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Mobile Virtual Synchronous Machine for Vehicle-to-Grid Applications

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Abstract

The Mobile Virtual Synchronous Machine (VISMA) is a power electronics device for Vehicle to Grid (V2G) applications which behaves like an electromechanical synchronous machine and offers the same beneficial properties to the power network, increasing the inertia in the system, stabilizing the grid voltage, and providing a short-circuit current in case of grid faults. The VISMA performs a real-time simulation of a synchronous machine and calculates the phase currents that an electromagnetic synchronous machine would produce under the same local grid conditions. An inverter with a current controller feeds the currents calculated by the VISMA into the grid.

In this dissertation, the requirements for a machine model suitable for the Mobile VISMA are set, and a mathematical model suitable for use in the VISMA algorithm is found and tested in a custom-designed simulation environment prior to implementation on the Mobile VISMA hardware. A new hardware architecture for the Mobile VISMA based on microcontroller and FPGA technologies is presented, and experimental hardware is designed, implemented, and tested. The new architecture is designed in such a way that allows reducing the size and cost of the VISMA, making it suitable for installation in an electric vehicle.

A simulation model of the inverter hardware and hysteresis current controller is created, and the simulations are verified with various experiments. The verified model is then used to design a new type of PWM-based current controller for the Mobile VISMA. The performance of the hysteresis- and PWM-based current controllers is evaluated and compared for different operational modes of the VISMA and configurations of the inverter hardware.

Finally, the behavior of the VISMA during power network faults is examined. A desired behavior of the VISMA during network faults is defined, and experiments are performed which verify that the VISMA, inverter hardware, and current controllers are capable of supporting this behavior.

Kurzfassung

Die mobile Virtuelle Synchronmachine (VISMA) ist eine leistungselektronische Komponente für Vehicle to Grid (V2G) Anwendungen, die sich wie eine elektromechanische Synchronmaschine verhält und damit zusätzliche Netzdienstleistungen erbringt, wie die Erhöhung der Trägheit im System, Momentanreserve, die Stabilisierung der Netzspannung und die Bereitstellung eines Kurzschlussstromes bei Netzstörungen. Die VISMA führt eine Echtzeitsimulation einer Synchronmaschine durch und berechnet die Phasenströme, die eine elektromagnetische Synchronmaschine unter den gleichen lokalen Netzbedienungen erzeugen würde. Ein Umrichter mit einem Stromregler speist die durch die VISMA berechnete Sollströme ins Netz.

In dieser Dissertation werden die Anforderungen für ein Maschinenmodell zur Beschreibung der mobilen VISMA dargelegt. Dazu wird ein mathematisches Modell für den Einsatz im VISMA-Algorithmus erarbeitet und vor der Implementierung auf der Mobilen VISMA Hardware in einer speziell dafür entwickelten Simulationsumgebung getestet. Eine neue, auf Mikrocontroller und FPGA-Technologien basierte, Hardware-Architektur für die Mobile VISMA wird vorgestellt und eine experimentelle Hardware entwickelt und getestet. Die neue Architektur wird derart konzipiert, dass Größe und Kosten der VISMA verringert werden können, was den Einbau der VISMA in ein Elektrofahrzeug ermöglicht.

Ein Simulationsmodell des Wechselrichters mit einem Phasenstromregler wird entworfen und die Simulationen mit verschiedenen Experimenten verifiziert. Das verifizierte Modell wird verwendet, um einen neuartigen PWM-basierten Stromregler für die Mobile VISMA zu entwickeln. Die Eigenschaften der Hysterese- und PWM-basierten Stromregler werden für verschiedene Betriebsarten der VISMA und für verschiedene Konfigurationen des Wechselrichters untersucht und verglichen.

Schließlich wird das Verhalten der VISMA während Stromnetzstörungen untersucht. Das gewünschte Verhalten der VISMA während Netzstörungen wird definiert und experimentell verifiziert.

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Chapter 1

Introduction

1.1 Motivation

The power distribution system was originally developed using a top-down architecture, where large central generators are responsible for generating most of the power. In this architecture, the flow of power is unidirectional, from the producer to the consumers, and the grid operator is responsible for maintaining power quality throughout the grid. With the deregulation of energy markets and a growing penetration of renewable energy resources, the architecture of the grid has been changing to what is known as a distributed grid. In a distributed grid, there are many small-scale generation facilities, e.g. combined heat and power plants, wind turbines, and solar generators, which vary in size and output power. The principle of power generation in centralized and distributed grids differs significantly, which has consequences on both power quality and grid stability. Whereas large power plants almost exclusively use synchronous machines for power generation, distributed generators often use other generation principles and must be coupled to the grid through grid-tie inverters.

In the coming years, we can foresee a substantial growth in the electric vehicle market, which will influence electric power usage, and, in effect, the power distribution network. Figure 1.1 shows the architecture of a power network with a high penetration of distributed generators using renewable energies (solar, wind) and electric vehicles connected to the grid.

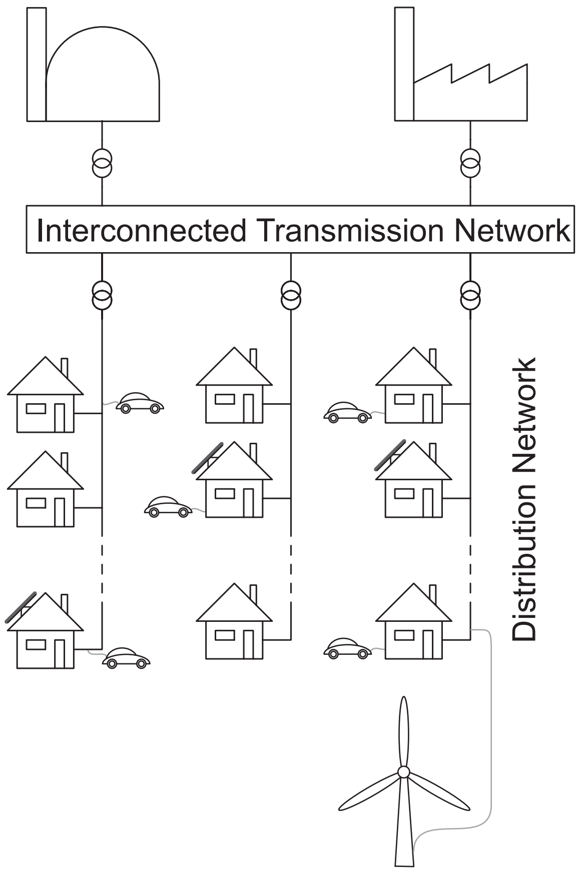

FIGURE 1.1: Architecture of electrical power network with high penetration of distributed generators using renewable energy resources (solar, wind) and electric vehicles

In power generating facilities using synchronous generators, kinetic energy is stored in the rotating mass of the rotor and turbines. This kinetic energy is useful when an unbalance occurs between generation and demand, as the inertia limits the rate of change of frequency of the grid voltage. With a greater penetration of inverter-coupled generating facilities in the power network, the total inertia in the system decreases, which can cause dynamic stability problems. One way to increase the inertia in a power system is to add kinetic energy storage directly, e.g. using flywheel technology, as was suggested in [1]. This concept involves installing synchronous machines coupled with a flywheel in the power network. The problem with this method is the additional cost of installing and maintaining the flywheel system.

At the Institute of Electrical Power Engineering (IEE) of the Clausthal University of Technology, a control concept for a power inverter was invented by Ralf Hesse, which allows the inverter to behave like a synchronous machine, and, like a real