Multi-Functional Distributed Secondary Control for Autonomous Microgrids

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Multi-Functional Distributed Secondary Control for Autonomous Microgrids

Ph.D. Thesis

by

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Abstract

Microgrids (MGs)–the building blocks of the smart grid– are local grids comprise different technologies such as power electronics converters, distributed renewable and non-renewable energy sources, energy storage systems, and telecommunications which can operate either in islanded mode or connected to the main grid. Apart from the obvious benefits of MGs, their introduction into the traditional distribution network raises many new challenges, thus, a hierarchical control concept has been introduced for these systems. While the decentralized primary control of this hierarchy ensures the system stability and adjusts the frequency and voltage according to the active and reactive powers, the secondary control level is often used to regulate the system frequency and voltage to the rated values, eliminating deviations produced by primary level. The tertiary control is in charge of regulating power exchange with external grid or/and with other MGs and includes functions related to efficiency and economic enhancement.

This thesis is focused on development of distributed control strategies for secondary control of autonomous ac and dc MGs to avoid a central controller and complex communication network, thus offering improved reliability and expandability. The special emphasis has been given to consensus-based protocols where the mathematical analysis has been also studied and presented. The proposed methodologies based on this approach are fully distributed meaning that each MG source requires to exchange information with only its direct neighbours through a sparse communication network. Loss of sources and communication links do not affect system operation as long as the communication graph remains connected. Moreover, they are scalable, for that prior knowledge of the system is not required, as a new component enters the MG. The proposed control frameworks for ac MGs include two modules, namely, voltage regulator, and reactive power regulator. The voltage regulator boosts the voltage across the MG to satisfy the global voltage regulation, while the reactive power regulator handles the proportional reactive power sharing considering transmission line impedances. Moreover, the proposed controllers are able to proportionally share the load power even at the presence of different control parameters and initial values.

This thesis also proposes a distributed hierarchical control framework for dc MG clusters to ensure smooth connection and reliable operation of these systems. A decentralize adaptive droop method is introduced for primary control level which determines droop coefficients according to the state-of-charge (SOC) of batteries automatically. Then a small signal model is developed to investigate effects of the proposed method parameters and the system parameters on the stability of these systems, as well as to tune the control parameters. Finally, a consensus-based distributed control framework is proposed which provides all features of distributed control methods. It eliminates the average voltage deviation over the MGs while regulating the power flow control between the MGs according to their local SOCs at the same time. The proposed approach only needs neighbor-to-neighbor communication through a spars communication infrastructure.

Experimental and simulation studies are presented to demonstrate the application and effectiveness of the proposed strategies in different scenarios.

Keywords: Microgrids, DC Microgrid clusters, secondary control, distributed control, cooperative control, sparse communication, adaptive droop, frequency regulation, voltage regulation, proportional power sharing, power flow control.

Abstrakt

Microgrids (MGs)- byggestenene i smart grid- er lokale net, som omfatter forskellige teknologier såsom effektelektroniske omformere, distribuerede vedvarende og ikke-vedvarende energikilder, energilagringssystemer og kommunikation, som kan operere selvstændigt i enten isoleret tilstand eller tilsluttet hovednettet. Bortset fra de åbenlyse fordele ved MGs, forårsager deres indførelse i det traditionelle distributionsnet mange nye udfordringer, hvorfor et hierarkisk styringskoncept er blevet indført til disse systemer. Mens den decentrale primære kontrol i dette hierarki sikrer systemets stabilitet og justerer frekvensen og spændingen i henhold til den aktive og reaktive effekt, bruges det sekundære kontrolniveau ofte til at regulere systemets frekvens og spænding til de nominelle værdier, hvilket fjerner afvigelser produceret af det primære niveau. Den tertiære kontrol er ansvarlig for at regulere effekt-flowet mellem det eksterne net og / eller med andre MGs og indeholder funktioner relateret til effektivitet og økonomisk udbytte.

Denne afhandling fokuserer på udvikling af distribuerede kontrolstrategier til sekundær kontrol af autonome ac og dc MGs for at undgå en central styreenhed og et komplekst kommunikationsnetværk, og dermed forbedre systemets pålidelighed samt gøre det mere skalerbart. Særlig vægt er lagt på konsensus-baserede protokoller, hvor den matematiske analyse også undersøges og præsenteres. De foreslåede metoder baseret på denne fremgangsmåde er skalerbare, hvilket betyder, at hver MG kilde kun behøver at udveksle oplysninger med dens naboer gennem et mindre kommunikationsnetværk. Tab af kilder og kommunikationsforbindelser påvirker ikke systemets drift, så længe kommunikationsnetværket er tilsluttet. Desuden er de skalerbare, idet der ikke kræves forudgående kendskab til systemet, når en ny komponent indføres i et MG. Den foreslåede kontrolstruktur for ac MG kontrol omfatter to moduler, nemlig en spændingsregulator og en regulator til reaktiv effekt. Spændingsregulatoren øger spændingen af MG for at tilfredsstille det globale spændingskrav, mens den reaktive effekt regulator håndterer proportional reaktiv effekt fordelingen medregnende transmissionlinjernes impedanser. Desuden er de foreslåede regulatorer i stand til at fordele effekt-belastningen proportionalt, selv i tilfælde af forskellige parametre og startværdier.

Denne afhandling foreslår også en distribueret hierarkisk kontrolstruktur for dc MG klynger for at sikre en pålidelig tilslutning og drift af disse systemer. En decentraliseret adaptiv droop metode indføres til det primære kontrolniveau, der automatisk bestemmer droop koefficienter i henhold til state-of-charge (SOC) for batterier. En små-signals-model er udviklet til at undersøge virkningerne af den foreslåede metode og systemets parametre på stabiliteten af disse systemer, samt til at tune kontrolparametrene. Slutteligt foreslås en konsensusbaseret distribueret kontrolstruktur, som opfylder alle funktioner af distribuerede kontrol metoder. Det fjerner den gennemsnitlige spændingsafvigelse over MGs, og regulerer effekt flowet mellem hver MG i henhold til deres lokale SOC. Den foreslåede fremgangsmåde har kun behov for nabo-til-nabo kommunikation, hvilket giver en mindre kommunikationsinfrastruktur.

Eksperimentelle undersøgelser og simuleringer præsenteres for at demonstrere anvendelsen og effektiviteten af de foreslåede strategier i forskellige scenarier.

Nøgleord: Microgrid, DC Microgrid klynger, sekundær kontrol, distribueret kontrol, kooperativ kontrol, sparsom kommunikation, adaptiv droop, frekvensregulering, spændingsregulering, proportional effektfordeling, effekt flow kontrol.

Thesis Details and Publications

Thesis Title: Multi-Functional Distributed Secondary Control for Autonomous Microgrids

Ph.D. Student: Qobad Shafiee

Supervisor: Prof. Josep M. Guerrero, Aalborg University

Co-supervisor: Assist. Prof. Juan C. Vasquez, Aalborg University

Publications in refereed journals

- Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed Secondary Control for Islanded Microgrids – A Novel Approach," *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 1018–1031, Feb. 2014.
- Q. Shafiee, C. Stefanovic, T. Dragicevic, P. Popovski, J. C. Vasquez, and J. M. Guerrero, "Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids," *IEEE Transactions on Indusrtial Electronics*, vol. 61, no. 10, pp. 5363–5374, Oct. 2014.
- Q. Shafiee, T. Dragicevic, J. Vasquez, J. M. Guerrero, "Hierarchical control for multiple DC-microgrids clusters," *IEEE Transactions on Energy Conversion*, Early Access, 2014.

Publications in proceedings with review

- Q. Shafiee, T. Dragicevic, F. Andrade, J. Vasquez, J. M. Guerrero, "Distributed Consensus-Based Control of Multiple DC-Microgrids Clusters," *40th annual Conference on IEEE Industrial Electronics Society (IECON)*, Oct. 2014, pp. XX–XX.
- Q. Shafiee, V. Nasirian, J. M. Guerrero, F. L. Lewis, A. Davoudi "Team-oriented Adaptive Droop Control for Autonomous AC Microgrids," *40th annual Conference on IEEE Industrial Electronics Society (IECON)*, Oct. 2014, pp. XX–XX.
- Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Modeling, Stability Analysis and Active Stabilization of Multiple DC-Microgrids Clusters," *IEEE International Energy Conference, EnergyCon 2014*, May 2014, pp. 1284–1290.
- Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Hierarchical control for multiple DC-microgrids clusters," *11th International Multi-Conference on Systems, Signals and Devices, SSD 2014*, Feb. 2014, pp. 1–6.

- Q. Shafiee, T. Dragicevic, J. C. Vasquez, J. M. Guerrero, C. Stefanovic, and P. Popovski, "A novel robust communication algorithm for distributed secondary control of islanded MicroGrids," *Energy Conversion Congress and Exposition, ECCE 2013*, Sept. 2013, pp. 4609–4616.
- Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed secondary control for islanded MicroGrids – A networked control systems approach," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Oct. 2012, pp. 5637–5642.

This present report combined with the above listed scientific papers has been submitted for assessment in partial fulfilment of the PhD degree. The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

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This thesis is the result of my research carried out at the Department of Energy Technology, Aalborg University. The thesis has been submitted to the Faculty of Engineering, Science and Medicine at Aalborg University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Aalborg, 30 September 2014.

to my wife

Contents

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Introduction

1.1 Microgrids and Hierarchical Control

The electrical power system has been experiencing some major structural changes in the recent years. One of the most affecting changes is the trend from centralized generation and hierarchical structure, where the production follows a top-down principle under strict control of the electricity supply companies towards decentralized producers in the form of distributed generation (DG). This trend is mainly due to the installations of the distributed energy resources (DERs), which include various generators, renewable energy sources (RES) and energy storage systems (ESS). Renewable energy technologies, e.g. photovoltaics (PV) and wind turbines (WT), are characterized by strong fluctuations due to weather conditions, having some major differences from classical large power plants. They are often small units widely distributed, which do not possess the inherent synchronization mechanism of coupled synchronous generators. This continuous shift from centralized power generation to distributed fluctuating power generation, as well as integration of DGs the traditional power system involve several new challenges, particularly regarding the stability of power systems. On the other hand, future power system control concepts must follow the developments in the power generation to a more decentralized and distributed structure. Thus, both the operation of large power system and the analysis of its dynamics require new technologies and new control concepts. One of these concepts that has received increasing interest recently are the so-called *Microgrids* [1–3].

A microgrid (MG) is defined as a localized cluster of heterogeneous DGs and loads, placed in low voltage (LV) or/and medium voltage (MV) distribution networks, which is able to be either coupled to the main grid or operates autonomously in isolated mode [4–6]. It is usually interfaced to the grid through a bypass switch at a single point, often referred to as the point of common coupling (PCC) [7] (see Fig. 1.1). Microgrid can ensure power quality independence from utility mains with its ability to perform hot-swap islanding in case of grid contingencies. Conversely, when connected to grid, it appears like a singular and flexible entity from the overhead power system perspective, which makes it a valuable building block in the future *Smart Grid*.

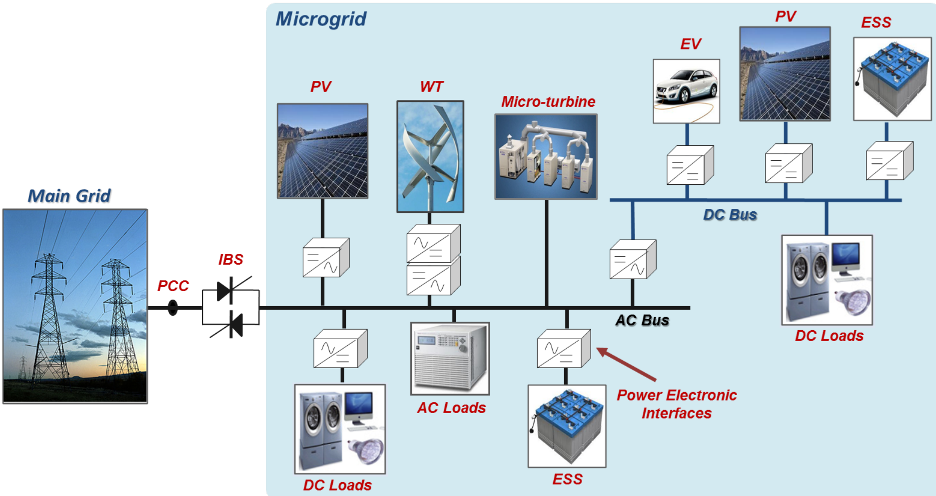

Figure 1.1: Configuration of a typical Microgrid

In the grid-connected mode, the voltage of PCC is dominantly determined by the host grid, hence the main role of the MG is to accommodate the local load demand and the active/reactive power generated by the DGs. The MG can participate in reactive power support or regulating the voltage at the point of connection, if it is permitted by the host utility, by injecting reactive power. Moreover, it can help to improve the power quality in the utility grid. In the isolated mode, the MG operates as an independent entity and must provide voltage and frequency regulation as well as active/reactive power balance.

Microgrids are divided into ac MGs [2–4] and dc MGs [8–11], depending on whether DGs and loads are connected on the basis of ac or dc grid. However, hybrids dc-ac MGs [12–14] are often implemented by means of power-electronic interfaces, being necessary to control the power flow between dc and ac parts. Figure 1.1 indicates typical configuration of a MG.

1.1.1 AC Microgrids

At present time, most of DGs especially RESs directly produce dc or variable frequency/voltage AC output power which are not compatible with the ac systems, and hence power electronics interfaces have become the key elements in order to realize the MGs [15]. Examples of the DGs that produce the ac output power include wind turbines, hydro, biogas, and wave turbines [16]. These DGs normally require the ac-dc-ac power converters to enable their stable coupling with the distribution networks. On the other hand, the DGs with dc output power can be connected to the ac bus of the system using dc-ac inverters [17]. In addition, the dc loads utilize the ac-dc power converters in order to be connected to the ac networks, while the ac loads are directly connected (see Fig. 1.1).

In the power electronic based MGs which entire ac power is injected through the inverters, it is obvious that all control operations are to be ensured through the control of the inverters. The main control objectives in ac MGs are

- Stabilizing the voltages and synchronizing the inverters frequencies to a rated value,
- Sharing the load (active and reactive power) among the inverters proportionally to their ratings,
- Providing ancillary services for the main grid.

1.1.2 DC Microgrids

DC Microgrids have gained research interest recently to facilitate integrating of modern electronic loads and alternative energy sources with dc output type such as PV systems, fuel cells (FC), and ESSs (e.g., secondary battery and super capacitor) [18–22]. Normally, dc MGs are proposed for power supply of applications with sensitive and/or dc loads, e.g., consumer electronics, electric vehicles, naval ships, space crafts, submarines, telecom systems and rural areas [21] which benefits from increased power quality, and higher reliability and efficiency. The advantages of dc MGs are summarized as

- Conversion loss from sources to loads is reduced, thus enhancing the efficiency,
- There is no need for control of frequency and phase, reactive power, and power quality, which are all big challenges in ac MGs,
- No synchronization requirement is needed for DGs to be connected to the dc bus,
- Any blackout or voltage sag that may happen from the grid side does not affect the units inside the dc MG.

Nevertheless, protection is still a big challenge in this new concept for dc systems and it is normally needed to construct new dc distribution lines while implementing dc MGs [8].

Various types of DGs can be used for these dc systems, however, PV and FC are more appropriate to be used as they produce dc power. On the other hand, due to transient response of sources, and the fact that they cannot be always available (in the case of RESs), ESSs are mandatory to be connected to the MG if it is operated in islanded mode [21]. Normally secondary batteries, super capacitors, and flywheels are used as an ESS. Batteries and capacitors can be directly connected to the dc bus, but flywheels are connected through a machine and a converter [11]. Nevertheless, it is desired to connect the ESSs to the dc bus through converters for full controllability. The main control objectives in dc MGs are

- Regulating the dc voltage at the rated value,
- Sharing the current (power) among the converters proportionally to their ratings,
- Regulation of the current (power) flow from/to an external stiff dc source which can be a medium voltage dc system, another dc MG, or a dc-ac power converter connected to the ac system.

1.1.3 Hierarchical Control of Microgrids

Taking the concept from the traditional power system, the control structure of a MG can be categorized into three hierarchical layers, namely the primary, secondary, and tertiary controls, according to generally accepted terminology in the literature [5].

The first level of this hierarchy is *primary control* which responds to system dynamics and ensures that the system voltage and frequency track their setpoints [2, 4, 23, 24]. Primary control is performed locally for every DG inside the MG, based on local measured signals. This level of control is generally made of inner control loops and droop control. *Secondary control* is the next level of control which includes slow control loops and low bandwidth communication systems. The main function of secondary control is to perform restorations of voltage and frequency levels to the nominal values by determining the set points for the primary control, shifting the droop characteristics of associated DGs. This level of control is decoupled from primary control by choosing a slower time frame. For example, the primary loop reaches its steady state before the secondary controller updates the set point. *Tertiary control* is in charge of regulating power exchange with external grid or/and with other MGs. It can also include advanced functions related to efficiency and economic enhancements which constitute a higher management level, commonly referred to as the energy management system (EMS) [25–28]. This level of control sets the long term set points of lower levels based on the information received about the status of the DGs, market signals, and other system requirements.

It should be noted that the bandwidth of control levels gets gradually decreased when climbing up the hierarchy. Although centralized architectures can be used for primary control [29], decentralized control loops are normally employed at each unit in the MG locally without using digital communication technologies. Unlike primary control, digital communication is required for the upper control levels. Usually, centralized control strategy is utilized for tertiary level, while the secondary control can be implemented in both centralized and distributed way.

1.2 Secondary Control of Microgrids

1.2.1 Why Secondary Control?

Power electronic interfaces became prevalent through voltage source converters (VSC) to integrate emerging DGs. Depending on the objectives and the control structure, a VSC is classified to voltage-controlled VSC and current-controlled VSC. Voltage-controlled VSCs facilitate the voltage and frequency regulation of DGs, while current-controlled VSCs controls the active and reactive power delivery [30,31]. For instance, RESs in MPPT mode [32] and batteries in charging mode [33] are preferred to be used as a current-controlled VSC. However both RESs and ESSs can also participate in voltage and frequency regulation. ESSs, e.g. batteries, are better choice for use as a voltage-controlled VSC because of their bidirectional capability.

Droop control [34] is normally employed in the primary control level to be added to the inner control loops for parallel connection of these voltage-controlled VSCs inside the MG, thus sharing power load between them. In ac systems, the droop control strategy has different forms according to the type of the output impedance. The active power-frequency, P–ω, and reactive power-voltage, Q–V, droops are used when the output impedance is inductive [34–37]; the reactive power-frequency, Q–ω, and active power-voltage, P–V, droops are employed when the output impedance is resistive [38]. However, active power-voltage droop, P–V or output current-voltage droop i_o–V is utilized for dc systems [5].

The main drawback of droop method is poor voltage and frequency (in case of ac MGs) regulation. Once the power sharing is improved among the MG units, the voltage/frequency drop increases. The larger droop gain is, the more voltage/frequency deviation and the more accurate is load sharing between the sources. Therefore, the droop method has an inherent trade-off between voltage/frequency regulation and load sharing. As primary control is not able to return the MG to the normal operating conditions, secondary control is employed to restore the voltage and frequency. In addition, power load sharing can be also achieved between the MG sources by implementing a secondary control loop, in cases the primary control is unable to do that due to line impedances and/or different control parameters [39, 40].

1.2.2 Secondary Control Strategies

1.2.2.1 Centralized Secondary Control

Conventional secondary controller is unique for the whole MG, relies on centralized communication infrastructure and is, among other functions, implemented within the MG central controller (MGCC) [5, 39, 41, 42]. Figure 1.2 shows centralized secondary control architecture for a MG consisting of a number of DG units controlled by local primary control and one central secondary controller, which collects measured variables transferred by means of a low bandwidth commu-

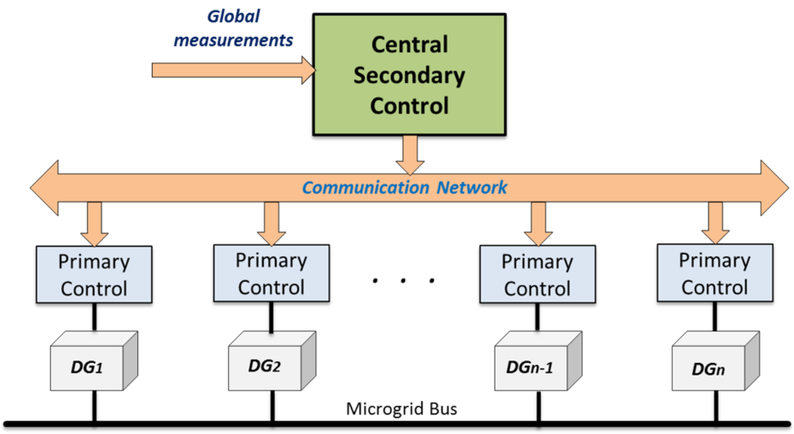

Figure 1.2: Centralized secondary control structure.

nication system. Those variables are compared with the references in order to calculate appropriate compensation signals by secondary controller, which sends them through dedicated communication channels back to primary control of each unit.

The centralized approach requires point-to-point communication, which adds complexity to the system and compromises its reliability due to a single point of failure issue. Alternatively, distributed control methods have attracted a lot of interests in MG research community recently [43–45], due to their attractive features as they accommodate more reliable and sparse communication networks.

1.2.2.2 Distributed Secondary Control

Distributed secondary control (DSC) is an alternative which avoids a single centralized controller and therefore improves reliability of the MG. The idea is to merge primary and secondary control together into one local controller. However, for proper operation, these local controllers need to talk with their companions, as shown in Fig. 1.3. Their conversation is typically processed through neighboring communication, resulting in a control system that is in literature generally referred to as distributed control [46].

The basic working principle of DSC is to exchange the information through the neighboring communication, by utilizing a distributed protocol and achieving a consensus, e.g. the average value of measured information. As opposed to frequency, voltages are local variables, implying that their restoration can be done either in selected critical buses, or on the total average level. In the latter case, DSC can be exploited to generate a common signal which is compared with a reference and passed through a local PI controller, which produces appropriate control signal to be sent to the primary level for removing associated steady state

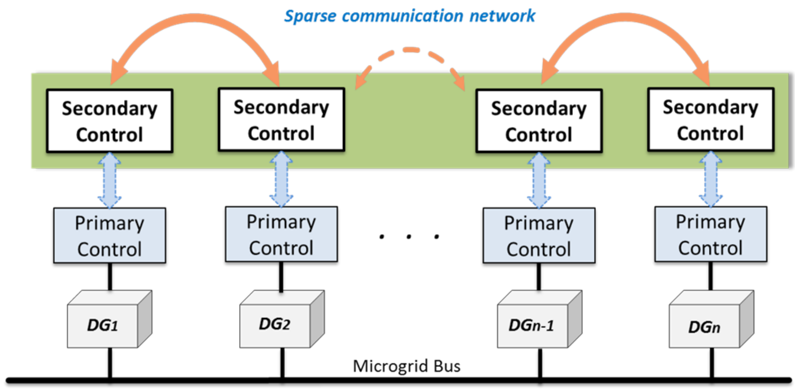

Figure 1.3: Distributed secondary control structure.

errors. It should be noted that the type of protocol, which is essential for making the secondary control distributed, influences the feasibility and performance of DSC. Several distributed control methods have been introduced in the literature out of which consensus- [46, 47] and gossip-based [48] algorithms have recently received significant attention mostly because of their implicitness and robustness for distributed information exchange over networks.

1.2.3 Main Functions of Secondary Control

The main functions of secondary control are to simultaneously shift the droop characteristics of associated DGs in order to perform restorations of voltage and frequency levels to nominal values while keeping active and reactive power shared between the units. Moreover, secondary control can encompass synchronization loop, as well as power quality regulation capability, optionally. The synchronization control loop can be consider in this level of control to seamlessly connect/disconnect the MG to/from the distribution ac networks [49]. This loop is designed to synchronize the voltage, frequency and phase of MG with the main grid. In addition, global objectives regarding voltage control and power quality of the MG, such as voltage unbalance and harmonic compensation can be also considered as a function for secondary control [50, 51]. As the focus of this thesis will be on the main functions of secondary control, we limit our discussion here only to that functions.

1.2.3.1 Frequency and Voltage Regulation

Load frequency control (LFC), as a major function of automatic generation control (AGC) in large power systems, is in its essence a centralized secondary controller based on a slow PI regulator with a dead-band that restores the frequency of the grid when the deviation is higher than a certain value due to mismatch

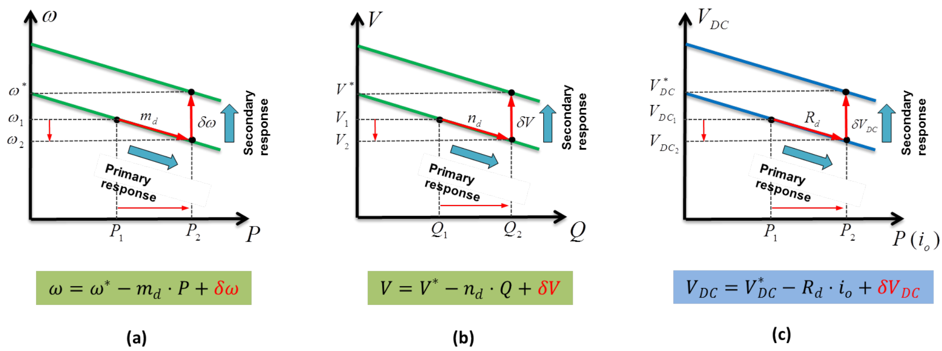

Figure 1.4: Secondary control main functions; (a) frequency restoration in inductive ac MGs, (b) voltage restoration in inductive ac MGs, (c) voltage restoration in dc MGs.

between generation and consumption [52]. Inspired by this idea, a centralized integral secondary controller is implemented in the MGCC in order to regulate the frequency of the MG [2, 5, 53]. Corresponding distributed approach is to use frequency control locally at selected MG units, so that their local controllers slowly add increments to the primary level until the network frequency deviation gets eliminated [54–56].

As opposed to the network frequency, voltage amplitude is not a global variable. Voltage values will normally be distinct at different connection points in the MG due to line impedances. In large power systems, voltages at generator stations are fixed by local automatic voltage regulators (AVR) which act on the excitation system [57]. In MG, this type of voltage regulation is inherently included into a definition of secondary control. Figure 1.4 shows how secondary control removes frequency and voltage deviation caused by droop control in MGs. For instance, Fig. 1.4(a) demonstrates that the secondary control output signal influences the voltage reference of primary control by shifting the droop lines up and down, so that frequency can finally reach the nominal value.

1.2.3.2 Active/Reactive Power Sharing

In large power systems, sharing of reactive power is typically not a major concern due to capacitive compensation along the transmission lines and at load connection points [57]. On the contrary, it is an important issue in power electronic based MGs. In a typical MG, as sources respond to more power demand, onboard droop controllers reduce their frequency/voltage to handle load sharing and prevent overload. In that sense, precise voltage and frequency measurements are essential to achieve the effectiveness of the droop mechanisms. Unlike frequency, which is a global variable, the voltage varies across the MG due to the distribution line impedances. These voltage mismatches incapacitate the droop mechanism and result in a poor voltage regulation and load sharing. Similar effect occurs when trying to proportionally share the active power of units using P-V droop in ac MGs with highly resistive lines. Moreover, in dc MGs current/power sharing follows the same phenomenon [19]. A good alternative to share power between the MG units is deploying a power sharing loop in the secondary level. In this control strategy, all the units must reach the same value considering their power rates and obtain the same reference. This way, proportional power sharing can be achieved independently from voltage sensing mismatches or line impedances in the MG.

1.3 Background and Motivation of the Work

Motivated by the mentioned benefits of MGs, academic community has therein found a particularly fertile research field and a notable progress has been made in real-time operation and control of both ac and dc MGs. A particular attention in that sense was devoted to elimination of problems that come with paralleling multiple power electronic converters in ac systems without the use of dedicated communication infrastructure. The early works by Chandorkar et al. [34], Tuladhar et al. [58] and Coelho et al. [59] transferred the concept of *conventional droop control* from classical synchronous generators to parallel multiple inverters in inductive networks. Droop control was introduced as a way to ensure the main control objective in MGs, when Lasseter proposed the idea of these small grids for the first time in [1]. Initially reported solutions based on local droop control method showed promising performance for power electronics-interfaced small systems and MGs [15, 35, 37, 60]. Although, classical droop control minimize the communication needs and have plug-and-play capability, its limitations in practical applications have soon come to light: (i) its suitability only for dispatch-able generators, (ii) inherent voltage/frequency deviations, and (iii) inter-dependence of control parameters with power sharing accuracy and stability, to name a few. Therefore, several works have been recently done in the literature to improve performance of the classical droop in the primary level [61,62].

In this decentralized control approach, differences in the droop coefficients allow the sharing of the total load power requirement among the converters according to a predefined ratio. In the conventional method, a fixed droop coefficient is normally defined according to rated power of converters, however, sometimes is needed to share load power in different ways. In this regard, several adaptive droop methods based on different system parameters have been presented recently for both AC [63,64] and DC [21,22,65,66] MGs. However, this area is still open to research.

Although significant progress has been made for the equal sharing of loads [37,38], it is still a problem to share loads accurately in proportion to the power ratings of the converters [15, 61, 67]. To provide accurate proportional load sharing when the conventional droop control scheme is adopted, (i) parallel-operated converters should have the same per-unit impedance, (ii) the droop controllers should generate the same voltage set-point. Both conditions are difficult to meet in practice, which results in errors in proportional load sharing [62]. Depending on the nature of interconnecting power lines, active and reactive power can be more or less decoupled. In inductively dominant lines, active power sharing is always achieved by the droop control method easily as frequency is global in the whole system. However, reactive power is related with voltages and it cannot be accurately distributed due to differences in line impedances that lead to diverse voltage drops [15, 35]. Similar effect can also be found for current sharing in DC MGs [66,68]. With dominantly resistive lines, active power sharing would be more problematic [35]. One way or another, droop control laws need to be appropriately tuned for MG applications in order to achieve proper load sharing and also accurate voltage and frequency regulation.

Secondary control has been introduced for MGs in the literature [2, 5] as an alternative to overcome limitations of the conventional droop control. The first presented works were based on centralized control architecture. A centralized secondary control was proposed in [5], to be implemented in MGCC as second level of a control hierarchy in order to remove frequency and voltage deviations. In this work, power sharing has not been take into account as a task for secondary control. In [41], a potential function-based method is introduced for secondary voltage control of MGs . The potential functions associated with each MG units, however, the MGCC is used to minimize each potential function, determining the setpoints. The authors in [40] and [39] address some limitation of conventional droop control and proposes a central secondary control for reactive power sharing of single-phase MGs. Line impedances which is the main reason that effects reactive power sharing accuracy, has been considered in these works.

The requirements for a central controller and complex communication networks reduce the system reliability. Although it is easy implementing, scalability of the centralized control strategy is not straightforward. Moreover, it has an inherent drawback of the single point of failure, i.e., a failure terminates the secondary control action for all DGs. Additionally, it should be noted that because of the desired plug-and-play capability of MGs, their physical and communication structures can be time varying. Distributed control strategies have attracted a lot of interests as an alternative recently, as it provides easier scalability, simpler communication network, and improved reliability [46].

The usage of distributed control for MG application has been considered recently [43–45]. Consensus-based multi-agent schemes have been introduced for different purposes such as load restoration [43], fault recovery [45] and cooperative frequency control [44]. Some distributed secondary control methodologies have been recently proposed for MGs at the same time that this PhD research has been done [19, 54–56, 66, 68–71]. Secondary voltage and frequency control schemes based on the distributed cooperative control of multi-agent systems are introduced in [54, 55, 71] for ac MGs. In these works, reactive power sharing either has not been take into account or it is not enough accurate as the authors has tried to regulate the voltage to a predefined reference. In addition, two separate distributed control loop are presented to regulate the frequency and active power, which require both frequency and active power measurements. The recent work in [56] extends the primary droop-control by a distributed secondary-control scheme, called the distributed averaging PI (DAPI) controller. This secondary control permits to dynamically regulate the network frequency to its nominal value while preserving the proportional power sharing and without time-scales separation. It gives a novel analytic sufficient and necessary parametric condition for the existence of a unique and locally exponentially stable steady state in a lossless frequency droop-controlled network with constant bus voltages. Nevertheless, voltage regulation was not considered in this works and frequency measurement is still required for this control methodology. Further results and analysis on distributed control of ac MGs can be found in [69]. Similarly, distributed control has been proposed for secondary control of dc MGs. Distributed secondary/primary controllers are introduced in [68] and [66] for voltage regulation and proportional current sharing of dc MGs. The performance of proposed controllers are evaluated by different experimental studies where all features of distributed control are successfully verified. The results show that the proposed controllers precisely handle the transmission line impedances as well.

Although, a lot of research have been done in the field of MGs, no research work exist to improve the stability and reliability of MGs while they are connected. Moreover, overall control of these systems, voltage/frequency regulation, and control of power flow between the MGs is still open to research.

1.4 Thesis Contribution

To address the challenges mentioned in the previous subsection regarding centralized secondary control and also limitation of conventional droop, this thesis proposes distributed secondary strategies for both ac and dc MGs. Three different distributed strategies are studied and introduced in this work: (i) normal averaging method, (ii) gossip-based algorithms [48, 72], and (iii) consensus-based protocols [46, 47]. The control methodology proposed by each of these distributed strategies for ac MGs includes three separate modules; (i) frequency regulator and active power sharing, (ii) voltage regulator, and (iii) reactive power regulator. The first module restore the system frequency to the nominal value and removes the deviations produced by droop control. The voltage regulator maintains the average voltage of the MG at the rated value, while the reactive power regulator monitors the reactive power sharing and adjusts the setpoints to provide power load sharing. Unlike centralized strategy, proposed distributed control methodologies does not require complicated communication and mostly sparse communication can be used to exchange information between the controllers.

The thesis introduces multi-functional distributed consensus-based methodology for droop-controlled ac MGs. The methodology uses dynamic consensus protocol to estimate the average voltage across the MG and accordingly regulates the average voltage of the system on the rated value. Moreover, its reactive power regulator, dynamically fine-tunes the droop coefficients, adjusting the voltage setpoints to handle the proportional reactive power sharing considering transmission line impedances. We also studied the mathematical analysis of the consensus-based methodology for all the control modules. The proposed protocols support all feature of distributed control, e.g., communication link failure resiliency, plug-and-play capability, and DG failure. For this control approach, a sparse network of communication links is needed across the system to facilitate data exchange; i.e. each MG source requires information exchange with only a few other sources, those in direct contact through the communication infrastructure.

To address the challenge mentioned before about fixed droop coefficient, this thesis proposes an adaptive droop method for the primary level of dc MGs which determines droop coefficients according to the state-of-charge (SOC) of batteries automatically. This method does not require communication; it is based on local information of batteries. In addition, we develop a small signal model to investigate effects of the proposed method parameters, the control parameters, and constant power loads. The presented model is expanded then for multiple dc MG clusters, where effects of line impedances between the MGs on stability of these systems can be studied.

Finally, a consensus-based distributed secondary control framework is introduced to ensure smooth connection and reliable operation of dc MG clusters. The proposed framework includes two control modules; voltage regulator and power flow regulator. The voltage regulator eliminates the average voltage deviation over the MGs which allows the power flow control between the MGs to be achieved at the same time. The distributed power flow policy regulates the power flow among the MGs according to their local SOCs. In the proposed approach, the controllers on each MG needs to communicate with only the neighbor MGs through a spars communication infrastructure.

1.5 Thesis Objectives

The research objective of this thesis are the following:

- To review previous secondary control methods applied to MGs. To study centralized secondary control, and investigate its limitations.
- To study different distributed control strategies for possible implementation on secondary control of both ac and dc Microgrids,
- To develop three different distributed control strategies for secondary control; (i) normal averaging method, (ii) gossip-based algorithms, (iii) consensus-based algorithms, based on the availability and exchange of information between different units.
- To develop distributed control policies for secondary control of droop-controlled ac MGs. The proposed control methodologies will be able to regulate voltage of the system properly while maintaining the power sharing

properties of droop control even at the presence of line impedances and different control parameters.

- To analyses the proposed consensus-based control methodology mathematically for both steady state and transient response of the sytem.
- To develop an SOC-based adaptive droop control method for sharing load power in dc Microgrids.
- To develop small-signal stability model for dc Microgrids in order to study impact of different parameters of the system on the stability. To study effect of line impedances between dc MG clusters on the stability of the system.
- To develop distributed voltage controller to regulate voltage in dc MGs and dc MG clusters. To establish a cooperative algorithm for regulating power flow between dc MGs in a cluster.

Performance of proposed control methodologies will be realized by means of simulation and experimental verification. Simulation studies was considered for verification of proposed control strategies for dc MGs, where dc voltage of 48 V was chosen for all the simulations. However, all the proposed control strategies for ac MGs was verified using experimental setups in Green Power Lab (GPL) and Intelligent Microgrid Laboratory (IMGL) at Department of Energy Technology, Aalborg University. Rated voltage and frequency of the ac MG system was selected 230 V and 50 Hz.

1.6 Thesis Outline

This thesis is organized in ten chapters and one appendix, as follows:

Chapter 2 presents the first paper, published in IEEE Transactions on Power Electronic. This paper demonstrates application of the first proposed distributed approach, normal averaging method, for secondary voltage and frequency control of ac MGs as well as reactive power sharing. Details of centralized secondary control and its advantages/disadvantages is presented in the paper. The operation of proposed approach is verified through on-site experimental results. The performance of proposed strategy in response to large disturbances as well as communication impairments, e.g., delay and packet loss, is assessed and compared with the centralized secondary control.

Chapter 3 presents the second paper, published in IEEE Transactions on Industrial Electronics. This paper introduces the distributed gossip-based algorithm and studies its application for secondary control of ac MGs. Similar to the first paper, three control modules are proposed to achieve frequency, voltage and reactive power regulation. Real-time simulation and experimental studies are both presented in order to evaluate the feasibility and robustness endowed by the proposed algorithm.

Chapters 4 presents a conference paper which introduces the distributed consensus-based control frameworks for droop-controlled ac MGs. This paper presents two separate distributed control modules. The paper introduces a voltage regulator that maintains the average voltage of the system on the rated value, keeping all bus voltages within an acceptable range. Moreover, a reactive power regulator is introduced in this paper that dynamically fine-tunes the droop coefficients to handle the proportional reactive power sharing. Simulation studies are used to verify the proposed control methodology, where different test scenarios such as load change, link failure, DG outage are carried out. In the Journal version of paper, mathematical analysis will be done for all the modules separately, and experimental studies are performed to verify the effectiveness of proposed control methodology.

Chapter 5 presents the work proposed in a conference paper. The paper develops small signal model for dc MGs and dc MG clusters. Impact of different parameters on the stability of these systems are investigated. Then, an active-damping method which is a feed-forward compensation loop, is proposed to stabilize dc MG clusters when they are connected. The paper is concluded with verification of simulation results.

Chapter 6 presents the third Journal paper, accepted to be published in IEEE Transactions on Energy Conversion. This papers proposes a distributed hierarchical control framework to ensure reliable operation of dc MG clusters. An adaptive droop method is proposed for the primary level which determines droop coefficients according to SOC of batteries automatically. Distributed consensus-based policies are then introduced to regulate dc voltage among the MGs and to manage the power flow between the MGs. In order to analyse the system stability and also to tune the proposed control control parameters, a small signal model developed in Chapter 5 is expanded for interconnected dc MGs including all the control loops. The effectiveness of proposed hierarchical scheme is verified through detailed hardware-in-the-loop (HIL) simulations.

Chapter 7 discusses conclusions of the thesis, summarizes its contributions, and recommends directions for future works.

2

Paper 1

Distributed Secondary Control for Islanded Microgrids – A Novel Approach

Q. Shafiee, J. M. Guerrero, and J. C. Vasquez

The paper has been published in
IEEE Transactions on Power Electronics, Vol. 29, no. 2, pp. 1018–1031, Feb. 2014.

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Paper 2

Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids

Q. Shafiee, C. Stefanovic, T. Dragicevic, P. Popovski, J. C. Vasquez, and J. M. Guerrero

The paper has been published in
IEEE Transactions on Industrial Electronics, Vol. 61, no. 10, pp. 5363–5374, Oct. 2014.

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Paper 3

Team-oriented Adaptive Droop Control for Autonomous AC Microgrids

Q. Shafiee, V. Nasirian, J. M. Guerrero, F. L. Lewis, and A. Davoudi

The paper has been published in
Proceeding of 40th Annual Conference of IEEE Industrial Electronics Society (IECON14), 2014.

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Paper 4

Modeling, Stability Analysis and Active Stabilization of Multiple DC-Microgrid Clusters

Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero

The paper has been published in
Proceeding of IEEE International Energy Conference (EnergyCon14), pp. 1284–1290, May 2014.

6

Paper 5

Hierarchical control for multiple DC-microgrids clusters

Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero

The paper will be published in
IEEE Transactions on Energy Conversion, 2014.

7

Concluding remarks

In this final chapter, the key findings of the thesis are presented and arising conclusions are summarized. Then, the novelties of the methods that have been developed are highlighted by comparison of their respective features with existing approaches, showing the actual scientific contributions. Finally, some possibilities of the future research framework that may arise from the one carried out within this thesis is suggested.

7.1 Summary

This thesis proposes distributed control strategies for secondary control of islanded ac and dc Microgrids to improve their reliability and expandability. The multi-functional distributed secondary controllers were developed for frequency and voltage regulation, proportional load power sharing of islanded ac MGs, as well as for voltage and power flow regulation of dc MG clusters.

The first distributed approach, normal averaging, and its specific operational requirements for autonomous ac MGs was carried out in chapter 2 where the first published paper has been presented. The operation of proposed approach was tested through on-site experimental results. The performance of proposed strategy in response to large disturbances as well as communication impairments, e.g., delay and packet loss, was assessed and compared with the centralized secondary control. The results showed better performance of the proposed distributed approach in comparison to the central one. Nevertheless, the proposed distributed policy has some drawbacks: (i) although the secondary controllers are embedded locally, all sources must communicate with all other sources in order to calculate the average of information, and hence the method still requires complicated communication. While this is potentially feasible in parallel operation, in more general MG scenarios it is likely impractical. (ii) the gains of the frequency controller must be finely tuned in order to maintain active power sharing provided by droop control. (iii) The gains of distributed reactive power regulators must be also the same in order to have proportional reactive power sharing. In addition, transmission line impedance has not been considered while regulating reactive power.

The gossip-based distributed approach was introduced in Chapter 3 where the second published paper has been presented. Similar to the first approach presented in chapter 2, the application of this distributed method for secondary control of ac MGs was studied. The proposed methodology consists of three control modules, i.e. frequency regulation, voltage regulation, and reactive power regulation. Real-time simulation and experimental studies were both presented in order to evaluate the performance of the proposed algorithm. The results indicated robustness and effectiveness of the proposed distributed algorithm even at the presence of communication impairments. As gossip-based distributed algorithms are asynchronous, the proposed scheme requires synchronization and transmission scheduling among MG sources, which can be also established using gossip algorithms and could be executed in the initial, set-up phase of the network. Nevertheless, distributed synchronization and scheduling should be re-established whenever the network topology changes, and the corresponding communication exchanges triggered by detection of such events.

Chapters 4 has been devoted to development of distributed consensus-based protocols and its application for secondary control of ac MGs. The proposed consensus-based methodology has addressed all the challenges in the first and second methods and does not have any of the mentioned problems. It consists of two parts in general, namely, voltage regulator, and reactive power regulator. The proposed control framework provides all that operational requirements even when the gains of controllers are not the same and the transmission line impedance is not neglected. For the purpose of validation of newly developed control methodology, simulation results for an islanded MG test includes four VSC-based sources were performed. The reported results have shown excellent behaviour in terms of distributed control features, e.g. disturbance rejection, plug-and-play, communication link failure, inverter failure. To sum up, the proposed methodologies using consensus-based, in comparison to the previous two distributed policies, are fully distributed meaning that each MG source requires to exchange information with only its direct neighbours through a sparse communication network. Mathematical analysis for both steady state and transient response of the methodology and also experimental studies have been presented in the journal version of the work.

The small signal model was developed for dc MGs and dc MG clusters from the control point of view in Chapter 5. The model was utilized to assess the stability of these systems, taking into account the system parameters, constant power loads (CPLs) as well as line impedances between the MGs. The results showed that negative impedance of CPLs have negative impact on damping and stability of the system. In addition, when connecting dc MGs if the line inductance becomes bigger and the line resistance gets smaller than some special values, the system moves toward unstable region. Moreover, the active-damping method which is a feed-forward compensation loop, was proposed to stabilize dc MG clusters when they are connected. Drawback of this compensation loop is that it requires fast digital communication to receive the disturbance currents.

The consensus-based distributed hierarchical control was introduced for dc MG clusters in Chapter 6, to ensure smooth connection and reliable operation of these systems. To determine droop coefficients according to batteries parameters adaptively rather than power rate of converters, the decentralized adaptive droop method was proposed. The small signal model developed in Chapter 6 was an important asset for proper design of adaptive droop functions. Distributed consensus-based policies were then introduced to regulate dc voltage among the MGs and to manage the power flow between the MGs. The methodology is fully distributed, i.e. a spars communication infrastructure is only required and it provides all aforementioned features of distributed control. Finally, the developed small signal model was expanded for MG clusters with all the proposed control loops. The effectiveness of proposed hierarchical scheme was verified through detailed hardware-in-the-loop (HIL) simulations.

All the proposed control strategies and studies were performed in Matlab Simulink® environment and dSPACE® 1103/1006 which is a real time platform used as an interface between the electrical part and control part.

7.2 Contributions

The concrete contributions that arose from the work performed within this PhD research can be brought out as follows:

- Development of three different distributed control strategies for secondary control of MGs, and enhancement of reliability of these systems by eliminating central controllers.
- Development of fully distributed dynamic consensus protocol and cooperative algorithm for voltage regulation and proportional reactive power sharing which is operational at the presence of line impedances and different control parameters. The fundamental principles of proposed strategy is presented in Chapter 4.
- Development of small signal model for assessing stability analysis and tuning control parameters of dc MGs and dc MG clusters. Moreover, the adaptive, SOC based, droop method has been proposed in order to accommodate the parallel operation of multiple paralleled battery in MGs stacks in both charging and discharging conditions. The adaptive droop method was elaborated in Chapter 6. The developed model was presented in Chapter 5 but also used in Chapter 6.
- Development of the cooperative consensus-based algorithm and and the dynamic consensus protocol for secondary control of dc MG clusters that is able to not only control the voltage within acceptable range across the MGs but also regulates power flow between them. This contribution is accomplished in Chapter 6.

7.3 Future Work

This dissertation proposes novel strategies and introduces new concepts. The results from this thesis may be used as a groundwork for several future research directions at both a scientific and industrial level:

- Distributed control for power quality enhancement: As already mentioned in the introduction part of the thesis, power quality enhancement is an optional function that has been recently defined for secondary control of MGs. This thesis was focused on the main functions of secondary control, i.e. frequency and voltage regulation, and also proportional load power sharing. Therefore, application of distributed control protocols for power quality issues is still open to research.
- Grid connection of MGs - This aspect has not been studied in this thesis as the focus was on distributed control of the MG sources in autonomous mode. However, in a future scenario where MGs will be connected to the main grid for participation in grid support services, the power exchange between the bulk grid and MG may lead up to new control priorities. Thus, distributed control strategies could be a proper alternative.
- Hierarchical control of multiple ac MG clusters: This thesis proposed distributed hierarchical control for dc MG clusters. However, similar concepts can be also used for ac MGs but considering total power rate of MGs for power flow regulation among them.
- Nonlinear control strategies for secondary control: As some of the robust nonlinear controllers already showed superior performance in comparison with their linear counterparts, realization of PI controllers in secondary control using nonlinear controllers may give a promising research direction.
- Application of proposed distributed protocols for the other systems: New concepts such as HEV charging stations has been already researched for frequency supports. These systems could be a good application for distributed control algorithms to participate not only in the frequency supports but also in voltage regulation.

Bibliography

[1] R. Lasseter, “Microgrids,” in *Proc. IEEE Power Eng. Soc. Meeting*, vol. 1, pp. 305–308, 2002.

[2] J. A. Peas Lopes, C. L. Moreira, and A. G. Madureira, “Defining control strategies for microgrids islanded operation,” *IEEE Trans. Power Syst.*, vol. 21, pp. 916–924, May 2006.

[3] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, “Microgrids,” *IEEE Power Energy Mag.*, vol. 5, pp. 78–94, July 2007.

[4] F. Katiraei, M. R. Iravani, and P. W. Lehn, “Micro-grid autonomous operation during and subsequent to islanding process,” *IEEE Trans. Power Del.*, vol. 20, pp. 248–257, Jan 2005.

[5] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, “Hierarchical control of droop-controlled ac and dc microgrids –a general approach toward standardization,” *IEEE Trans. Ind. Electron.*, vol. 58, pp. 158–172, Jan 2011.

[6] J. M. Guerrero, M. Chandorkar, T. Lee, and P. C. Loh, “Advanced control architectures for intelligent microgrids; part I: Decentralized and hierarchical control,” *IEEE Trans. Ind. Electron.*, vol. 60, pp. 1254–1262, April 2013.

[7] “Ieee standard for interconnecting distributed resources with electric power system,” *IEEE Std 1547-2003*, pp. 1–28, 2003.

[8] H. Kakigano, Y. Miura, and T. Ise, “Low-voltage bipolar-type dc microgrid for super high quality distribution,” *IEEE Trans. Power Electron.*, vol. 25, pp. 3066–3075, Dec 2010.

[9] A. Kwasinski, “Quantitative evaluation of dc microgrids availability: Effects of system architecture and converter topology design choices,” *IEEE Trans. Power Electron.*, vol. 26, pp. 835–851, March 2011.

[10] R. S. Balog and P. T. Krein, “Bus selection in multibus dc microgrids,” *IEEE Trans. Power Electron.*, vol. 26, pp. 860–867, March 2011.

[11] D. Salomonsson, L. Soder, and A. Sannino, “Protection of low-voltage dc microgrids,” *IEEE Trans. Power Del.*, vol. 24, pp. 1045–1053, July 2009.

[12] X. Liu, P. Wang, and P. C. Loh, “A hybrid ac/dc microgrid and its coordination control,” *IEEE Trans. Smart Grid*, vol. 2, pp. 278–286, June 2011.

[13] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with ac and dc subgrids,” *IEEE Trans. Power Electron.*, vol. 28, pp. 2214–2223, May 2013.

[14] X. Lu, J. M. Guerrero, K. Sun, J. C. Vasquez, R. Teodorescu, and L. Huang, “Hierarchical control of parallel ac-dc converter interfaces for hybrid microgrids,” *IEEE Trans. Smart Grid*, vol. 5, pp. 683–692, March 2014.

[15] Y. W. Li and C.-N. Kao, “An accurate power control strategy for power electronics interfaced distributed generation units operating in a low-voltage multibus microgrid,” *IEEE Trans. Power Electron.*, vol. 24, pp. 2977–2988, Dec 2009.

[16] J. J. J., F. Mwasilu, J. Lee, and J.-W. Jung, “Ac-microgrids versus dc-microgrids with distributed energy resources: A review,” *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 387 – 405, 2013.

[17] M. H. Rashid, *Power electronics handbook: devices ,circuits, and applications.* 2011.

[18] T. Dragicevic, J. M. Guerrero, and J. C. Vasquez, “A distributed control strategy for coordination of an autonomous LVDC microgrid based on power-line signaling,” *IEEE Trans. Ind. Electron.*, vol. 61, pp. 3313–3326, July 2014.

[19] S. Anand, B. G. Fernandes, and M. Guerrero, “Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage dc microgrids,” *IEEE Trans. Power Electron.*, vol. 28, pp. 1900–1913, April 2013.

[20] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, “An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy,” *IEEE Trans. Power Electron.*, vol. 29, pp. 1800–1812, April 2014.

[21] T. Dragicevic, J. M. Guerrero, J. C. Vasquez, and D. Skrlec, “Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability,” *IEEE Trans. Power Electron.*, vol. 29, pp. 695–706, Feb 2014.

[22] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang, “State-of-charge balance using adaptive droop control for distributed energy storage systems in dc microgrid applications,” *IEEE Trans. Ind. Electron.*, vol. 61, pp. 2804–2815, June 2014.

[23] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Trans. Industrial Electron.*, vol. 53, pp. 1398–1409, Oct 2006.

[24] J. C. Vasquez, J. M. Guerrero, M. Savaghebi, J. Eloy-Garcia, and R. Teodorescu, "Modeling, analysis, and design of stationary-reference-frame droop-controlled parallel three-phase voltage source inverters," *IEEE Trans. Ind. Electron.*, vol. 60, pp. 1271–1280, April 2013.

[25] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power Energy Mag.*, vol. 6, pp. 54–65, May 2008.

[26] A. Tsikalakis and N. Hatziargyriou, "Centralized control for optimizing microgrids operation," *IEEE Trans. Energy Convers.*, vol. 23, pp. 241–248, March 2008.

[27] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. C. Green, "Energy management in autonomous microgrid using stability-constrained droop control of inverters," *IEEE Trans. Power Electron.*, vol. 23, pp. 2346–2352, Sept 2008.

[28] J. Lagorse, M. G. Simoes, and A. Miraoui, "A multiagent fuzzy-logic-based energy management of hybrid systems," *IEEE Trans. Ind. Appl.*, vol. 45, pp. 2123–2129, Nov 2009.

[29] A. Mohd, E. Ortjohann, D. Morton, and O. Omari, "Review of control techniques for inverters parallel operation," *Electric Power Systems Research*, vol. 80, no. 12, pp. 1477 – 1487, 2010.

[30] S. Dasgupta, S. Mohan, S. Sahoo, and S. Panda, "A plug and play operational approach for implementation of an autonomous-micro-grid system," *IEEE Trans. Ind. Inf.*, vol. 8, pp. 615–629, Aug 2012.

[31] E. Serban and H. Serban, "A control strategy for a distributed power generation microgrid application with voltage- and current-controlled source converter," *IEEE Trans. Power Electron.*, vol. 25, pp. 2981–2992, Dec 2010.

[32] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Convers.*, vol. 22, pp. 439–449, June 2007.

[33] T. David Linden, *Handbook of Batteries*. McGraw Hill, 2002.

[34] M. C. Chandorkar, D. M. Divan, and R. Adapa, "Control of parallel connected inverters in standalone ac supply systems," *IEEE Trans. Ind. Appl.*, vol. 29, pp. 136–143, Jan 1993.

[35] J. M. Guerrero, J. Matas, L. G. de Vicuna, M. Castilla, and J. Miret, "Wireless-control strategy for parallel operation of distributed-generation inverters," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1461–1470, Oct 2006.

[36] J. M. Guerrero, J. C. Vasquez, J. Matas, M. Castilla, and L. G. de Vicuna, "Control strategy for flexible microgrid based on parallel line-interactive ups systems," *IEEE Trans. Ind. Electron.*, vol. 56, pp. 726–736, March 2009.

[37] J. Guerrero, L. Garcia de Vicuna, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected ups inverters with wireless load-sharing control," *IEEE Trans. Ind. Electron.*, vol. 52, pp. 1126–1135, Aug 2005.

[38] J. . M. Guerrero, J. Matas, L. G. de Vicuna, M. Castilla, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 994–1004, April 2007.

[39] A. Micallef, M. Apap, C. Spiteri-Staines, and J. M. Guerrero, "Secondary control for reactive power sharing in droop-controlled islanded microgrids," in *IEEE Intern. Symp. Ind. Electron. (ISIE)*, pp. 1627–1633, May 2012.

[40] A. Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero, and J. C. Vasquez, "Reactive power sharing and voltage harmonic distortion compensation of droop controlled single phase islanded microgrids," *IEEE Trans. Smart Grid*, vol. 5, pp. 1149–1158, May 2014.

[41] A. Mehrizi-Sani and R. Iravani, "Potential-function based control of a microgrid in islanded and grid-connected modes," *IEEE Trans. Power Syst.*, vol. 25, pp. 1883–1891, Nov 2010.

[42] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, and L. de VicuÃśa, "Hierarchical control of intelligent microgrids," *IEEE Ind. Electron. Mag.*, vol. 4, pp. 23–29, Dec 2010.

[43] Y. Xu and W. Liu, "Novel multiagent based load restoration algorithm for microgrids," *IEEE Trans. Smart Grid*, vol. 2, pp. 152–161, March 2011.

[44] W. Liu, W. Gu, W. Sheng, X. Meng, Z. Wu, and W. Chen, "Decentralized multi-agent system-based cooperative frequency control for autonomous microgrids with communication constraints," *EEE Trans. Sustain. Energy*, vol. 5, pp. 446–456, April 2014.

[45] H. Liang, B. J. Choi, W. Zhuang, X. Shen, A. S. A. Awad, and A. Abdr, "Multiagent coordination in microgrids via wireless networks," *IEEE Wireless Commun.*, vol. 19, pp. 14–22, June 2012.

[46] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Trans. Autom. Control*, vol. 49, pp. 1520–1533, Sept 2004.

[47] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," *Proceedings of the IEEE*, vol. 95, pp. 215–233, Jan 2007.

[48] T. C. Aysal, M. E. Yildiz, A. D. Sarwate, and A. Scaglione, "Broadcast gossip algorithms for consensus," *IEEE Trans. Signal Process.*, vol. 57, pp. 2748–2761, July 2009.

[49] C. Cho, J.-H. Jeon, J.-Y. Kim, S. Kwon, K. Park, and S. Kim, "Active synchronizing control of a microgrid," *IEEE Trans. Power Electron.*, vol. 26, pp. 3707–3719, Dec 2011.

[50] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Secondary control scheme for voltage unbalance compensation in an islanded droop-controlled microgrid," *IEEE Trans. Smart Grid*, vol. 3, pp. 797–807, June 2012.

[51] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Secondary control for voltage quality enhancement in microgrids," *IEEE Trans. Smart Grid*, vol. 3, pp. 1893–1902, Dec 2012.

[52] H. Bevrani, *Robust Power System Frequency Control.* 2009.

[53] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans. Smart Grid*, vol. 3, pp. 1963–1976, Dec 2012.

[54] A. Bidram, A. Davoudi, F. L. Lewis, and J. M. Guerrero, "Distributed cooperative secondary control of microgrids using feedback linearization," *IEEE Trans. Power Syst.*, vol. 28, pp. 3462–3470, Aug 2013.

[55] A. Bidram, A. Davoudi, F. L. Lewis, and Z. Qu, "Secondary control of microgrids based on distributed cooperative control of multi-agent systems," *IET Gener. Transm. Distrib.*, vol. 7, pp. 822–831, Aug 2013.

[56] J. W. Simpson-Porco, F. Dorfler, and F. Bullo, "Synchronization and power sharing for droop-controlled inverters in islanded microgrids," *Automatica*, vol. 49, no. 9, pp. 2603 – 2611, 2013.

[57] N. J. B. P. Kundur and M. G. Lauby, *Power system stability and control.* 1994.

[58] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed ac power systems with consideration of line impedance effect," *IEEE Trans. Ind. Appl*, vol. 36, pp. 131–138, Jan 2000.

[59] E. Coelho, P. Cortizo, and P. Garcia, "Small-signal stability for parallel-connected inverters in stand-alone ac supply systems," *IEEE Trans. Ind. Appl*, vol. 38, pp. 533–542, Mar 2002.

[60] J. Guerrero, L. Garcia de Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. Power Electron.*, vol. 19, pp. 1205–1213, Sept 2004.

[61] H. Liang, B. J. Choi, W. Zhuang, and X. Shen, "Stability enhancement of decentralized inverter control through wireless communications in microgrids," *IEEE Trans. Smart Grid*, vol. 4, pp. 321–331, March 2013.

[62] Q.-C. Zhong, "Robust droop controller for accurate proportional load sharing among inverters operated in parallel," *IEEE Trans. Ind. Electron.*, vol. 60, pp. 1281–1290, April 2013.

[63] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez, and R. Teodorescu, "Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes," *IEEE Trans. Ind. Electron.*, vol. 56, pp. 4088–4096, Oct 2009.

[64] H. Bevrani and S. Shokoohi, "An intelligent droop control for simultaneous voltage and frequency regulation in islanded microgrids," *IEEE Trans. Smart Grid*, vol. 4, pp. 1505–1513, Sept 2013.

[65] N. R. Chaudhuri and B. Chaudhuri, "Adaptive droop control for effective power sharing in multi-terminal dc (MTDC) grids," *IEEE Trans. Power Syst.*, vol. 28, pp. 21–29, Feb 2013.

[66] V. Nasirian, A. Davoudi, and F. L. Lewis, "Distributed adaptive droop control for dc microgrids," in *Proc. 29th IEEE Appl. Power Electron. Conf. Expo. (APEC)*, pp. 1147–1152, March 2014.

[67] C. T. Lee, C. C. Chu, and P. T. Cheng, "A new droop control method for the autonomous operation of distributed energy resource interface converters," *IEEE Trans. Power Electron.*, vol. 28, pp. 1980–1993, April 2013.

[68] V. Nasirian, S. Moayedi, A. Davoudi, and F. L. Lewis, "Distributed cooperative control of dc microgrids," 2014.

[69] H. Bouattour, J. W. Simpson-Porco, F. Dorfler, and F. Bullo, "Further results on distributed secondary control in microgrids," in *IEEE 52nd Ann. Conf. Decision and Cont. (CDC)*, pp. 1514–1519, Dec 2013.

[70] J. W. Simpson-Porco, F. Dorfler, F. Bullo, Q. Shafiee, and J. M. Guerrero, "Stability, power sharing, amp; distributed secondary control in droop-controlled microgrids," in *IEEE Intern. Conf. Smart Grid Commun. (SmartGridComm)*, pp. 672–677, Oct 2013.

[71] A. Bidram, A. Davoudi, and F. Lewis, "A multi-objective distributed control framework for islanded ac microgrids," 2014.

[72] D. Shah, *Gossip Algorithms, Foundations and Trends in Networking*. 2009.