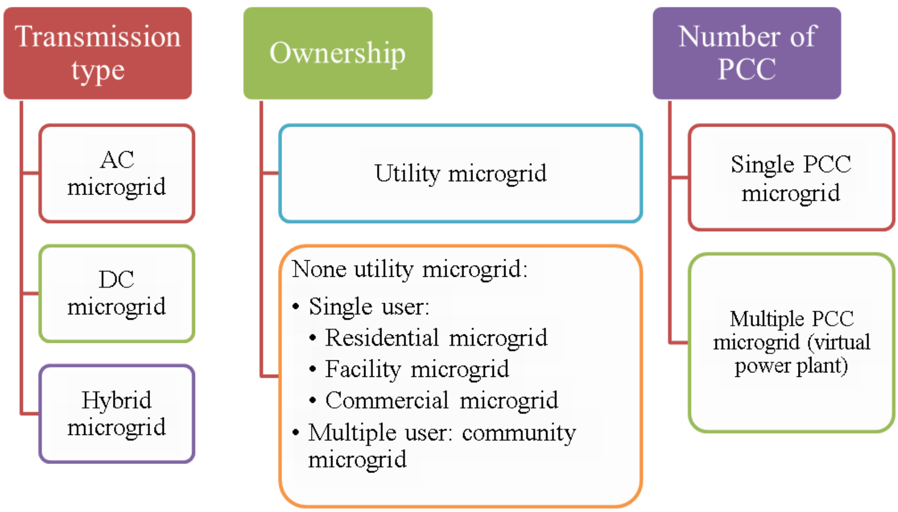


Figure 1.2. Classification of microgrids in distribution system

The future microgrid will be an indispensable part of the distribution system to scalable integrate various kinds of DERs which ranging from solar, wind to fuel cells and electrified transportation fleet. Moreover, with the increasing load such as customer electronics and DERs like energy storage and solar panel are actually DC in nature, more DC microgrids will also appear in the distribution system [11]−[14]. Interaction between the DC microgrid and AC microgrid can form a hybrid microgrid.

The physical structure of the future distribution system can be seen as is showed in Fig. 1.3, which manifests itself as a cluster of interconnected microgrids. This definition of the physical structure for the distribution system is also consistent with the classification of microgrid in term of the transmission type, which makes the microgrid as its building block viable.

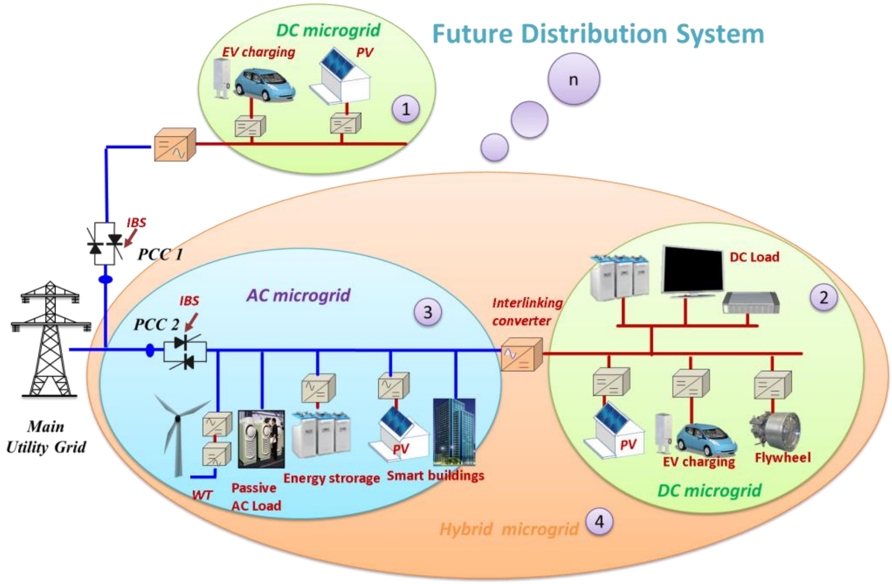


Figure 1.3. Cluster of microgrids as building blocks of future distribution system

To make this physical structure more abstract, a fair analogy for the future distribution grid can be depicted as the topology of multiple cellular microgrids interconnected and interacted together, which is represented as inter-linked hexagons. For a larger microgrid, there might be smaller microgrid inside. One of the convenient examples is the community microgrid with smart home as smaller microgrid inside. In some part, a microgrid can even be built by different parts from other microgrids. This structure is necessary in that the future prosumers might share the common DREs. This abstraction can be illustrated as Fig. 1.4.

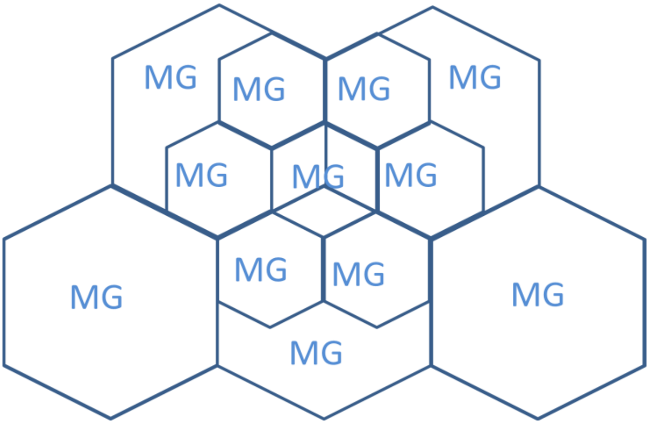


Figure 1.4. Abstract structure of future distribution system formed by microgrids

With a microgrid becoming the building blocks of the future distribution system, more requirements will be imposed on the control system of the microgrid. The features are summarized by the author in the following part.

1.1.2. SYSTEM COORDINATION FRAMEWORK OF MICROGRID IN SMART GRID

Future distribution system desires a control system with following qualities during operation [1]:

1. Security
2. Efficiency
3. Minimum environmental footprint
4. Reliability
5. Flexibility (scalability and plug and play)

To achieve all these qualities, the microgrid, as the building block, needs to response differently to all the possible internal or external disturbances according to different response speed requirements and different objectives. To list a few, it will encompass a myriad of elements: primary droop control, frequency and voltage regulation, power quality enhancement, economic dispatch, power balancing, stabilization and so on [8]. All these valid elements are required to be fulfilled by adequate visibility and controllability by the aid of the development of information and communication system (ITC). The ITC architecture of the community microgrid control system can be illustrated as in Fig. 1.5.

The control applications which fulfil the sub-objectives can be implemented in either centralized or distributed way. As the system physical components are distributed in nature, the distributed control is gaining more popularity. However, the topper the application, the large the amount of information and sophisticated calculation are required for analysis and therefore a centralized controller is still needed in this way. Two different kinds of implement methods for the application are shown as in Fig. 1.6. For the centralized control method, it requires that all the local controllers have to establish the communication connection with the centralized controller. In this way, the centralized controller can make decisions based on the collective information gathered. For the distributed control, there is no such centralized controller, the local controllers need to “talk” to other local controllers with an agreed mechanism to get the global information of the system and cooperatively act toward a common goal locally.

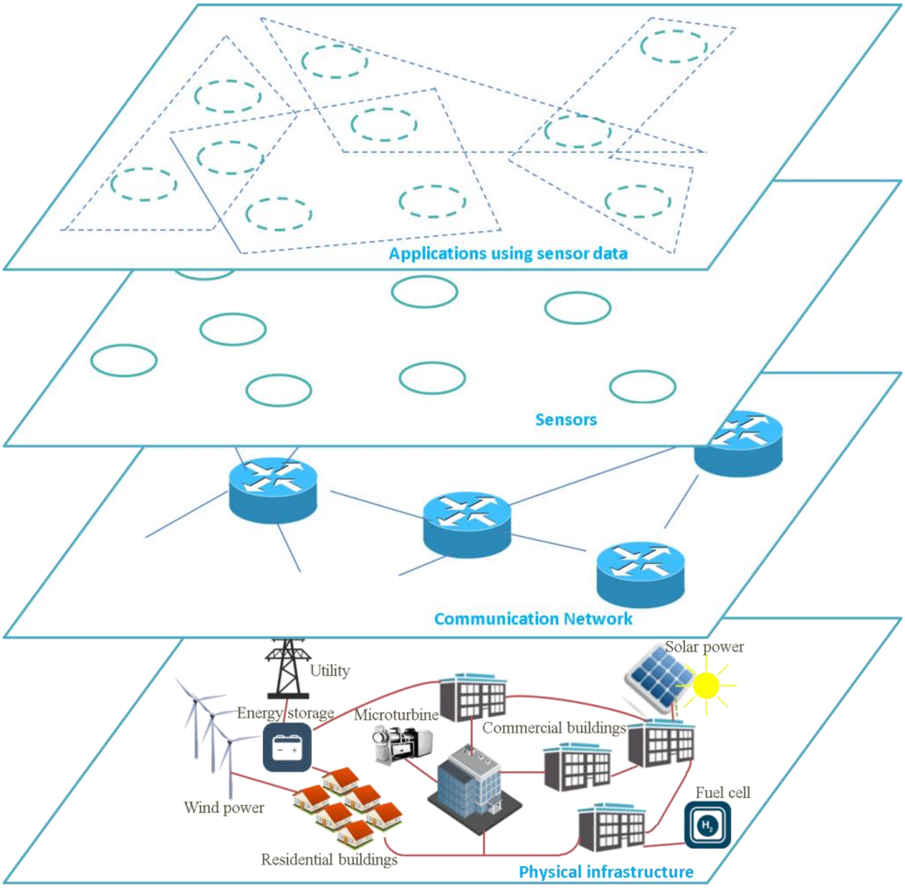
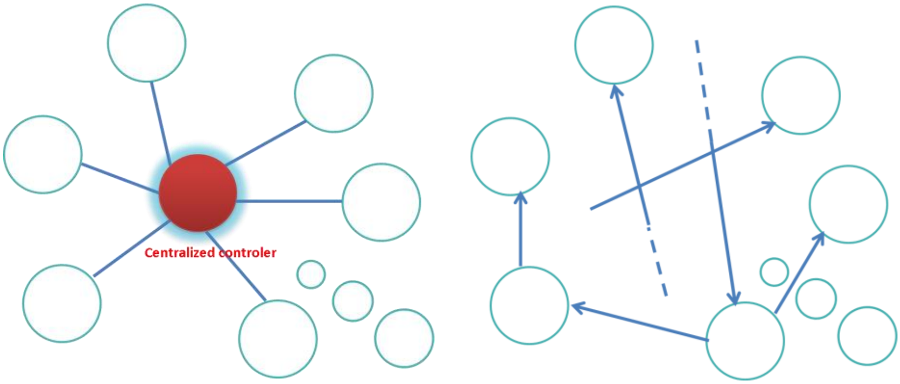


Figure 1.5. ITC architecture of the microgrid control system



(a) Centralized control way

(b) Distributed control way

Figure 1.6. (a) Centralized and (b) distributed control

As control is divided across many sub-applications and the process of aligning control (coordination) must take into account the structure of control in the whole microgrid. This does not mean that the coordination framework of the future microgrid and its extension is an ad-hoc system; instead, the structure needs to be scalable and clearly defined. One of the appealing possibilities of it can be formulated as in the Fig. 1.7. The applications that fulfil different control objectives are organized in a layered structure, where a lower layer top application can become the sub-application for an upper layer application, no matter how they are implemented − either by a centralized way or distribution method. The lowest layer will be composed by the Sensor Notes (SN), which are closest to the physical components, and collect the primary data for the control system. All these applications will make a collective effort to make all the desired qualities of the system fulfilled.

1.2. MOTIVATION OF THIS WORK

As both the centralized and distributed control are crucial elements for the synthesized control system of microgrids. The fundamental technology and its applications are significant for the integration of the whole control system. In an effort to contribute to the whole control system for the microgrid as the constitutional element in the future smart grid, as most of the centralized applications require the power flow analysis as the sub-function, and Multiagent System (MAS) is the one of the trendy technologies for realizing distributed control, the work of the author involves both these two concepts and their applications, as is in the five papers attached in this collection.

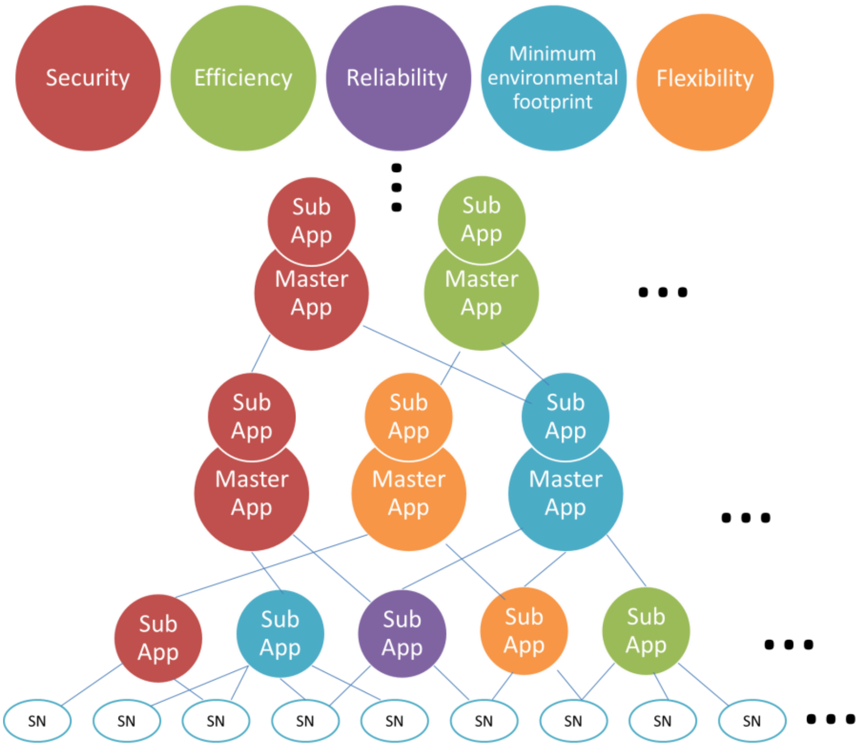


Figure 1.7. System coordination framework for microgrid control

1.2.1. POWER FLOW ANALYSIS AND ITS APPLICATION IN THE CONTEXT OF CENTRALIZED CONTROL FOR MICROGRIDS

1.2.1.1 Motivation for new formulation of power flow for AC and DC microgrids

As a basic steady state analysis tool for any electrical network, power flow analysis is essential to get the overall view of the system for both design and operation. Normally, this kind of application is implemented in a centralized manner by the utility or the Independent System Operator (ISO) [15]. As a fundamental element, this can be the applied for various importance functions of the control system. The typical applications of power flow analysis in a microgrid network can be illustrated as are listed in Fig. 1.8, which covers both the planning stage and operation stage in the system. The work of this thesis takes the application in the operation stage as the focus, as it is involved most in the control system of the microgrid.

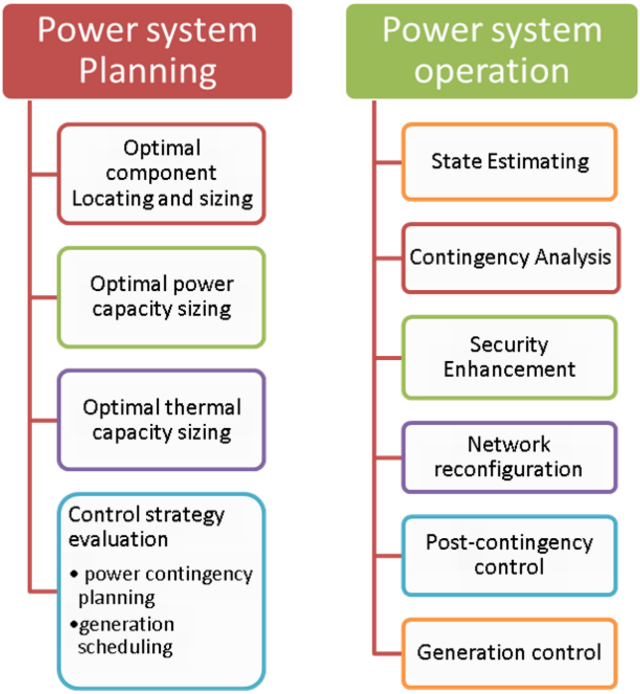


Figure 1.8. Power flow analysis application domain

The traditional power flow analysis is challenged by the ever-changing grid structure. The limitation of previous power flow formulations for AC microgrids mainly lies in the following items [16] and [17]:

1) The amount of the power supplied by each DG unit is usually not pre-specified, and thus these DG units cannot simply be modelled as PQ buses;

2) Despite more flexible control of power electronic interfaces for distributed generators, the limited capacity of a single DG unit makes it impractical to be taken as the slack bus, especially in islanded mode, while in conventional methods at least one slack bus must be assigned to balance the real and reactive power losses;

3) In islanded mode, the frequency of the microgrid is no longer fixed but changes frequently within a range due to the uncertainty of primary resources, load and intra-day market factors [18], and this cannot be shown in traditional methods. In addition, the emerging concept of DC microgrid requires more research on power flow analysis to take its special steady state characteristics into account [19].

The problem of tailoring conventional power flow programs for microgrid applications has been recently addressed in [20], [21] and [22]. The study performed in [20] emphasizes modelling the AC system in the sequence-component frame to represent all the control purposes, but it still uses the traditional method in each component frame by assuming the existence of a slack bus. In [21], a two-step power flow analysis approach is proposed so as to represent electronically-coupled DG units, with the feature to calculate the internal variables of each DG unit. However, in most cases, the impact of different internal variables on the system is of more interest but cannot be evaluated by this approach. The method proposed in [22] represents correctly the actual distributed slack buses by modelling the DG units as droop buses. However, the traditional droop control with P-f and Q-V droop is derived from the approximation of power flow equations under the assumption that the output impedance of the converter is inductive. It might not be the case when the transmission line is not inductive, and in this situation traditional droop will not be valid due to the coupling of the active and reactive power [7], [23]. Although some variations of the droop method, such as resistive droop, are proposed to address the resistive output impedance, they cannot be generalized [13], [23] and [24]. To make P-f and Q-V droop control valid, virtual impedance loops should be added to local controllers of the converters to provide the desired output impedance and to increase the stability of the system in AC microgrids [25], [26] and [27]. In addition, these studies do not consider the case of DC microgrids. In a DC microgrid, the load sharing mechanism is achieved by droop control through feeding back the output current via a virtual resistance to the voltage loop. Power flow analysis methods which do not consider virtual impedance compromise the accuracy of the power flow results.

In order to solve the aforementioned problems, new power flow analysis with new formulation taking the concept of virtual impedance into consideration is needed for both AC and DC microgrid.

1.2.1.2 Motivation for optimal power flow for DC community microgrid

The proposed power flow tool mentioned previously will replace the old power analysis as a sub-function for optimal power flow (OPF), which has the potential for many optimization applications. The generalized flowchart for optimal power flow program can be seen as in Fig. 1.9.

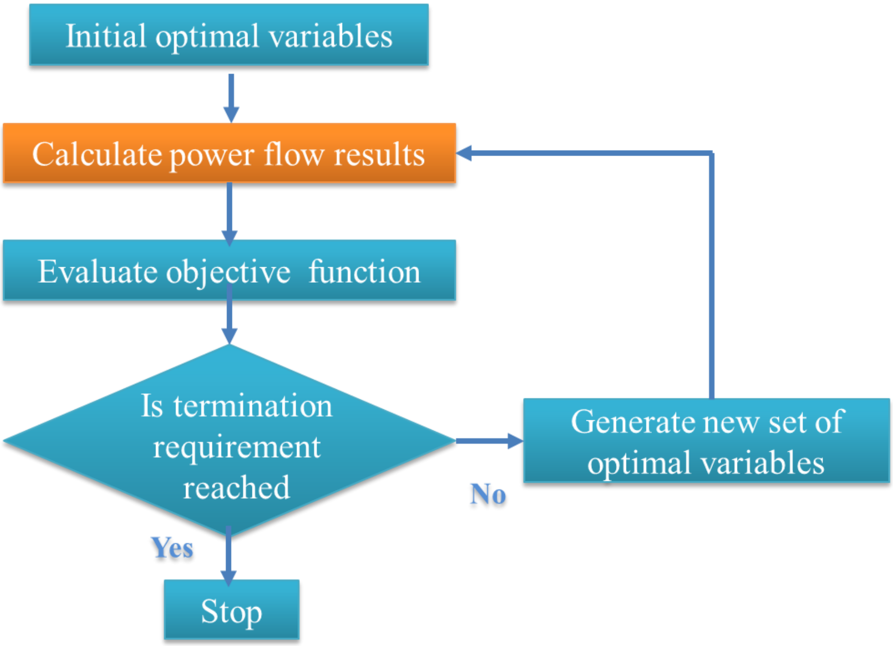


Figure 1.9. Generalized flowchart for optimal power flow program

As the cable resistance impact is no longer neglected and increasing time-varying pricing is adopted on the residential side as demand response, optimization of a community DC microgrid in the operation stage needs to take all these parts into consideration [28]-[32].

Previous works have been conducted to optimize similar DC systems. A way to improve the system efficiency by coordinating Energy Storage System (ESS) is proposed in [33]. However, no other microgrid components except ESS are considered in this work. In [34], the authors provide a method to maximize the utility of the power produced in a microgrid by each load to improve the system efficiency. In this case, the retail electricity price in the demand response is not taken into account. In [35], a coordinated control for the economic operation of a grid-connected DC microgrid is presented. However, no details about dispatch strategy for the tertiary control are given. In [36], researchers formulate a multi-objective optimization problem for a DC microgrid. Nevertheless, the power losses in the electricity transmission network are not considered, which often contribute up to 5% of the total power losses [37]. Furthermore, an optimal demand response model is provided to minimize the total daily cost of electricity consumption for a household application, which needs to add the cost of other backup generation into the model for a microgrid application [38]. In contrast, [39] considers the distribution network of a microgrid, while optimizing the dispatch of the system through decomposing the problem into unit commitment and optimal power flow. However, this approach does not consider the primary control of the microgrid, which requires the modification of the traditional power flow models due to the lack of slack bus, otherwise leading to inaccuracy in the calculation results [40].

In light of the previous limitations, in this work, utilizing the new formulation of DC microgrid power flow analysis, an optimal power flow is applied to minimize the operation cost of for DC community microgrid

1.2.2. MULTIAGENT SYSTEM AND ITS APPLICATION IN THE CONTEXT OF DISTRIBUTED CONTROL FOR MICROGRIDS

An MAS is a computerized system composed of multiple interacting intelligent agents within an environment, with the agent act autonomously on the basis of information from the environment or other agents to fulfil a global task of the system [41].

The coordination mechanism of MAS is the way different agents reach an agreement regarding a certain quantity of interest which depends on the state of all the agents [42]. There are basic the following ways as are shown in Fig. 1.10.

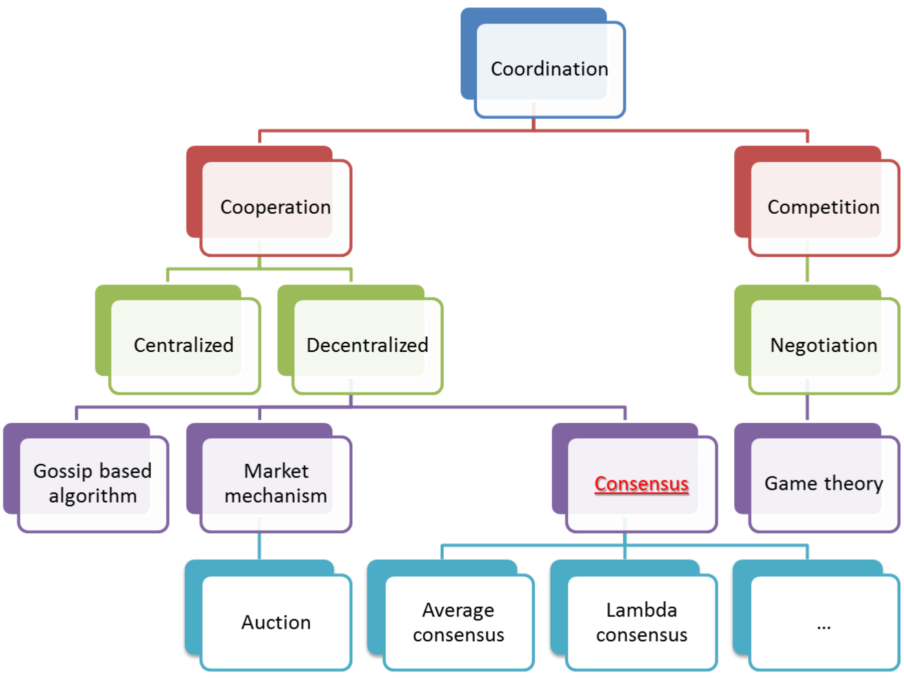


Figure 1.10. Agent coordination mechanism of MAS

The decentralized category is matching more with the distributed characteristic of the agent and widely used in the real-time control of the dynamic system. The merit of this also lies in lower computation cost, higher fault tolerance, higher flexibility, and expendability. In light of these, author tried to explore ways to establish this kind of mechanism to facility the application of microgrid control.

1.2.2.1 Motivation for State of Charge Balancing Control for Distributed Energy Storage Units in AC Microgrids based on MAS

Distributed energy storage (DES) is an indispensable part throughout the entire grid. Due to the high price of the battery, DES is still among the most costly part in a microgrid. To ensure the possibly high cycle life, the application of it needs extra attention paid to the management of DES to make sure the battery life is not deteriorated during various operation modes [43]. One of the main factors to look at is State of Charge (SoC) in DES units. To ensure higher efficiency and State-of-Health (SoH), DES units need to maintain their SoC within a certain range which depends on specific technology that different batteries are produced, e.g. between 20% and 80%. It is desired that for multiple DES units, the SoC of them stays equal throughout the operation. In this way, the power capacity of the DES is maximized all the time, since not a single unit tends to go out of allowable SoC band and to be forced offline consequentially, simply because no single unit is allowed to charge/discharge more than other units in the DES.

There are several previous works made the effort to achieve the SoC balancing of the system. The works that made the effort to achieve SoC balancing can be roughly divided into three categories. One is based on the centralized controller [44], [45] and [46], one is based decentralized way, the third is based on distributed approach. For the first category, either a special topology is necessary [46], or a centralized controller is required as a master to delegate the specific amount of power that one DES unit should support to maintain SoC balance [44], [45]. This class of the methods was mainly proposed to act as the battery manage system) (BMS) for controlling the units which are not far away in distance and thus can be easily implemented by standard field communication in industry.

The modern methods suitable for the microgrid application, as the energy storage system goes more into the structure of distributed system, are mainly based on the droop control which is the primary control in a hierarchical approach [7]. These methods can further be identified as decentralized and distributed ones. For the first sub-category, the control is fully decentralized without any aids from the communication [47]–[49]. Yet in the distributed method, all the controllers are local and the low-band communication is required [50], [51]. In this way, it can improve the system’s robustness under communication changes or failures compared with the methods using the centralized controller, and at the same time, endow more flexibility compared with the system fully decentralized. Therefore, this paper aims to explore a distributed method to achieve SoC balance.

1.2.2.2 Motivation for operation cost minimization of droop-controlled AC and DC microgrids based on MAS

The higher lever control can be classified into two types according to how they realize the economic dispatch [52]. One is based one centralized control [53]–[56], while the other is based on distributed control [57]–[70]. In order to dispatch the power optimally, in [53]–[56] authors use a centralized controller to make the decision for generating the optimal power generation command based on the generation cost. In [54], the regulation of the power generation is realized through directly changing the droop coefficients according to the stability constrained optimization. Although centralized control enjoys the merits of accurate control and easy implementation, it encounters these aforementioned disadvantages compared with distributed control. In [57] and [58], the operation cost information is incorporated in a weighted droop expression through calibrating the minimum and maximum operation cost in a linear way with respect to the droop gain. Although it works very well under most of the cases, it will lose the effectiveness when two DG units have the same maximum and minimum generation costs. Another work improves this idea by introducing a weighted droop expression which considers the nonlinear characteristic of the operation cost function [59]. However, despite the merits that there is no communication overhead, this method lacks the adaptation to external change of the cost without communication, which enables the higher level control to obtain cost information timely.

Multiagent system has been applied to the control of the microgrid for economics in many previous works [60]–[66]. By combining the advantage of MAS with simplicity, various consensus algorithms are proposed to manage the resources of a microgrid in the economic fashion previously [67]–[70]. In [67], a consensus-based algorithm is proposed to coordinate ESS units of a microgrid according to the efficiency. However, one leader agent is needed to broadcast the total active power deviation, thus compromising the feature of decentralization. In [68], although a consensus algorithm is developed to optimize the cost, it is only validated by using numerical simulations. In [69] and [70] an incremental cost consensus is proposed in the smart grid context, nevertheless, the details of the power regulation realization are not given.

To overcome the limitations of previous work, a new way of realizing operation cost minimization is worth exploring based on MAS for both AC and DC microgrid [71]–[73]. Moreover, the impact of implementation of consensus algorithm on the system is also worthy investigation [74]–[77]. The stability of the system considering the interaction different control layer is worthy more work with this new paradigm [78]–[80].

1.3. ORGANIZATION OF THESIS

The thesis is organized into seven chapters with the five of the chapters consisted by five attached papers. Two of the paper are related to the centralized control which based on the power flow analysis proposed by the author. Three different applications using MAS have been explored in the following three papers, which cover from state of charge balance of the energy storage system to economic dispatch problem for both AC and DC microgrid. The structure is as follows:

Chapter 2 gives the first paper, which is published in IEEE Transactions on Smart Grid as early-accepted paper. This paper has presented the formulation and implementation of power flow analyses for AC and DC microgrid in the LV network. By considering the virtual impedance in both AC and DC microgrid, the proposed methods obtain more accurate calculate the result for the power flow analyses. In the DC system, with proposed formulation, it realized the distributed slack buses which avoid the impractical single slack bus in the system formulation. In the AC system, with modelling the virtual impedance in the power flow formulation, calculation accuracy is improved compared with those using traditional methods. The improvement is especially remarkable for the reactive power. This feature can be more attractive, if in the future reactive power will participate in the electricity market. Comparing with the method considering only the droop control, the improvement is not with a high cost—the computation overhead only increased slightly.

Chapter 3 presents the second paper, which has been submitted to in IEEE Journal of Emerging and Selected Topics in Power Electronics. This work is an application of power flow analysis proposed in the first paper for DC microgrid. In this work, in order to improve the system efficiency of a 380V DC microgrid network while participating in demand response, an optimal power flow problem is formulated. The cost function represents not only the operation cost within the microgrid incurred by the fuel and efficiency of the components and the power loss in the transmission line, but also the demand response requirements from the utility by considering the real-time pricing. The proposed algorithm is implemented by means of a heuristic method based on Genetic Algorithm. A six-bus DC microgrid is tested to verify the proposed algorithm in a 24-hour span. Test results show that Genetic Algorithm can find the optimal control parameters to manage optimally the dispatchable resources. Finally, the proposed algorithm successfully reduces the operation cost compared to the case study in which the system is managed without optimization.

Chapter 4 presents the third paper, which has been submitted to in IEEE Transactions on Industry Applications. This paper proposed a distributed control method to achieve SoC balance for DES based on MAS. Instead of using adaptive droop gain, the possibility of modifying the frequency given is explored. A simple method based on the dynamic consensus is implemented to discover the information of average SoC in DES. Frequency scheduling method is analysed through small signal model to give the guidance for choosing the control parameters of it. The convergence characteristics of the dynamic consensus are also investigated to guide the control parameter choosing. Proposed distributed control algorithm is verified through experiments with different case studies. Promising features of the proposed approach with robustness to communication failure, scalability, and “plug and play” are tested.

Chapter 5 presents the fourth paper, which has been submitted to Energies. In this work, an MAS based distributed operation cost minimization method is proposed to dispatch the power economically based on the different generation cost of DG units. Each DG unit is acting as an agent which regulates the power according to the command obtained by the consensus algorithm with only using communication with direct neighbours. Detailed power regulation method based on frequency scheduling is proposed, analysed, and implemented. An incremental cost consensus algorithm is designed to obtain the power dispatch command for each DG unit. The proposed algorithm is verified in a testbed microgrid with three different DG units. With this strategy, the operation cost is reduced effectively. Further, the system is robust under communication failures and the unplanned trip of a generation unit.

Chapter 6 gives the fifth paper, which has been presented in 2016 IEEE Applied Power Electronics Conference and Exposition (APEC). In this paper, a multiagent system is proposed aiming at minimizing the operation cost for DC microgrids. Each local controller for each converter is taken as an agent, which optimizes the local converter autonomously in a hierarchical way with only communication with their neighbours. Compared with methods without optimization, the operation cost is reduced effectively under different load conditions. The impact of communication issues on the MAS convergence is investigated to shed light on the system design. Experimental results are expected in the future work.

Chapter 7 presents the conclusions of this thesis, which highlights the contributions and offers the remarks regarding future research directions in light of the limitation of the conducted work.

CHAPTER 2. PAPER A

Power Flow Analysis for Low-Voltage AC and DC Microgrids Considering Droop Control and Virtual Impedance

Chendan Li, Sanjay K. Chaudhary, Mehdi Savaghebi, Juan C. Vasquez, and Josep M. Guerrero

The paper has been accepted by *IEEE Transactions on Smart Grid,*
Earlier accessible version is available at
http://dx.doi.org/10.1109/TSG.2016.2537402
(the manuscript has been attached in Appendix A)

2.1. PAPER INTRODUCTION

Abstract— In the Low-Voltage (LV) AC microgrids (MGs), with a relatively high R/X ratio, virtual impedance is usually adopted to improve the performance of droop control applied to Distributed Generators (DGs). At the same time, LV DC microgrid using virtual impedance as droop control is emerging without adequate power flow studies. In this paper, power flow analyses for both AC and DC microgrids are formulated and implemented. The mathematical models for both types of microgrids considering the concept of virtual impedance are used to be in conformity with the practical control of the distributed generators. As a result, calculation accuracy is improved for both AC and DC microgrid power flow analyses, comparing with previous methods without considering virtual impedance. Case studies are conducted to verify the proposed power flow analyses in terms of convergence and accuracy. Investigation of the impact to the system of internal control parameters adopted by distributed generators is also conducted by using proposed method.

CHAPTER 3. PAPER B

Economic Dispatch for Operation Cost Minimization under Real Time Pricing in Droop Controlled DC Microgrid

Chendan Li, Federico.de Bosio, Fang Chen, Sanjay K. Chaudhary, Juan C. Vasquez, and Josep M. Guerrero

The paper has been submitted to *IEEE Journal of Emerging and Selected Topics in Power Electronics*
(the manuscript has been attached in Appendix B)

3.1. PAPER INTRODUCTION

Abstract— In this paper, an economic dispatch problem for total operation cost minimization in DC microgrids is formulated. To each generator in the microgrid, including the utility grid, an operation cost is associated, which combines the cost-efficiency of the system with demand response requirements of the utility. The power flow model is included in the optimization problem, thus the transmission losses can be considered for generation dispatch. By considering the primary (local) control of the grid-forming converters of a microgrid, optimal parameters can be directly applied to this control level, thus achieving higher control accuracy and faster response. The optimization problem is solved in a heuristic method. In order to test the proposed algorithm, a six-bus droop-controlled DC microgrid is used in the case studies. The simulation results show that under variable renewable energy generation, load consumption, and electricity prices, the proposed method can successfully reduce the operation cost by dispatch economically the resources in the microgrid.

CHAPTER 4. PAPER C

Multiagent Based Distributed State of Charge Balancing Control for Distributed Energy Storage Units in AC Microgrids

Chendan Li, Ernane A. A. Coelho, Tomislav Dragicevic, Juan C. Vasquez, and Josep M. Guerrero

The paper has been submitted to *IEEE Transaction on Industry Applications,* (the manuscript has been attached in Appendix C)

4.1. PAPER INTRODUCTION

Abstract— In this paper, a multiagent based distributed control algorithm has been proposed to achieve state of charge (SoC) balance of distributed energy storage (DES) units in an AC microgrid. The proposal uses frequency scheduling instead of adaptive droop gain to regulate the active power. Each DES unit is taken as an agent and they schedule their own frequency reference given of the real power droop controller according to the SoC values of all the other DES units. Further, to obtain the average SoC value of DES, dynamic average consensus algorithm is adapted by each agent. A generalized small-signal model of proposed frequency scheduling for the proposed frequency scheduling is developed in order to verify the stability of the control system and guide control parameters design. The convergence characteristics for the dynamic consensus adapted in multiagent system are also analysed to choose the proper control parameter. Experimental results verified the effectiveness, the robustness against communication topology changes, and capability of plug and play of the proposed multiagent system through different case studies.

.

CHAPTER 5. PAPER D

Multiagent-based Distributed Control for Operation Cost Minimization of Droop-Controlled AC Microgrids

Chendan Li, Mehdi Savaghebi, Juan C. Vasquez, and Josep M. Guerrero

The paper has been submitted to *Energies*
(the manuscript has been attached in Appendix D)

5.1. PAPER INTRODUCTION

Abstract— Recently, microgrids as promising technologies to integrate renewable energy resources in the distribution system, are gaining increasing research interests. Although many works have been done on droop control applied to microgrids, they mainly focus on achieving proportional power sharing based on the power rating of the power converters. With various types of distributed generator (DG) units in the system, factors that closely related to the operation cost, such as fuel cost of the generators and losses should be taken into account in order to improve the efficiency of the whole system. In this paper, a multiagent based distributed method is proposed to minimize the operation cost in AC microgrids. In the microgrid, each DG is acting as an agent that regulates the power individually using a novel power regulation method based on frequency scheduling. An optimal power command is obtained through carefully designed consensus algorithm by using sparse communication links only among neighbouring agents. Experimental results for different cases verified that the proposed control strategy can effectively reduce the operation cost.

CHAPTER 6. PAPER E

Convergence Analysis of Distributed Control for Operation Cost Minimization of Droop Controlled DC Microgrid Based on Multiagent

Chendan Li, Juan C. Vasquez, and Josep M. Guerrero “

This paper has been presented in 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, 2016, in press.
(the paper has been attached in Appendix E)

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6.1. PAPER INTRODUCTION

Abstract—In this paper we present a distributed control method for minimizing the operation cost in DC microgrid based on multiagent system. Each agent is autonomous and controls the local converter in a hierarchical way through droop control, voltage scheduling and collective decision making. The collective decision for the whole system is made by proposed incremental cost consensus, and only nearest-neighbor communication is needed. The convergence characteristics of the consensus algorithm are analyzed considering different communication topologies and control parameters. Case studies verified the proposed method by comparing it without traditional methods. The robustness of system is tested under different communication latency and plug and play operation.

CHAPTER 7. CONCLUDING REMARKS

7.1. SUMMARY OF MAIN RESULTS

In this work, the contribution involves analysis and control for both the centralized control and distributed control of microgrids. Firstly, new formulations of power flow analyses are proposed for both AC and DC microgrid by considering the concept of the virtual impedance. It improves the accuracy of calculation results as well as brings more controllability into the analysis and its applications. By using this, a DC community microgrid is optimized in term of operation cost minimization by adjusting the virtual impedance of dispatchable generators. Secondly, by applying the MAS based on different algorithms designed, different objectives such as SoC balancing for AC microgrid, operation cost minimization for both AC and DC microgrid are achieved. Moreover, the system analyses of these systems are also explored, which investigate the communication impact on theses networked controlled system along with other traditional control parameters related to droop control. The work conducted will facilitate the microgrid into being the building blocks for future smart distribution grid.

7.2. RESEARCH PERSPECTIVES

Although many aspects have been documented in this thesis for advanced analyses and control for AC and DC microgrids, there are still a lot of possibilities for theoretical and technology improvement. Some issues of high interest for future investigations are listed below:

1) More realistic and timely applications of power flow analysis for the microgrids and distribution system considering different system requirements can be further investigated. For example, in the planning, it can address how the specific kind of emerging renewable resource and new devices such as PV and EV charging will influence the existing grid and what is the mitigation solution considering advanced control capability provided by power electronics. In the operation stage, this tool again can be sub-function of the decision-making component to facilitate system control in different modes and scenarios.
2) The algorithm of power flow analysis and optimal power flow themselves are also worth more research work. For power flow analysis, to make it implemented also in a distributed way will be an interesting endeavour. For the optimal power flow, to make it non-deterministic by taking account of uncertainty will be very necessary for the increasing penetration of intermitted resources. Moreover, multi-objective optimization can be combined with OPF to analyse the system in different angles.

3) For the distributed control based on MAS, there also open doors for a myriad of existing control problems while shedding a new light on the new applications by adding more intelligence to the local controllers to form new system and new methodology to solve new problems. One of the possibilities will be the application of it into domestic EV chargers, to make them forming a charging network based on MAS.
4) The system analysis modelling and method of MAS is worth exploring more for taking account of different factors in synthesizing the networked system.
5) Moreover, to make a microgrid really work, issues from policy, regulation, economics, and finance are needed to be taken into account in the planning and operation as a holistic solution for the control system.

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Appendix Paper A~E

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