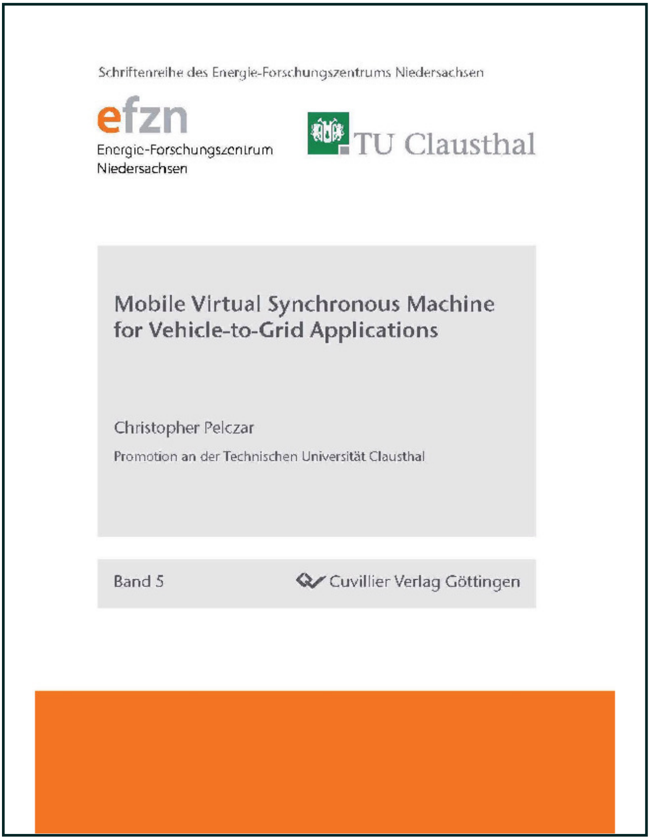
Christopher Pelczar (Autor)

Mobile Virtual Synchronous Machine for Vehicle-to-Grid Applications



https://cuvillier.de/de/shop/publications/60

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.

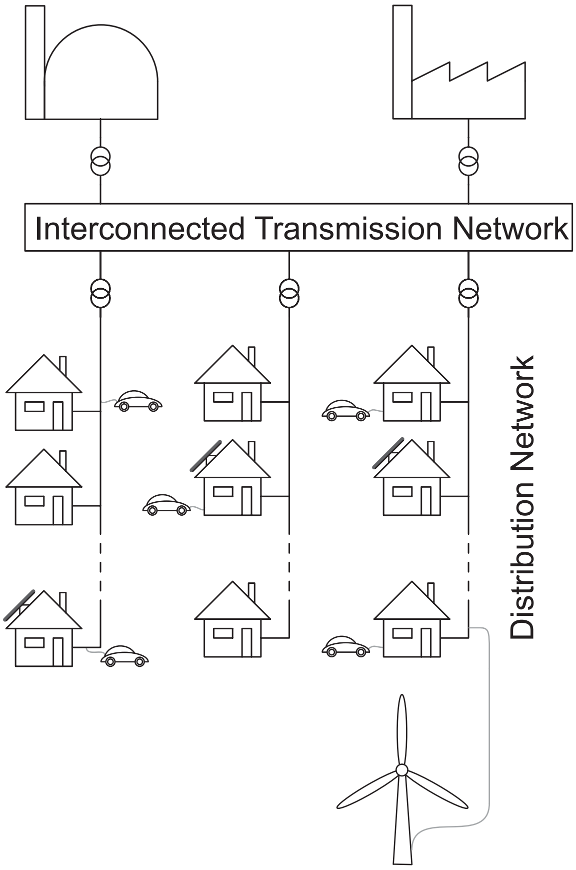


FIGURE 1.1: Architecture of electrical power network with high penetration of distributed generators using renewable energy resources (solar, wind) and electric vehicles

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 synchronous machine, increase the system inertia and provide other features beneficial to grid stability and power quality [2, 3]. The system developed by Hesse is known as a Virtual Synchronous Machine (VISMA). The VISMA performs a real-time simulation of a synchronous machine where the grid voltage is measured and the phase currents that an electromagnetic synchronous machine would produce under the same grid conditions are calculated. A current-controlled inverter then feeds these currents into the grid. With the VISMA, the inverter used by the distributed generator for feeding power into the grid improves grid stability.

Concepts similar to the VISMA have been gaining in popularity recently, and there are several projects worldwide which try to equip inverters with synchronous machine properties in order to increase inertia in the grid and improve grid stability. One of these projects is the Virtual synchronous machines for frequency stabilization in future grids with a significant share of decentralized generation (VSYNC) project [4–9]. The goal of the VSYNC project is to provide virtual rotational inertia to distributed generators by equipping them with intelligent grid-tie inverters with short-term energy storage, allowing them to operate like Virtual Synchronous Generators (VSGs), which, for short time intervals, exhibit some of the desired properties of synchronous machines [8] and contribute to the stabilization of grid frequencies caused by large load fluctuations in the grid [4]. There are two test sites for the VSYNC project, one in the Netherlands with ten 5 kW, single-phase VSGs, and one in Romania with a 100 kW VSG [8].

The power exchange equation of a VSG is given as [5]:

$$P_m = \omega_g \cdot J \cdot \left(\frac{d}{dt} \omega_g(t) \right) \tag{1.1}$$

Where P_m is the mechanical power needed to accelerate the rotating mass with an inertia J, and is equal to the electrical power drawn from the grid by the VSG, and ω_g is the grid frequency. The VSG therefore only models the inertia of a synchronous machine, but does not consider other synchronous machine properties. The VSG feeds power into the grid using a PWM-controlled inverter [8].

Another concept similar to the VISMA is that of the synchronverter [10] conceived by researchers from the UK and Israel. The synchronverter also performs a real-time simulation of a synchronous machine. Unlike the VISMA, which measures the voltages at the Point of Common Coupling (PCC) with the grid and outputs currents, the synchronverter measures the phase currents and uses a PWM-controlled inverter to output voltages equal to the back-Electromotive Forces (EMFs) that a synchronous machine would produce under the same conditions on the grid. The synchronverter synchronous machine model does not include damper windings. Instead, damping in the system is implemented as mechanical damping. Also, the synchronverter machine model assumes that the input to the machine's field winding is a current and not a voltage, simplifying the machine equations. The VISMA, on the other hand, uses a more complex model of the synchronous machine which includes damper windings and voltage input to the field winding. This allows the control of the VISMA as if it were an electromechanical synchronous machine.

Recently a research team from Canada proposed its model of a virtual synchronous machine [11], where the synchronous machine is modeled as a damping and synchronizing torque which are proportional to the rotor speed deviation and rotor angle deviation, respectively. Another team from Japan is investigating VSGs [12] based on VSYNC VSGs [5] expanded to include damping that models the synchronous machine's damper windings.

Compared to the alternatives to the VISMA presented here, which only have a part of the static and dynamic properties of a synchronous machine, the VISMA possesses the complete static and dynamic properties of a synchronous machine [13]. The machine model foreseen by the VISMA concept most closely represents an electromechanical synchronous machine, and the well-known and tested control concepts for electromechanical synchronous machines can be transferred directly to the VISMA.

The concept of the Mobile VISMA arose with the realization that the VISMA can be used for Vehicle to Grid (V2G) applications. A V2G system is a system where a plug-in electric vehicle is used to support the power network when plugged in for charging. Plug-in electric vehicles have energy storage capacity in their batteries, which has many potential applications. The support to the grid offered by electric vehicles may involve the provision of ancillary services e.g. frequency regulation or spinning reserve as well as peak load shaving and reactive power support. Without using some form of smart charging, a growing penetration of electric vehicles can have a negative effect on the power grid, because of the vehicles' high-consumption of electric energy. Uncoordinated charging may increase the power losses in the distribution grid and lead to voltage deviations, which may be unacceptably high, especially during the evening peak [14]. V2G systems can be classified into unidirectional V2G systems [15, 16] (also known as V1G), where the vehicle supports the grid while drawing power to charge the battery, and bidirectional systems, where the vehicle can feed power back into the grid. There are numerous V2G concepts proposed in literature. An overview of some these concepts and an analysis of the profitability of different V2G scenarios with consideration of the effect on battery life can be found in [17].

In the power network energy cannot be stored, and supply and demand must be matched at all times. If supply is greater than demand, an increase in the frequency of the grid voltage can be observed. If supply is smaller than demand, the frequency decreases. One of the problems with renewable energy resources such as wind and solar is that they are non-dispatchable in the traditional sense, i.e. their output power cannot be adjusted to match demand. Their output power depends on weather conditions and can be calculated a day ahead using simulation and prognoses, but it cannot be regulated. The intermittent nature of wind and solar power and the high cost of creating electrical energy storage facilities is one of the main problems for the realization of a reliable power network based on renewable energies. Using V2G technologies, the reliability of power networks with a high penetration of renewable generation can be improved.

The VISMA allows bidirectional transfer of power between the grid and the battery. It can be operated in generator mode, supplying power to the grid, or in motor mode, drawing power from the grid. In the stationary VISMA developed at the IEE, it was assumed that the VISMA would be connected to a renewable energy generator, e.g. solar or wind generator. The VISMA would by default run in generator mode, feeding power into the grid. The mobile VISMA on the other hand is designed to be integrated in electric vehicles, which, with the exception of plug-in hybrid vehicles and vehicles with range extenders, are not equipped with power generating capability and are net consumers of electrical energy. From the vehicle owners point of view, connecting the vehicle to the grid is done to charge the on-board batteries. Any grid stabilizing services which the mobile VISMA may provide should not interfere with this objective and should not lead to a deterioration of the lifespan of the batteries.

In electric vehicles, the most popular batteries used are lithium-ion batteries due to their high energy density. The cycle life of a battery is the number of charge-discharge cycles until its nominal capacity drops below 80% of the initial capacity.

Although the battery may still be usable afterwards, the resulting decrease in the driving range may not be acceptable to the vehicle owner. The deeper the a lithium-ion battery is discharged, the faster its capacity deteriorates. The relationship between the Depth of Discharge (DOD) and the number of charge/discharge cycles for lithium-ion batteries is strongly non-linear, and the cost of storage of energy in the battery in €/kWh decreases significantly for shallow discharge [17]. With the current price of batteries for electric vehicles, using a Mobile VISMA operated in generator mode for services such as peak shaving may not be feasible, but offsetting peak demand can still be accomplished by throttling the charging rate without affecting the battery lifespan. Used in motor mode to charge an electrical vehicle's batteries, the VISMA also has properties beneficial to the grid which include increasing the inertia in the power network and voltage stabilization [18].

1.2 Dissertation Goals and Structure

Three problems are tackled in this dissertation. The first problem is how to create a VISMA system which can be installed in a passenger car, which is a design optimization and system integration problem. The second problem is to design a current controller for the VISMA which will allow feeding in of the currents calculated by the VISMA into the grid with the minimum tracking error. The final problem is to verify the behavior of the VISMA and the current controller during faults in the power network.

The structure of this dissertation is as follows. In Chapter 2 a mathematical model of the synchronous machine is presented which can be used in the VISMA algorithm. In Chapter 3 the design of the Mobile VISMA hardware is discussed. Chapter 4 introduces a simulation model of the Mobile VISMA inverter and hysteresis current controller, and the validity of the simulation model is verified with experiments. In Chapter 5 the developed simulation model is used to design a PWM-based controller for the VISMA. Next, the performance of the PWM-based and hysteresis current controllers is compared in Chapter 6. Chapter 7 examines the behavior of the VISMA and current controllers during power network faults. The results of this dissertation are summarized in Chapter 8.

Chapter 2

VISMA Synchronous Machine Model

This chapter deals with the mathematical model of the synchronous machine that can be simulated on a microcontroller platform in real time. The requirements for the mathematical model of the synchronous machine are introduced, and a brief history of the VISMA is provided with focus on machine model implementation issues. A machine model which is suitable for the Mobile VISMA is introduced and numerical methods for simulation are discussed.

2.1 Machine Model Requirements and Implementation History

There are numerous ways to set up the mathematical equations which describe the behavior of a synchronous machine. For the simulation model used in the VISMA the inputs to the system are the three phase voltages measured at the PCC with the grid, a virtual exciter voltage, and a virtual mechanical torque. The outputs of the simulation are the desired phase currents.

A mathematical model is needed which can be used in a real-time simulation of the machine. This puts limits on the type of solver used for solving the differential equations describing the synchronous machine. The solver should be computationally simple, preferably Euler, to facilitate implementation on a low-cost microcontroller. State-of-the-art microcontrollers used for industrial applications have 32-bit Central Processing Units (CPUs) and Floating Point Units (FPUs) which can handle single-precision (32-bit) floating point numbers, so the simulation should be stable with single-precision floating point variables.

The original VISMA [3] developed at the IEE of the Clausthal University of Technology was implemented on a dSpace rapid prototyping system. The dSpace system allows the graphical modeling of processes using Matlab/Simulink and automatic code generation for dSpace real-time hardware. The machine model was implemented as a block diagram in Simulink, and code for the dSpace system was automatically generated from the Simulink model. The problem with this approach is its lack of transparency. Although the generated code can be successfully executed on the dSpace system, the internal structure of the code remains unknown. The code generated from Simulink can be viewed, but the legibility of the code is poor. Until now, well written manual code can be more efficient than automatically generated code, and it gives the designer more control over the structure and execution sequence of the program.

The first attempt to implement the VISMA on a microcontroller was the Mini VISMA [19]. The program code for the Mini VISMA was written in C and implemented on an Infineon Tricore TC1796 microcontroller [20]. The mathematical model of the synchronous machine used in the Mini VISMA came from the original VISMA as described in [3], and the Mini VISMA used the Euler integration method for solving the machine differential equations.

Two problems were found with the synchronous machine model used in the original and Mini VISMAs. Firstly, the model was not stable when the measured grid voltages were not ideal sine waves or if there was noise present in the measured voltages. The engineers working on the Mini VISMA circumvented this problem by using ideal sine waves as input voltages to the synchronous machine model. These ideal sine waves were obtained using a Phase-locked Loop (PLL) synchronized with the grid voltage. The disadvantage of this method is that some of the dynamic properties of the synchronous machine are lost, as the machine can no longer quickly react to changes in the grid voltage or frequency.

The second problem with the original machine model was that the simulation proved to be stable only if double-precision (64-bit) floating point variables were used in the simulation model. Like most 32-bit microcontrollers, the TC1796 microcontroller used in the Mini VISMA does not have a double-precision FPU, without which mathematical operations on double-precision floating point numbers are time consuming. In the Mini VISMA, the execution of the real-time simulation with a frequency of 10 kHz uses the microprocessor almost to capacity, leaving little time for other tasks.

There is ongoing research at the IEE and Lower Saxony Energy Research Center (EFZN) to improve the machine model used for the VISMA. To check whether a VISMA machine model would be suitable for microcontroller implementation, I created a synchronous machine simulation platform in the C# programming language, where the synchronous machine can be simulated using different solver methods (e.g. Euler, Runge-Kutta) and using variables with different number formats (e.g. single- and double-precision floating point numbers and fixed point numbers). Using recorded grid voltages as inputs, simulations can be performed to evaluate the stability of a machine model for a given solver method and number format. Since the code used for the simulations is written in C#, which has high similarity to C, the VISMA mathematical model and simulation code can easily be ported to C for implementation on a microcontroller.

One synchronous machine model tested by IEE researchers on a dSpace system showed stability with real, measured grid voltages, and does not require the use of a PLL. Using the new C#-based simulation platform, I verified that the model is stable with noisy voltage measurements, using single-precision floating point variables, and using Euler's integration method for the solver, making the model suitable for microcontroller implementation. The simulation model was ported to C for implementation on the microcontroller used in the Mobile VISMA hardware (Infineon Tricore TC1796) and is used in the VISMA algorithm in this dissertation. The details of the mathematical model of the synchronous machine used in this algorithm are presented in the following section. This synchronous machine model is based on the synchronous machine model used in the SimPowerSystems toolbox of Matlab/Simulink and is thoroughly described in [21].