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DOI (link to publication from Publisher):
10.5278/vbn.phd.tech.00026

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Angjelichinoski, M. (2017). *Advanced Bus Signaling Methods for DC MicroGrids*. Aalborg Universitetsforlag. https://doi.org/10.5278/vbn.phd.tech.00026

ADVANCED BUS SIGNALING METHODS FOR DC MICROGRIDS

BY
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DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

Advanced Bus Signaling Methods for DC MicroGrids

Ph.D. Dissertation
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Dissertation submitted: October 2017

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PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Electronic Systems

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-081-4

Published by:
Aalborg University Press
Skjernvej 4A, 2nd floor
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2017

Curriculum Vitae

Marko Angjelichinoski

Marko Angjelichinoski received the Dipl.-Ing. and M.Sc. degrees in telecommunications from the Saints Cyril and Methodius University in Skopje, Macedonia, in 2011 and 2014, respectively. From 2011 to 2014, he was appointed as a Research Assistant and member of the Wireless Networking Group with the Faculty of Electrical Engineering and Information Technologies. He is currently a Ph.D. Fellow at Aalborg University, Denmark. His research interests are in the areas of statistical signal processing, estimation, detection and information theory with applications in next generation systems, such as cognitive radio networks, and smart grid systems.

Abstract

This thesis introduces a novel bus signaling technique for communication over the powerlines among decentralized control agents in direct current MicroGrids. The solution is termed power talk and it proposes each controller to modulate the messages, that need to be exchanged with other controllers, into the parameters of the local droop control loop. This will lead to subtle deviations of the steady state bus voltages from which remote controllers across the MicroGrid can demodulate the desired information. In contrast, the traditional networked control approach assume that the controllers are equipped with dedicated communication hardware and the control messages are exchanged over external communication links; the motivation for developing power talk lies in the recent concerns about the adequacy of the traditional design paradigm to the evolving smart grid ecosystem. In this context, power talk is envisioned to serve as a solution that offers several inherent advantages compared to external communication systems in terms of the service requirements, cost and security. The concept also promotes the self-sustainability principle of distributed power systems since it does not require any additional hardware and can be implemented via software upgrades of the power electronic interfaces where the control loops reside.

Power talk can be formally seen as an explicit communication technique over an implicit communication channel, represented by the steady state of the MicroGrid. The general communication problem is a non-standard one and imposes several unique challenges, not encountered frequently in common communication setups. In light of this, the contributions of the thesis can be divided into two categories. First, the thesis presents a set of concepts, techniques and practical solutions for designing reliable power talk interfaces and communication protocols in challenging circumstances. Afterward, the focus shifts on applying power talk for common control applications such as monitoring, optimization and cyber-secure control. The results from the performance evaluations indicate that power talk is indeed a promising solution for autonomous, self-sustainable direct current MicroGrids.

Resumé

Denne Ph.d. afhandling introducerer en ny bussignaleringsteknik for kommunikation over strømledningsnet mellem decentrale kontrolapparater i jævnstrømsmikroledningsnet. Løsningen er navngivet *power talk*, der foreslår at kontrolapparaterne modulerer beskederne, der skal udveksles med andre kontrolapparater, ind i parametrene af den lokale droop-kontrolløkke. Dette vil føre til småafvigelser i busspændingerne i ligevægtstilstand, hvorfra fjerntliggende kontrolapparater overalt i mikroledningsnettet kan demodulere den ønskede information. Til sammenligning antager den traditionelle netværkskontrolmetode at kontrolapparaterne er udstyret med dedikeret kommunikationshardware, og at kontrolbeskederne er udvekslet over eksterne kommunikationslinks; motivationen for at udvikle power talk ligger i de nylige bekymringer omkring tilstrækkeligheden af de traditionelle designparadigmer til udviklende smart grid økosystemer. I den forbindelse forestilles power talk at være en løsning, der bringer flere fordele sammenlignet med eksterne kommunikationssystemer i forhold til servicekrav, pris og sikkerhed. Konceptet fremmer ogsåselvbæredygtighedsprincippet i distribuerede elnet, eftersom det ikke kræver yderligere hardware og kan implementeres gennem softwareopgraderinger af de grænseflader til ledningsnettet, hvor kontrolløkkerne er installeret.

Power talk kan formelt ses som en eksplicit kommunikationsteknik over en implicit kommunikationskanal, der er repræsenteret af ligevægtstilstanden i mikroledningsnettet. Det generelle kommunikationsproblem er et ikke-standard problem og pålægger flere unikke udfordringer, der ikke typisk findes i kommunikationsopsætninger. I lyset af dette, kan bidragene i denne afhandling deles op i to kategorier. Først præsenterer afhandlingen en række koncepter, teknikker og praktiske løsninger til at designe pålidelige power talk grænseflader og kommunikationsprotokoller under udfordrende omstændigheder. Dernæst skifter fokusset til anvendelse af power talk til almene kontrolapplikationer såsom monitorering, optimering og cybersikker kontrol. Resultaterne fra ydelsesevalueringerne indikerer, at power talk ganske vist er en lovende løsning til autonome, selvbæredygtige jævnstrømsmikroledningsnet.

Contents

Preface

I like challenges. The idea of exploring a research topic that is quite remote from anything I've done before is what convinced me, a wireless communication engineer with slight affinity to statistical signal processing, to do a PhD in MicroGrids, even though in August 2014 I had only vague notion of what they are. Besides this, there is also a principle, a belief to which I commit myself regularly. This is the belief that no matter what you begin with, hard work can bring you so much more. And this is precisely how I feel now. So far the journey has been nothing short of amazing.

There are several people without whom this would have not been possible. First and foremost, my supervisor Petar. Words cannot express the gratitude I feel for everything you did for me, since our first meeting (i.e., interview) at café Aquarius in Ohrid. The mentoring, the talks, the advices, the opportunity to observe you visionary brain at works - all of that has had a defining impact on me both professionally and personally. Then, there is Čeda, the co-supervisor who is always there to help you break the wall when you get stuck in dead-end, and who reminds you that the best you can is yet to come, maybe even with the next draft iteration. Čedo, my friend, on several occasions you also helped me go though the dimmed corridors of the journey and that's something that I'll never forget.

Special acknowledgment goes to Charlotte, our section administrator. Her professional assistance and kindness was key for my seamless transition to Denmark and the overcoming of few stumbling blocks.

I would also like to thank the people that I collaborated with during the PhD study. First, Frede, who's openness to new ideas gave power talk the vital spark it needed at the beginning. Then, there is Anna, whose lab I visited in spring 2016. Her all-encompassing technical knowledge helped me find new ways of thinking about my research. Of course, my office mate Pietro; together we brought Petar's idea about software-defined MicroGrid into being. Finally, I extend my gratitude to everyone who was part of my narrative in these past three years, all my colleagues, friends and acquittance. Without them I doubt I would have been able to come to this point.

At the end, I would like to dedicate this thesis to my family in Macedonia. My mom, my dad, my brother, my sister, my brother-in-law and my three beautiful nephews Ružica, Haralampie and Jovan. The people that always manage to lift my sails up even when the winds seem to have stopped blowing. The people that I love unconditionally.

To all those mentioned above, thank you.

Marko
Aalborg University, October 5, 2017

Part I

Overture

Chapter 1

Introduction

The existing power grid is designed as a centrally controlled system that produces electrical energy in large, remote power plants and delivers it to the consumers using unidirectional flow, offering little flexibility for seamless adaptation to evolving trends. The concept of Smart Grid (SG) is envisioned as the 21st century enhancement of the 20th century power grid. The SG uses two-way flow of electricity and information, relying on modern communication/computation technologies to create a widely distributed and automated energy delivery network that is capable of generating, delivering, storing and utilizing electric power more efficiently while dynamically adapting to the changes in the grid [1].

One of the key elements in SG is the concept of a MicroGrid (MG) which emerged as a result of the high penetration of small-scale Distributed Energy Resources (DERs). MGs are defined as localized clusters of DERs and loads connected in parallel to common MG bus(es) through programmable Power Electronic Converters (PECs) [2–5]. The MG can operate either in grid-connected or standalone mode, in autonomous manner. In either case, the MG itself is responsible for the control and management of its internal resources and it appears to the rest of the power grid as a single, controllable entity with capability to operate autonomously when needed. Direct current (DC) MGs have attracted particular attention in residential areas due to the absence of reactive power and the seamless integration with renewable generation, energy storage systems and emerging smart loads, most of which are DC in nature [4, 5]. Due to the growing hype, the focus of the thesis is on DC MGs.

The control system is of crucial importance for proper operation of the MG [2, 4]. The traditional design approach of the control architecture in power grids, thereby also in MGs, is within the Networked Control Systems (NCS) framework where the feedback control loop is closed by a separate, external communication system [2, 4, 6, 7]. However, in recent years there is a growing concern about the adequacy of this design approach in the evolving SG ecosystem that is becoming significantly more dynamic, sporadic and unpredictable especially in the distribution part of the grid [4–6, 8–12]. The arguments put a particular emphasis on the aspects of (i) limited availability/reliability/security of the external communication system in relation to the service requirements of the MG control applications, (ii) the installation and operational costs of the external communication system and (iii) the violation of the self-sustainability principle promoted by distributed power systems.

The goal of this thesis is to present a novel powerline communication solution that addresses the problems of the traditional NCS design in DC MGs. The solution is termed *power talk* and operates as follows: instead of installing dedicated communication hardware on top of the existing MG equipment, the control messages are modulated into the local control loops of the PECs; this causes disturbances of the steady state bus voltages from which remote controllers can demodulate the necessary information. Evidently, power talk (i) draws from the reliability/availability/security of the MG itself, (ii) does not require any additional hardware but only upgrades of the existing software in the PECs i.e., it fosters the self-sustainability principle, and (iii) retains the networked nature of the control system.

The communication-theoretic setup of power talk is a non-standard one. In light of this, the first half of the technical content of the thesis revolves around designing reliable power talk physical interfaces and communication protocols under several challenging circumstances. The second half of the contributions is more focused on applying the developed techniques in several representative control applications, such as economic dispatch, system identification, state estimation and cyber-secure secondary control.

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Chapter 2

Background and Motivation

This chapter gives a condensed introduction to the state-of-the-art DC MG technology; many of the notions presented below will repeat later in part II in some form or another. In addition, the reader should be aware that the symbolic notation used here reflects the notational system used in the most recent papers and it might differ from the notation used in earlier works.

1 Physical Configuration of DC MGs

When referring to a DC MG, what we usually have in mind is a small, localized residential/industrial collection of DERs and loads interconnected between each other via low voltage network, consisting of buses and distribution lines, see Fig. 2.1 [1]. The DERs interface the buses and the distribution network through programmable PECs which are responsible for controlling the system via several algorithms operating in different frequency bands. The flexibility, modularity and adaptivity introduced by the PECs is the distinguishing characteristic of the DC MGs in comparison to the traditional power grid, and is usually considered as a paradigm shift in power systems design [1–4]. This section briefly reviews the MG components individually, except the PECs; more on PECs will follow in Section 2.

1.1 Components

Buses and Distribution Network

Fig. 2.2 depicts a diagram of general DC MG with multiple buses in steady state. The total number of buses is denoted with N. A bus (a.k.a. bus-bar) is a point in the MG characterized by real and non-negative DC voltage; all components connected to bus $n = 1, \ldots, N$ observe the same voltage v_n. Buses n

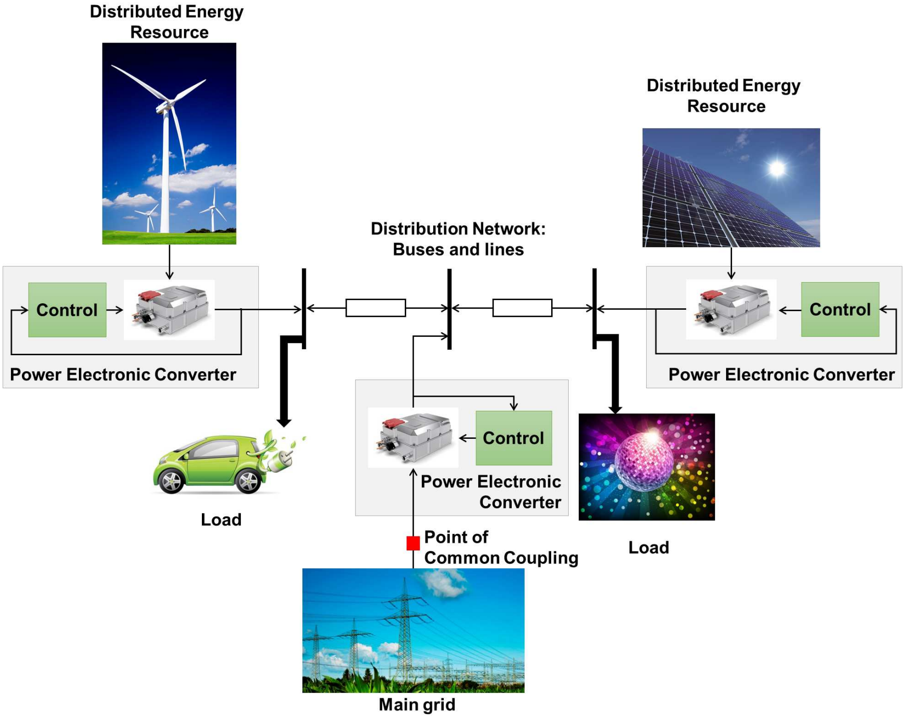

Fig. 2.1: An example of DC MG system.

and m are connected between each other via distribution lines, characterized by a non-negative resistance $r_{n,m}$, or, equivalently, non-negative admittance $y_{n,m} = r_{n,m}^{-1}$, $n, n = 1, \ldots, N$, forming the distribution network. Note that $y_{n,m} = 0$ in case buses n and m are not directly connected, or if $n = m$; also $y_{n,m} = \infty$ if buses n and m are the same physical point. The distribution network naturally induces a graph, characterized with $N \times N$ admittance matrix, denoted with $\mathbf{Y}$; the admittance matrix is convenient to work with due to its sparsity.

Distributed Energy Resources

The total number of buses is denoted with U; for generality, each bus is assumed to host $0 < U_n \leq U, n = 1, \ldots, N$ DERs supplying a common bus load. A DER can be (i) power source of renewable energy (RES) such as solar panels, wind turbines or hydro, (ii) small-scale distributed generator (DG) based on traditional fossil fuel, or (iii) energy storage (ES), i.e., battery, storage banks, flywheels and so on [1, 4]. The instantaneous output power of DER u connected to bus n is denoted by $p_u = i_u v_n$, $u = 1, \ldots, U$, $n = 1, \ldots, N$,

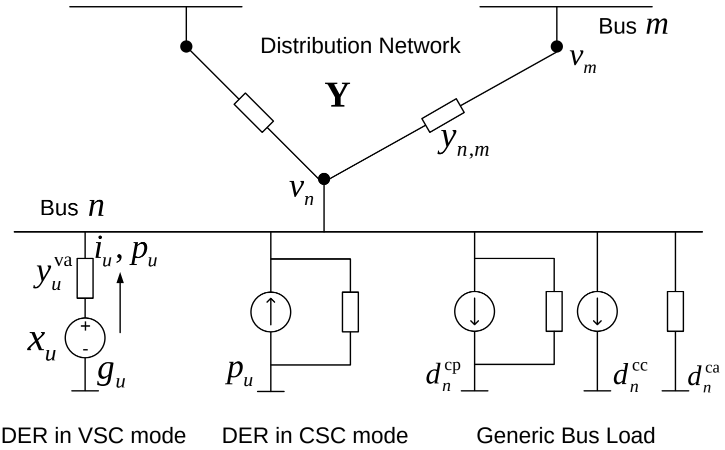

Fig. 2.2: General diagram of DC MG in steady state.

with i_u denoting the output current; the output power at any time should not violate the generation limits of the DER, i.e. $l_u \leq p_u \leq g_u$, where g_u is the upper generation limit, i.e., the generation capacity, which determines the maximum instantaneous rate at which the DER can inject energy in the system, and l_u is lower generation limit; the values of g_u and l_u depend on the DER type. For instance, RES or DG has non-negative generation capacity $g_u \geq 0$ with lower limit equal to zero $l_u = 0$ (unless coupled with a battery). ESs, on the other hand, also have a non-negative generation capacity $g_u \geq 0$ and negative lower limit $l_u \leq 0$. In this case, g_u determines the maximum instantaneous rate at which the ES can discharge; conversely, $|l_u|$ gives the maximum instantaneous charge rate. It is very important to note that the generation capacities of RESs and the charge/discharge rates of ESs vary over time and their instantaneous values are determined by endogenous influences, such as the load consumption, as well as exogenous influences, e.g., weather conditions [1, 4].

Loads

Each bus supplies a local load. A common way to model the load is via the so called ZIP model which represents the aggregate bus load as a mixture of three different electrical components [5]: (1) a component that has constant resistance/admittance, with rated power demand d_n^{ca}, (2) a component that consumes constant current with rated power demand d_n^{cc}, and (3) a component that consumes constant power with rated demand d_n^{cp}; the rated demands correspond to a rated voltage, denoted by x and they are specified by the manufacturer of the appliances; using the rated demands, the equivalent electrical parameters of the model, namely the constant resistance/admittance, current and power can be easily computed. It is important to note that constant power loads act as non-linear electrical components in DC environments [1]. In addition, constant power loads in steady state are modeled as current sources in parallel with negative resistance; due to the negative resistance, constant power loads are the main source of instability in DC MGs [1].

1.2 Architectures and Topologies

We briefly review several common classifications of DC MGs regarding the number of buses, the distribution network and access to the main grid [1, 2].

Multiple- and Single-Bus MG

The MG model described above is valid for any number of buses $N \geq 1$ and we refer to this general model as Multiple-Bus DC MG. The special case when $N = 1$, i.e., there is only one bus to which all DERs and loads are connected, is a special case commonly referred to as Single-Bus DC MG. In real world, the Single-Bus is useful when considering very small, localized MGs (a.k.a. NanoGrids) with only few DERs, serving a dedicated load and strongly connected distribution network [1]. In such system, the effect of the transmission lines on the power flow is virtually negligible and all components can be assumed to observe and measure the same voltage v. The model has been widely used to represent houses and small communities such as buildings and small neighborhoods. In this context, Multiple-Bus DC MGs can be thought of as systems that interconnect several Single-Bus DC MGs, covering large areas, such as urban and suburban neighborhoods, industrial complexes, rural areas and remote villages [1]. Due to its importance in the power engineering community, large portion of our earlier work focuses on Single-Bus DC MGs, whereas more recent findings focus on general Multiple-Bus systems.

Meshes, Rings and Cut-Rings

Chronologically, the MG concept emerged from uninterrupted power supply (UPS) systems used mainly in critical applications such as hospitals and industrial complexes [1, 2, 6]. UPS systems are characterized by a ring or cut-ring topology, where each DER/load is connected to, at most, two other components; in cut-rings, the ring is cut at some point, effectively forming a line. The admittance matrix of both rings and cut-rings is tridiagonal; in case of rings, there are two additional non-zero elements, namely the elements in the top-right and bottom-left corner, to capture the fact that the ring is closed. Due to the sparsity and regularity of the distribution network of rings and cut-rings, it is significantly easier to manage some common technical inconveniences; therefore, large portion of the earlier literature on DC MGs has been focused rings and cut-rings. As a result, these topologies still dominate when designing practical MG systems [7].

We refer to any other configuration of the distribution network as mesh topology. Meshes have received more attention in the power engineering community only recently with the explosion of foreseen MG applications and the developments power electronics. Natural modeling framework for meshes is the Multiple-Bus DC MG and most of our recent work focuses on this type of topology.

Grid-connected and Standalone MG

Another widespread categorization of MGs is w.r.t. whether they maintain a physical connection to the main grid. So, we have grid-connected and standalone (a.k.a. islanded or off-grid) MGs. Clearly, standalone MGs operate autonomously without support from the mains and they standardly appear as dedicated power supply in non-commercial applications such as airplanes, ships, tactile and military systems. Grid-connected MGs, on the other hand, are more common in commercial applications. In these systems, the MG is connected to the main grid at a point of common coupling (PCC) via bidirectional PEC; both interfaces of the PEC. i.e., the one facing the grid and other facing the MG, are controlled independently. This implies that, even though connected to the mains, the MG itself is responsible for controlling its internal state and managing the local resources, ultimately viewing the main grid as just another power source/storage (albeit with infinite capacity). Similarly, the grid views the MG as a separate, autonomous subsystem, capable of disconnecting and operating on its own. The models considered and developed in this thesis are agnostic and can be applied to either grid-connected or standalone system.

2 Control

As stated at the beginning of the Section 1, the PECs that interface the DERs to the buses and the distribution network, implement a set of control algorithms that regulate and monitor the state of the MG, manage the available resources in the most cost-efficient manner and address common security threats such as attacks, faults and outages. Based on their frequency, the control algorithms are organized in a dual-layer hierarchy, comprising fast primary layer and slower upper layer (further split into secondary and tertiary layers) [1]. This section briefly goes through the most important aspects and functions of the control layers.

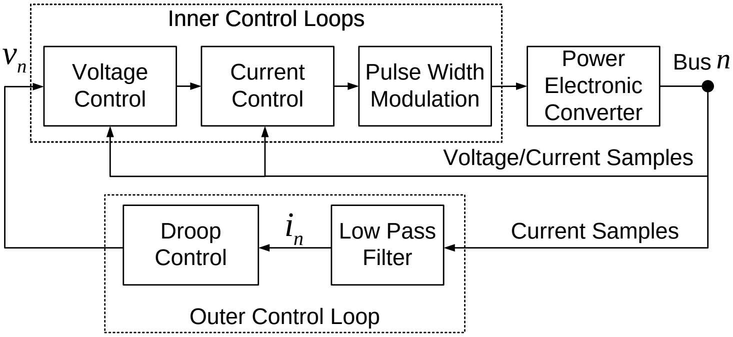

Fig. 2.3: VSC control mode.

2.1 Primary Layer Control

The primary control is responsible for maintaining the state of the DC MG, represented by the bus voltages v_n, $n = 1, \dots, N$ within the recommended margins, i.e., $v_{\min} \leq v_n \leq v_{\max}$ and fostering proportional and fair power sharing among the DERs. It is the fastest control layer, operating in the range $100 - 0.01$ kHz and it is implemented in decentralized manner. This means that local primary controllers are implemented in each PEC separately and they only use local voltage and/or current measurements, i.e., they do not require any feedback from other controllers. In other words, the primary control layer does not require any exchange of information among peer controllers. Each primary controller is further composed of two nested control loops, each of them operating on different frequency within the primary control band, see Fig. 2.3. We have the inner current and voltage control loops, organized in a cascade with the voltage preceding the current loop; they operate with frequency equal to the sampling frequency of the PEC's front-end, which is of the order of several tens up to several hundreds of kHz and their role is to regulate the output voltage and/or current following predefined references via local measurement feedback. On top of the inner control loops, we have the outer control loop which generates the reference for the inner control loops with frequency of the order $1 - 0.1$ kHz, which is several orders of magnitude smaller than the frequency of the inner control loops. Depending on the configuration of the outer control, two control modes for the PEC are commonly used in practice: Voltage Source Converter (VSC) and Current Source Converter (CSC).

Voltage Source Converter

A general digram of VSC control mode is depicted in Fig. 2.3. The VSC is a closed-loop type of control, where the outer control loop generates volt-

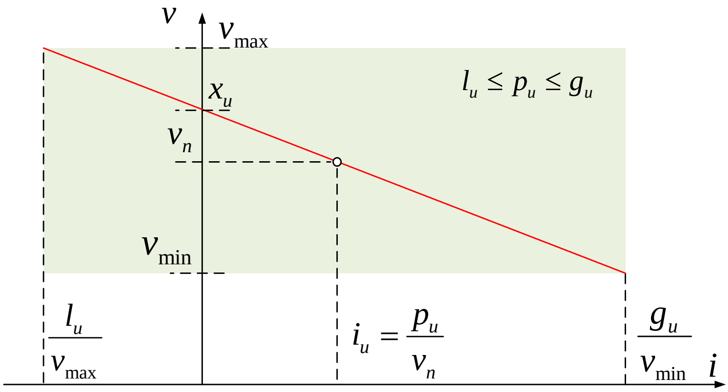

Fig. 2.4: $v - i$ diagram of droop control configured for proportional power sharing.

age reference for the inner voltage loop using filtered current feedback. A widespread technique is the decentralized droop control law, given with the following equation (DER u is again assumed to be connected to bus n) [1]:

$$v_n = x_u - r_u i_u,\ u = 1, \ldots, U,\ n = 1, \ldots, N. \tag{2.1}$$

We see from (2.1) that the output bus voltage is adjusted in response to variations of the output current of the DER; this is reminiscent and, in fact, inspired by the conventional droop control law in alternating current (AC) MGs where the frequency/voltage amplitude is adjusted with variations in the active/reactive power of the generator [4]. The parameters x_u and r_u are the reference voltage and the virtual resistance, respectively, and their values are controllable; they are usually set such that the output voltages satisfy $v_n \in [v_{\min}, v_{\max}]$ and the loads are shared (approximately) proportionally among the DERs in VSC control mode, based on their instantaneous generation limits. An example of droop law that meets the above conditions is the one depicted in Fig. 2.4 with droop control parameters [1, 4]:

$$x_u = \frac{g_u v_{\max}^2 + |l_u| v_{\min}^2}{g_u v_{\max} + |l_u| v_{\min}},\ r_u = \frac{v_{\max} v_{\min} (v_{\max} - v_{\min})}{g_u v_{\max} + |l_u| v_{\min}}. \tag{2.2}$$

Clearly, as the load demand in the MG increases, forcing the DER to move from its lower limit all the way to its generation capacity, the output bus voltage drops from $v_{\max}$ to $v_{\min}$; the operating point of the DER, defined by the pair (v_n, i_u) slides along the droop line defined with (2.2). In steady state, DERs in droop-controlled VSC mode are modeled as voltage sources with voltage x_u and series resistance r_u.

Current Source Converters

The CSC control mode is an open-loop type of control where the outer control loop is not closed via local feedback and the inner voltage control loop is absent. The reference for the inner control loop is generated via an external algorithm and is usually set such that the output power of the DER is constant. In other words, DERs in CSC control mode do not participate in voltage regulation and inject/absorb fixed to/from the MG, regardless of its state. CSC control mode is very common primary control configuration for RESs and ESs when operating close to full State-of-Charge [1, 8]. From architectural perspective, DERs in CSC control mode are equivalent to constant power loads but with opposite signs and, similarly as constant power loads, they behave as non-linear electrical components, although they do not impose big stability concern as the constant power loads, since they are modeled via positive resistance.

Steady State

Once the control modes are assigned, the steady state behavior of the MG is governed by the Ohm's and Kirchhoff's laws; when applied to an arbitrary bus n, they yield a system of N quadratic power balance equations:

$$v_n^2 \left(\sum_{\text{VSC}} \frac{1}{r_u} + \sum_{m=1}^{N} \frac{1}{r_{n,m}} + \frac{d_n^{\text{ca}}}{x^2} \right) - v_n \left(\sum_{\text{VSC}} \frac{x_u}{r_u} + \sum_{m=1}^{N} \frac{v_m}{r_{n,m}} - \frac{d_n^{\text{cc}}}{x} \right) + d_n^{\text{cp}} - \sum_{\text{CSC}} p_u^{\text{cp}} = 0, \tag{2.3}$$

where the VSC/CSC summing is over all DERs u connected to bus n that are configured in VSC/CSC control mode. The implicit function theorem guarantees the existence of an explicit solution to the non-linear power balance equations that expresses the steady state bus voltage v_n as a unique function of the primary control parameters, the load demands and the admittances of the distribution lines; however, finding this solution in closed form is out of reach in general case.

2.2 Upper Layer Control

In contrast to the primary layer which deals with state regulation and fast compensation of high frequency dynamics, the upper layer control operates on a significantly slower time scales, within the band $100 - 0.01$ Hz. Its functionalities cover wide range, from voltage restoration and elimination of power sharing mismatches, to state estimation and tracking, system identification, energy management, long-term planing and optimization, to fault detection, diagnosis and dealing with security threats. A common approach is to distinguish between a secondary and tertiary layer. In a nutshell, the secondary control layer encompasses only voltage restoration and power sharing mismatch compensation, operating in the band $100 - 10$ Hz, i.e., very close to the frequency band of the outer droop control in the primary layer; the rest of the applications form the tertiary layer and they operate with very low frequencies, around $0.1 - 0.01$ Hz which are several orders of magnitude smaller than the primary control frequencies. Depending on the size and scope, a typical MG would implement only a fraction of the tertiary layer control applications. The secondary control on the other hand, is optional in DC MGs; it is however still required in systems that predominantly serve loads which are sensitive to load variations.

Secondary Control

A well known fact is that under decentralized primary control, such as the one in (2.1), the steady state bus voltages vary in the interval $[v_{\min}, v_{\max}]$ and the loads are not shared exactly proportionally due to unmatched power loses over the distribution lines. The role of the secondary control is to alleviate these drawbacks and restore the bus voltages to a predefined global reference and eliminate the power sharing mismatch. In the literature, this is done by adding correction offsets to the reference voltage control parameter of the local droop loop of the VSCs, generated by local Proportional-Integral (PI) controllers which, in turn, use global bus voltage and output power averages to generate the correction offsets [1, 4]. It is implemented in either centralized or distributed manner. In the case of distributed implementation, the VSCs use average consensus protocol to obtain the corresponding averages used to generate the correction offsets, with convergence guarantees only if the communication graph is globally connected.

Tertiary Control

The tertiary control, a.k.a. intelligent energy management system, encompass all other control applications, except voltage restoration and sharing mismatch elimination and, traditionally, it is implemented in either centralized or distributed manner. Although application-dependent, the overarching goal of tertiary control is to adapt the operation of the MG to changes in conditions caused by both endogenous and exogenous influences, by reconfiguring the primary control layer. A simple example would be the Optimal Economic Dispatch (OED) that determines the optimal generation policies of the DERs that minimize the total generation cost, by taking into account the instantaneous generation capacities and load demands; using these policies, the OED then computes the optimal primary control references (the droop control parameters for instance) and feeds them back to the primary controllers as control directives.

2.3 Traditional Networked Control Design

Unlike the primary, the upper layer is traditionally designed within the framework of NCS; this means that the feedback loops of both the secondary and the tertiary control algorithms are closed via dedicated communication and monitoring infrastructure. Common wireless communication solutions, such as IEEE 802.11 or cellular systems, are widely used for this purpose [9–12]. We say that the operation of the upper layer is critically coupled to the performance of an external communication enabler whose performance cannot be influenced by the MG in any way.

Challenges

The networked control design of the upper layer in emerging power systems has sparked a debate about the adequacy of the approach to the evolving SG ecosystem [1, 2, 7, 9–18]. The concerns usually revolve around common topics, which can be summarized in the following key points:

- *Reliability and availability*. The upper layer control applications require low throughput but impose very strict constraints on the reliability and latency of the service. Unless designed specifically for such applications, majority of the existing wireless communication standards in use today fail to provide such service guarantees [11]. This will ultimately reduce the efficiency of the MG, and it might compromise its stability. The main reason for the inadequacy is the fact that SG applications have only emerged recently and the effort to address their service requirements with common wireless communication technologies is currently under way in 5G standardization [11, 19].

- *Security*. The cyber-security aspects of modern power systems whose control critically relies on external communication systems, have attracted significant attention, as conventional security attacks might compromise the performance of the system, even if firewalls are erected for its protection, leading to blackouts, equipment damage, data theft and investment losses. A common example in DC MGs is distributed secondary control that uses WiFi; conventional jamming attack can easily jeopardize the operation of the control and compromise the stability of the MG.

- *Cost*. Unlike their traditional counterpart, i.e., the main power grid, MGs are significantly more dynamic, sporadic and ad-hoc in nature with DERs and loads “entering” and “leaving” the infrastructure dynamically (e.g. electric vehicles). Therefore, even if the service requirements of the upper layer in MGs and the QoS is not the prime concern, the installation, running and maintenance of the external communication enabler might prove to be cost-inefficient and impractical.

- *Self-sustainability*. The principle of self-sustainable design suggests that the future power grids, including MGs, should be able to operate, reconfigure, adapt and optimize using only the computation resources in the existing equipment, without requiring access to external communication infrastructure. In this context, coupling the upper layer of the MG with an external communication system and using it to drive its operation, contradicts the principle of self-sustainability.

Review of Existing Remedies

Addressing the points outlined above has led to various solutions. An obvious, direct solution to the problems introduced by a networked upper control layer would be to remove the upper layer completely and run the MG only on primary level [1, 4]. While the system can, in principle, operate only with decentralized primary control if the droop controllers are properly dimensioned, the approach itself is not sustainable simply because global stability can not be guaranteed. Specifically, the unpredictable, dynamic nature of the MG will often push the system in situations which were not accounted for when dimensioning the primary controllers; this practically limits the design approach only to very narrow set of applications where the MG is small and the generation/load static or fairly predictable. In any other case, at least some form of upper layer control management, optimization or fault-tolerance should be included.

The classical DC bus signaling has risen as a natural evolution of the above idea [20–25]. It uses the variations of the steady state bus voltage as an implicit coordination signal that tells the MG units what to do and how to behave in specific conditions. This is achieved by defining operational modes and assigning DC voltage thresholds that separate the modes; each mode is defined as a specific combination of control duties of the DERs, covering given range of operating conditions. If the DC voltage crosses one of the predefined thresholds, it signals that the conditions have changed and the current mode is no longer valid; the DERs then adjust their local control parameters to the new operational mode. Since its initial inception, classical bus signaling has been applied to a variety of settings including both DC and AC MGs (where the same concept of separating operational modes has been achieved by quantizing the fundamental frequency). Clearly, the solution has inherent reliability/availability/security advantages over traditional networked design and also fosters self-sustainability of the MG since it requires only software modifications of the PECs. However, it lacks modularity since the specific coordination scheme, i.e., the assignments of operational modes and voltage thresholds should be done for each specific MG individually. Moreover, the range of upper layer control applications that can be supported is quite narrow since they should be mapped to predetermined coordination strategy. This is due to the fact that DC bus signaling is not exactly an explicit communication solution and the controllers do not actually exchange any information but are merely reacting to changes in operating conditions in predefined manner.

Another line of research, suggests to use standard powerline communications PLC solutions as an alternative to wireless technologies typically considered in networked control design of the upper layer [26, 27]. The inherent advantage of using PLC is the fact that some of the security concerns can be alleviated as now the information is exchanged through the powerlines and an attacker would need physical access to the grid. In addition to this, the networked control design paradigm is retained and multitude of upper layer control applications can be supported. Nevertheless, PLCs are still essentially an external communication system coupled to the control of the MG since they require installation of dedicated modems even though the actual communication takes place over the powerlines.

In light of the discussion above, the thesis introduces a novel PLC-type of solution, termed power talk, that aims to address the disadvantages of the traditional networked design of the upper layer in DC MGs, by combining the advantages of both, DC bus signaling and standard PLC solutions. In other words, the proposed solution reuses the existing power electronic hardware as in DC bus signaling, but offers the capability of exchanging messages explicitly over the powerlines as PLCs do.

3 Power Talk

This section presents the underlying idea of power talk and reviews its main properties.

3.1 Core idea

In a nutshell, power talk modulates the control messages that need to be sent to remote upper control peers into the parameters of the local primary control loop; this will cause subtle deviations of the steady state bus voltages from which remote controllers can demodulate the necessary information. In other words, power talk closes the feedback loop of the upper layer through the primary layer. To illustrate the idea formally, consider the steady state power balance equation (2.3); for simplicity, let us assume that all DERs in the MG are configured in droop-controlled VSC mode. As stated already in Section 2, the implicit function theorem guarantees the existence of a solution of (2.3) of the following form:

$$v_n = f_n(x_1, r_1, \dots, x_U, r_U),\ n = 1, \dots, N, \tag{2.4}$$

even though, obtaining the functions f_n for any n in closed form is technically out of reach in general case. The above equation describes the input-output relation of a general power talk channel with inputs represented by the droop control parameters $x_u, r_u,\ u = 1, \dots, U$ and outputs given by the steady state bus voltages $v_n,\ n = 1, \dots, N$.

3.2 Properties

The main properties of the general power talk channel (2.4) can be summarized as follows:

- *Power talk is ultra-narrowband (UNB) PLC technique.* From (2.4), we see that power talk is implemented in the outer droop control loop; as such it should comply with the bandwidth of the droop controllers to allow the bus reach a steady state, ultimately allowing for theoretical peak rates not larger than 1 kBaud. These rates are usually more than enough for tertiary layer control applications, however they might be insufficient for secondary control applications.

- *The power talk channel is non-linear.* A challenging property of (2.4) is the fact that even if one tries to construct an estimate of the functions $f_n, n = 1, \dots, N$, the resulting channel will still be non-linear. Majority of modern modulation/demodulation and coding techniques have been developed for linear channels, which practically leaves us no choice but to look for other alternatives.

- *The power talk channel is configuration-dependent.* This property is related with the previous one in the sense that, constructing an estimate of the input-output functions, requires complete knowledge of the physical configuration of the MG such as load values or admittance matrix. Such knowledge is generally unavailable on primary layer. From communication-theoretic perspective, the configuration determines the state of the power talk channel; hence, is it safe to assume that a VSC engaged in power talk communication will not have full channel state information.

- *Power talk supports full-duplex (FD) communication mode.* This property arises naturally from the definition of power talk as a communication techniques established over the steady state of the MG; we see from (2.4) that the steady state bus voltage is jointly determined by all VSCs in the system, meaning that one VSC can transmit and receive information from all other VSCs in the same time. It should be noted that the all-to-all property will diminish as the system scales, i.e., particular VSC will "hear" better VSCs that are more strongly connected to it and it will be more difficult to decode information from far away VSCs.

- *Power talk is constrained by the MG.* The capacity of power talk is determined by the electrical constraints of the DC MG itself, namely how much power dissipation and voltage deviation the system can tolerate. As general rule of thumb, power talk modulations should be designed such that they adhere to certain stability and power dissipation thresholds set by the MG system.

The above aspects impose rather non-conventional communication-theoretic settings, not encountered frequently in standard communication problems. Designing reliable power talk physical interfaces and protocols amid these challenges is the major focus of the first half of the papers included in Part II.

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Chapter 3

Technical Content

This chapter gives an overview of the specific contributions and the overall structure of the thesis. It should serve as guideline to navigate though the main body of the thesis, namely Part II, which presents the papers.

1 Contributions

Chapter 2 already introduced the main contribution of the thesis: that is, novel communication solution for DC MGs, termed power talk, that modulates the upper layer control messages into the parameters of the droop control loops of VSCs, causing subtle deviations of the steady state bus voltages from which remote VSCs can demodulate the necessary information. The specific contributions can be further divided into two parts: (i) designing reliable power talk interfaces and protocols (mainly covering the first half of the PhD study), and (ii) applying power talk in representative upper layer control applications (covering the second half of the PhD study).

1.1 Reliable Communication Interfaces

As outlined in Chapter 2, power talk exhibits some non-conventional properties which should be managed in order to be able to communicate reliably over the channel. The main challenge that triggered the largest amount of work in the thesis is the problem of communicating reliably over non-linear, implicit channel without knowledge of the physical configuration of the MG, given the fact that the configuration can change arbitrarily while communicating (e.g. via load variation). It should be noted that the thesis mainly refrains from fundamental, information-theoretic investigations of power talk; instead the focus is directed on finding physical layer tools, such as modulation/demodulation strategies that enable design of reliable communication protocols, without considering whether some specific solution is optimal in information-theoretic sense. The techniques developed in the thesis can be further classified into full range and linear techniques as detailed below.

Full Range Techniques

The power talk communication techniques developed in the papers covering this part exploit the full, non-linear dynamic range of state variations that the MG can tolerate, without access to detailed knowledge of the physical configuration of the MG. They employ a non-conventional, configuration-agnostic approach, where the channel is represented through a "black box" and only its aggregate effect on the channel outputs is considered. Depending on the specific modulation and multiple access scheme, the "black box" can be shape-shifted into well known and widely studied communication channels over which reliable communication is possible. It should be noted that this part mainly operates over the Single-Bus DC MG model with linear load; however, we do note that the presented concepts are straightforwardly applicable to general non-linear Multiple-Bus systems.

Linear Techniques

This class of techniques is actually a special case of the class of full range techniques, mentioned above, in the regime of small average power dissipation, i.e., the case when the deviations of the droop parameter perturbations are expected to be very small relative to their preset values. In such case, first-order Taylor's approximation can be used to linearize the input-output relation of the general power talk channel. Clearly, the "black box" in this case is transformed into a linear channel whose coefficients carry the aggregate information about the impact of the MG configuration on the channel. An inherent advantage in obtaining linear channels is the fact that one can resort to the vast set of techniques that have been designed for reliable communication over linear channels.

1.2 Applications

Once reliable communication protocols have been designed, the natural progression would be to apply them for upper layer control. Application in both tertiary and secondary control has been considered; the details are summarized below.

Monitoring and Optimization

The sampling rate of the tertiary layer is several orders of magnitude smaller than the sampling rate of the primary controllers; clearly, for these applications, power talk can serve as a standalone communication enabler. Two representative and widespread tertiary layer control applications are considered; one from optimization and the other one from monitoring. The first application is OED. The goal of OED is to determine the optimal power generation policies for the DERs such that the total generation cost is minimized and the load is balanced. The other application is System Identification and State Estimation (SISE). The objective of SISE is to (i) infer the instantaneous physical configuration of the MG, which includes the generation capacity status of DERs, the power demands on loads and the status of the distribution network topology, and (ii) generate an estimate of the steady state voltages, using noisy local measurements. Solving the SISE problem uniquely, depends on whether two key conditions are satisfied: (i) is the MG is observable, and (ii) are there enough temporal state observations, i.e., is the MG excited sufficiently excited. In the papers covering SISE, power talk plays crucial role in guaranteeing that both the observability and sufficient excitation conditions are met.

As it turns out, the information acquired by the SISE is sufficient to run the OED; this implies that the SISE and the OED can be jointly coupled in a common decentralized control architecture suitable for self-sustainable DC MG without access to external communication/monitoring hardware.

Cyber-secure secondary control

Secondary control typically runs with significantly higher frequency compared with the tertiary control layer, i.e., with frequency that is of the same order as the outer droop control loop; hence, it requires larger communication bandwidth than the one offered by power talk which practically rules out the possibility of using power talk as a standalone communication solution for secondary control. However, it can still be used as a low-rate, side communication channel to complement the external communication system. This becomes important in situations when the security system of the main communication enabler is compromised; for instance, if the wireless interface of one or several VSCs is jammed, the secondary control will not run properly and might lead to power sharing mismatch and circulating currents. In such cases, one can resort to the inherent security benefits that power talk channel offers, to resolve on-going security threats and restore the confidentiality of the external communication system. It should be noted that the work in this part serves only as a proof of concept; a detailed performance analysis is outside the scope of this thesis and is part of an on-going work.

2 Structure

2.1 Outline

Part II covers the following 9 papers, 8 of which have been already published and 1 is still under review.

Paper A:	Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski, Hongpeng Liu, Poh Chiang Loh, Frede Blaabjerg. "Power Talk: How to Modulate Data over a DC Micro Grid Bus Using Power Electronics". *IEEE Global Communications Conference (GLOBECOM)*. December 2015, pp. 1-7.
Paper B:	Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski, Frede Blaabjerg. "Power talk in DC micro grids: Constellation design and error probability performance". *IEEE International Conference on Smart Grid Communications (SmartGridComm)*. December 2015, pp. 1-7.
Paper C:	Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski, Hongpeng Liu, Poh Chiang Loh, Frede Blaabjerg. "Multiuser Communication Through Power Talk in DC MicroGrids", *IEEE Journal on Selected Areas in Communications (JSAC)*. May 2016, vol. 34, no. 7, pp. 2006-2021.
Paper D:	Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski. "Power Talk for Multibus DC MicroGrids: Creating and Optimizing Communication Channels". *IEEE Global Communications Conference (GLOBECOM)*. December 2016, pp. 1-7.
Paper E:	Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski. "Modemless Multiple Access Communications Over Powerlines for DC Microgrid Control". *International Workshop on Multiple Access Communications (MACOM)*. November 2016, pp. 30-44. (**Best Paper Award**)
Paper F:	Marko Angjelichinoski, Anna Scaglione, Petar Popovski, Čedomir Stefanović. "Distributed estimation of the operating state of a single-bus DC microgrid without an external communication interface". *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*. December 2016, pp. 1-4.

Paper G: Marko Angjelichinoski, Anna Scaglione, Petar Popovski, Čedomir Stefanović. "Decentralized System Identification via Primary Control Perturbations and Application in Economic Dispatch for Autonomous DC MicroGrids". *IEEE Transactions on Signal Processing (submitted)*. October 2017, pp. 1-16.

Paper H: Marko Angjelichinoski, Pietro Danzi, Čedomir Stefanović, Petar Popovski. "Secure and robust authentication for DC MicroGrids based on power talk communication". *IEEE International Conference on Communications (ICC)*. May 2017, pp. 1-7.

Paper I: Pietro Danzi, Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski. "Anti-jamming strategy for distributed microgrid control based on Power Talk communication". *IEEE International Conference on Communications (ICC)*. May 2017, pp. 1-7.

Papers A, B and C cover the full range power talk interfaces and protocols, whereas Paper D presents the linearized power talk channel. Papers E, F and G cover the applications of power talk as standalone communication solution in tertiary layer control. Finally, papers H and I focus on using power talk as secure, side channel for cyber-secure secondary control.

In addition to papers A-I, the following papers, also written during the PhD study are included in the Appendix but not in the main body of the thesis:

Paper J: Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski, Frede Blaabjerg. "Communication-Theoretic Model of Power Talk for a Single-Bus DC Microgrid". *Information*. March 2016, vol. 7, no. 1, pp. 1-18.

Paper K: Marko Angjelichinoski, Pietro Danzi, Čedomir Stefanović, Petar Popovski, Frede Blaabjerg. "Towards self-sustainable power systems: DC MicroGrid optimization via power talk". *IEEE International Conference on DC MicroGrids (ICDCM)*. June 2017, pp. 378-382.

Paper L: Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski, Anna Scaglione, Frede Blaabjerg. "Topology identification for multiple-bus DC MicroGrids via primary control perturbations". *IEEE International Conference on DC MicroGrids (ICDCM)*. June 2017, pp. 202-206.

Paper M: Pietro Danzi, Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski. "Distributed Proportional-Fairness Control in Micro-Grids via Blockchain Smart Contracts". *IEEE International Conference on Smart Grid Communications (SmartGridComm)*. October 2017, pp. 1-6.

All papers, except for paper G which is still under revision, are published. Their layout in the thesis has been adapted to the requirements of the template. In the process, special attention has been devoted to the unification of the figure format to the extent possible; we kindly advise the reader to take a glance at the published versions, available online through their respective publishing channels, if some figure details appear to be small.

2.2 Paper Summaries

We provide brief digests of the technical content of the papers in Part II.

Paper A

Chronologically, this paper is the first work on power talk. Its main goal is to (i) introduce the general idea of communicating over the bus via primary control perturbations and several related concepts, and (ii) provide initial guidelines on how to design reliable communication protocols, by representing the general power talk channel into well studied channels.

The first part of the paper formalizes the notion of one-way power talk communication in a basic Single-Bus DC MG with two DERs operated as droop-controlled VSCs, serving a resistive load. In power talk, the information-carrying channel inputs are the droop control parameters while the output is the steady state bus voltage. The load is modeled as a sporadically varying electrical component, which can alter the bus voltage unpredictably and independently and is, therefore, the main communication impairment. The key concept of signaling space is introduced as a two-dimensional set of permitted droop control parameter values that keep the bus voltage and the output powers of the DERs bounded within their stability margins. Assigning an average power dissipation cost metric to every point in the signaling space, defined relatively to a nominal droop control point (i.e., the point in the signaling space with zero power dissipation), we devise a tool for efficient design of power talk symbol constellations.

The remaining part focuses on simple, binary power talk protocols, where the transmitting VSC switches between two power talk symbols, i.e., two different droop control points in the signaling space, and modulates information bits into the bus voltage following predetermined waveforms. The receiving VSC infers the transmitted power talk symbol based on the observed bus voltage relative to a detection threshold set by a pilot symbol; a natural choice would be to use the nominal droop control point. This detection mechanism is truly configuration-agnostic as long as the detection threshold remains between the bus voltage levels induced by the power talk symbols; the paper shows how to design constellations that satisfy such criteria. A change in the load alters the detection threshold which might lead to burst of symbol errors; devising an efficient strategy to deal with load change events is tightly connected to the specific waveform used to modulate bits. In particular, two waveforms are considered: (i) simple binary signaling where each bit is directly represented via single power talk symbol, and (ii) Manchester coding on bit level where each bit is represented via sequence of two alternating symbols. With simple binary signaling, the power talk channel on bit level is transformed into binary asymmetric channel (BAC), whereas the bit-level Manchester code yields binary asymmetric erasure channel (BAEC). The paper analyzes and compares the performance of the two waveforms in representative MG settings, concluding that using bit-level Manchester code is indeed a simple and viable option for reliable communication over the DC MG bus.

Paper B

This paper extends the concepts of Paper A to symbol constellations of arbitrary order using the same Single-Bus DC MG model with two DERs sharing a common resistive load. In doing so, it adopts a slightly more structured way of dealing with the lack of detailed knowledge of the physical configuration of the MG. First, the DC MG from the perspective of the transmitting VSC is represented via an equivalent Thevenin circuit; both the transmitter and the receiver are assumed to know the corresponding parameters of the Thevenin equivalent. Second, the receiving VSC applies a detection method where the objects to be detected are one-dimensional affine subspaces in the signaling space. This is motivated by the fact that the power talk channel, as introduced in Paper A, is represented by an under-determined mapping from the two-dimensional signaling space into the one-dimensional space of bus voltage values; hence, the receiving VSC, using the observed bus voltage can only determine one-dimensional line on which the transmitted power talk symbol lies. This line is shown to rotate around the symbol in the signaling space as the load changes; the set of all line parameters over the dynamic range of the load, for a given power talk symbol form a segment in a so called detection space where the actual detection of symbols is performed by the receiving VSC. Physically, a point in the detection space is an estimate of the actual power injected by the transmitting VSC; similarly as the signaling space, the detection space is a key concept in power talk and is heavily utilized in Paper C (in a slightly modified variant). The main idea is to correctly detect the actual segment in the detection space for any value of the load. To avoid ambiguities due to load changes, the key requirement is to find symbol constellations in the signaling space that produce non-intersecting segments in the detection space. The paper then derives the Maximum Likelihood detector, analyzes its symbol error probability and shows how to design adaptive symbol constellations that improve the detection performance uniformly.

Paper C

Paper C combines and extends the concepts presented in Paper A and B in several ways.

First, a Single-Bus DC MG with arbitrary number of DERs is considered. The aim is to devise reliable multiple access communication strategies, under variable load, by applying the same configuration-agnostic approach introduced in Papers A and B. It introduces a dedicated training phase, in which all VSCs go through predetermined power talk symbol sequences; the aim is to enable each receiving VSC to learn all possible power talk channel outputs by simply observing them, provided that the training sequences are globally known. The local observation maps formed by each VSC is conceptually identical to the detection space introduced in Paper B, since, as discussed in Paper C, all channel outputs observed by a specific VSC will lie on a one-dimensional subspace, i.e., line segment determined by the local droop control configuration of that particular VSC. The solution can be also considered as a viable candidate for Multiple-Bus DC MGs of arbitrary configuration, arbitrary symbol constellation sizes and arbitrary multiple access schemes, including all-to-all, full duplex transmissions; however, it should be noted that the number of possible channel outputs when the VSCs engage in all-to-all communication, i.e. they transmit and receive in the same time, grows exponentially with the number of communicating units, ultimately limiting the applicability to small systems (i.e., not more than 10 simultaneously transmitting units).

The rest of the paper focuses on binary constellations and considers two special multiple access schemes: (i) Time Division Multiple Access (TDMA), and (ii) Full Duplex (FD) all-to-all scheme. With TDMA, each VSC during training constructs separate two-point detection space for each transmitting VSC. In the FD case, if the power talk symbols satisfy certain conditions, we obtain the Multiple Access Adder Channel with Binary Inputs (MAAC-BI); hence, each VSC construct a single detection space with number of point that grows linearly with the total number of VSCs. The paper then derives the optimal Maximum Likelihood detection for both schemes and analyzes its bit error performance. Similarly as in the previous two papers, a change in the load modifies the detection space, i.e., the outputs are shifted along the one-dimensional segments, invalidating the previously used detector; this means that an up-to-date detection space should be reconstructed entailing training phase activation. The paper considers two training phase activation schemes: (i) periodic, and (ii) on-demand, i.e., wherever load change is detected and investigates the impact of load changes and training on the net transmission rates for both TDMA and FD schemes. Finally, a preliminary methodology for evaluating the actual monetary cost of power talk in the context of tertiary level control applications is introduced; the brief analysis shows that with present electricity prices, the power dissipation incurred by power talk leads to no more than few dollars per year.

Paper D

Chronologically, this is the first paper that introduces the general model of Multiple-Bus DC MG with non-linear bus loads and establishes the notion Single-Bus systems as a special case when the loses over the power lines are negligible. The paper derives the first-order approximation of the bus voltage responses to small droop parameter perturbations (namely the reference voltages); this yields the linear power talk channel, where the information-carrying input symbols are now represented with the perturbations of the droop control parameters from their nominal values, whereas the outputs are given by the deviations of the bus voltages. Given that the measurement noise is Gaussian, the resulting channel for fixed values of the channel coefficients is real all-to-all full duplex Gaussian Multiple Access Channel (G-MAC). The paper then discusses the properties of the channel matrix and reviews the same model in the context of Single-Bus DC MGs. Remarkably, the random load now determines the values of the channel coefficients; since it changes infrequently, the channel resembles block fading wireless channel. We note that, due to its advantage of immediate familiarity - result of the existing body of work on linear communication techniques - we have applied the linear power talk channel model extensively in papers E an G.

In addition to introducing the model, the paper delves deeper into some fundamental, information-theoretic properties of power talk. In particular, once the linear model is obtained, one can determine the capacity regions of the equivalent channels as functions of the channel coefficients. However, it quickly become clear that that the channel coefficients are functionally dependent on the nominal droop control points of the VSCs; hence, by modifying the nominal droop parameters, the channel coefficients can be also modified. In other words, investing part of the total average power constraint into the act of modifying the nominal droop parameters, can, potentially, lead to improvement of the achievable information rates. This peculiar aspect was not immediately clear for us when working on the full range techniques. To obtain a sense on how much improvement can be expected, the paper focuses again on one-way communication in simple three bus DC MG with two

DER buses and one load bus. The capacity of the one-way channel is given by the well known Shannon formula and the paper formulates a capacity maximization problem as a constrained optimization, trying to find nominal droop parameters in the signaling space that maximize the signal-to-noise ratio under total power constraint shared with the information symbols. The paper concludes with numerical study which shows that in this specific case, the capacity can be increased by 3 dB.

Paper E

The objective of the paper is to (i) introduce a power talk protocol through which DERs exchange the information that is necessary to run OED in a decentralized manner, and (ii) to present a methodology for quantifying the additional monetary cost entailed by using power talk. It considers the variant of the general OED problem with linear cost functions; specifically, the DERs are divided into ordered cost groups, with the DERs in the same group having the same cost per unit of generated power. Solving the OED in such case yields a closed form solution which can be implemented in a decentralized manner. To so so, each controller needs to know (i) the cumulative generation capacity of DERs in lower cost groups, and (ii) the cumulative generation capacity of DERs from the same cost group. Building upon these observations, the paper then proceeds to introduce a decentralized scheme, where the OED runs periodically. At the beginning of each OED period the DERs engage into communication phase using the linear power talk interface. During the power talk phase, DERs from the same cost groups transmit quantized, binary and uncoded representations of their local generation capacities in full duplex mode, while the DERs from the same and higher cost groups detect directly the cumulative capacity of the transmitting DERs using integer sum detector (with complexity that grows linearly in the number of concurrently transmitting DERs), instead of demodulating the messages from each DER individually; hence, the scheme does not require multiple access coding. The paper quantifies the additional operational cost entailed by power talk and compares it with the minimal cost, i.e., the cost attained by OED is the required information is available perfectly and instantly; the results show that the average cost increase is less than 1% of the optimal cost, yielding yet another strong argument for the practical viability of power talk.

Paper F

This paper sets the foundations for the work presented in paper G; it targets the SISE problem in the special case of Single-Bus DC MGs, where all controllers are connected to the same bus and observe and measure the same bus voltage; hence, in this setup, the controllers naturally meet the observability condition and it is not necessary to disseminate their local bus voltage measurements to the other controllers. Then, the main objective of the paper is to introduce a tool which enables each controller to meet the sufficient excitation condition, i.e., a tool that generates sufficient number of steady state realizations and observations. In this context, the paper proposes a solution based on decentralized, deterministic training; specifically, the controllers inject small, deterministic and a priori known perturbations in the droop control parameters, referred to as training sequences, for a limited period of time, inducing subtle steady state bus voltage deviations. If the training sequences satisfy predefined rank conditions, we say that the MG is sufficiently excited and each controller infers the configuration parameters of the MG via Maximum Likelihood estimation.

Paper G

Paper G generalizes and extends the work presented in Paper F, blending the SISE and OED application together and introducing a complete communication, monitoring and optimization framework for self-sustainable DC MGs that do not have access to external communication hardware. In a nutshell, the paper presents decentralized, dual-layer control architecture for general Multiple-Bus DC MGs in which the primary controllers (i) engage in decentralized training, ensuring that the sufficient excitation and observability conditions are both locally met, (ii) solve the SISE problem via Maximum Likelihood estimation, and (iii) use the estimated information to determine the optimal OED policy locally.

The first part of the paper focuses on solving the SISE problem in nonlinear Multiple-Bus DC MGs. First, it presents a decentralized training protocol organized into two sequential phases. In the first phase, the controllers perform deterministic training (similarly as in paper F) with training sequences that satisfy the sufficient excitation condition, and measure the steady state voltage responses at the local bus, generating a sequence of local measurements. In the second phase, the controllers disseminate the local measurements acquired in the first phase to all other controllers over a linear, all-to-all power talk interface using amplitude modulation of the reference voltages, and, in the same time, demodulate the measurement sequences transmitted by remote controllers, attaining full observability. After the training, the controllers solve the SISE problem via iterative Maximum Likelihood algorithm, generating local estimates of the generation capacities of remote DERs, the load demands at remote buses and the distribution network topology; in addition, the performance of the estimation algorithm is characterized via the Cramer-Rao Lower Bound and numerically verified to be asymptotically efficient.

In the second part of the paper, the proposed training protocol is applied for solving the OED in a fully autonomous decentralized manner, similarly as in paper E; namely, the OED runs periodically and at the beginning of each OED period, the controllers invoke the training protocol, allowing them to extract the information necessary for solving the OED locally. The paper concludes with a detailed study of the operating cost of the proposed system; specifically, the paper shows that by optimizing the configuration of the training protocol, namely its duration and droop control deviation amplitudes, one can minimize the average increase in monetary cost, relative to the minimal cost, reaching values as low as 1%.

Paper H

The secondary control system in this paper is assumed to be centralized: the VSCs send their local bus voltage and current measurements to a central controller (CC) which computes the correction offsets for the local droop control loops and feeds them back to the VSCs. Clearly, any VSC before joining the set of secondary control agents needs to authenticate to be able to access the wireless channel. In this context, the paper considers the following security threat: if the WiFi interface of an incoming VSC, which is requested to join the secondary control, is jammed while performing the cryptographic handshake, the VSC will be unable to authenticate to the network and will fail to join the set of secondary control agents. To resolve the above situation, the paper proposes to perform the cryptographic handshake procedure over a dedicated power talk interface; this way the authentication procedure becomes practically invisible for the conventional jammer. The power talk interface includes a periodically recurring set of time slots in which the incoming VSC sends the initial authentication request to the CC. Upon request detection, the CC allocates additional power talk slots for the rest of the handshake; the transmission and reception techniques for power talk are identical as in paper A. The PLECS simulation results verify the feasibility of the solution.

Paper I

The paper adopts the common distributed secondary control architecture where each VSC exchanges the local bus voltage and current measurements with its one-hop neighbors and relies on average consensus protocol to generate the input for the local PI controllers that eventually generates the droop control correction offsets. It is well known from average consensus theory that the distributed solution will converge if the WiFi communication graph is globally connected. In this context, the paper considers the following situation: if one or more VSCs that are already authenticated and actively participating in secondary control voltage restoration and power sharing regulation are jammed, the communication graph might split, forming multiple subsets of disconnected sub-graphs, i.e., clusters of VSCs that perform secondary control locally. Even though the voltage restoration capability of the secondary control will be maintained by the clusters, the power sharing will not be regulated, leading to potentially dangerous circulating currents between the clusters. The situation is addressed by using side power talk interface (the same interface presented in paper H) in the following manner. As soon as any of the jammed VSCs detects the jamming locally, it alarms the rest of the DERs in the system. The VSCs then switch the secondary control off, the CSCs switch to droop-controlled VSC mode and they all engage in TDMA-based power talk communication (using the transmission and receptions methods presented in Paper C), broadcasting a list of one-hop neighbors that they hear over the WiFi interface. At the end, all DERs have the same global list of one-hop neighbors. Then, they find a new globally connected subset among all DERs, excluding the jammed ones; this subset now forms the new VSC set of secondary control agents. The PLECS simulations verify the applicability of the technique and its capability to restore the proportional power sharing among the VSCs.

Part II

Papers

Paper A

Power Talk: How to Modulate Data over a DC MicroGrid Bus using Power Electronics

Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski,
Hongpeng Liu, Poh Chiang Loh and Frede Blaabjerg

Published in
IEEE Global Communications Conference (Globecom), 2015.

The layout has been revised.

Paper B

Power Talk in DC Micro Grids: Constellation Design and Error Probability Performance

Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski
and Frede Blaabjerg

Published in
IEEE International Conference on Smart Grid Communications (SmartGridComm),
2015.

Paper C

Multiuser Communication through Power Talk in DC MicroGrids

Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski,
Hongpeng Liu, Poh Chiang Loh and Frede Blaabjerg

Published in
IEEE Journal on Selected Areas in Communications (JSAC), Vol. 34(7),
pp. 2006-2021, 2016.

The layout has been revised.

Paper D

Power Talk for Multibus DC MicroGrids: Creating and Optimizing Communication Channels

Marko Angjelichinoski, Čedomir Stefanović and Petar Popovski

Published in
IEEE Global Communications Conference (GLOBECOM), 2016.

The layout has been revised.

Paper E

Modemless Multiple Access Communications over Powerlines for DC Microgrid Control

Marko Angjelichinoski, Čedomir Stefanović and Petar Popovski

Published in
International Workshop on Multiple Access Communications (MACOM), 2016.
(**Best Paper Award**)

Paper F

Distributed Estimation of the Operating State of a Single-Bus DC MicroGrid without an External Communication Interface

Marko Angjelichinoski, Anna Scaglione, Petar Popovski and
Čedomir Stefanović

Published in
IEEE Global Conference on Signal and Information Processing (GlobalSIP), 2016.

The layout has been revised.

Paper G

Decentralized System Identification via Primary Control Perturbations and Application in Economic Dispatch for Autonomous DC MicroGrids

Marko Angjelichinoski, Anna Scaglione, Petar Popovski and
Čedomir Stefanović

Submitted to
IEEE Transactions on Signal Processing, 2017.

The layout has been revised.

Paper H

Secure and Robust Authentication for DC MicroGrids based on Power Talk Communication

Marko Angjelichinoski, Pietro Danzi, Čedomir Stefanović and
Petar Popovski

Published in
IEEE International Conference on Communications (ICC), 2017.

The layout has been revised.

Paper I

Anti-Jamming Strategy for Distributed Microgrid Control based on Power Talk Communication

Pietro Danzi, Marko Angjelichinoski, Čedomir Stefanović and Petar Popovski

Published in
IEEE International Conference on Communications (ICC) Workshops, 2017.

The layout has been revised.

Part III

Epilogue

Chapter 4

Concluding Remarks

This chapter wraps-up the main content of the thesis by outlining the key benefits of power talk when compared to existing solutions that address the concerns on the traditional networked control design approach of the upper layer in DC MGs. Several directions for possible future extensions and research are also provided.

1 Advantages of Power Talk

Power talk can be viewed as a solution that combines the advantages of both classical DC bus signaling and PLC; in a nutshell, it inherits the reliability/availability/security and self-sustainability features of DC bus signaling, but it also offers the capability of transmitting explicit information, paving the way for variety of upper layer control applications as standard PLCs do. More specifically, unlike DC bus signaling which is merely a coordination scheme relying on the implicit signal about the present state of the system, "encoded" in the bus voltage variation, power talk is designed as an explicit communication solution, where the primary controllers deliberately move the steady state of the MG through different operating points with an aim to transmit locally available information which may or may not be directly related with the system status.

Alternatively, power talk can be seen as a novel PLC communication solution designed specifically for DC MGs. In this sense it bears conceptual similarities with few well known PLC solutions such as Ripple Carrier, Two-Way Automatic Control System (TWACS) and Turtle in the sense that they are all in-band techniques, modulating information into subtle perturbations of the fundamental carrier. However, applying standard PLC solution for upper layer control still requires installation of the dedicated modems and this is where power talk has strong advantage; it is implemented into the primary control loops and requires only software upgrades without any additional hardware. Hence, it fits well the self-sustainability paradigm of the MGs, i.e., it supports the notion that truly autonomous and self-sustainable MGs should be able to operate, reconfigure, adapt and optimize their performance relying solely on the the signal processing capabilities of their own hardware components.

The advantages of power talk w.r.t. the cyber-security of the MG are particularly strong, since the solution is resilient to most of the conventional attacks; in fact, compromising the upper layer control through power talk now requires physical access to the MG through dedicated PEC, which makes it significantly more difficult for conventional attackers to tame the MG operation. Finally, power talk does not entail installation cost, besides the cost of the additional software which would ultimately depend on the policies of specific PEC vendors. The operational cost on the other hand, reflects in slight power dissipation due to the sub-optimality of the sequence of operating points through which the MG passes while power talking; ultimately, quantifying the power wastage depends on the specific upper layer control application, its specific definitions of utility functions and service requirements. The results presented in Part II suggest that the additional operational cost due to power talk related wastage in typical DC MG setups is no larger than 1% from the minimal cost, i.e., the cost corresponding to an ideal, costless communication solution. Adding the other inherent benefits summarized above, makes power talk a strong candidate solution for truly self-sustainable DC power systems of the future.

2 Directions for Future Research

The power talk concept and the various techniques developed in the thesis can be extended in several directions.

To begin with, a technical feasibility study on real hardware is needed to determine the actual communication rates of power talk. The initial investigation has been already conducted, see [1]; the results confirmed that power talk can support signaling rates of up to several hundreds of kbps, but the actual number is strongly dependent on the transient behavior of the MG and the sampling frequency of the PECs, implying that more practical testing is needed to obtain conclusive results. Furthermore, advanced MG configurations such as interconnected meshes of individual MGs pave the way for designing advanced, hierarchical power talk protocols; such setups have not been yet considered in the papers of the thesis, but should be the focus of any future work. Another line of research would be deeper, information-theoretic investigation of power talk which is also largely omitted in the thesis, although paper D provides a promising glimpse on the topic.

Extension in AC MGs is also foreseen as technically possible since the fundamental frequency is also allowed to vary, albeit in significantly tighter interval, i.e., ±1% around the nominal frequency. Moreover, in AC MGs there is separate droop control law that regulates the voltage amplitude with variations in reactive power. In the general case, the two droop laws, namely the frequency/active power and voltage amplitude/reactive power, are coupled, i.e., one law impacts the other and vice versa; however, in predominantly inductive systems, the frequency and the voltage amplitude become close to independent and the laws decouple. Hence, an interesting idea would be to introduce concepts similar to power talk defined on the voltage amplitude, reflected in deviations of the reactive power component, while keeping the frequency close to its nominal value. The idea is attractive since AC systems in general are predominantly inductive; for instance, the standard solution to keep AC MGs inductive is via virtual inductive impedance in series with the droop controllers. Extensions of power talk within the AC realm would open directions for designing power talk solutions for advanced hybrid AC/DC power systems, and possibly extensions in medium and high voltage networks.

Finally, it should be mentioned that on an abstract level MGs form a subclass of a broader class of dynamic and decentralized cyber-physical systems with dual-layer control architecture. Hence, it we like to contemplate that the conceptual contributions of this thesis are applicable to any such cyber-physical system, after proper modification; we scratch this notions only on the surface in paper G. However, from purely academic perspective, reformulating the power talk problem in general context, i.e., as an explicit communication among individual controllers over an implicit communication channel, represented by the dynamic state of decentralized control system is probably the most exciting endeavor that might prove to be conceptually disruptive and therefore worth pursuing in future.

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Part IV

Appendix

Paper J

Communication-Theoretic Model of Power Talk for a Single-Bus DC Microgrid

Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski
and Frede Blaabjerg

Published in
Information, Vol. 7(1), pp. 1–18, 2016.

The layout has been revised.

Paper K

Towards Self-sustainable Power Systems: DC MicroGrid Optimization via Power Talk

Marko Angjelichinoski, Pietro Danzi, Čedomir Stefanović, Petar Popovski and Frede Blaabjerg

Published in
IEEE International Conference on DC MicroGrids (ICDCM), 2017.

The layout has been revised.

Paper L

Topology Identification for Multiple-bus DC MicroGrids via Primary Control Perturbations

Marko Angjelichinoski, Čedomir Stefanović, Petar Popovski,
Anna Scaglione and Frede Blaabjerg

Published in
IEEE International Conference on DC MicroGrids (ICDCM), 2017.

Paper M

Distributed Proportional-Fairness Control in MicroGrids via Blockchain Smart Contracts

Pietro Danzi, Marko Angjelichinoski, Čedomir Stefanović and
Petar Popovski

Published in
IEEE International Conference on Smart Grid Communications (SmartGridComm),
2017.

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-081-4

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