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Technical Report TA User Project

TEAM-VAR 2

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Executive Summary

Future power distribution networks will be characterized by distributed and intermittent microgeneration, charging facilities for a widespread electric mobility infrastructure, and increased overall demand subject to strict reliability specifications. Grid congestion is expected to occur increasingly often, and the operational constraints of the grid (e.g. over- and under- voltage limits) will become a bottleneck to the efficient implementation of this transition.
An extremely promising avenue consists in exploiting the electronic power converters available at every micro generator as a finely distributed network of reactive power compensators. If properly controlled, these devices have the potential of regulating the feeder voltage profile, increasing grid efficiency, and ultimately extending its hosting capacity without any structural reinforcement.
Purely local real-time control strategies for these devices have been proposed and are getting incorporated in grid codes and industrial practice, given their modularity and their simple deployment. Fully centralized solutions, where a central control unit has access to the entire system state and can dispatch optimal reactive power set-points to each device, are deemed as non-scalable and impractical, due to the large amount of measurements that they require.

The proponent of this project has recently shown that purely local strategies are provably suboptimal: they might fail to drive these devices to reactive power set-points that guarantee satisfaction of the voltage limits, even if such feasible set-points exist. Moreover, he showed that optimality can be recovered by just adding a minimal amount of peer-to-peer communication between these power converters, without any monitoring of the load demands or of the grid state.

The proposed research aimed at giving a proof-of-concept demonstration of this fundamental result in a real test feeder, i.e., a portion of distribution grid that hosts both micro generators and loads. Different (local / distributed / centralized) real-time reactive power compensation strategies have been tested in order to obtain an exhaustive characterization of the trade-off between communication complexity and performance.

Multiple conclusions can be drawn based on the collected data:

- even in a relatively simple and small distribution feeder, power generation from renewable sources (wind and solar) may need to be curtailed because of overvoltage contingencies;
- as predicted, purely local controllers can barely mitigate this problem; the reactive power capability of the generators that experience overvoltage are generally limited and insufficient to regulate the voltage;
- model-based approaches, based on the centralized solution of an ORPF problem, has limited applicability because of the model uncertainty and measurements errors;
- networked solutions exhibit the cooperative behaviour that was expected, therefore unleashing the full potential of a distributed network of reactive power compensators;
- local controllers can make the overvoltages worse leading to an even higher curtailment of renewable power infeed;
- the networked controller is very robust and needs nearly no model information, which enables a plug and play rollout to the power grid;
- a distributed implementation without a central unit was implemented and performed well;
- triggered by the physical experiments we numerically analyzed the scalability of the control approach. It scales well with the number of inverters on the grid;
- furthermore, we found out that one should perform as many communication steps in between actuations steps as possible;

1 General Information of the User Project

User Project

User Project Acronym	TEAM-VAR 2
User Project Title	Networked feedback control of distributed energy resources for real-time voltage regulation
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TA Call no.	4
Main scientific/technical field	Distributed control
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Access provider

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Installation	PowerLabDK / SYSLAB
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2 Research Motivation

Future power systems will be characterized by a large penetration of renewable energy sources, typically characterized by intermittent and partially unpredictable behaviour. As an aggregate, these sources have already happened to cover three quarters (and more) of the total power demand of a regional grid. One of the main challenges connected to this shift is that the vast majority of these sources are connected to the distribution grid, rather than the transmission grid where traditional generation takes place.

Meanwhile, technological advances and policy changes driven by environmental concerns are promoting the widespread adoption of plug-in electric vehicles in the near future. The charging stations of these vehicles will introduce an unprecedented power demand on the distribution grids, because of their peak power consumption and of their unique spatial-temporal patterns.
It is believed that current power distribution networks will need a structural reinforcement in order to host these new classes of consumers while ensuring that the complex physical constraints of the grid (voltage limits, power line capacity, voltage stability) are satisfied.

This project challenges such ideas.

It contributes to the development of control strategies for the real-time actuation of the grid based on the measurements obtained from a distributed sensing infrastructure, exploiting the unused flexibility of the available power converters.

2.1 Objectives

The project aims at validating a control approach that departs from both the traditional model-based optimization that is currently employed for the management of power systems, and from the simplistic, purely local, control strategies which have been recently proposed in the literature, and have even appeared in grid code drafts. It is a real-time feedback strategy, therefore robust against parametric uncertainty and unmodeled disturbances, and superior with the respect to dynamic control loop performance. Most importantly, it is a networked strategy, i.e., it enables coordination and cooperation between the different converters, in order to drive their operation to an optimal configuration in which all voltage constraints are satisfied.

The experiments proposed in this project have the potential of validating, in a proof-of-concept prototype, a two-fold fundamental claim:
1. Communication between converters is necessary for effective voltage regulation
2. Scalable distributed communication architectures are as good as centralized ones

These results have far-reaching implications, in terms of specifications for the design of smart distribution grid infrastructures. In line with ERIGRID goals, this project shows how it is possible (and necessary) to analyse and evaluate the complex interactions that emerge in these cyber-physical systems.

From a technological point of view, the results of this project will provide sound underpinnings to the engineering on the communication architecture of this new generation of distribution grids. As of today, many competing solutions are being considered, but a rigorous analysis of the implications of these choices for the overall performance, reliability, and efficiency, of these systems is often overlooked. This project shows how this analysis is possible, and how it should be performed.

Ultimately, the scientific and technological results of this project will contribute to the development of methodologies and tools for the virtual reinforcement of distribution grids, yielding larger hosting capacity via an efficient use of the available physical infrastructure, removing the bottlenecks for larger diffusion of electric mobility, higher penetration of distributed microgeneration from traditional and renewable sources, and superior grid reliability.

2.2 Scope

The project’s scope spans different domains: the local control of power converters, the sensing infrastructure, the algorithmic aspects of a network-wide control strategy, and the communication layer that allows exchange of information between individual units.

As the experiments aims at identifying the fundamental trade-off between control performance and communication complexity, it will mostly focus on the ICT (communication and control) domain. It is assumed that local DERs can accept reactive power set-points from the control algorithm under test, and that accurate voltage measurement are available both for feedback control and for monitoring/logging purposes.

The low-level control of different devices (batteries, PV panels, converters, etc.) that allows the device to inject the commanded reactive power reference is outside the scope of the project.

State estimation is outside the scope of the project, as complete observability of the grid state is guaranteed by the redundant sensor architecture.

The communication strategy (and in particular whether communication between DERS is allowed) is within the scope of the project, while the communication protocol and implementation are not.

3 State-of-the-Art

Traditionally, the main task of the power distribution grid was to deliver power from the transmission grid to the consumers, in a mono-directional fashion. Proper operation of these grids has therefore been mostly a planning/design problem (*fit-and-forget*) for the distribution network operator, based on a worst-case analysis of the power demand. However, today's power distribution grid is witnessing unprecedented challenges [1][2][3] including a large penetration of distributed micro generators from renewable power sources and a larger diffusion of electric mobility.

Because of that, a fit-and-forget approach will not suffice any more. In particular, the voltage profile of low and medium voltage networks is affected by these bidirectional active power flows, and both overvoltage and under voltage conditions are expected to happen increasingly often.

An avenue that is currently being explored consists in providing micro generators with sensing and computation capabilities, and to exploit the flexibility of their power electronic interface to inject (or draw) reactive power from the grid. If properly controlled, these devices can act as **a finely distributed network of reactive power compensators**.

Because of the lack of full state monitoring of the distribution grid, most of the efforts towards reactive power control for voltage regulation have focused on **purely local feedback strategies**. According to these strategies, the reactive power injection of the power inverter is adjusted based on real time measurements that can be performed at the point of connection of the power inverter to the grid [4]. Different variations have been proposed. In most cases, the reactive power reference is computed as a static function of the measured voltage amplitude, often with a dead band and/or saturation [5]. Since the former strategies could lead to oscillatory behaviours, smoother incremental algorithms have been also proposed [6][7]. In some strategies, the static feedback is complemented by a feed-forward term, function of the local active and reactive power demand [8]. In other works, the authors build a separable cost function and then perform a gradient projected descend, until they reach the equilibrium [9]. Finally, a local incremental controller has been proposed in [10]. Purely local reactive power control strategies have also been considered for inclusion in the latest revisions of some distribution grid codes [11][12].

At the complete opposite of the spectrum, in terms of communication complexity, we can find **centralized solutions** which directly descend from widely adopted (and well understood) optimal power flow (OPF) techniques used by transmission grid operators. In fact, if the entire state of the distribution grid is monitored in real-time and is promptly available to a central controller, it is possible to formulate a large-scale optimization problem to compute the best set-points for the reactive power injection of each micro generator. The literature on the application of OPF tools to distribution grids is quite vast, and a recent review is available in [13][14]. OPF-based solutions can be considered as benchmark strategies, as they return – by definition – the optimal working point of the grid, at the cost of complete communication and exact knowledge of the system state.

In a very recent paper by the proponent of this project [15], it has been shown that purely local strategies are provably suboptimal. In other words, given a distribution grid, it is possible to construct practical cases in which the voltage regulation problem is feasible (i.e., there exists a solution to the OPF problem), but purely local controllers would fail to drive the grid to that solution. This result introduces a **fundamental trade-off** between communication complexity and control performance, and the aforementioned strategies lie in opposite corners, as depicted in the figure.

A crucial question is therefore the following: “**How does this communication-performance trade-off look like?**”

In particular, a rigorous understanding of what performance can be achieved with a minimal, but strategic, amount of communication, is still largely missing. Networked control strategies for voltage regulation have been proposed (see for example the references in [16]), but they still have not found their position in this communication-performance plane. Given the technological implications of this assessment, answering this question is a timely and relevant goal in this field.

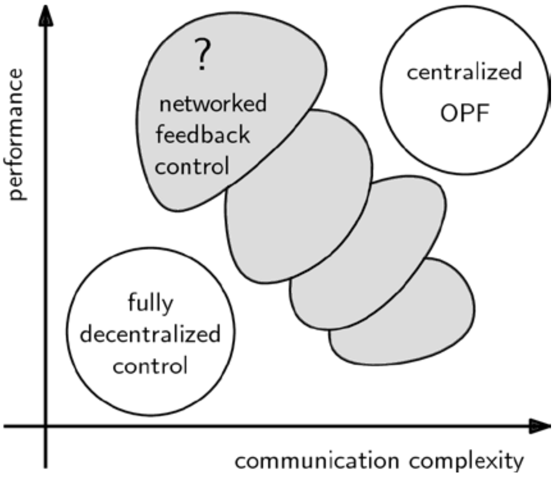

Figure 1: Tradeoff chart in performance / communication complexity domain

4 Executed Tests and Experiments

4.1 Test Plan

The experiments were executed as stated in the description of the project, in order to have a structured way to approach the problem in the available time frame. The whole investigation was organized into three sub-experiments.

Experiment 1 – Benchmark scenario
The goal of this experiment is to identify a benchmark, i.e., a grid topology so that, in the presence of typical generation and power demand patterns, under- and/or over- voltage phenomena are observed if reactive power is not controlled.

Experiment 2 – Suboptimal local Volt/VAR control
A set of local reactive power control algorithms was run in Experiment 2. The goal of this experiment is to validate the fact that purely local reactive power control policies (i.e. based on local voltage and reactive power measurements, without communication) cannot regulate the feeder voltage profile to the desired level, even if the problem is feasible (that is, there exist reactive power set-points for the power converters that achieve so).

Experiment 3 – Networked Volt/VAR control
The goal of this experiment is to show how a networked feedback control law, in which the reactive power injection of each converter is controlled based on both local voltage measurements and information coming from other converters, can perform practically as good as the benchmark ORPF solution.

Experiment 4 – Distributed networked Volt/VAR control
The goal of this experiment is to implement a distributed networked controller that controls the voltage without a central unit. It is supposed to show that communication between neighboring converters is sufficient to enable an optimal reactive power dispatch.

Table 1: Planned and actual experiment schedule.

	Week 1	**Week 2**	**Week 3**	**Week 4**
Planned Experiment	1	2/3	3	4
Actual Experiment	1	2/3	3	3/4

4.2 Standards, Procedures, and Methodology

Multiple tasks preceded the actual experiments. These tasks consisted of

- designing a candidate test grid topology
- implementing the desired test grid topology in the test system
- completing the software interface between the centralized MATLAB controller and the low-level java code which controls the components directly
- validating a grid model that was developed during TEAMVAR 1

During the four experiments, the relevant configuration (no control, local control, networked control, distributed control) was implemented and executed for repeated time windows of 10 to 22 minutes. Time series of all the relevant grid quantities (voltage, active and reactive power) at all the components' connection to the grid and at every bus bar were collected in a centralized location. For experiments 2 and 3 the controllers were implemented in a centralized Matlab instance, where set points for all the reactive power compensators were computed in 10 second intervals. For experiment 4 the controller was implemented in Python and was running on the computer connected to the power converters. The communication between the computer was implemented through zeromq.

In order to induce the mentioned voltage violation, the active power injection at the end of the feeder was set to a constant value. The overvoltage band was defined to be 5% over the nominal voltage. This allowed the possibility of overvoltages which did not trigger safety measures of the connected devices which act at 10% overvoltage.

4.3 Test Set-up(s)

The following is a brief overview of the grid components and the grid topology.

Table 2: Overview of the used components.

Component	**Controllable**	$P_{max}[kW]$	lim $[kVAr]$ Q
PV 1	Yes	10	± 6
PV 2	Yes	10	± 6
Vanadium redox battery	Yes	15	± 10
Static load	Yes (but kept constant)	48 (used at 12)	0

Using the components in Table 1 a simple linear feeder was created by using the remote tool for breaker operation. The base case in order to show the benefits of the proposed controller, consists of at least two nodes with devices that can control reactive power. In order to show the benefits of a controller with communication, only the devices at the end of the feeder should register a voltage violation and react to it whereas the voltage at the device close to the grid connection is within the bounds.

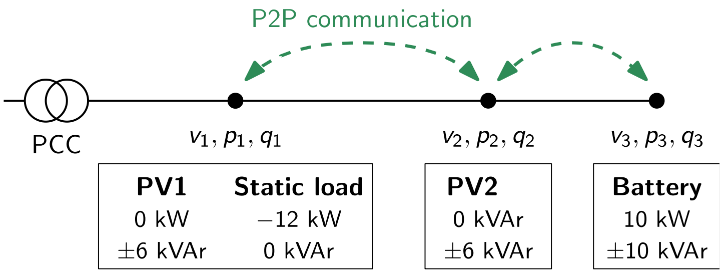

Figure 4: The grid topology adopted as a benchmark for the experiment.

The grid topology used during the experiments is depicted above in simplified manner. At node 3 a large amount of active power is generated. The static load is taking this power up and is drawing power from the grid connection at the point of common coupling (PCC). The PV panels at node 1 and node 2 are passive, meaning that they do not inject any active power. Since node 2 and 3 are separated by a rather long line/weak connection and the connection between 1 & 2 is short/strong, nodes 1 & 2 will be at a similar voltage, while the voltage at node 3 will be significantly higher.
This deliberately simple grid topology allows to maintain a complete understanding of the fundamental reasons that prevent local controller from being effective. To ensure consistency in the results, this grid topology and the described voltage behaviour in the grid were used to test all of the control algorithms.

MATLAB was used as a central controlling unit. All the measurements were brought in, control outputs computed and then sent to the grid devices via java interface. The whole java platform was already in place and used in many different experiments before this one, whereas the MATLAB controllers were implemented specifically for the ongoing investigation. For the purely local controllers, the controllers were run independently for every device in the grid not knowing the status of any other component. For the centralized controller the voltages at all generators were communicated to the centralized controller which then calculated the new reactive power set points for the generators which were then communicated back to the generators.

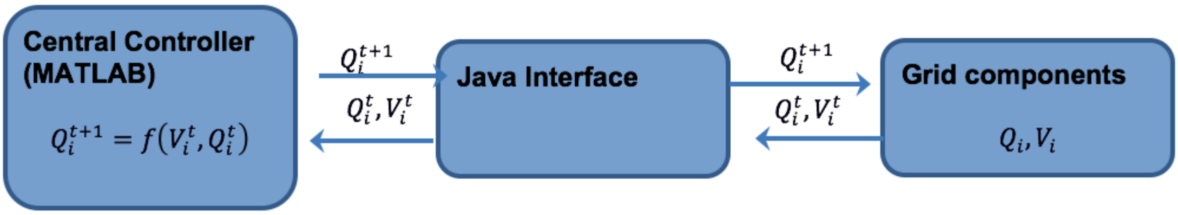

Figure 7: Schematic illustration of the controller architecture

4.4 Data Management and Processing

An architecture for data collection and archiving was already in place and allowed logging of all the measurements from all components and bus bars in 1 second intervals. These measurements range from the typical grid state measurements like voltage and current to individual component measurements like wind speed for the wind turbine or SOC for the battery.

These measurements were saved in an HDD file, facilitating post-experiment visualisation of the grid states and of the control sequences, and also enabling verification of the results against the grid simulator.

5 Results and Conclusions

The following experiment-specific results can be reported at this time, before an accurate analysis of the recorded experiments is completed.

Experiment 1

- A suitable scenario (i.e. grid topology, power generation set points, loading) capable of inducing overvoltage contingencies (and therefore, indirectly, curtailment of renewable generation) was identified. A deliberately simple grid configuration was selected in order highlight the complete generality of this phenomenon, and to provide a benchmark for the rest of the experiments. This benchmark is also valuable *per se*, as an example of distribution grid *congestion*.

Experiment 2

- Local controllers were generally simple to tune, but most of the time ineffective. As predicted in the preparation of the experiments, the reactive power capability of individual devices is often insufficient to regulate its voltage, and therefore the control action will often saturate at the maximum allowed set point, see Fig. 4. Proportional-integral strategies didn't exhibit any relevant difference in performance.

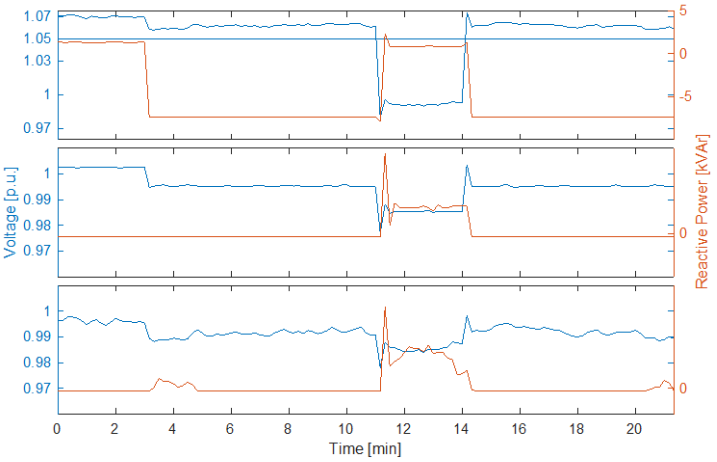

Figure 4: Performance of local droop control as supposed in the new grid standard.

Experiment 3

- The networked algorithm proposed in [15] was implemented and tested. The computational complexity was minimal, and compatible with the available communication infrastructure and time sampling.
- The networked solution exhibit the cooperative behaviour that was expected, therefore unleashing the full potential of a distributed network of reactive power compensators; DERs which were not experiencing overvoltage were commanded to inject power based on the information shared by other devices which could observe a voltage contingency (but were not able to counteract it). See Fig. 5.
- The controller tuning was easy and intuitively.
- The networked controller was very robust to noise and model uncertainty. Furthermore, the controller still performs well with only minimal model knowledge. More accurately, only the sensitivities of the voltages with respect to a change in the reactive power infeed needs to be known. This enables a plug and play rollout to the grid.

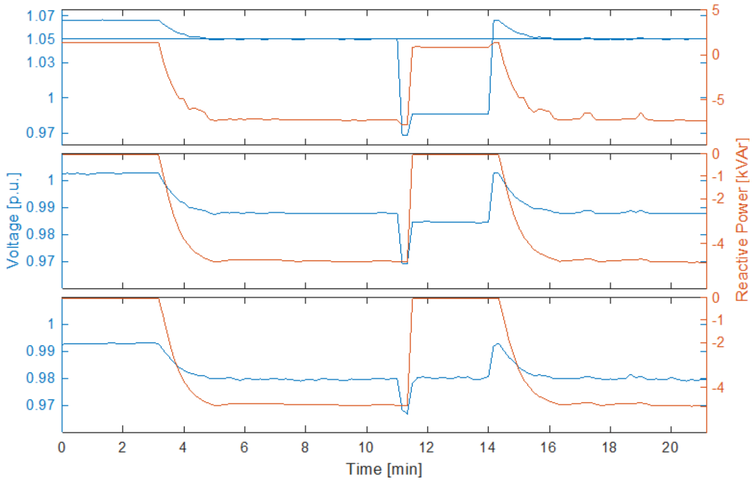

Figure 5: Performance of centralized networked controller

Experiment 4

- The distributed implementation of the controller proposed in [15] performed equally to its centralized implementation of experiment 3, see Fig. 6.
- The amount of communication to solve the optimization problem from which the control decision arises was compatible with the available communication infrastructure.
- The experiment showed, that neighbour to neighbour communication is sufficient to recover optimality of the reactive power dispatch.
- triggered by the physical experiments we numerically analyzed the scalability of the control approach. It scales well with the number of inverters on the grid;
- furthermore, we found out that one should perform as many communication steps in between actuations steps as possible;

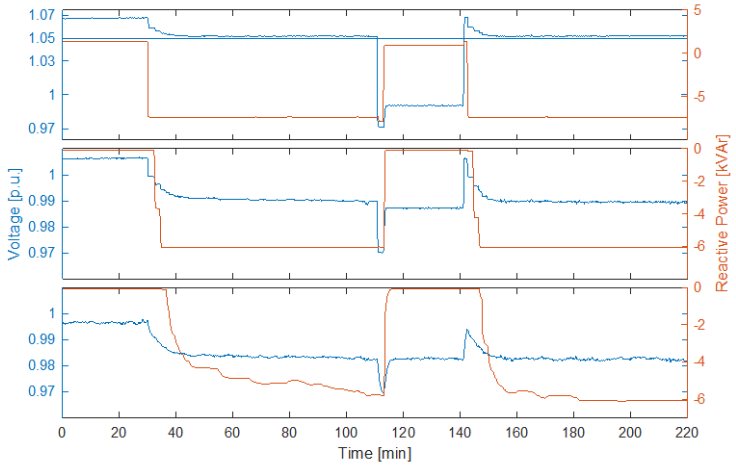

Figure 6: Performance of the distributed network controller.

6 Open Issues and Suggestions for Improvements

For the distributed networked controller the devices need to know who their neighbours are. It is an ongoing research area to determine the location of a device on a feeder given minimal information.

In the case of a persistent overvoltage the networked controller experiences a windup of the dual variables. This is a well-known behaviour of integral controllers. An anti-windup can easily be implemented for the centralized implementation. For the distributed controller implementation such an anti-windup scheme has to be found.

7 Dissemination Planning

Using the results obtained with the data that we gathered during the research stay we submitted two papers to the Power Systems Computation Conference [17], [18].

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9 Annex

9.1 List of Figures

9.2 List of Tables