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# Hierarchical Control for Optimal and Distributed Operation of Microgrid Systems

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# HIERARCHICAL CONTROL FOR OPTIMAL AND DISTRIBUTED OPERATION OF MICROGRID SYSTEMS

**PH.D. THESIS**

By

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# ABSTRACT

The distributed generation, storage and consumption, as well as the sustainability consideration prompt a revolution to the existing electric power grid. Microgrids (MG) concept has been proposed to liberate the operation of each distribution system fraction, forming in that way a flexible and sustainable grid. To achieve autonomous operation for MGs, hierarchical control was proposed with primary, secondary and tertiary control levels differentiated. In conventional hierarchical scheme, primary control is issued for power sharing, secondary control takes care of power quality, and tertiary control manages the power flow with external grids, while the economic and optimal operation of MGs is not guaranteed by applying the existing schemes.

Accordingly, this project dedicates to the study of real-time optimization methods for MGs, including the review of optimization algorithms, system level mathematical modeling, and the implementation of real-time optimization into existing hierarchical control schemes. Efficiency enhancement in DC MGs and optimal unbalance compensation in AC MGs are taken as the optimization objectives in this project. Necessary system dynamic modeling and stability analysis are also conducted in order to ensure safe operation during the optimization procedure.

In addition, as the secondary and tertiary controls require global information to perform the functions, they are usually implemented in centralized fashion. In this sense the communication links are required from the central unit to each local unit, a single point of failure in the central controller may jerpodize the safety of the whole system, and the flexibility of the system is limited. Consequently, this project proposes the application of dynamic consensus algorithm (DCA) into existing hierarchical control scheme aiming at achieving fully distributed secondary and tertiary controls. The primary purpose of DCA is to allow a number of distributed units to obtain global information that is necessary for the control layers. Also by applying DCA the communication links are only needed between nearby units. Based on these features, this project proposes distributed control schemes for power quality regulation in three-phase AC MGs, as well as voltage/current control in DC MGs.

Moreover, in order to provide analytical method for evaluating the system stability with such kind of distributed control scheme, a discrete-time domain modeling method is proposed to establish an accurate system level model. Taking into account the different sampling times of real world plant, digital controller and communication devices, the system is modeled with these three parts separately, and with full consideration of the underlying communication features (sampling

time, topology, parameters, etc.). System dynamics and sensitivity analysis are conducted based on the proposed model.

A MG central controller is also developed based on the experimental system in the intelligent MG lab in Aalborg University for providing a comprehensive platform for MG related study purposes. LabVIEW software is used as the programming language, UDP/IP based Ethernet communication links are built between the central controller and each setup. System performance is shown by experimental examples.

Finally, to verify the effectiveness and performance with the proposed control schemes and modeling methods, experimental and hardware-in-the-loop simulation studies are conducted in the intelligent MG lab. The successful realization of online optimization and distributed control functions is expected to be able to provide guidance for real world implementation of similar approaches. The generalized discrete-time modeling method, with verified correctness and accuracy, can give insight view of the distributed control scheme and the impact of communication part on system dynamics.

**Keywords:** microgrids, hierarchical control, optimization, distributed control, dynamic consensus algorithm, power quality, efficiency, system modeling, microgrid central controller.

# ABSTRAKT

Den distribuerede elproduktion, energilagring og forbrug, samt den bæredygtige tankegang kræver en revolution af det eksisterende el-net. Microgrid (MG) konceptet præsenteres med det mål at frigøre den fraktion som opstår i energinettet. På den måde dannes der et fleksibelt og bæredygtigt MG. For at opnå en uafhængig process for MG - hierarkisk styring foreslåes 3 forskellige kontrolniveauer; det primære, det sekundære, og tertiære. I et konventionel hierarkisk system anvendes primær kontrol (1) til energideling, sekundær kontrol (2) beskæftiger sig med spændingskvaliteten og den tertiær kontrol (3) styrer elbørsen med eksterne net.

Den økonomiske og optimale drift af MGs er ikke sikret ved anvendelse af de eksisterende system. Som følge heraf er denne afhandling dedikeret til at studere realtids-optimeringsmetoder til MGs, herunder en evaluering og udvikling optimeringsalgoritmen, matematisk modellering og gennemførelse af real-time optimering i eksisterende hierakiske kontrolsystemer. Optimering af effektiviteten i DC MGs og optimering af ubalance kompensation medtages i optimeringsmålene.

Nødvendige system dynamisk modellering og stabilitetsanalyser foretages også med det formål at sikre en sikker erstatning i AC MGs. Nødvendige dynamiske modellering og stabilitetanalyser af MGs er gennemført for at garantere en sikker drift.

Hertil kommer, at sekundære og tertiære kontroller kræver global information for at udføre deres funktioner - de er som regel implementeret centralt. På denne måde er det påkrævet med kommunikationsforbindelser fra den centrale enhed til hver lokal enhed.

En enkelt fejl i den centrale styreenhed enhed kan bringe sikkerheden i hele systemet i fare, og fleksibiliteten i systemet er begrænset. Som en konsekvens af dette foreslår denne afhandling at der anvendes dynamiske konsensus algoritmer (DCA) i eksisterende hierarkiske kontrolsystemer med det formål at opnå fuld kontrol af de sekundære og tertiære kontroller. Det primære mål med DCA er at tillade et antal distribuerede enheder at opnå den globale information, som er nødvendig for kontrolfunktioner. Ved brugen af DCA er der tilmed kun brug for kommunikationsforbindelser. Baseret på disse funktioner, foreslår projektet distribueret kontrolsystemer for spændingskvalitet regulering i trefasede AC MGs, samt spænding/strøm kontrol i DC MGs.

For at tilvejebringe en analytisk metode til evaluering af systemets stabilitet med distribuerede kontrolsystem, foreslås en diskret-tid domæne modellering metode til at etablere en nøjagtig systemniveausmodel.

Tages de forskellige sampletid af virkelige verdensanlæg, digitale kontroller og kommunikationsenheder, er systemet modelleret med tre dele enkeltvis og med fuld hensyntagen til de underliggende kommunikationsfunktioner (sampletid, topologi, parametre, etc.). Systemsdynamikken og følsomhedsanalyse er foretaget ved den valgte model.

En MG central kontroller er udviklet i det intelligente MG lab ved Aalborg Universitet som har leveret en omfattende platform for MG relaterede studier. LabVIEW software bruges som programmeringssprog, UDP / IP baserede Ethernet kommunikationsforbindelser er bygget mellem den centrale kontroller og hver enkelt opsætning. Systemets ydeevne er vist ved eksperimentelle eksempler.

Endelig, for at verificere effektiviteten og ydeevnen af de foreslåede kontrolsystemer og modelleringsmetoder, eksperimenterende og hardware-in-the-loop simulering undersøgelser foretaget i det intelligente MG lab. Realiseringen af online optimering og distribuerede kontrolfunktioner har til formål at frembringe virkelige verden gennemførelse af lignende metoder. Den generaliserede diskret-tid modellering metode, med verificeret korrekthed og nøjagtighed, kan give indsigt i distribuerede kontrolsystemer og essentiel viden om systemets dynamik.

# THESIS DETAILS AND PUBLICATIONS

**Thesis Title:** Hierarchical Control for Optimal and Distributed Operation of Microgrid Systems

**Ph.D. Student:** Lexuan Meng

**Supervisor:** Josep M. Guerrero

**Co-supervisor:** Tomislav Dragicevic

**Co-supervisor:** Juan C. Vasquez

**1st Authored Journal Publications:**

- Meng, L.; Zhao, X.; Tang, F.; Savaghebi, M.; Dragicevic, T.; Vasquez, J.; Guerrero, J., "Distributed Voltage Unbalance Compensation in Islanded Microgrids by Using Dynamic-Consensus-Algorithm," *Power Electronics, IEEE Transactions on* , vol.PP, no.99, pp.1,1
- Lexuan Meng; Fen Tang; Savaghebi, M.; Vasquez, J.C.; Guerrero, J.M., "Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids," *Energy Conversion, IEEE Transactions on* , vol.29, no.4, pp.802,815, Dec. 2014
- Meng, L.; Dragicevic, T.; Roldan-Perez, J.; Vasquez, J.C.; Guerrero, J.M., "Modeling and Sensitivity Study of Consensus Algorithm-Based Distributed Hierarchical Control for DC Microgrids," Smart Grid, IEEE Transactions on , vol.PP, no.99, pp.1,1
- Meng, L.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M., "Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC-DC Converters," Smart Grid, IEEE Transactions on , vol.PP, no.99, pp.1,1

## Co-authored Journal Publications:

- Tang, F.; Guerrero, J.M.; Vasquez, J.C.; Wu, D.; Meng, L., "Distributed Active Synchronization Strategy for Microgrid Seamless Reconnection to the Grid Under Unbalance and Harmonic Distortion," *Smart Grid, IEEE Transactions on* , vol.PP, no.99, pp.1,1

## Selected 1st Authored Conference Publications:

- L. Meng, M. Savaghebi, F. Andrade, J. C. Vasquez, J. M. Guerrero, and M. Graells, "Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University," *in Proc. IEEE APEC 2015*
- L. Meng, T. Dragicevic, J. C. Vasquez, J. M. Guerrero, and J. Roldan, "Modeling and sensitivity analysis of consensus algorithm based distributed hierarchical control for dc microgrids," *in Proc. IEEE APEC 2015*
- Lexuan Meng; Guerrero, J.M.; Vasquez, J.C.; Fen Tang; Savaghebi, M., "Tertiary control for optimal unbalance compensation in islanded microgrids," *Multi-Conference on Systems, Signals & Devices (SSD), 2014 11th International* , vol., no., pp.1,6, 11-14 Feb. 2014
- Lexuan Meng; Dragicevic, T.; Guerrero, J.; Vasquez, J.; Savaghebi, M.; Fen Tang, "Agent-based distributed unbalance compensation for optimal power quality in islanded microgrids," *Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on* , vol., no., pp.2535,2540, 1-4 June 2014
- Lexuan Meng; Dragicevic, T.; Guerrero, J.M.; Vasquez, J.C., "Dynamic consensus algorithm based distributed global efficiency optimization of a droop controlled DC microgrid," *Energy Conference (ENERGYCON), 2014 IEEE International* , vol., no., pp.1276,1283, 13-16 May 2014
- Lexuan Meng; Dragicevic, T.; Guerrero, J.M.; Vasquez, J.C., "Stability constrained efficiency optimization for droop controlled DC-DC conversion system," *Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE* , vol., no., pp.7222,7227, 10-13 Nov. 2013
- Lexuan Meng; Dragicevic, T.; Guerrero, J.M.; Vasquez, J.C., "Optimization with system damping restoration for droop controlled DC-DC converters," *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE* , vol., no., pp.65,72, 15-19 Sept. 2013

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孟乐轩

Lexuan Meng

May 2015

Aalborg

# CONTENTS

# CHAPTER 1. INTRODUCTION

## 1.1. MICROGRIDS – A GENERAL INTRODUCTION

Energy crisis, environmental issues and grid reliability considerations result in an ongoing revolution to the existing electric power grid. Centralized and fossil fuel based conventional generation stations, suffering from long distance transmission, low efficiency/reliability, heavy pollution and energy resource shortage, will be gradually substituted by distributed and renewable energy based generation plants. To adapt to the distributed on-site generation ideal, microgrids (MGs) concept [1], [2] has been proposed to liberate the operation of power distribution fractions, reduce the complexity of grid management, and further improve the flexibility and reliability of the whole grid.

Even though the clear identification of a MG is still open to debate, the definition from the U.S. Department of Energy (DOE) is referred here as an example [3], [4]: a MG is 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 MG can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode. The typical configuration of a MG system, as that shown in Fig. 1.1, includes major components like sorts of conventional or renewable generation units, energy storage systems, interfacing power converters, non-/controllable loads, and so on. With proper control and management, MGs based power grid can offer a number of advantages, typical ones of them are, i.e. [3]:

- Higher efficiency because of localized generation and combined electricity/heat generation/storage;
- Higher reliability and security due to grid independent capability, on-site generation and distribution level protection;
- Reduced total operation cost with localized on-site generation and demand side management for peak shaving;
- Enhanced sustainability by reducing the amount of fuel based generation, and increasing the penetration of renewable energy.

## 1.2. HIERARCHICAL CONTROL FOR MICROGRIDS

With the development and increasing utilization of power electronic devices, the voltage/current regulation, power flow control and other advanced control functions can be realized in MGs by properly operating the interfacing power converters. As widely accepted, MGs control and management is actually multi-objective task

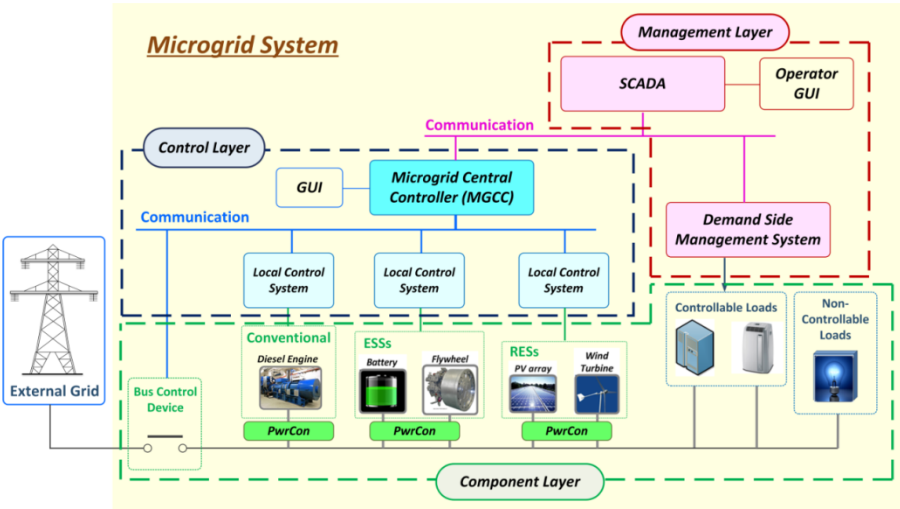



**Figure 1.1. Microgrid architecture – a typical configuration.**

which covers different technical areas, time scales and physical levels. The domains of interest include the above mentioned issues, for which a hierarchical control scheme [4], [5] has been proposed and widely accepted as a standardized solution for efficient MGs management. It comprises three principal control levels, as shown in Fig. 1.2:

- Primary level: primary control performs the control of local power, voltage and current. It normally follows the setting points given by upper level controllers and performs control actions over interface power converters.
- Secondary level: in the existing hierarchy, secondary control appears on top of primary control. It deals with power quality control, such as voltage/frequency restoration, voltage unbalance and harmonic compensation. In addition, it is in charge of synchronization and power exchange with the main grid or other MGs.
- Tertiary level: conventionally tertiary control is issued with the task of managing the power flow between MG and external grid. In recent studies, the aim of tertiary control is to introduce intelligence in the whole system. To that end, tertiary control will attempt to optimize the MG operation based on merits of interests, mostly efficiency and economics. Knowledge from both MG side and external grid are essential to execute the optimization functions. Information and communication technology (ICT) is a key enabling technology for that matter. Optimization algorithms can be employed to process the gathered information and take proper actions.

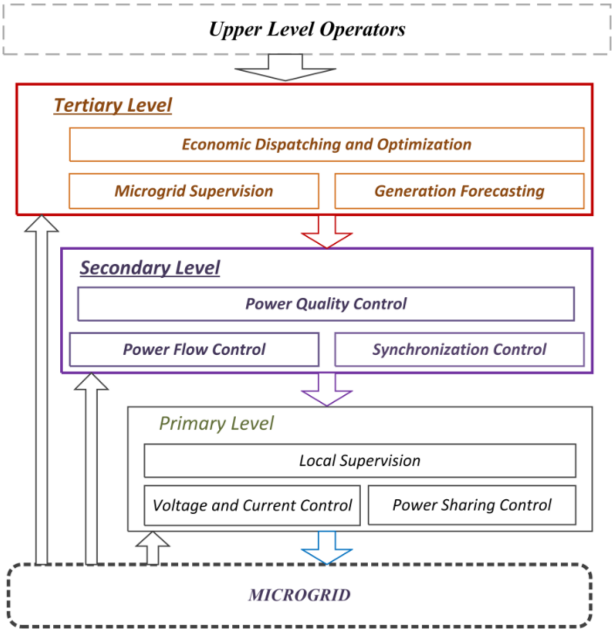



**Figure 1.2. Hierarchical control scheme.**

## 1.3. CHALLENGES IN MICROGRIDS CONTROL AND MANAGEMENT

The future paradigm of flexible distribution systems includes the widespread adoption of MGs, realizing the flexible and economic operation of each distribution system fraction. While on the other hand the perfect ideal always comes with great challenges, such as reliable protection scheme, local and global stability, power flow management, interoperation between supplier and consumer, and so on. Regarding the control and management aspects, the following issues are usually considered of the upmost importance [3]–[8]:

- Voltage and current control. The islanding operation requires some of the distributed generators (DGs) providing voltage support to the isolated system, and some of the DGs injecting power following certain references. Proper voltage and current control schemes need to be developed and applied for operating each single unit.
- Power sharing control. Although distributed fashion of generation and consumption enhance the efficiency of the entire system, power sharing among DGs becomes critical issue, since over loading of some of the DGs

may cause unexpected unit trip/offline, and finally result in instability and power shortage.

- Coordination between different sorts of DGs. DGs can be generally classified into three categories as that shown in Fig. 1.1, including conventional generators (fossil fuel powered generation), energy storage systems (ESS, i.e. battery, flywheel, super capacitor, etc.), and renewable energy resources (RES, photo-voltaic panel, wind turbine, hydropower, etc.). The coordination and proper utilization of these DGs have the direct bearing on the system security and stability.
- Economic dispatching and optimization. Optimal operation of the system demands pertinent mathematical representation of the system, appropriate formulation of optimization problem, and besides, a powerful and suitable algorithm. Moreover, with the penetration of renewable energy and active participation of consumer sides, generation and consumption uncertainties have to be taken into consideration.
- Power quality issues. Deteriorated power quality, such as voltage unbalances and harmonics due to existence of unbalanced or electronic loads, may cause abnormal operation of sensitive equipment, incur additional power losses and affect system stability. To alleviate the problem, efforts need to be put on the impedance analysis and filter design, selection of converter topology and driver, advanced control methods to realize multi-functional converters.
- Distributed control and management. As the generation, storage and consumption become more and more distributed, centralized control methods are facing obstacles considering the implementation/computation cost, single point of failure (SPOF), and flexibility. While from the other point of view, distributed control and management methods are still under studying and designing process. Information sharing and distributed control oriented system modeling are main tasks. Information and communication technology play pivotal role in those schemes.
- Small inertia and stability issues. Without large number of synchronous generators, the MG systems are characterized as low inertia systems which require careful design of control mechanism. Local system dynamic may have significant influence over global stability, also the interactive behavior between local systems need to be taken into consideration. System modeling and stability analysis are necessary steps during the controller design stage.

## 1.4. SCOPES OF THE PROJECT

Based on the hierarchical control scheme, this project explores the possibility of integrating advanced control and optimization functions realizing real-time optimal operation of MG systems. System efficiency enhancement and optimal power quality regulation are taken as the objectives in this project. Moreover, in order to achieve flexible operation, applications of distributed algorithms are also within the concern. Modelling and analysis are carried out for ensuring the system stability considering as well the communication effects.

## 1.5. OPTIMIZATION FOR MICROGRIDS – GENERAL INTRODUCTION AND MOTIVATIONS

### 1.5.1. OPTIMIZATION FUNDAMENTALS

In order to realize intelligent and optimal operation of MGs, optimization techniques are necessarily needed. Optimization is a methodology that tries to make ‘something’ as perfect as possible, where ‘something’ can be a process, a product, a system, an operation strategy, and so on [9], [10]. The optimization procedure includes several general steps [9]–[11]:

- Identifying objectives. One or several objectives must be first identified and translated into quantitative measurement (objective function) which can represent the level of satisfaction with the objective under study. In microgrids, the objective could be profit, time, energy consumption, customer comfort or a combination of them.
- Defining decision variables. The decision variables are taken as the adjustable quantities that can affect the objective function value and define the final characteristic of the system/process/design/etc.. The optimal solution is a set of decision variables that achieves maximization or minimization of the objective function value.
- Mathematical modeling of the system/process/design/etc.. The model is used to evaluate the objective function value with different sets of decision variables, which can be considered as the most important step in the optimization procedure. Too simplified model may be lack of insights into the practical system, while too complicated model can be too difficult or time consuming to be solved.
- Problem formulation considering objectives, variables and constraints.
- Optimization algorithm selection/development. Once the optimization problem is fully formulated, a proper optimization algorithm needs to be selected or developed to solve the problem. Among numerous algorithms, each of them is tailored for specific kind of problem. An appropriate algorithm can largely improve the quality and speed for solving the problem.
- Solution checking and algorithm tuning. Optimality checking is necessary for evaluating and improving the performance of the optimization procedure,

which ensures that the algorithm gives satisfying solutions within acceptable computational cost.

Based on the description above, the mathematical formulation of an optimization problem can be generally written as:

$$\min_{x\in R^n} or \max \ f(\mathbf{x})$$
$$\text{subject to: } \begin{cases} c_i(\mathbf{x}) = 0, & i \in \mathrm{E} \\ c_i(\mathbf{x}) \geq 0, & i \in \mathrm{I} \end{cases} \tag{1.1}$$

where $\mathbf{x}$ is the set of decision variables, $f$ and each $c_i$ are objective function and constraint functions of $\mathbf{x}$, $i$ is the index. The optimization algorithm tries to find an optimal set of $\mathbf{x}$ that can minimize or maximize the value of the objective function, while also ensures that no constraints are violated during the process.

### 1.5.2. TYPES OF OPTIMIZATION PROBLEMS

As discussed before, a proper optimization algorithm needs to be selected according to the type of the problem. Generally the typical form of the optimization problem (1.1) can be categorized according to the nature of the objective/constraint functions (non-/linear, non-/convex) or smoothness of them (non-/differentiable). Although it is difficult to provide a detailed classification of optimization because of large number of subfields and multiple links, a generalized taxonomy is given by NEOS (Network Enabled Optimization System) [9] as shown in Fig. 1.3, which mainly shows the deterministic branch with single objective and can provide guidance to the reader to select appropriate algorithms.

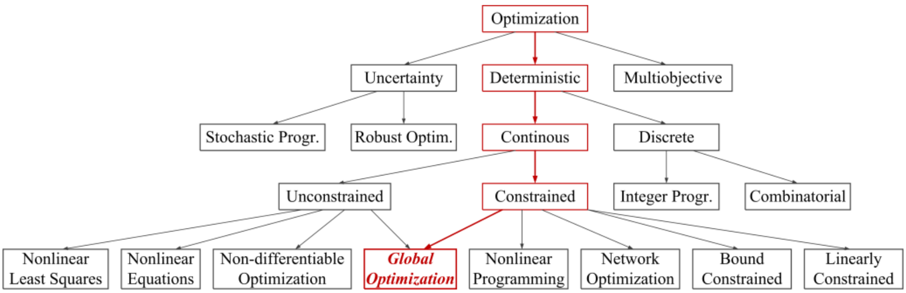



**Figure 1.3. Optimization taxonomy.**

*A. Deterministic Optimization vs. Stochastic Optimization*

In deterministic optimization, the information and data of the problem are assumed to be accurately known, while in some cases, due to the measurement error or uncertainty about future condition, the exact information cannot be obtained beforehand, which calls for stochastic optimization methods with more robustness.

*B. Continuous Optimization vs. Discrete Optimization*

Continuous optimization allows the variables to take any real value, while in some cases the variables can be only taken from discrete set, such as a subset of integers, namely discrete optimization. Continuous optimization problems are generally much easier to solve since the objective function and constraint function around a certain point can be deduced and evaluated. In contrast, in discrete optimization problems points which have close values may result in markedly different function values, and it is also not possible by simply doing an exhaustive search in the finite set with large number of elements.

*C. Constrained Optimization vs. Unconstrained Optimization*

It can be easily understand that unconstrained optimization problem refers to the cases where the variables are not limited by equalities or inequalities. Also sometimes unconstrained problems can be reformulated from constrained problems by integrating the constraints into objective function with penalty terms. On the other hand, constrained problems include explicit limitations on the variables.

The optimization issues dealt in this project are actually deterministic optimization with continuous form of problem formulation. Constraints are integrated into objective function to form unconstrained problems. Considering the nonlinearity and non-convexity of the problems, global optimization methods are applied. Introduction is given in the following part.

### 1.5.3. GLOBAL OPTIMIZATION AND GENETIC ALGORITHM

In many nonlinear problems, the objective function may contain a number of local optimum where conventional analytical methods are usually tricked and not able to find the ‘real’ global optimum. Two quartic function based examples are shown in Fig. 1.4 to explain the difference between local and global optimum. A local optimal solution of an optimization problem is a solution that is minimal or maximal within a neighboring set of solutions, while in contrast, global optimal solution is the optimal solution among all possible solutions.

The fastest optimization methods seek only a local optimum, such as gradient and hill climbing methods, which start from an initial point and repeatedly move towards better neighboring points until there is no better neighboring solutions [10], [11]. However, the quality of the final solution (local or global optimum) depends on the initial point, as shown in Fig. 1.4 (a). By using local search methods, the searching that starts from initial point 1 will stop at local optimum, while the one from initial point 2 can reach global optimum.

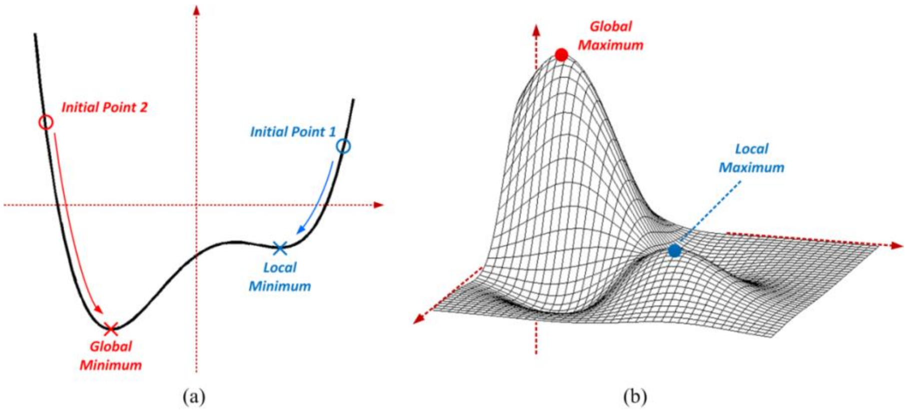



**Figure 1.4. Local and global optimum – examples.**

Accordingly, in some cases where global optimum is required, global optimization methods are preferred, as they have the capability of finding global optimum or near global optimum. The global optimization methods can be generally classified into three categories [9], [11]: a) deterministic methods, such as Cutting Plane methods, Branch and Bound methods, etc.; b) stochastic methods, such as Simulated Annealing, Direct Monte-Carlo sampling, etc.; c) meta-/heuristic methods, such as Evolutionary methods and Swarm based methods.

In last decades, Evolutionary Algorithms (EA) [11]–[13] have been more and more explored and applied into engineering/industrial areas because of easy utilization, high complexity problem handling and robustness. Genetic algorithm (GA) [14]–[16], as one of the most frequently used EAs, is applied in this thesis, as it is a suitable algorithm for the kind of optimization problems related to analysis with complex models. It offers many advantages, some of them are [16]: 1) it does not require derivative information of the objective function, so it can be applied to solve non-continuous, non-differentiable optimization problems; 2) it reduces the risk to be trapped in local optimal;  3) it can deal high dimension issues with a large number of variables while provide a list of solutions.

The general steps of GA processing are shown in Fig. 1.5 [15]. It starts with randomly generated population and initial evaluation of the objective function *f*. Then iterations begin with stop criterion checking at the beginning of each loop. If the stop condition is not met, the mating, crossover and mutation process will be repeated until a satisfying set of population is obtained or the maximum number of iterations is reached. Crossover is a process of taking more than one parent solution and producing a child solution from them mimicking the natural process of reproduction and biological crossover. While mutation tries to alter one or more 'gene' values in a chromosome (solution) from its original state in order to maintain genetic diversity. The performance of GA depends on the well operating of crossover and mutation process. Due to these features, GA is able to search solution space from multiple initial points to different directions at once. It can perform well, if properly configured, in problems even the objective function is complex, discontinuous, noisy, time-variant or has a number of local optima.

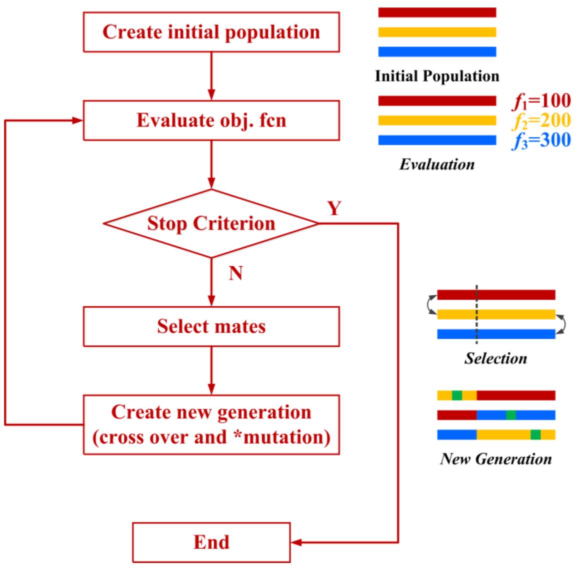



**Figure 1.5. Genetic algorithm flowchart.**

Consequently, this project applies GA into two optimization issues for system efficiency improvement and optimal power quality regulation, respectively.

### 1.5.4. OPTIMIZATION FOR DC MICROGRIDS – MOTIVATIONS

In DC MG, droop control by means of virtual resistance (VR) control loops can be applied to paralleled dc-dc converters for achieving autonomous equal power sharing [4], [5]. However, equal power sharing does not guarantee an efficient operation of the whole system. In order to improve the conversion efficiency, a number of research efforts have been made on reducing the power loss of each single converter [17]–[24]. A typical efficiency curve is shown in Fig. 1.6, even though constant input and output voltages are assumed, the converter efficiency changes with its output current. It is recognized that converter efficiency is relatively lower in light load conditions where more improvements are expected [18], [20], [21], [25]. Accordingly, apart from improving the design and control for a single converter, the system level control strategy for operating all the converters can also be optimized. As an example, in light load conditions, instead of making two converters equally share the load current, the sharing proportion can be differentiated so as to improve the overall system efficiency, as that shown in Fig. 1.6. However, in order to achieve this objective, a static system model for power loss estimation is required, and a smooth change of the output current of each converter needs to be guaranteed.

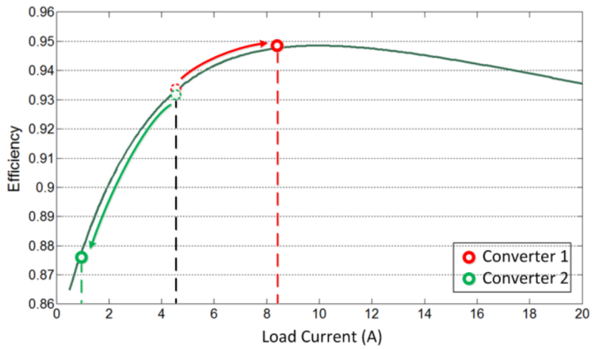



**Figure 1.6. Typical efficiency feature of power converters.**

In addition, stability issues may appear when the optimization tries to change some control parameters, such as VR values. Small signal analysis is usually applied in order to guarantee the stability [26]–[30]. In [26], suitable VRs are calculated according to small signal analysis results for keeping stable operation. In [29], a stability margin for droop gains when executing energy management is set. In order to achieve proper load sharing while keeping stable operation especially in high gain angle droop conditions, a supplementary droop control is introduced in [30]. Necessarily, small signal analysis method for ensuring system stability needs to be studied in order to ensure safe operation.

Based on the consideration above, this project dedicates to the optimization for enhanced system efficiency and better dynamic performance. Primary challenges in this work include the proper steady state modeling for optimization purpose and dynamic modeling for stability analysis, as well as the integration of the hierarchical control system.

### 1.5.5. OPTIMIZATION FOR AC MICROGRIDS – MOTIVATIONS

Voltage unbalance is regarded as one of the main power quality issues in three-phase systems [31]. It has significant impact at the distribution level, causing serious problems to voltage sensitive equipment, especially induction motors [32], [33]. The nature of the unbalance includes not only the amplitude differences between phase voltages, but also the phase angle deviation and different harmonic distortions in three phases. Uneven distribution of single-phase loads is one of the major reasons causing voltage unbalance.

Conventionally, series active power filter can be implemented in series with the distribution lines for reducing the level of voltage unbalances [34]–[36]. Another possible way is to inject negative sequence current to balance the current in the distribution lines and consequently compensate unbalances [37]–[39]. However, all these methods require additional compensation equipment which may increase the total investment cost. In MGs system, the prevalent utilization of interfacing inverters and communication network make it possible to employ DG units as distributed compensators, such as the work demonstrated in [40]–[44].

More specifically, a hierarchical control was proposed in [43] and [44] to compensate voltage unbalance in sensitive load bus of an islanded MG. However, to ensure the low voltage unbalance level in SLB, the power quality in local buses (LBs) and DG sides is deteriorated. A study case MG is shown in Fig. 3 (a) in which two DG units (DG1 and DG2) can be used to compensate the unbalances in the critical bus (CB). The compensation is actually set the negative sequence voltage in DG sides ( $V_S^N$ ) to inversed direction with the negative sequence voltage in CB ( $V_{CB}^N$ ) as shown in Fig. 1.7 (b). The negative sequence voltage in LBs ( $V_{LB1}^N$ and $V_{LB2}^N$ ) are also influenced, and because of the transmission line difference the negative sequence voltage in LB1 and LB2 may be out of acceptable limits. In order to keep the best power quality in CB while also taking care of the voltage unbalance limits in LBs, the negative sequence equivalent circuit needs to be established so as to analyse the unbalanced system. An optimization problem can be formulated so as to adjust the compensation efforts of each DG. The control hierarchy is shown in Fig. 1.7 (b).

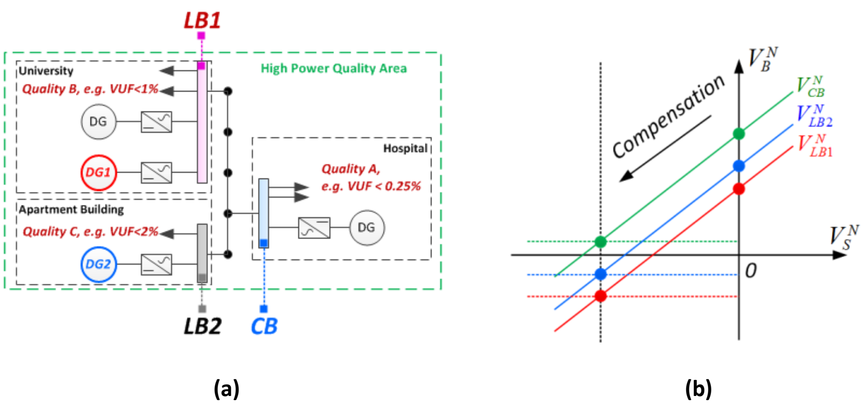



**Figure 1.7. Voltage unbalance compensation in a multi-bus microgird.**

Accordingly, the project tries to apply online optimization method to ensure the acceptable power quality in both CB and LBs. However, the challenges appear to be the modeling of the unbalanced system, formulation of the optimization problem and implementation of the algorithm.

## 1.6. DISTRIBUTED CONTROL FOR MICROGRIDS – GENERAL INTRODUCTION AND MOTIVATIONS

### 1.6.1. CENTRALIZED AND DISTRIBUTED CONTROL

Based on the same hierarchy shown in Fig. 1.2, the way of implementing the control levels can be centralized or distributed, as shown in Fig. 1.8. The level of decentralization is defined by the functionality and intelligence of local controllers (LCs), which can be used just to execute commands from upper level or make their own decisions. A general comparison is made concerning different aspects and levels of decentralization of the control system, as shown in Fig. 1.9. Either way has advantages and disadvantages which determine its appropriateness of application on the specific MG type (residential, commercial or military), and the legal and physical feature (location, ownership, size, topology, etc.).

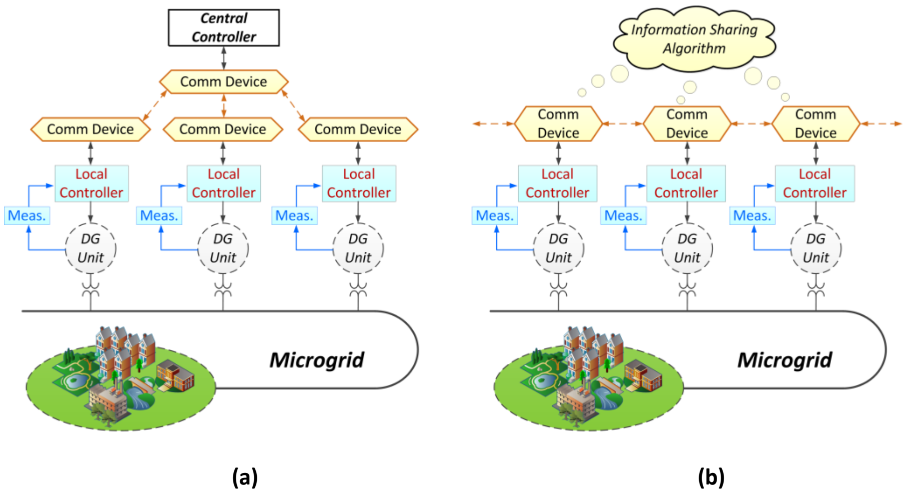



**Figure 1.8. Comparison between (a) Centralized Control and (b) Distributed Control.**

Centralized control and management [45]–[63] usually require data collection from all the essential MG components, where communication links are required from the central controller to each LC, as shown in Fig. 1.8(a). Based on the gathered information, control and management procedures can be executed in the central controller to achieve proper and efficient operation. The advantages of centralized control include real-time observability of the whole system and straightforward implementation. If designed properly, it provides a strong supervision over the system. However, it entails a SPOF, and its breakdown will cause the loss of all the functions. Other disadvantages are reduced flexibility/expandability and a necessity for a lot of computational resources. Therefore, centralized control hierarchy is usually more suitable for localized and small size MGs where the information to be gathered is limited and centralized optimization can be realized with low communication and computation cost [45], [56], [59], [61], [64].

On the other hand, in order to achieve more flexible operation and avoid SPOF, distributed control systems have been brought to stage [65]–[67]. A general structure is shown in Fig. 1.8(b). Instead of information concentration in a central controller, a distributed information sharing algorithm is needed for all the LCs to obtain essential global information. Recent progress in alternative communication technologies [68] (WiFi, Zigbee, etc.) and information exchange algorithms [69]–[73] (Peer-To-Peer, Gossip, Consensus etc.) enable the possibility of distributed control and management in practical applications. In that sense, functions provided by conventional centralized control mechanism, such as frequency and voltage restoration, DER coordination, energy management, can also be realized in a distributed way, while the level of decentralization can range from centralized to fully distributed.

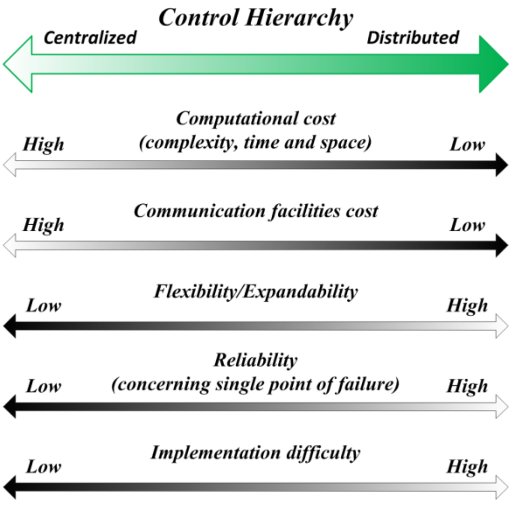



**Figure 1.9. Comparison between centralized and distributed control hierarchy.**

In summary, decentralized control and energy management can, to some degree, reduce the centralized data acquisition and avoid high complexity of centralized computation. Another advantage is that the realization of plug-and-play functionality is much easier, which considerably enhances MG flexibility.

However, from another point of view, the difficulty of overall system analysis increases since the representation of the system becomes much more mathematically involved. Control and information sharing schemes need to be well designed to fulfill the objectives.

### 1.6.2. DYNAMIC CONSENSUS ALGORITHM

Motivated by the distributed control and management objectives, dynamic consensus algorithm (DCA) [74]–[76] has been introduced into MGs. Study of consensus problems originates from computer science area for distributed computing and decision-making. During recent decades, more and more researchers have been attracted to the application of DCA into different areas, like automatic vehicles control, distributed sensor network, satellites coordination and so on.

The general purpose of consensus algorithms is to allow a set of agents to arrive an agreement on a quantity of interest by exchanging information through communication network, while these agents are only required to communicate with direct neighboring agents, as shown in Fig. 1.10. Each of the agents holds its own information state $x_i$ ($i$=1,2,…$N$, $N$ is the total number of agents). The information state update between agents is modeled by a difference equation. $\dot{x}_i$ denotes the dynamic state of agent $i$, $a_{ij}$ denotes the weight value on communication edge between node $i$ and $j$, which defines the dynamics of the information consensus. After certain number of iterations, the final consensus can be achieved as the average value of the states of all the agents. The consensus algorithms provide the following advantages and features [74]–[81]:

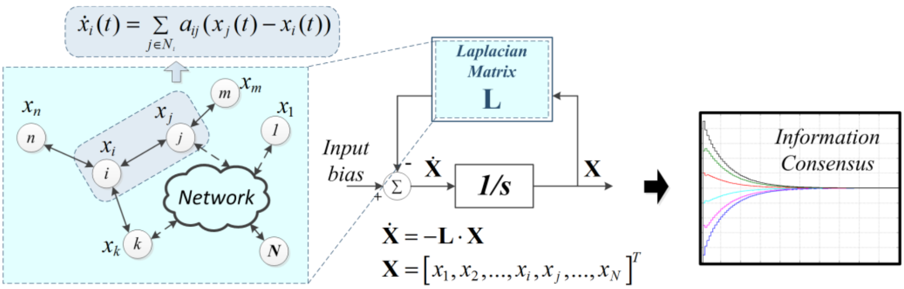



**Figure 1.10. Fundamentals of consensus algorithm in a network of agents.**

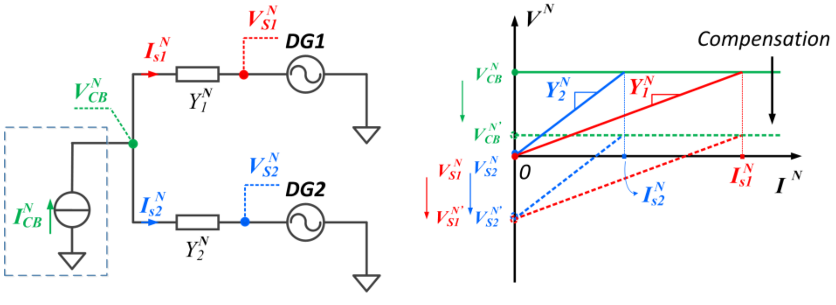
- The cost of communication links can be reduced as communications are only necessary between neighboring agents. A tradeoff between converging speed and number of communication links exists so that the topology of the communication network can be optimized.

- The fastest convergence of global information can be guaranteed by proper design of the weight matrix. Local degree weights are suitable for distributed system and can be adaptive to communication topology change.
- The convergence speed and consensus dynamics can be analytically evaluated so as to assist the control system design and coordination.

Based on those features, this project applies DCA into both DC and AC MGs for distributed operation.

### 1.6.3. MODELING AND DISTRIBUTED CONTROL FOR AC MICROGRIDS – MOTIVATIONS

Although it was demonstrated in [40]–[44] that DGs can be used as distributed filters and compensators, power sharing issues were not taken into consideration, especially considering the negative sequence quatities under unbalanced conditions. An example is shown in Fig. 1.11 (a), where two DG units are supplying a common bus. If unbalanced load is connected, negative sequence voltage and current appear in the system ($V_{CB}^N, I_{CB}^N$). The compensation process is generalized in Fig. 1.11 (b), the negative sequence voltage at the common bus ($V_{CB}^N$) can be reduced to $V_{CB}^{N'}$ by decreasing the negative sequence voltage in DG sides (from $V_{S1}^N, V_{S2}^N$ to $V_{S1}^{N'}, V_{S2}^{N'}$, respectively). By applying this approach, the voltage unbalance on CB can be controlled to a relative lower level in order to keep the good power quality. However, it can be also seen from Fig. 1.11 (b) that the negative sequence current is not well shared if the distribution line admittances are different ($Y_1^N \neq Y_2^N$). With the same compensation references, the DG unit with larger admittance will provide more current which may cause overcurrent fault to the DGs which are located near to the compensating point. Because of the existence of voltage unbalance and negative sequence quantities, conventional droop control and virtual impedances are not able to achieve accurate current sharing among DGs.




(a) (b)

**Figure 1.11. Negative sequence current sharing and distributed compensation issues in three-phase AC microgrids.**

Centralized control, such as the cases presented in [82], [83], is a typical way to achieve the accurate total power sharing. However, under distributed generation, storage and consumption paradigm, centralized control is facing obstacles because of the high communication and implementation cost, limited flexibility and low reliability due to its SPOF feature. In recent years, distributed control methods have been more and more studied and applied in MGs. Consensus algorithms are actually attractive methods as they offer effective information sharing among distributed agents, facilitating in that way the distributed coordination and control of DGs.

However, in order to achieve distributed voltage unbalance compensation and negative sequence current sharing, the unbalanced system needs to be first modelled and analyzed to explore the possibility for distributed control. Hierarchical control scheme needs to be well designed to integrate communication layer and control layer. Because of the using of DCA, the interaction between DG units and the system behavior under different communication rates needs to be tested and evaluated to ensure the stable operation.

### 1.6.4. MODELING AND DISTRIBUTED CONTROL FOR DC MICROGRIDS – MOTIVATIONS

In DC MGs, the main control objectives are the voltage regulation and current sharing. Up to date, several kinds of approaches were proposed for achieving those objectives, such as droop control and master-slave control [5], [84], [85]. Master-slave control facilitates the well regulation of the bus voltage and sharing of total load current, however, a SPOF of the master unit compromises the safety of the entire system [85]. Droop control can achieve communication-less current sharing among converters, but voltage deviation and current sharing error usually exist. On top of droop control, conventional centralized secondary control can be implemented to eliminate those errors, but the issue of SPOF still exists in the central controller [5]. Also communication links are required from the central control to every local unit which causes high communication cost, and lower reliability and flexibility. In order to achieve fully distributed control for DC MGs, this project proposes DCA based distributed hierarchical control method to realize accurate current sharing and voltage restoration. Compared with above mentioned methods, the approach applied in this paper is a fully distributed control method avoiding the problem of SPOF, and communication links are only required between nearby units. System flexibility is enhanced with plug-and-play function.

Moreover, the inclusion of consensus algorithm in the finite-speed-communication links becomes a challenge when paired with dynamics of electrical network. In the existing studies [86]–[88], consensus algorithm is modeled with MG system in continuous domain, the correctness and accuracy of which has never been evaluated. Considering the discrete nature of communication system and different feature of electrical, digital control and communication network, s-domain continuous-time (CT) model is then not accurate enough to represent the overall system behavior. As an example system shown in Fig. 1.12, the electrical part, which includes the filter, transmission lines and loads, is actually a CT system, while the digital controller and communication network are discrete-time (DT) systems [89]. Moreover, sampling times of control and communication (for communication part sampling time corresponds to transmission rate) significantly differ with typical times for the matter being in μs range and ms range respectively. All those issues appear as the main challenges to the modeling, analysis and distributed control for DC MGs, which are also the main focus of the project.

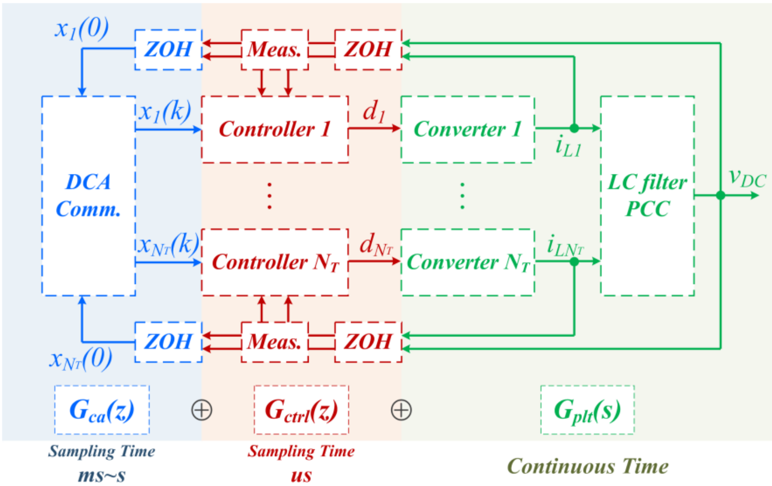



**Figure 1.12. Real world power electronics systems considering features of different parts.**

## 1.7. THESIS CONTRIBUTION

To address the issue mentioned above regarding optimization for system efficiency enhancement and system dynamic consideration in DC MGs, a complete hierarchical control scheme is proposed in this project. Conventionally, load current is equally shared among converters that the system efficiency is low, especially in light-load conditions. Hierarchical control conception is adopted and improved in this project so as to realize system efficiency enhancement while ensure desirable system damping: (i) adaptive VR method is employed in the primary control level achieving proportionally adjustment of load sharing among converters and well interfacing with tertiary optimization; (ii) voltage secondary control takes charge of voltage deviation restoration, also system dynamic model is established, the root locus and dynamic performance is evaluated resulting in a new secondary control scheme for better system damping; (iii) GA is integrated in the tertiary level to enhance the system efficiency by solving an optimization problem, the system model is simplified formulating a proper mathematical model for optimization purpose, and online optimization is actualized.

For the optimal power quality control in multi-zone AC MGs, an unbalanced system modeling and optimization method as well as a complete control hierarchy are proposed. The proposed hierarchy includes three levels: primary level for power sharing control, secondary level for unbalance compensation control and tertiary level for global power quality optimization. The general idea of this method is to assign a tertiary compensation gain (TCG) for each DG, and common compensation reference given by secondary control is first multiplied by TCG and then sent to the respective DG. The tertiary control inherently is an optimization solver. Accordingly, it is necessary to build a mathematical model to obtain a link between TCG and VUF. An example system is modeled and simulated with all the control levels. HIL results are presented to demonstrate that the proposed method is capable of controlling the unbalance level on each bus according to their limitations and power quality requirements. This method realizes accurate unbalance control among buses in an islanded system considering different power quality requirements of the buses and compensation limitation of DGs. This method also enables the possibility of higher level scheduling and management for power quality control in MGs to realize economic and technical objectives.

Considering the needs of distributed compensation control in AC MGs, this project proposes a DCA based hierarchical control scheme to realize distributed negative sequence current sharing and voltage unbalance compensation. Although former studies demonstrated the possibility of using DGs as distributed compensators, the negative sequence current cannot be well shared by only applying droop control, which may cause overcurrent condition for DGs located close to the CB. In order to improve the current sharing while considering the distributed fashion of future MG systems, this paper proposes a DCA based control method. An additional negative sequence current sharing loop is included. The unbalanced system is modeled with compensation and current sharing analysis. The proposed control scheme is implemented in a dSPACE based experimental setup to verify the effectiveness of the method. The results demonstrate that the proposed control scheme is able to realize voltage unbalance compensation while ensuring the accurate total current sharing among DGs. Also, the online excluding/including unit processes are tested showing the enhanced system flexibility by applying such a scheme. Note that thanks to the distributed nature of the proposed approach, the controller does not need to be implemented in a centralized fashion, which may be dedicated to other management operations of the MG.

Similarly, DCA can be also applied to DC MGs. A DCA based hierarchical control scheme is proposed in this project realizing voltage restoration and accurate current sharing in DC MGs. Besides, this piece of work also investigates the modeling method for such kind of distributed control system with full consideration of underlying communication topology. The hierarchical control includes inner voltage and current control loops, VR and secondary voltage and current control loops aiming at realizing accurate current sharing and keeping rated voltage amplitude in the PCC. Compared with conventional methods, the proposed scheme is a fully distributed control method avoiding the problem of SPOF, and communication links are only required between nearby units. System flexibility is enhanced with plug-and-play function. Considering the stability issue, as the performance of the secondary controller is based on the knowledge from dynamic consensus algorithm, the distributed units interact with each other not only through the electrical network but also the communication links. The system becomes more interactive compared with conventional centralized methods. Accordingly, this paper also proposes a modeling method in discrete time domain in order to properly analyze the interactive feature of this kind of system. Taking into account the different sampling times of the plant, the digital controller and the communication devices, the system is modeled with these three parts separately. Zero order hold and Tustin methods are used to discretize the models and integrate them into a complete system state-space model. By comparing with Simulink/Plecs based model, the correctness of the state-space model is justified. Finally, based on this model, the system dynamics and parameter sensitivity are studied and analyzed. Conclusions and recommendations have been given for implementing such kind of control algorithm.

In order to establish a testing platform of MG related comprehensive studies, a microgrid central controller (MGCC) is developed in the intelligent MG lab (iMG) in Aalborg University. LabVIEW is used to create a user interface and programming the control functions. UDP/IP based communication network is established for the information sharing between MGCC and experimental setups. Several hierarchical control schemes, such as coordinated control, power quality regulation and flywheel management, have been implemented and tested in this platform which demonstrates the capability of the system.

## 1.8. THESIS OBJECTIVES

The research objectives of this project are listed below:

- To review the optimization techniques applied to MGs, study the possibility of real-time optimization.
- To study the optimization for efficiency enhancement in DC MGs, develop hierarchical control scheme for optimal operation of DC system.
- To study the power quality issues in AC MGs, especially voltage unbalance issue, establish equivalent mathematical model, and develop hierarchical

control scheme achieving online optimization for power quality regulation in multi-zone MGs.

- To investigate distributed algorithms, and their possible applications in MGs.
- To propose distributed control method to achieve distributed voltage unbalance compensation considering also the accurate current sharing in AC MGs.
- To propose distributed control method for DC MGs realizing voltage restoration and accurate current sharing.
- To propose a general discrete-time modeling method for MG systems.
- To model and analyze the MG system with distributed control algorithm considering different underlying communication technologies and topologies,
- To design and establish a MGCC in the iMG lab in Aalborg university for system supervision and management.

The proposed control schemes have been validated by either simulations or experiments. Simulink, Plecs and dSPACE based hardware-in-the-loop (HiL) platform are chosen as the simulation environment for DC MGs related studies. Experimental setups in the iMG lab are used to verify the control and management algorithms proposed for AC MG systems.

## 1.9. THESIS OUTLINE

This thesis is organized as follows:

***Chapter 2*** gives the first paper, published in *IEEE Transactions on Smart Grid*, which introduces the hierarchical control and optimization for enhanced system efficiency and improved system dynamics in DC MGs. The system efficiency objective is analyzed, based on which an optimization problem is formulated. GA is implemented in the tertiary control for solving the problem. In order to guarantee desirable system dynamics, the dynamic state-space model of the complete system is established, according to which a system damping secondary control is proposed. The proposed control algorithm is tested in the iMG lab with dSPACE based HiL setups.

***Chapter 3*** presents the second paper, published in *IEEE Transactions on Energy Conversion*, which introduces the hierarchical control and optimization for optimal voltage unbalance compensation in AC MGs. The power quality issue in an example multi-zone MG is first introduced. Unbalanced system is modeled and analyzed for optimization purposes, and based on which the optimization problem is formulated. As the involved objective function and constraints are actually nonconvex and nonlinear, GA is used to solve the problem. The proposed control algorithm is tested in the iMG lab with dSPACE based HiL setups. The optimality of the solutions is also demonstrated.

***Chapter 4*** presents the third paper, published in *IEEE Transactions on Power Electronics*, which introduces the distributed hierarchical control for voltage unbalance compensation and negative sequence current sharing in three-phase AC MGs based on dynamic consensus algorithm. The unbalanced system is first modeled stating the issues of voltage unbalance compensation and current sharing. The distributed hierarchical control scheme is designed based on the model and proper utilization of DCA. Experimental results have been extracted in iMG lab and presented in this work, which demonstrate the effectiveness of the scheme. Effect of different communication rates is evaluated, plug-and-play function is also verified with the proposed strategy.

***Chapter 5*** presents the fourth paper, published in *IEEE Transactions on Smart Grid*, which introduces the modeling and distributed hierarchical control scheme in DC MGs. Voltage restoration and current sharing are the two main objectives. The complete hierarchical control scheme and the implementation of DCA are introduced. Discrete-time modeling method is proposed, based on which the system model is established. System performance under different communication topology, units fault and communication loss conditions are simulated to verify the capability and flexibility of the proposed control algorithm. Step responses of the established state-space model are compared with Simulink-Plecs based simulation system which indicates the correctness and accuracy of the proposed modeling approach. Sensitivity study is conducted based on the model, giving analytical hints to the design and implementation of such kind of control system.

***Chapter 6*** gives the fifth paper, presented in *Applied Power Electronics Exposition (APEC) 2015*, in which the development of a MGCC in the iMG lab in Aalborg University, Denmark, is introduced. The iMG lab aims to provide a flexible experimental platform for comprehensive studies of MGs. The complete control system applied in this lab is based on the hierarchical control scheme for MGs and includes primary, secondary and tertiary control. The structure of the lab, including the lab facilities, configurations and communication network, is introduced. On the basis of this lab, a LabVIEW-based MGCC is also developed. A study case is introduced and tested in the iMG lab for voltage/frequency restoration and voltage unbalance compensation. Experimental results are presented to show the performance of the whole system.

***Chapter 7*** gives the conclusion, summarizes the contribution of the project and plans the future work.

# CHAPTER 2. PAPER 1

## Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC-DC Converters

Lexuan Meng, Tomislav Dragicevic, Josep M. Guerrero, Juan C. Vásquez

The paper has been published in

*IEEE Transactions on Smart Grid, 2015*

vol.PP, no.99, pp.1,1, June, 2015

# CHAPTER 3. PAPER 2

## Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids

Lexuan Meng, Fen Tang, Mehdi Savaghebi, Juan C. Vasquez, Josep M. Guerrero

The paper has been published in

*IEEE Transactions on Energy Conversion*,

vol.29, no.4, pp.802,815, Dec. 2014

# CHAPTER 4. PAPER 3

## Distributed Voltage Unbalance Compensation in Islanded Microgrids by Using Dynamic-Consensus-Algorithm

Lexuan Meng, Xin Zhao, Fen Tang, Mehdi Savaghebi, Tomislav Dragicevic, Juan C. Vasquez, Josep M. Guerrero

The paper has been published in

*IEEE Transactions on Power Electronics,*

vol.PP, no.99, pp.1,1, Feb. 2015

# CHAPTER 5. PAPER 4

## Modeling and Sensitivity Study of Consensus Algorithm Based Distributed Hierarchical Control for DC Microgrids

Lexuan Meng, Tomislav Dragicevic, Javier Roldán-Pérez,

Juan C. Vasquez, Josep M. Guerrero

The paper has been accepted for publication in

*IEEE Transactions on Smart Grid*

vol.PP, no.99, pp.1,1, May 2015

# CHAPTER 6. PAPER 5

## Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University

Lexuan Meng, Mehdi Savaghebi, Fabio Andrade, Moisès Graells, Juan C. Vasquez, Josep M. Guerrero

The paper has been published in

*Proceeding of 2015 Applied Power Electronics Exposition (APEC),*

15-19 Mar. 2015

Charlotte, NC, U.S.

# CHAPTER 7. CONCLUDING REMARKS

## 7.1. SUMMARY

This thesis proposes hierarchical control schemes integrating online optimization methods for optimal operation of MGs. Efficiency enhancement in DC MG and optimal power quality regulation in three-phase AC MG are taken as objectives, which demonstrate the possibility of real-time optimization by properly establishing optimization problems and designing the control hierarchy. Besides, in order to improve the flexibility of MG operation, distributed control approaches are proposed and applied based on the existing hierarchical control scheme. Distributed control for voltage unbalance compensation in AC MG and for voltage/current regulation in DC MG have been achieved. As in the distributed control scheme, communication part has significant influence over system dynamics, this thesis proposes a discrete-time modeling method taking into account the features of different parts of the system. Sensitivity analysis is carried out based on the established model. Detailed conclusions are given as following in different aspects:

**Optimization in microgrids**

To achieve optimal operation of MGs, optimization algorithms are implemented in the tertiary level of the hierarchical control scheme. The critical steps to achieve online optimization include: a) identify the objective(s) and define the objective function(s) which can represent the satisfying level with the objective(s); b) define a set of decision variables that are adjustable and can affect the objective function value, also the feasibility and system stability need to be considered when choosing the decision variables; c) establish proper mathematical model of the system, which can provide insights into the practical MGs and estimate the objective function value based on accessible information; d) review and choose a suitable optimization algorithm according to the type of the problem; e) integrate the optimization algorithm into the control scheme, set proper optimization interval and decouple the dynamics between different layers.

However, it has to be pointed out that, the performing of optimization functions usually requires essential global information. A tradeoff always exists between optimization quality and computation/communication cost. Also uncertainties, such as the renewable generation prediction, distribution line impedance estimation, etc., need to be taken into consideration. System stability has to be evaluated when the optimization involves online changing of control parameters.

**Distributed control in microgrids**

Distributed control methods have been proposed based on the proper utilization of DCA. The purpose of DCA is to share essential information among a number of distributed units, and based on the information the secondary and tertiary control functions can be performed in a distributed fashion. The advantages gained from this scheme include: a) central controller is not necessarily needed and SPOF can be avoided; b) communication links are only required between nearby units which reduces the cost for building communication system; c) even if some communication links are failed or disconnected system can keep normal operation as far as all the units are remain connected; d) plug-and-play function can be realized achieving flexible operation of the system.

From another point of view, as the performing of some control functions relies on the information from communication, the system dynamics can be affected by the communication algorithm which requires carefully design of information sharing scheme and control parameters in order to ensure stable operation.

**Discrete-time modeling considering communication algorithm**

In order to analytically evaluate the stability of distributed control based MG, the thesis proposes a discrete-time modeling method taking into account the different sampling times of the plant, the digital controller and the communication devices. The system is modeled with these three parts separately. Proper discretization methods, such as zero-order-hold or Tustin, are used to discretize the models and integrate them into a complete system state-space model.The correctness and accuracy of the model has been verified by comparing with simulation studies. Sensitivity analysis is carried out to evaluate the significance of different parameters in distributed control based MG, which can be summarized as following: a) communication system, in sense of the topology, tranmission rate, package loss, etc., has considerable impact over the dynamic of the system, higher algerbraic connectivity and transmission rates can guarantee faster convergence of the communication algorithm and finally give wider bandwidth for the lower level controller, however, a tradeoff exist between the communication cost (number of communication links and tranmission rate) and the dynamic of the system; b) control parameters need to be well tuned according to the feature of the underlying communication system, especially the convergence speed of the communication algorithm, which means the speed (bandwidth) of the control layer is actually limited by the fastest convergence speed of the communication algorithm.

All the proposed control strategies and modeling methods have been verified in Matlab/Simulink, Plecs and dSPACE 1006 based environments. Simulation or experimental results are presented in each piece of work.

## 7.2. CONTRIBUTIONS FROM THE AUTHOR'S POINT OF VIEW

From the author's point of view, the contributions of the thesis are summarized as following:

- Development and integration of real-time optimization function into existing hierarchical control scheme of MGs, realizing optimal operation of the system. As examples, efficiency enhancement in DC MGs and optimal voltage unbalance compensation in three-phase AC MGs have been achieved with proposed control schemes.
- Propose novel secondary control for desirable system damping based on the small signal modeling and root-locus analysis of DC MG systems.
- Modeling of unbalanced AC MG for optimization and distributed control purposes, which also gives an insight view of the unbalance compensation process in such systems.
- Development of consensus algorithm based distributed control strategies for both DC and AC MGs achieving fully distributed operation of DG units and plug-and-play functions. Distributed voltage unbalance compensation in three-phase AC MG and distributed voltage/current regulation in DC MG are taken as examples.
- Propose novel discrete-time modeling method with full consideration of different features of the real world plant, control system and communication system. The correctness and accuracy of the method have been demonstrated, and based on which sensitivity study is carried out which gives analytical view of distributed control based MGs.
- Development of MG central controller in the iMG lab in Aalborg University providing a platform for comprehensive MG related studies.

## 7.3. FUTURE RESEARCH POSSIBILITIES

**Multi-objective optimization for microgrids**

Considering different types of components and operation objectives in MG, the optimization problem can be multi-objective, i.e. power loss minimization, state-of-charge balancing, long-term operational cost reduction, consumer comfort level regulation, etc.. In some cases, the objectives can be conflicting making it difficult to agree to a common decision. Multi-objective optimization methods can be a potential solution, however, the challenges exist on the optimization oriented system modeling, problem formulation and interfaing with control system.

**Integration of energy management into existing hierarchical control scheme**

Apart from real-time optimization issues, the short-term and long-term operation goals are also of high importance for the continuous and economic operation of MGs. Although a number of studies have been carried out working on the demand side management and generation side scheduling, a link is missing between the energy management level with hierarchical control levels. The interfacing and coordination between energy management system and hierarchical control layers is actually a challenge issue considering practicability and system stability.

**Distributed management of multiple MGs**

The current studies put most efforts on the distributed control for units within a single MG system, while the future paradigm of power grid asks for the flexible operation of multiple MG systems. Accordingly, the modeling and control for DC and AC MG clusters are necessary. However, the system level control schemes and accessible interfacing parameters have not been well explored and designed, standardized operations for interfacing multiple MGs are still missing.

**Modeling and stability analysis of interconnected multiple MGs**

Modeling and stability analysis methods are of the utmost importance before actualizing the operation of multiple MGs. Impedance based stability analysis methods and local stability analysis considering coupling terms can be potential solutions for this kind of study. The realization of plug-and-play functions requires local parameter design that can keep global stability. Challenges exist not only on the system modeling and analysis, but also on the verification and demonstration.

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# *Attachment*

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- ***Paper 1:***
  Meng, L.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M., "Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC-DC Converters," Smart Grid, IEEE Transactions on , vol.PP, no.99, pp.1,1

- ***Paper 2:***
  Lexuan Meng; Fen Tang; Savaghebi, M.; Vasquez, J.C.; Guerrero, J.M., "Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids," Energy Conversion, IEEE Transactions on , vol.29, no.4, pp.802,815, Dec. 2014

- ***Paper 3:***
  Meng, L.; Zhao, X.; Tang, F.; Savaghebi, M.; Dragicevic, T.; Vasquez, J.; Guerrero, J., "Distributed Voltage Unbalance Compensation in Islanded Microgrids by Using Dynamic-Consensus-Algorithm," Power Electronics, IEEE Transactions on , vol.PP, no.99, pp.1,1

- ***Paper 4:***
  Meng, L.; Dragicevic, T.; Roldan-Perez, J.; Vasquez, J.C.; Guerrero, J.M., "Modeling and Sensitivity Study of Consensus Algorithm-Based Distributed Hierarchical Control for DC Microgrids," Smart Grid, IEEE Transactions on , vol.PP, no.99, pp.1,1

- ***Paper 5:***
  L. Meng, M. Savaghebi, F. Andrade, J. C. Vasquez, J. M. Guerrero, and M. Graells, "Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University," in Proc. IEEE APEC 2015