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Technical Report TA User Project

Transient Control in Microgrids

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Abbreviations

DER	Distributed Energy Resource
TA	Trans-national Access
PID	Proportional-Integral-Derivative Controller
VSI	Voltage Source Inverter

Executive Summary

The focus of the proposed research lies on transient control in weak low- and medium-voltage grids with a large amount of distributed generation. A novel optimization-based control design method is presented that makes it possible to tune the controllers of any number of VSIs in a single step, and guarantees closed-loop stability and performance. A main difference compared to existing methods is that only the frequency response of the plant is required for the design. This makes it possible to use very detailed and high-order models without increasing the complexity of the design process. Common performance specifications such as rise-time, maximum overshoot or decoupling are formulated as constraints on sensitivity functions, which allows for an intuitive but powerful problem formulation. The method also makes it possible to guarantee robustness towards plant modeling uncertainties and parameter changes using a multimodel approach.

To validate the performance of the developed approach, a realistic case study of a low-voltage distribution grid with multiple photovoltaic (PV) units is considered. The method is used to tune current controllers for the VSIs of the PV units, and the results are validated in numerical simulation as well as in an experimental fashion using a three-phase power-hardware-in-the-loop (PHIL) setup at NTNU Trondheim.

General Information of the User Project

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1 Research Motivation

In recent years, the increase in distributed generation, distributed storage and drive loads has significantly increased the proportion of power electronic devices in distribution grids. These devices are commonly connected to the grid through voltage source inverters (VSIs) with passive output filters. A desirable filter structure is the LCL filter, which exhibits many advantageous features. However, LCL filters also introduce new resonance frequencies to the system, which must be dampened. Furthermore, connecting multiple VSIs with LCL filters to the same grid introduces new coupling resonances in a range from hundreds of Hz to a few kHz that may result in harmonic instability if not taken into account during the current controller design.
Many active damping methods for single VSIs have been proposed in the literature. A common approach is to introduce active filter elements to the feedback loop, and tune the parameters based on the model of a single-inverter infinite bus system. However, using a single-inverter model neglects all coupling dynamics in the grid, and there is no guarantee for stability or performance in a system with multiple VSIs.
Furthermore, controller parameters are generally tuned using iterative approaches, where stability is evaluated a posteriori based on high-order small-signal models. A drawback of this approach is that for systems with large numbers of generation units the plant order and the number of design parameters becomes very high, which makes it difficult to tune all variables in an efficient manner. Furthermore, reaching explicit performance specifications is challenging when using manual tuning methods.

1.1 Objectives

The goal of this research project is to validate a new control design method that can be used to design VSI controllers that guarantee stability and robust performance. The method is based on convex optimization and makes it possible to tune the controllers of any number of VSIs in a single step. It is also possible to guarantee robustness towards plant modeling uncertainties and parameter changes. An important difference compared to existing methods is that only the frequency response of the plant is required for the design. This makes it possible to use very detailed and high-order models without increasing the complexity of the design process.

Preliminary results from numerical simulation are promising, but a lot of nonlinear dynamics have to be neglected in simulation.
Therefore, the objective of this project is to validate the obtained simulation results using a PHIL setup with multiple real VSIs. Such a setup is almost equivalent to the situation encountered in a real grid, and proves the applicability of the proposed method in an industrial setting.
The experimental results can also be used to indirectly prove the validity of the transfer function model used for the control design, which is a secondary objective of the test.

1.2 Scope

The scope of this project focuses on the device-level control of VSIs. The timescale of the controller is on the microseconds to milliseconds range, and generally there is no communication between different VSIs (although the proposed method could also be used to design distributed controllers).

2 State-of-the-Art/State-of-Technology

Many active damping methods for single VSIs have been proposed in the literature. A common approach is to introduce active filter elements to the feedback loop, and tune the parameters based on the model of a single-inverter infinite bus system. A comprehensive review of the state-of-the-art methods is given in [1]. However, using a single-inverter model neglects all coupling dynamics in the grid, and there is no guarantee for stability or performance in a system with multiple VSIs.

In [2] [3] [4] a state-space model of the complete system is constructed, and the resonance modes are classified based on modal participation factors. A drawback of this approach is that accurate representations with multiple generation units lead to very high-order models which become difficult to analyze. Another avenue is to use impedance-based transfer function models and frequency-domain analysis methods [5] [6] [7]. These approaches break the system into interconnected component models that are easier to handle than a complete model. Various approaches for tuning the current controllers of any number of parallel PV inverters are presented in [8] [9], however the stability analysis assumes that all inverters are identical. In [10] a multivariable transfer function model for grids with multiple VSIs is developed, and it is shown that the model can be used for stability analysis through Nyquist diagrams. The modeling approach is further used in [11] [12] to derive various design rules for proportional controllers based on root locus curves.

Attempts have been made to apply classical robust control design methods to the problem [13] [14] [15] [16]. This allows to guarantee robust stability and performance, and makes it possible to design higher-order controllers that would be very challenging to tune manually. Furthermore, in [17] [18] a method is proposed to design controllers that are robust towards parametric uncertainties in the plant model. A major drawback is that these methods require a state-space model of the system, but don't scale well with the number of states. This means that even moderately sized problems become very hard to solve efficiently. This limits the applicability of the methods in practice.

3 Executed Tests and Experiments

The experiment serves to validate the performance of the designed current controller on an experimental setup.

3.1 Simulation Setup

Based on a real case, in Fig. 1a) a rural 50~Hz/400~V distribution grid with four inverter-interfaced PV generation units is shown (for simplicity, the loads and the DC-side dynamics are neglected). As is often the case in this type of grid, if power generation is high the VSI buses suffer overvoltage problems. Also, since the lines are mostly resistive, reactive power injection has almost no effect on the voltage level. To resolve this issue, a Line Voltage Regulator (LVR) is added to the grid, which is tap-changing transformer that becomes active whenever an overvoltage situtation is detected. However, the LVR also increases the inductance of the line, which has a significant impact on the electromagnetic dynamics of the grid. For simulation, the LVR is modeled as an R-L element using the simplified equivalent circuit transformer model.

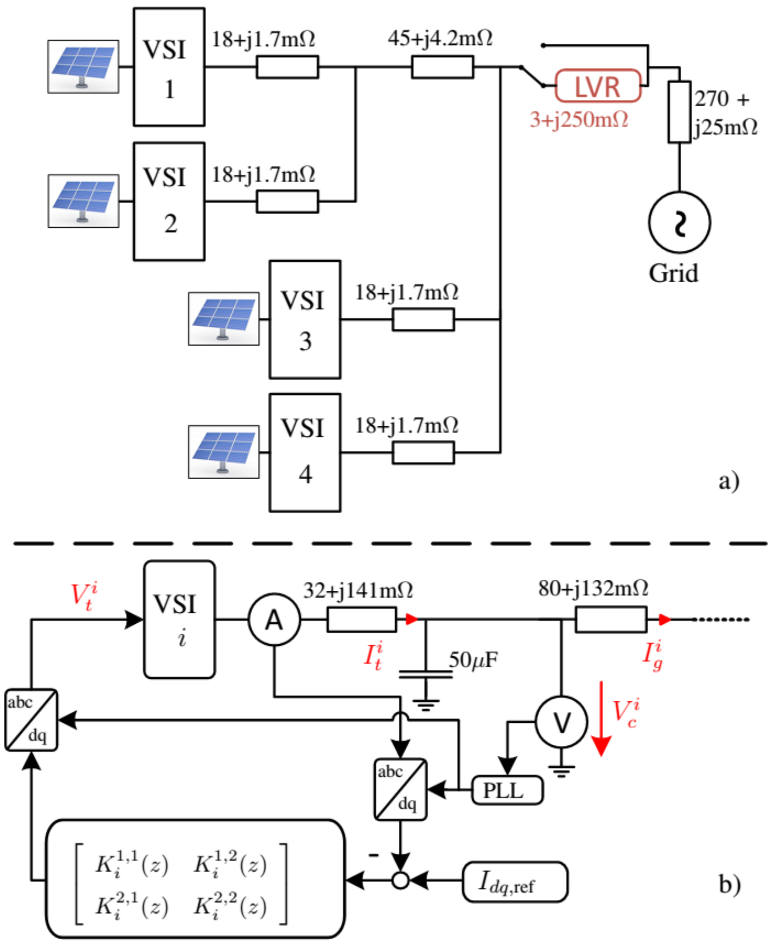


Figure 1. Electrical one-line diagrams: a) a rural distribution grid with 4 identical VSIs and a Line Voltage Regulator (LVR), b) the output filter configuration and controller block diagram of the VSIs.

Figure 1b) shows a single-line diagram of the output filter and current controller structure of an individual VSI, where K_i is the 2x2 transfer function controller of VSI i (traditionally a PI controller). A second-order generalized integrator based PLL (SOGI-PLL) is used due to its favorable robustness properties. The simulation is performed in Simulink using the Simpower toolbox. An averaged model is used for the VSIs, and the switching and DC-side dynamics are neglected.

3.2 Control Design

A novel frequency-domain, fixed structure control design method is used to design current controllers for all four VSIs in a single step. A full theoretical exposition of the method can be found in [19].
A decentralized, multivariable 4th-order controller with a sampling frequency of 10~kHz is designed, where every VSI has access only to its local current measurements. The structure of each controller is analogous to a 2x2 PI controller with filters. The final controller of each individual VSI contains 28 tunable parameters, which allows for many degrees of freedom during the design, but would be very difficult to tune manually. This demonstrates well the benefits of using an optimization-based approach.
The controller should satisfy the following performance specifications for both grid configurations (without and with the LVR):

1. Closed-loop bandwidth of at least 500 Hz
2. Small overshoot
3. Robustness towards modeling errors
4. Good decoupling of currents in d and q axis

The first and fourth specification are achieved through the following objective function:

$$\min_{X,Y}(\max(\|W_1 S_1\|_\infty, \|W_1 S_2\|_\infty)) \ , \ W_1 = \left(\frac{s\,\omega_{bw}}{s+\omega_{bw}}\right)^{-1}\mathbf{I}$$

where $\omega_{bw} = 2\pi \cdot 500$ is the desired closed-loop bandwidth and S_1, S_2 are the sensitivity transfer functions for both grid configurations.
The second and third specification are satisfied by placing a constraint on the closed-loop sensitivity T:

$$\|W_2 T_2\|_\infty < 1 \quad \|W_2 T_1\|_\infty < 1 \ , \ W_2 = \left(1.1\frac{\omega_{bw}}{s+\omega_{bw}}\right)^{-1}\mathbf{I}$$

Finally, a constraint is placed on the input sensitivity U to prevent input saturation:

$$\|W_3 U_1\|_\infty < 1 \ , \ W_3 = (5.5B)^{-1}\mathbf{I}$$

$$\|W_3 U_2\|_\infty < 1$$

where B is a second-order discrete-time Butterworth low-pass filter with a cutoff frequency of 2500 Hz. These constraints are combined to formulate the following robust control design problem, where γ is an auxiliary scalar variable:

$$\min_{X,Y} \gamma$$

$$\text{subject to:}$$

$$\|W_1 S_1\|_\infty < \gamma \ , \ \|W_1 S_2\|_\infty < \gamma$$

$$\|W_2 T_1\|_\infty < 1 \ , \ \|W_2 T_2\|_\infty < 1$$

$$\|W_3 U_1\|_\infty < 1 \ , \ \|W_3 U_2\|_\infty < 1$$

In [19] it was shown that this non-convex problem can be reformulated as a convex optimization problem, which can be solved iteratively to obtain a locally optimal solution of the original problem. The optimization is solved in Matlab using Yalmip and Mosek. The algorithm takes around 30 minutes to solve on a standard laptop computer in our simple implementation.

3.3 Test Set-up(s)

The following figure depicts the setup of the PHIL experiment.

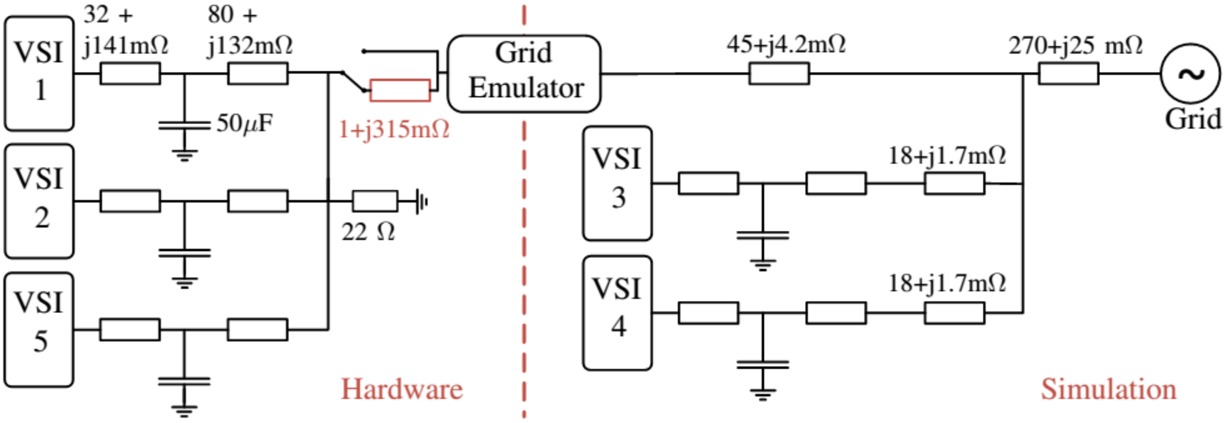


Figure 2. One-line diagram of the PHIL setup. The output filter impedances are identical for all VSIs.

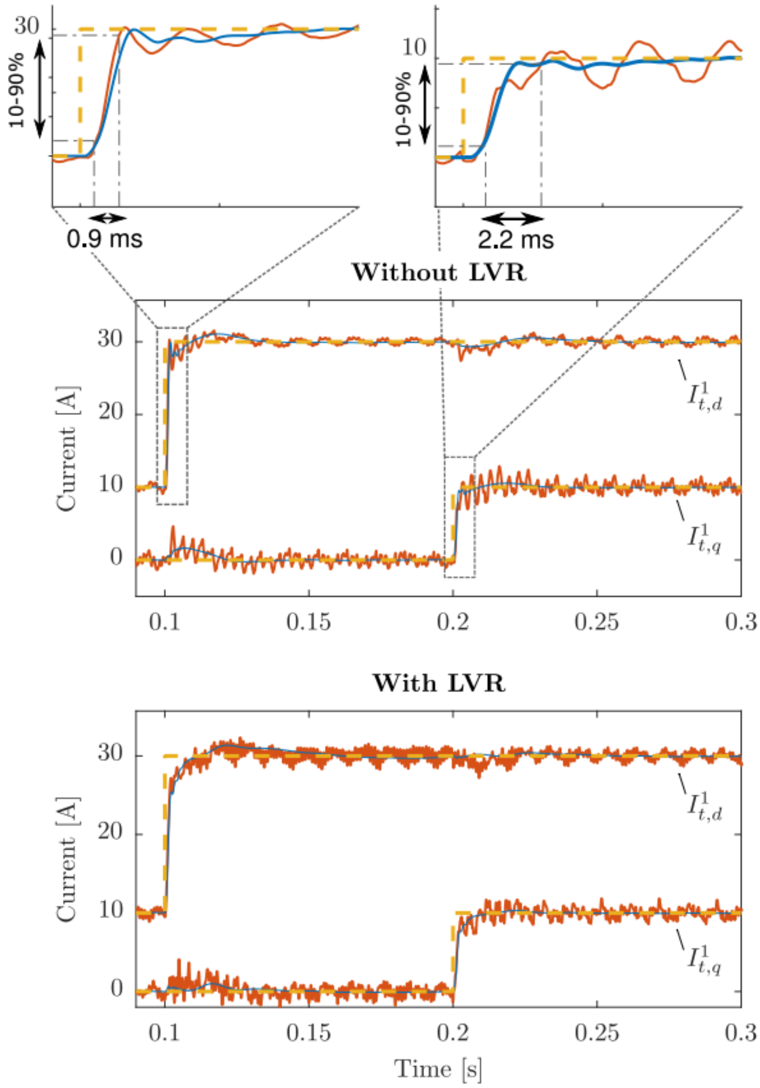
The hardware side comprises of 3 real VSIs and an inductor Z_{LVR} which represents a transformer that can be added or removed from the grid. The grid emulator is a 200 kW high bandwidth grid emulator (EGSTON-COMPISO). The three 2-level inverters are custom-designed prototypes with a rating of 60 kVA at 400 V ac (line-to-line RMS) and 700 V dc. They are identical in construction and are based on Semikron integrated IGBT modules. The converter terminals include an LCL filter on the ac side, and a dc bus capacitor with a capacitance of 4 mF. They are isolated from the grid though a decoupling transformer, the impedance of which is included in the grid impedance of the filter. The control of the converters is implemented entirely in the OPAL-RT platform where a custom programmed FPGA dedicated to sampling and conditioning of the measurements and to the generation of the gate signals is also included. The inverters are connected to the same busbars both on the dc and ac side.

3.4 Test Plan

The controller is validated by recording the step response of the output currents of the real inverters. Once the controller implementation has been verified in simulation on the HIL setup, the real VSIs can be added, and the step response can be recorded. Since we are interested in sub-second transient dynamics, the actual runtime of the experiment is less than a minute.
The obtained step response is then compared with the simulation results, and the obtained performance is compared with the specifications defined during the control design.

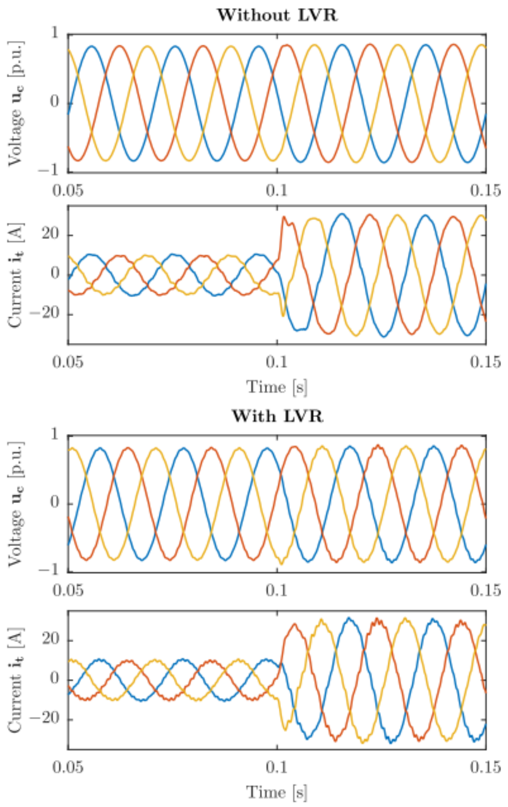
4 Results and Conclusions

The experiments were conducted successfully, and the controller performance in a realistic experimental setup was validated:



The step response of the inverter current of VSI 1 without and with the LVR is shown in red in the figure above. It can be seen that the designed current controllers are able to guarantee the stability for both grid configurations in a PHIL setting. The obtained performance is very close to the simulation results (shown in blue), which proves the performance and robustness of the designed controller.

The following figure shows the measured three-phase voltage and current during the steps. It can be seen that the waveforms are smooth, with some minimal distortion resulting from nonlinearities and switching dead-times.



5 Dissemination Planning

The results has been submitted to IEEE Transactions in Power Electronics, which is a high-impact journal in the field. A detailed dissemination of all results will be included in the PhD thesis of Christoph Kammer, which will be accessible to the public in Summer 2018.
The thesis is also part of the SCCER-FURIES project, which is a national project comprised of many academic and industrial partners with the goal of developing new technologies and strategies to satisfy the requirements of the Swiss Energy Policy 2050. The results of the conducted experiments will be made available to all partners of the project and was presented in dedicated workshops.

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