論 文 の 内 容 の 要 旨

論文題目　　Distributed DC Energy Network Using Interconnected Subgrids
（ 直流と蓄電池を用いて電力融通を可能とするオープンな電力網の構築とその制御法の研究 ）

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Adapting the power grid to renewable energy generation is one of the main challenges of the 21st century that spans over a variety of technologies, industries and regulations. Smart-grid approaches such as microgrids, nanogrids or Virtual Power Plants (VPP) are considered the most promising solutions for the gird challenge. Usually these approaches still depend on the traditional grid to avoid energy shortcomings and guarantee high reliability. Top-down approaches use intelligent devices to make the traditional grid smarter. On the other hand, recent studies try to approach the issue from the opposite direction: Interoperability and bottom-up interconnections between distributed generation and microgrids decrease grid dependence by increasing self-sufficiency and resilience.

While the potential of such approaches is now widely recognized in academia, few studies provide complete control systems that can handle both power stability as well as system automation goals. Especially the potential of methods using Direct Current (DC) for interconnections in facilitating bottom up power merging has not been sufficiently studied. For instance, new decentralized, non-droop based control methods have now become accessible thanks to digitally controlled, bidirectional DCDC converter with both voltage and current regulated mode, but few studies analyze them in the context of microgrids.

This thesis provides a complete framework for such a bottom up approach by proposing a multi-layer DC microgrid and with a decentralized control system. The research utilizes existing approaches and technologies, adapts and recombines them to provide both power infrastructure and information infrastructure. In this way, it pioneers a decentralized microgrid with a loosely coupled architecture that can be built bottom-up with gradual investment and that is potentially applicable to both on and off-grid areas.

The proposals are split according to two main axes (discussed in chapter 3 and 4):

- **Power Infrastructure: Multilayer DC Microgrid Concept**

Chapter 3 describes a new, bottom-up power infrastructure that allows exchanging energy in the form of DC in between houses of a community. DC subsystems including generation and storage are interconnected via a shared DC power bus and a communication line.

A decentralized, non-droop control procedure allows n-to-m power flow without central control or supervision. By handling power stability constraints and safety locally, flexibility and resilience is improved. Higher, community-wide control layers are freed from analog constraints. Furthermore, a recursive method is proposed to scale the system without introducing bottlenecks or tightly coupled components. With this approach, the main issue of interconnections, i.e. frequency regulation, is eliminated and power stability related goals can be managed locally. Special focus is given to the decoupling to higher layer, digital control goals such as managing demand response or battery State of Charge (SoC) balancing within the community. It uses only bidirectional DCDC-converter without requiring any central voltage regulation or monitoring (no fixed master).

It is thus bottle-neck free and allows intermittent control of the bus voltage in order to reduce losses. The absence of center and local stability management allows adding or removing new subsystems dynamically. As long as they fulfil interface requirements and comply with the same policy, subsystems are considered as black boxes can therefore support heterogeneity.

The concept is shown by giving an example of a 2-layer microgrid. A discussion on required preconditions gives indications for which type of community such a system would be viable.

The number of subsystems per layer is limited by the DCDC converter's ability to keep the voltage within an acceptable range. Therefore, instead of adding more nodes per layer, higher layers allow inter-community (inter-cluster) connections. I propose three methods of recursively to higher layers by ensuring that loose coupling between layers is maintained. Though this can be best achieved by an approach using gateway converters and buffer batteries between layers, solutions with lower hardware requirements may be preferable in practice.

- **Information Infrastructure: Fully Decentralized Control System**

The second axis proposes a decentralized control system both for the control structure and the control logic.

Three types of control structures based on Peer-to-Peer overlay networks are introduced: A hybrid P2P, a pure P2P and a cloud-based pure P2P approach. They provide the network infrastructure on which the control logic will be running and the actual energy management. Individual configuration and dynamic addition or removal of subsystems is supported (Plug & Play like functionality).

As control logic, an agent-based control paradigm is used in order to pursue digital goals such as improving self-sufficiency by balancing SoC levels. In practice, power deals are negotiated with a request-response approach. A master is dynamically elected among all exchanging units and will be in charge of executing the control procedure and supervise deals. This decentralized algorithm enables autonomous energy exchange within a community and balance demand/response fluctuations.

A vertical software layering is provided to explain how the P2P control structure and Multi-agent based paradigm are implemented and interacting. Loose coupling between goals and software layers increase flexibility, dependability and resilience.

In chapter 5, I verify these research proposals. Indeed a main contribution of this research is that individual mechanisms have been implemented in practice and extensively tested on different environments. A full scale platform made of 19 inhabited houses was used to test the autonomous exchange algorithm for over a year. There, important assumptions could be verified and flexibility was tested by adding and removing nodes dynamically. Resilience against scheduled and unscheduled blackouts is demonstrated: the microgrid continues DC exchange even when islanded from the main grid.

In chapter 6, the control scheme is evaluated through data analysis and simulations. For it, I used annual solar radiation data and demand data from Kyushu and from Okinawa. The impact of the PV / battery size ratio was analyzed, followed by a data analysis using measured power flows from the platform. The measured power flows are compared to simulated power flows using an emulator for physical power flow. Finally, different topologies for the current setup are simulated and performance indicators are calculated: the Self-sufficiency Ratio (SSR) is improved by 4.2% and Solar Operation rate by 8.6%. Since DC exchange can continue during blackouts, emergency scenarios could prioritize certain subsystems in order to keep critical loads running (for the case of Okinawa, up to 16.48 times the energy could be provided to a critical load.

Contribution and findings as well as recommendations for future works conclude this thesis.