Microgrid Positioning (uGrip)

Final report

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1. Introduction

Table 1.1: Overview over the project background. Source of file number: [ERA-NetSmartGridsPlusMicrogridPositioninguGrip2015]

Project title	*Microgrid Positioning*
Project identification (program abbrev. and file)	*uGrip* / 77229
Name of the program which has funded the project	ERA-NET SmartGrids Plus
Project managing company/institution (name and address)	University of Zagreb, Faculty of Electrical Engineering and Computing (*FER*)
Project partners	Technical University of Denmark (*DTU*), OFFIS Insitute of Informatics Oldenburg, KONCAR–KET Croatia
CVR (*central business register*)	TODO
Date for submission	31/03/2019

"The growing share of intermittent and partly predictable renewable energy sources (RES) requires a more flexible operation of the power system. Flexibility is a key to maximize the utilization of RES, while minimizing the negative impact of their associated variability and uncertainty." [ERA-NetSmartGridsPlusMicrogridPositioninguGrip2015] In addition to this disruptive trend other developments leading to higher requirements on the electricity grids can be observed as well, such as the electrification of the mobility sector. These trends add up to a need for adapting how we distribute and transform electric energy. Cp. [meibom_energy_2013,european_commission_energy_2012]. "An effective way of increasing system flexibility is the integration of price-responsive microgrids. […] A […] microgrid may perform arbitrage, provide flexibility thus increasing the utilization of RES, take part in corrective actions, provide voltage support, and defer investments in power lines and (distributed) generation."[ERA-NetSmartGridsPlusMicrogridPositioninguGrip2015] Improved control strategies are considered to optimize the overall economic performance of the system.

The "EEGI Research and Innovation Roadmap 2013-2022 recognizes the changes needed in the power system optimization process requiring that networks become smarter, stronger, favouring centralized and decentralized storage and allowing bi-directional power flows while maintaining the system reliability. This is also recognized in ENTSO-E Research and Development Implementation Roadmap 2013-2022 and other relevant documents. The transnational added value of the proposed project is the collaboration of four institutions, each bringing their expertise to the project: […] DTU will deliver expertise in electricity market and microgrid modeling and simulation […]."[ERA-NetSmartGridsPlusMicrogridPositioninguGrip2015]

The regulatory framework in Croatia, Denmark and Germany is analyzed in detail. Key barriers that hamper access to the market for new energy services are identified and their changes in legislation are proposed.

For example, in January 2016 Croatia adopted a new legislation package, shifting the remuneration of RES from a feed-in tariff system to a premium system. However, the premium system is still not in use due to the secondary legislation required for implementing the market premium system which has not been adopted yet. This secondary legislation should be adopted as soon as possible in order to enable RES to use the premium system. Doing this step forward is key to full market integration of RES. In Croatia, RES under premium system will be responsible for imbalances they cause unlike other RES under feed-in tariff system. Contrarily in Denmark all wind power plants have balancing responsibility.

One of the main results of this project is to identify and propose legislative changes that will facilitate the integration of RES into the market. The microgrid optimal operational management problem based on Economic Model Predictive Control in combination with hierarchical control strategies lead to reduced costs of energy services for producers and consumers / prosumers. This can be achieved in two ways.

The first one would be that prosumers may use their own flexibility for selling their energy in high electricity price periods. They can dispatch their distributed generation and discharge storage units in peak-demand periods in order to increase revenue gained from power injection.

The second way would be prosumers' involvement into both balancing and energy–only markets. Consequently prosumers are able to provide ancillary services to the network and by doing so create additional revenue stream based on network signals. More market participants will increase competition, which inevitably lead to reduced costs for energy services. It is also important to emphasize that the use of *DERs* to provide ancillary services at distribution level may improve the conditions in the network. System operators would have lower requirements for reserves, lower overall losses and better utilization of network resources. As a result of the aforementioned activities, we expect a reduction of costs for energy services (without reduction of quality). Integration of *DERs* into balancing market will introduce additional flexibility to the market. Removal of market barriers and the introduction of new market participants will enable them to provide ancillary services to the network. New market participants are i.e. aggregators, that represent a group of small generation units which enables their provision of ancillary services to the network.

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Table 1.2: Nomenclature.

Shortcut	Description
RES	Renewable Energy Sources
DER	Distributed Energy Resources

Shortcut	Description
FER–UNIZG	Faculty of Electrical Engineering of the University of Zagreb
AC–OPF	Alternating Current Optimal Power Flow
PID	Proportional-Integral-Derivative (Controller)
MPC	Model Predictive Control(ler)
EMS	Energy Management System
GAMS	General Algebraic Modeling System
PADRC	Predictive–Adaptive Disturbance Rejection Controller
AC	Alternating Current
DC	Direct Current
SCADA	Supervisory Control and Data Acquisition

2. Short description of project objective and results

2.1 English version

The goal of uGRIP is to serve as a lab demonstration of the technical feasibility and economic viability of microgrids as means to profit from local clean energy sources, enable the active participation of small consumers in the operation of power systems, increase system-–wide efficiency, reliability and security and support the transition towards low–carbon energy systems [uGrip first annual report p.7]. The laboratory used in this project is installed at *FER-UNIZG* (The faculty of electrical engineering of the University of Zagreb) and is used for evaluation purposes. The development of local power markets (to run microgrids) has been carried out during the second year of the project as one of the main results providing the mechanism to incentivize demand response and enable it towards the bulk power system [uGrip first annual report p.7]. uGRIP project results provided a comprehensive overview of the electricity market in Croatia and identified key obstacles that hamper the development of a well–functioning electricity market in Croatia and its further integration into internal electricity market in the EU. Some well–developed markets, i.e. German, Danish and Dutch markets, have been thoroughly evaluated. A road–map towards sustainable, consumer–oriented distribution–level market has been created. On the technical side, we derive a hierarchy of optimization routines dealing with assigned operational problems and corresponding complexity. We hereby utilize stochastic programming (SP) routines for the treatment of long–term predictions of uncertain processes. Model Predictive Control approaches are used for optimization of the real–time system using dynamic system models. The SP at the top of the hierarchy passes its solution to lower hierarchy levels informing the subsequent controllers. The Microgrid operation setup is coupled with real system components in the laboratory and simulated distribution system model implemented in NEPLAN using the co–simulation platform MOSAIK.

2.2 Danish version

Formålet med uGRIP er at demonstrere at det er teknisk muligt og økonomisk attraktivt at udnytte microgrids som et redskab til at udnytte lokale, vedvarende energikilder. Det skal ligeledes vise potentialet i at give de lokale forbrugere mulighed for at deltage aktivt i operationen af elsystemet, samt optimere systemets effektivitet, robusthed og sikkerhed, alt i mens the gerne skulle hjælpe overgangen til lavere CO2-udledning [uGrip first annual report p.7]. I dette projekt er evalueringsværktøjet installeret på FER-UNIZG (The faculty of electrical engineering of the University of Zagreb). Udviklingen af lokale el-markeder (for microgrids) er sket i løbet af projektets andet år, som et af hovedresultaterne til at incentivere forbrugerfleksibilitet og tilbyde det til resten af el-systemet [uGrip first annual report p.7]. Resultaterne fra uGRIP-projektet gav et omfattende overblik over elekticitetmarkedet i Kroatien og identificerede hovedudfordringerne ved at udvikle et velfungerende elektricitetsmarked indenfor EU. Nogle veludviklede markeder som fx. Tysklands, Danmarks og Hollands, er blevet grundigt analyseret. På baggrund af dette er der blevet fremsat milesten for at nå et bæredygtigt og forbrugerorienteret marked på distributionsniveau. Rent teknisk er dette sket ved at lave et hierarki af optimeringsalgoritmer der tager sig af specifikke operationelle problemer. Dette sker ved hjælp af stokastisk programmering (SP) der reagere på langsigtede prædiktioner af stokastiske fænomener. Model Prædiktiv Kontrol er brugt til at optimere systemet i reel tid ved hjælp af dynamiske modeller. SP'et i toppen af hierarkiet levere sin løsning til de lavere niveauer, der så bruger denne i deres optimering. Operationen af microgriddet er desuden koblet til det ægte systems komponenter i evalueringsværktøjet og det simulerede distributionssystem implementeret i NEPLAN ved at bruge co-simulationsplatformen MOSAIK.

3. Executive summary

The uGrip project started in summer 2016 with the kick–off meeting[1] in Zagreb and the goal to work towards the objectives outlined in the beginning of the Introduction:

- Provide solutions for the facilitated integration of Renewable Energy Sources (*RES*)
- Analyze market structures that help to achieve this goal
- Setup a laboratory platform that serves as test–bed for the evaluation of derived solutions
- Incorporate models that can sufficiently well mimic real–world components such that the set of available simulation scenarios can be expanded beyond the physically available laboratory setup

A detailed list of project objectives and goals is depicted in the appendix Sub–Section Project objectives and goals.

The work packages for the achievement of these goals have been setup as:

- Project Management (WP1)
  - with respect to the project as such and activities relating to the ERA–NET initiative as well as public relations.
- Microgrid Operation Modeling (WP2)
  - Stochastic Programming, Model Predictive Control strategies, Uncertainty Management and microgrid simulation.
- Distribution System Modeling (WP3)
  - Modeling of a distribution system containing the microgrid, interaction between the two systems and simulation of operating modes with respect to the distribution network.
- Communication and Control Infrastructure (WP4)
  - Development of communication concepts and implementation; co–simulation based validation.

    Treatment of the microgrid with respect to markets (*Aggregation*) is considered for the derivation of bids. Aggregation allows for smaller DERs to enter markets as part of an aggregated bid. The market entity placing these aggregated bids is in literature referred to as the *Aggregator*[2]. Partners at FER–UNIZG suggested new market mechanisms / structures that facilitate the operation of Microgrids; considering three different European countries: Croatia, Denmark and Germany.

The laboratory at FER–UNIZG encompasses deterministic (fully–controllable) units as well as stochastic (partly–controllable) units. Both alternating current fraction and direct current parts of the grid have been worked on. Laboratory tests have been carried out in order to test parts of the simulation setup, the co–simulation platform, the components and parts of the control hierarchy, see Section Work package 6: Laboratory demonstration. As co–simulation platform, MOSAIK has been utilized with interfaces for several simulation platforms.

Project partners at FER–UNIZG examined the role of storages in comparison to the role of lines. The transmission system has been considered via models in NEPLAN.

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[1] See http://ugrip.eu/.

[2] See as an example: [MoralesIntegratingRenewablesElectricity2014].

DTU Compute[3] worked within *WP2* on the improvement of system resilience through improved control approaches: Components are co–optimized at several levels within a control hierarchy. Indirect control approaches have been considered for the informed activation of the flexible demand side (Demand Response). Frequency stabilization and voltage control are considered regarding the system operation.

4. Project objectives

4.1 Project objectives and implementation of project

DTU was involved mainly in Work Package 2 (*WP2*):

- WP2: Microgrid Operation Modeling, including:
  - Creation of a basic microgrid model
  - Analysis of operation strategies and integration of the latter into this model, forming an optimized control version
  - Outperforming of the basic microgrid operation model with the developed advanced control strategies thereafter
  - Consideration of uncertainty

We investigated the following operative objectives:

- Derivation of optimal system trajectories: Uncertain process predictions; Market commitment of the Microgrid as Virtual Power Plant
  - Stochastic Programming formulations (*Energy Management System (EMS)*)
- Real–Time system operation and stabilization
  - Active Power control & frequency stabilization
    - Direct Control for the co–optimized operation of various microgrid assets (plants): Model Predictive Controller with modeled / identified system models
    - Indirect Control for the activation of price–sensitive consumers (demand response): Model Predictive Controller with estimated system models
  - Reactive Power control & voltage angle stabilization
    - Satisfaction of system requirements and inclusion of system knowledge using an AC-OPF in the loop
    - Disturbance rejection and real–time performance using an adaptive Model Predictive Controller
  - Re–dispatch including uncertainty hedging based on portfolio optimization techniques

The control objectives have been treated in a control hierarchy derived with respect to control objectives and complexity. See Figure 4.1.1.

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[3] DEFINITION NOT FOUND.

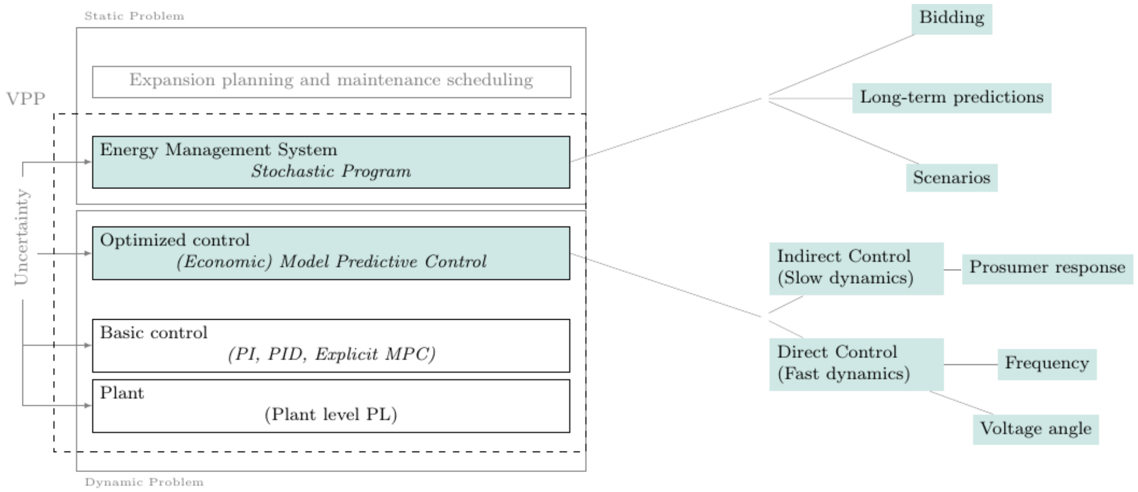

Figure 4.1.1: Hierarchy of controllers and considered scopes.

The EMS hereby derives optimized operation schedules (dispatch schedule) over a prediction horizon which is then provided to the real–time system controllers as reference.

> The use of advanced control strategies (Economic Model Predictive Control, EMPC) leads to facilitating the integration of renewable energy sources in the network and thereby increasing the share of renewable energy sources in generation mix which will indirectly lead to a reduction in greenhouse–gas emissions. Securing additional flexible resources within the power system allow higher penetration of renewable energy sources. This reduces overall greenhouse–gas emissions and provide grounds for carbon– free power systems. The microgrid optimal operational management problem based on EMPC formulation consists in taking decision on how to optimally schedule production within the microgrid to cover microgrid demand and minimize generators' running cost and the cost of imported electricity from the distribution network. Improvement of energy efficiency is one outcome of applying EMPC-based advanced control strategy. uGRIP does not consider directly how to encourage customers with their controllable loads to become part of the new flexible system. The savings achieved using the advanced control approach (EMPC) indirectly encourage consumers with their controllable loads to become part of the new flexible system. The use of EMPC results in increased energy efficiency in homes/districts/other private and public entities. Furthermore, one of the main project results is the development and definition of standardized communication protocols between the microgrid elements and the central computer in charge of the microgrid operation, as well as the microgrid and local (distribution level) electricity markets. As a result of this project, legal and technical prerequisites for aggregators participation in the electricity market will be accomplished.
>
> Source: [TheuGripprojectISGANAwardapplication2018]

4.1.1 Energy Management System: Optimal dispatch schedule & Market commitments

The Energy Management System (*EMS*) layer can be formulated as a stochastic program with two stages, where first stage decisions are:

- Market bids
- Switching events (e.g. minimum up–time)

The second stage considers the stochastic processes which may be clustered depending on the given correlation structure. Generally the problem can be formulated as stochastic unit commitment problem. We may consider the variables:

- Generated power by conventional generators
- Curtailment of RES

- Storage charging/ discharging

This optimization problem then takes the general form of a two stage stochastic problem (see for example [ConejoStochasticProgrammingFundamentals2010,PandzicCostEfficientReliableUnit2016]):

$$\begin{aligned}
\min \quad & c^T x + \sum_{\omega \in \Omega} \pi(\omega) q(\omega)^T y(\omega) && && (1) \\
\text{s.t.} \quad & Ax = b && && (2) \\
& T(\omega)x + W(\omega)y(\omega) = h(\omega) && \forall \omega \in \Omega && (3) \\
& x \geq 0 && && (4) \\
& y(\omega) \geq 0 && \forall \omega \in \Omega && (5)
\end{aligned}$$

An example of a stochastic program which is used within the uGrip–project can be found in the publication [VardanyanOptimalcoordinatedbidding2018]; this formulation is going to be used in a publication within the scope of the project.

4.1.2 Active Power control & frequency stabilization

Aspects that are considered in this control problem:

- Limited knowledge of the consumption side with respect to current and future behavior
- Fast dynamics, requires sampling rates in the range of a few seconds
  - Consequently, the optimization problem has to be kept light
- Price–sensitive units behavior is time–varying and uncertain
  - Demand–Response can help to stabilize the system and to improve economic performance of the system
- Uncertainty is to be compensated for in order to achieve balancing of the problem
- (Mild) coupling with the reactive power control loop
- Introduction:

  Active Power balancing is directly connected to the frequency in the grid, the latter has to be stabilized closely to the nominal grid frequency. Available system inertia influences the dynamics of this control problem; inertia hereby changes depending on the grid–composition and available inertia by means of connected units[4][UlbigImpactLowRotational2014]. The controller(s) providing decisions for the stabilization of grid frequency therefore have to provide decisions with respect to active power contributions sufficiently fast. The required controller sampling rate can hereby be approximated by analysis of system frequency, for example.

  Requirements to the controller sampling rate, related aspects such as computational complexity and resulting restrictions are discussed in Section Computational complexity.

  Recall the control structure depicted in Figure Extended Control Structure. The Energy Management System (EMS) provides a dispatch schedule that includes commitments which the real–time control have to relate to. We aim to control a microgrid with arbitrary architecture in a way such that we stabilize the system at real–time whilst respecting this dispatch schedule. Furthermore we have to account for arbitrary disturbances, system constraints and our goal is to include predictions of the considered process.

  - Predictions
    - allow for the derivation of decisions for our system at a given time that consider the expected future evolution of the system: We achieve pro–active decision making of the controller[5]. Furthermore we include input references in

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[4] Classically the latter refers to rotating systems.

[5] See related literature on Model Predictive Control, for example [rawlings_tutorial_2000].

a predictive way such that the controller can account for input reference changes in the rolling optimization. See Section Inclusion of predictions below.

  - System constraints
    - We co–optimize a system with different units with varying capabilities: Some units can ramp–up or ramp–down fast/slow, some have a limited capacity (storages), ... See Section System constraints below.
  - Disturbances
    - We have limited knowledge of the load–side: Smart–meters enable some degree of knowledge, but the dominant part of this process is unknown and has consequently to be estimated. A microgrid including RES is influenced by stochastic processes[6], some processes we can anticipate using forecasts, some residual remains unknown. See Section Disturbance estimation and rejection below.
  - Prices
    - allow for informed decision making: Prices are one common means to encapsulate information of the cost with respect to decisions. See Section Economic objective function terms below.

  An example of how this can be achieved is given in *Paper A* [BanisUtilizingflexibilityMicrogrids2018].

- Computational complexity:

  Frequency stabilization requires fast decisions with respect to the controls. This is especially true when it comes to a microgrid in islanded mode. Controls hereby are most often set points to the individual plants. We are in this project interested in informed decision making such that previously mentioned requirements are satisfied (system constraints for example). For this reason we aim for a co–optimization of the various units in the grid and denote the resulting decisions 'optimal' with respect to our formulated objective function (short: 'the objective').

  Failure to provide these *optimal* system decisions with sufficient sampling rate then requires non–optimal decision making in order to stabilize the system: Classical drooping is such a means to achieve this goal; these decisions hereby are non–informed with respect to our objective.

  The higher the achieved sampling rate of the optimization problem, the higher the share of dynamics in the system which we can cover with these decisions; the residual is left to non–optimal decision making such as drooping or *PID*–controls (gain–based controllers).

  From these requirements a trade–off results:

  - We aim for an objective function that can describe our system and its requirements: We can include potentially infinite amount of information as in theory every system is infinitely complex
  - Optimal decisions that are not provided in time requires non–optimal decision making as back–up to our control strategy

  We can therefore state the objective function differently depending on the system and available resources at hand.

  Effectively, precision in the optimal decisions is traded versus the rate at which decisions can be provided to the system.

  - A lighter computational problem
    - is to be maintained in order to achieve a satisfying share of informed decisions when the available computational resources are scarce. A more complex problem can be solved sufficiently fast when available computational resources are larger.

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[6] Such as wind, solar radiation, . . .

- A heavier computational problem
  - can be solved when the need for precision in the controls is higher: This is especially important when operating close to system constraints: these operating conditions are expected to become more relevant in the future when several bottlenecks in the grid become tightened.
- System constraints:

  Directly connected to computational complexity are system constraints: Equations defining the feasible operative region of the process at–hand.

  In the considered objective function, we utilize:

  - Absolute operative bounds
  - Ramp–rate constraints
  - Capacity bounds

  An example for the latter can be seen in Figure 4.1.2: Unit 1 (a storage unit) is ramped down prior to saturating; this allows the controller to make informed decisions with respect to the other controlled units.

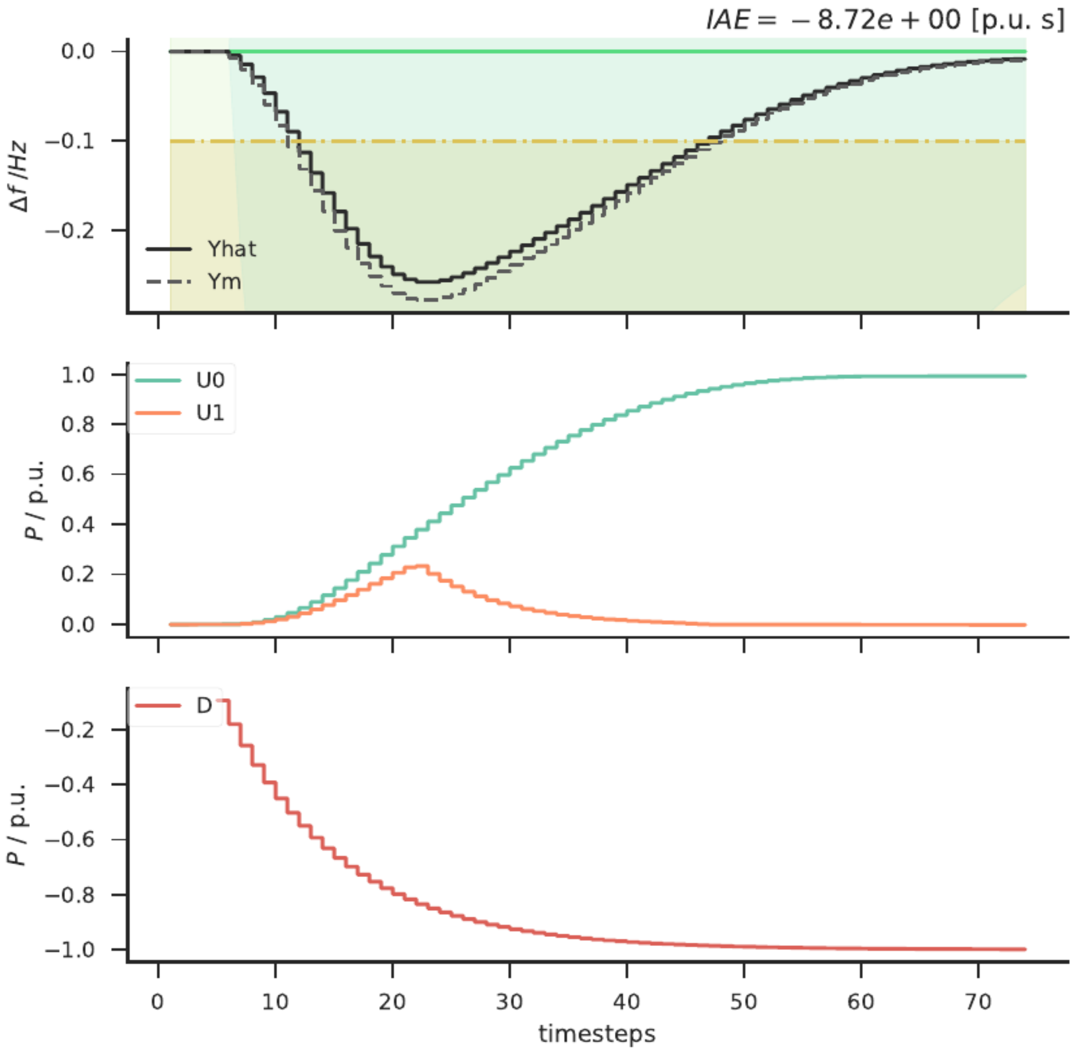

Figure 4.1.2: Storage constraint test: The ramping of the disturbance D (lowest graph) leads to a frequency–excursion (upper graph), requiring the controller to respond accordingly (central graph). Upon reaching the lower capacity bound (storage (U1) in discharge event), the storage related input is reduced in order to respect this unit–constraint.

Recall, as mentioned in Section Computational complexity, that frequency stabilization is a fast problem and hence the problem formulation solved online has to be computationally light enough such as to satisfy the operative requirements with regards to achieved sampling rate.

It is for this reason beneficial to manage constraints and problematic system requirements separately from the control optimization–problem. Problematic here relates to equations that are complex to solve: Logic is an example which can lead to a computationally complex problem. Constraints of the online–problem can then be dynamically updated incorporating the solutions retrieved from the complex problem.

- Disturbance estimation and rejection:

  We aim to control the frequency of the system being influenced by known and unknown processes. The unknown hereby is referred to as residual which we have to estimate in order to stabilize the frequency around the nominal frequency. An augmented Kalman filter[7] allows for estimating both the internal system state alongside this residual, subject to the derived (linear) system model and a guess on the disturbance dynamics. We follow the formulations outlined in [pannocchia_disturbance_2003] regarding input disturbance modeling.

  The dominant part of the mentioned residual is caused by the unknown consumption.

- Inclusion of predictions:

  Pro–active decision making is a central aspect in Model Predictive Control (MPC). For the derived controller we have limited available computational resources for each iterate due to the requirements outlined in Section Computational complexity.

  For this reason the prediction horizon is restricted to well–below one minute. Process predictions that shall be accounted for directly in this frequency–stabilization MPC have consequently to be available in a granularity of a few seconds over a horizon of several tenth seconds. An example where the inclusion of such predictions is reasonable are online wind–speed measurements: Prior to altered operating conditions of a wind–turbine or a wind–park the whole system operating point can be adjusted.

  Process predictions which are not available in a granularity sufficient to this requirement can be covered for indirectly by adjusting the input reference trajectories from the EMS.

  To summarize we are given several options for dealing with process predictions in this hierarchy of controllers:

  - Predictions can be directly treated in this MPC problem
    - Hereby the available prediction horizon is well–below one minute and consequently only predictions of sufficient granularity can be accounted for in this way.
  - Adjustment of the MPC input reference trajectory
    - This can be beneficial in order to prepare the system condition for disturbances that deviate considerably from the disturbance scenario treated in the last EMS–iterate. An example is a system where storage units are available: Adjusting the State–of–Charge of these units such that increased system resilience is available prior to the realization of such a disturbance can be beneficial with respect to system operation.

- Economic objective function terms:

  Prices allow for informed decision making. Several of such costs are of obvious nature: Operational cost of a plant is an example. The challenge arises when the objective function terms cannot be fully clearly stated using meaningful prices: Some control aspects hardly have a directly available "price–tag". We have to estimate such costs and consequently they become uncertain.

- Sensitivity of active power control and reactive power control loops:

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[7] Using a dynamic Kalman filter allows for faster convergence compared to a static filter version.

Active power and reactive power control loops are mildly connected. For optimized overall system performance under operating conditions close to system constraints we expect the sensitivity of these two control problems to become relevant.

- Simulation examples:

  See an example of the frequency stabilization controller with input reference tracking in Figure 4.1.3.

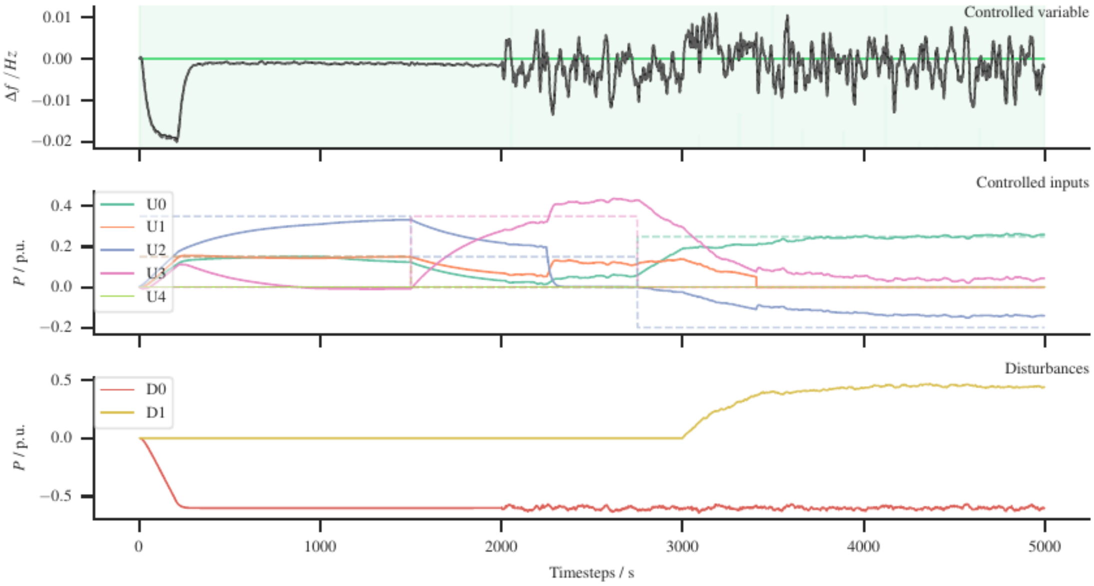

Figure 4.1.3: Frequency stabilization and input reference tracking example: Inputs follow imposed references with specified precision whilst respecting the primary controller objective: frequency regulation.

4.1.3 Reactive Power control & voltage angle stabilization:

Aspects that are considered in this control problem:

- Dynamics are slower compared to frequency stabilization
- The problem is potentially complex when aiming for precision in the optimized controls
- Reactive power is a 'local' control problem — the sensitivity of the distribution grid has to be taken into account
- Introduction:

  Reactive power control is directly linked to the voltage angles at the buses in the system. We aim to achieve a flat voltage profile in order to utilize the grid infrastructure optimally and distribute active power efficiently. Reactive power control differs from frequency stabilization in several ways. It is a less dynamic (slower) problem, still it is computationally more demanding in case high precision is required. The nature of this problem leads to a control structure considering the dynamics and requirements of the controllable units as well as the requirements and topology of the grid.

  The state–of–the art approach to derive optimal decisions for this problem is the AC–OPF[8]. This is a non–linear and non–convex problem: Several optimal solutions exist and the solution process is computationally heavy. Convex relaxations of the original AC–Power Flow equations lead to a lighter problem with a global unique solution. Achievable sampling rates with this problem in the loop are still considerably slower than using a linearized system model.

  In situations of increased system stress — caused for example due to a fluctuation of reactive power provision — higher sampling rates of optimized decisions can be

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[8] Alternating Current Optimal Power Flow.

beneficial. Hereby *near–optimal* refers to the satisfaction of a set of baseline linear system constraints, without the attempt to satisfy the whole set of constraints. A monitoring / supervisory system is then required to ensure that distance to critical constraints is maintained in order to allow for this control approach. Instead of relying mostly on sub–optimal controls (e.g. drooping), we can in this case use approximations of the optimal decisions with a higher sampling rate which support system operation optimization also in times of system transients, see 4.1.4.

A hierarchy of optimization routines for the voltage controls is yet again utilized as a means to split the operational problem with respect to dynamics and complexity: We derive a controller that can achieve sufficiently optimal solutions for the controls and is computationally light enough such that higher sampling rates can be achieved.

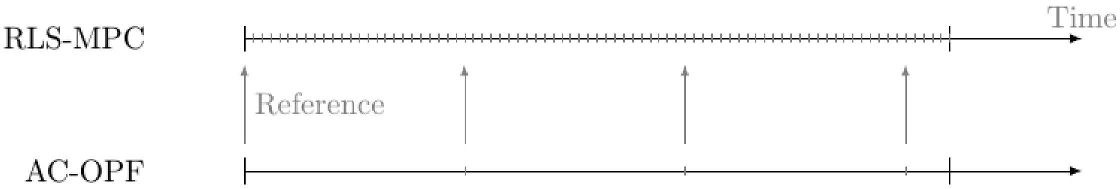

Figure 4.1.4: Control scheme: Recursive Least-Squares adaptive system identification Model Predictive Controller and AC–Optimal Power Flow problem in the loop. Whilst the RLS-MPC is stepped with substantially higher sampling rate than the AC-OPF, the AC-OPF provides references to the RLS-MPC due to its better knowledge of the underlying system.

- Alternating Current Optimal Power Flow:

  We formulate the AC–OPF for the test setup in the laboratory using pandapower[9], the test system is depicted in Eletrical Scheme of the laboratories' electrical network.

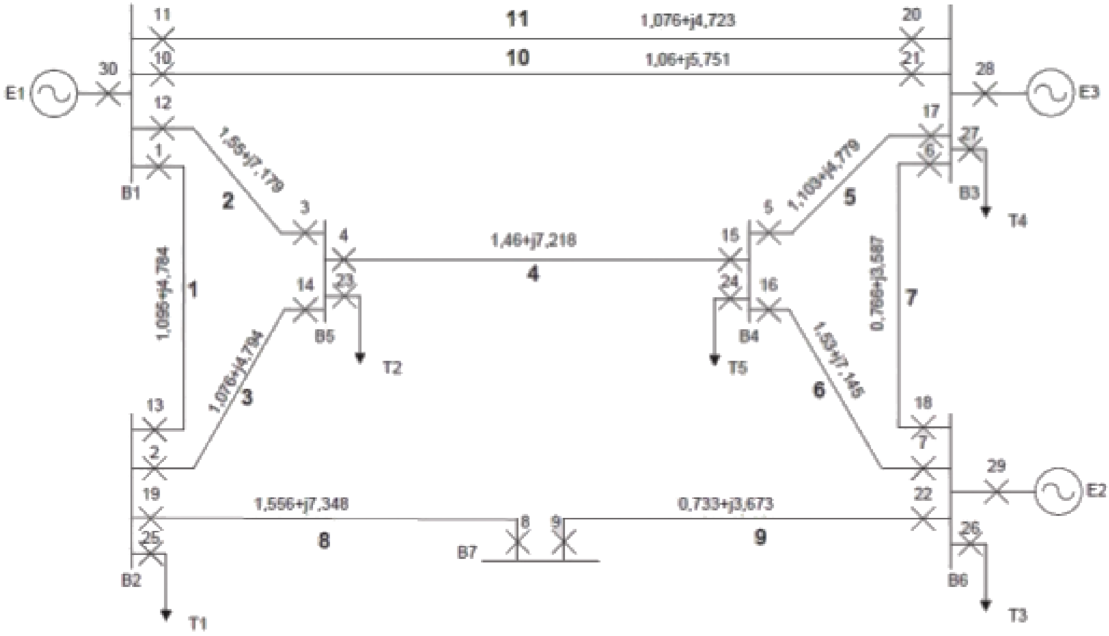

Figure 4.1.5: Electrical scheme of the laboratory setup at FER–UNIZG.

- Recursive Least–Squares Model Predictive Controller:

  A Generalized Predictive Controller (*GPC*) is developed using an identified second order system model of the hydraulic power plant in the laboratory. In order to prepare

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[9] https://www.pandapower.org/.

this GPC for model uncertainties, a Recursive Least–Square adaptive identifier is utilized. See Figure RLS GPC example.

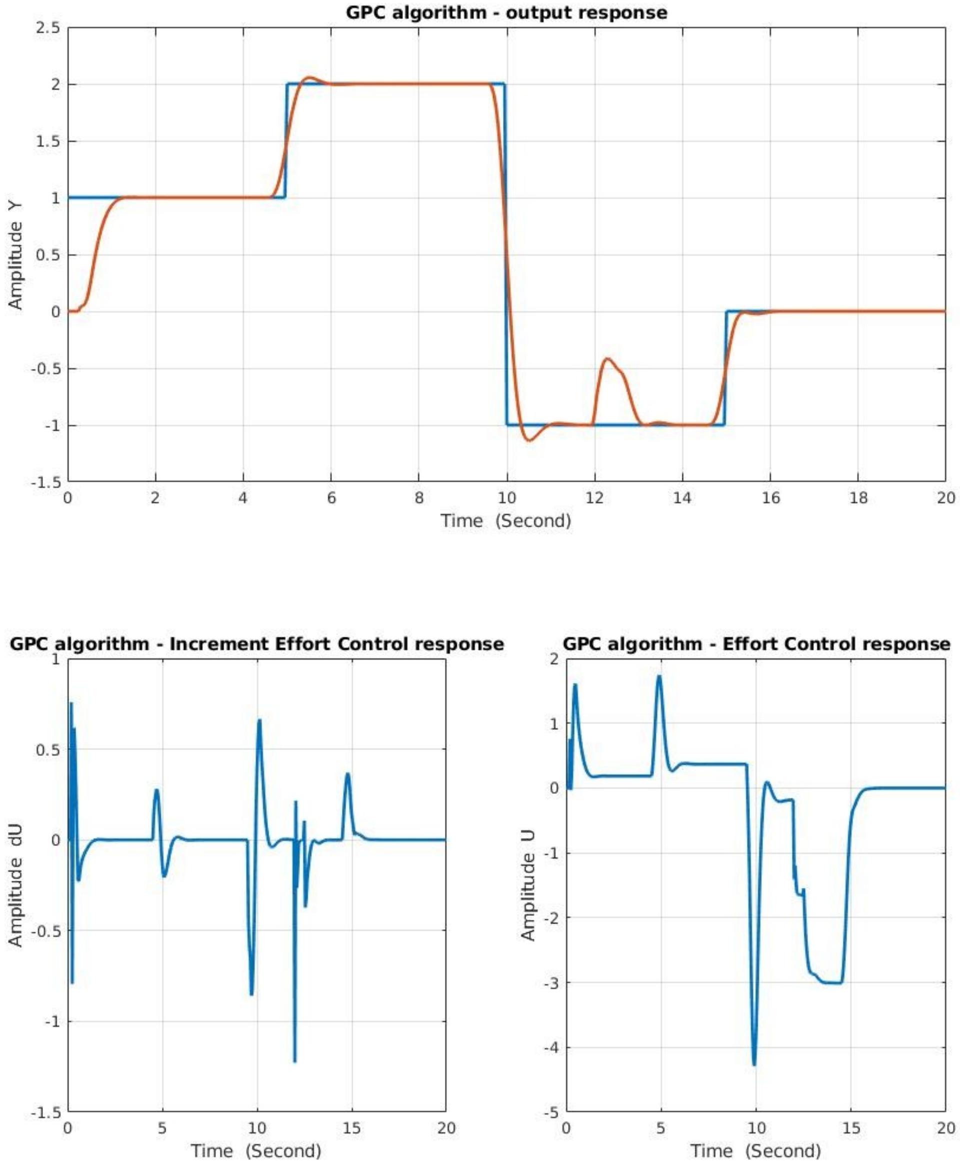

Figure 4.1.6: Adaptive GPC: In this simulation a stochastic model uncertainty with Gaussian distribution is exerted on the system after 12 seconds. The RLS system is able to re–identify the system parameters in around 1 second at can return the system to a stable condition whilst respecting the output reference.

- Disturbance estimation and rejection

4.1.4 *Indirect control (Leveraging system flexibility through price–offers):*

- Introduction:

In the controller architecture outlined in Section Active Power control & frequency stabilization above we consider directly controllable system units. In a microgrid most often price–sensitive units are present which can alter their behavior in a way beneficial from the system–operator perspective — these units are *indirectly* controllable through their price–sensitivity. This is often referred to as *Demand Response*: a dynamic price–signal is used indicating the need to adapt the consumptive behavior. The price–sensitivity is hereby time–varying and the system operator has only limited knowledge of the actual price–sensitive system. This is considered true in most cases — even given high penetration of smart metering technologies which may allow some knowledge of the price–sensitivity at a given time, privacy concerns restrict the amount of available information.

In order to account for these considerations we use online system identification in temporal clusters in order to infer the time–varying flexibility of price–sensitive units. Temporal clusters can hereby be specified arbitrarily, however it is reasonable to take some assumptions regarding the underlying flexibility structure into account: Considering a temporal grid of seven days and twenty four hours respectively is an example which we used in *Paper B*, see Figure 4.1.8.

The controller hierarchy is then augmented with a re–dispatch layer and indirect control layer. See Figure 4.1.7.

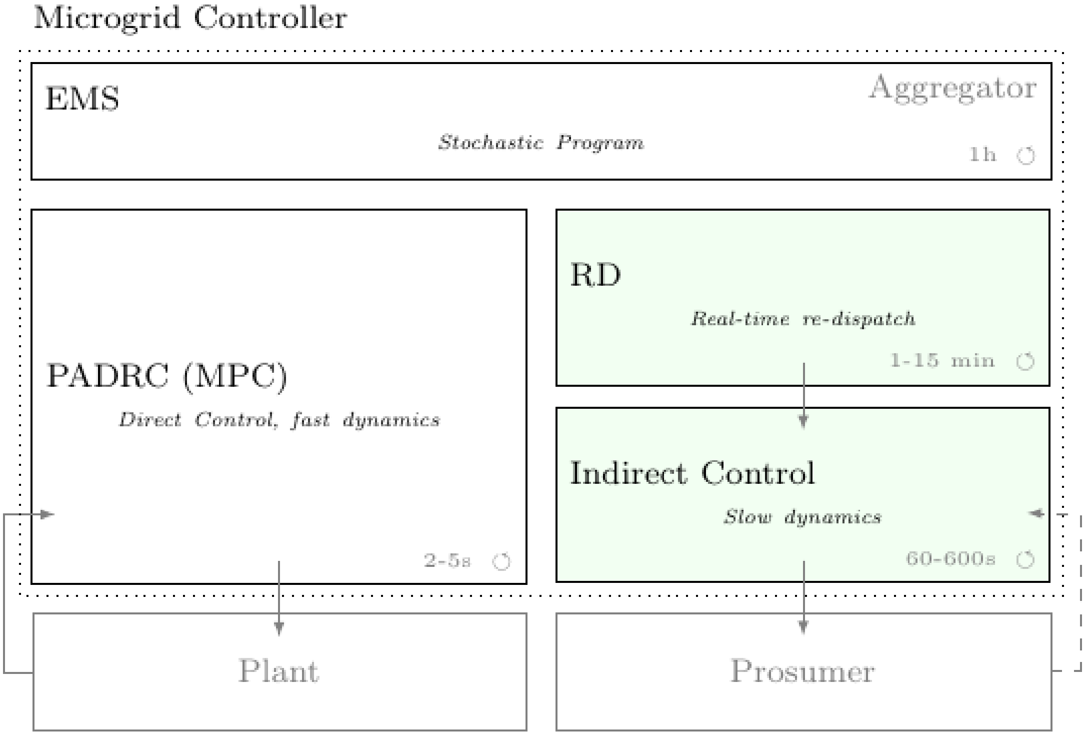

Figure 4.1.7: Control hierarchy: The EMPC (Economic Model Predictive Controller) derives economically optimal input sequences using an estimated price-sensitivity function.

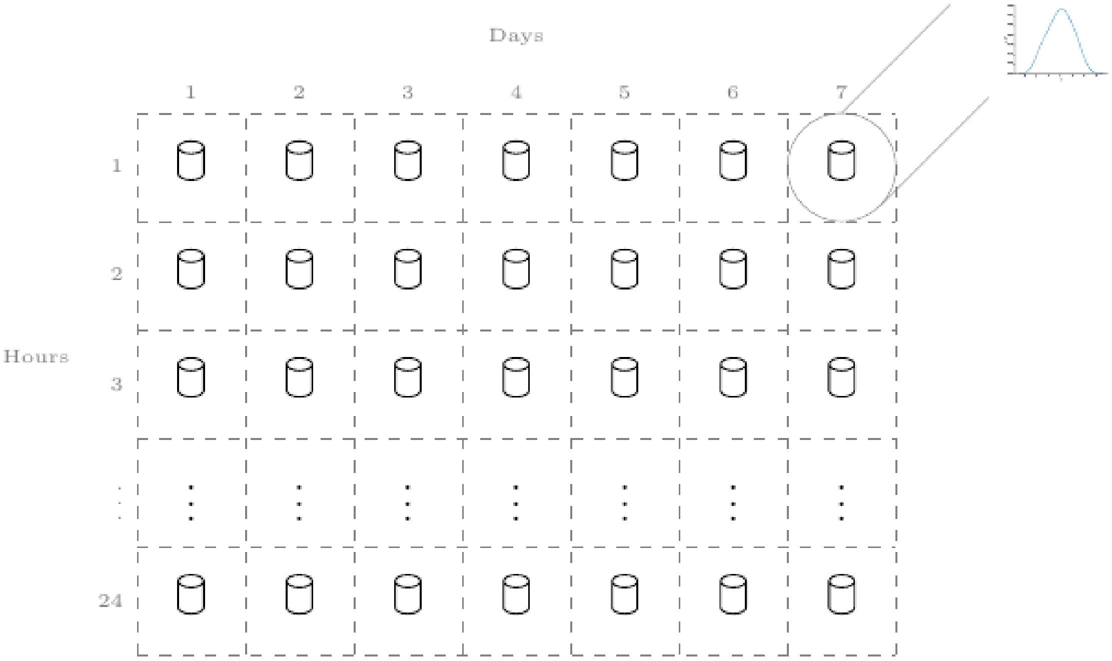

Figure 4.1.8: Example of parameter aggregation in temporal clusters: Temporal–grid of 7 days with 24 hours model parameters.

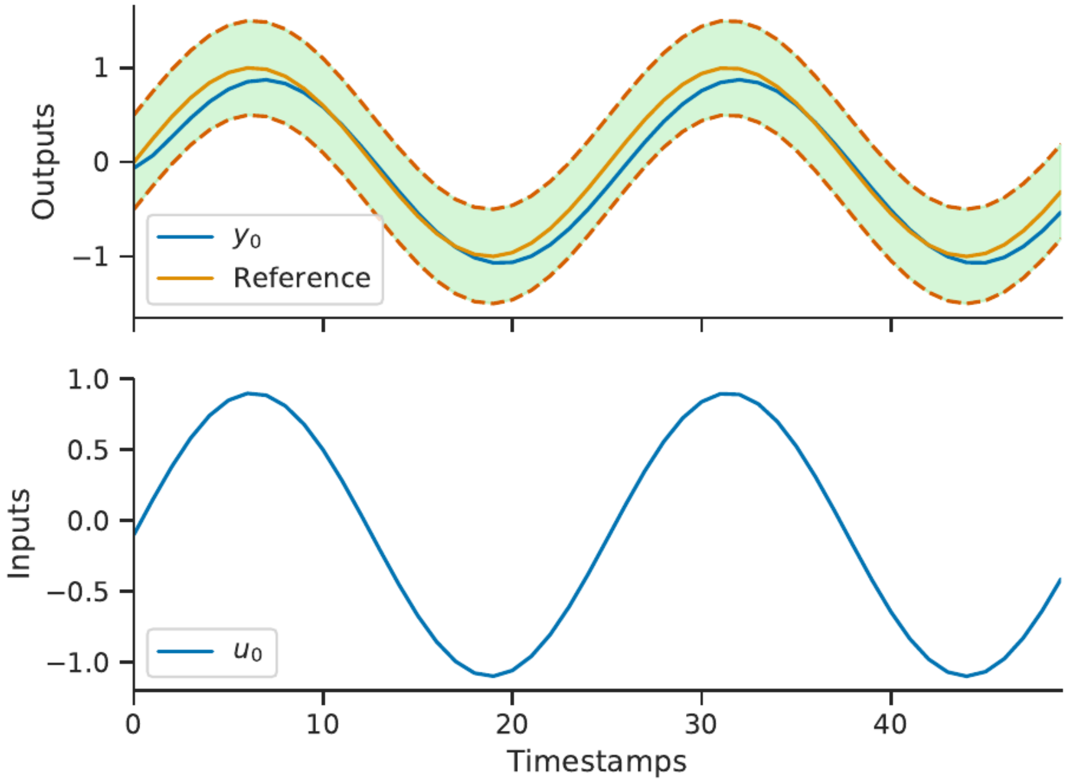

Figure 4.1.9: Indirect Control example: Using a price signal a price–sensitive unit is controller such that it follows a given goal–trajectory.

- Re–dispatch layer: Optimizing economics and uncertainty hedging:

  The re–dispatch layer considers both the available system model (directly controlled units) and estimated price–sensitivity via a co–optimization setup. For the directly controlled units unit–costs are available; for the price–sensitivity we can infer an uncertain unit cost. The latter is derived via the identified (uncertain) model.

Alongside system requirements the re–dispatch is capable of deriving optimized system trajectories that take the price–sensitive system model into account. We assume existence of only one dynamic price. The indirect control layer then aims to drive the price–sensitive units to the response determined ideal at a given time by the re–dispatch layer.

Both re–dispatch layer and indirect control layer are sampled considerably slower than the frequency stabilization problem which allows for a longer prediction horizon and higher problem complexity.

- Indirect control layer:

  We adopt the economic indirect control objective as formulated in [OlivierCorradiIntegrationfluctuatingenergy2011]:

$$\begin{aligned}
\min_{p} \quad & \mathbb{E}[\sum_{k=0}^{N} w||\hat{z}_k - z_{k,\mathrm{ref}}|| + \mu||p_k - p_{k,\mathrm{ref}}||] && \text{(1a)}\\
\text{s.t.} \quad & \hat{z}_{k+1} = f_c(p_k) && \text{(1b)}\\
& z_{k,\mathrm{ref}} = s(u^{\star}_{\mathrm{RD}}) && \text{(1c)}\\
& w + \mu = 1 && \text{(1d)}
\end{aligned}$$

The estimated price sensitivity f_c in the currently active cluster c is hereby:

$$f_c(p_k) = \tilde{b}_c + \sum_{i=k}^{N} \tilde{H}_{c,i}\ p_k \tag{1}$$

4.2 How did the project evolve?

Various scientific methods are employed in order to deliver the findings of this project. First, we develop mathematical models of microgrid and distribution network elements. In order to employ mathematical programming and model predictive control tools, we model microgrid and distribution network elements.

Secondly, we developed several market clearing engines. Replicas of the existing day- ahead, intraday and ancillary service markets to be used as a baseline are considered. EPEX, EEX and Nord Pool markets are chosen by the trading volumes and experience of the consortium members with modeling of these markets. These, along with the newly designed market clearing processes, are implemented using mathematical programs, specifically linear ones.

The principal computation environment for the design, as well as static and dynamic simulations are *MATLAB / SIMULINK* and *Python*. For the sake of optimization, *GAMS* environment, *CPLEX*, *GUROBI* and *OSQP* solvers are used.

Communication infrastructure is based on utilizing standards–compliant and commonly deployed networking devices which enables ad-hoc connection of the existing equipment and provides groundwork for further expansion of the lab. The scientific approach has been based on eliminating proprietary communications solutions, using mainstream IPv4/IPv6 networking equipment and reusing the existing telecom operator network backbone. By taking into account limitations of the existing communication network, the associated payloads of the data exchange between communicating entities have been considered when designing application specific protocols. Therefore, transfer time limitations implied by the communication standards such as IEC 61850 have been thoroughly analyzed in order to asses applicability of this protocol for large scale microgrid deployment.

The middleware used to combine real hardware components and software simulations is the co-simulation framework *mosaik [schutte_mosaik-smart_2012]*. Mosaik enables the interaction between different simulation tools in order to create a consolidated smart grid scenario. An important feature of mosaik is that it is based on discrete–event simulation, which means that the execution of the implemented simulators is performed in an event-based manner. In addition, mosaik’s main advantage is that it is capable of managing and integrating specialized (as well as multidisciplinary) simulation platforms allowing the creation of custom tailored scenarios according to the users needs (e.g., a renewable energy production scenario that incorporates market constrains and weather forecasting models). Furthermore, in mosaik simulators exchange data according to their required attributes, e.g., a grid and a household simulator share the common attribute power and are connected to each other, on this basis: the household can provide the power consumption information to the grid simulator.

In the uGRIP project, microgrid scenarios have been specified and simulated. Then, these test cases will be run in the laboratory in order to advance from simulation to real operation.

See Figure 4.2.1 for a process overview.

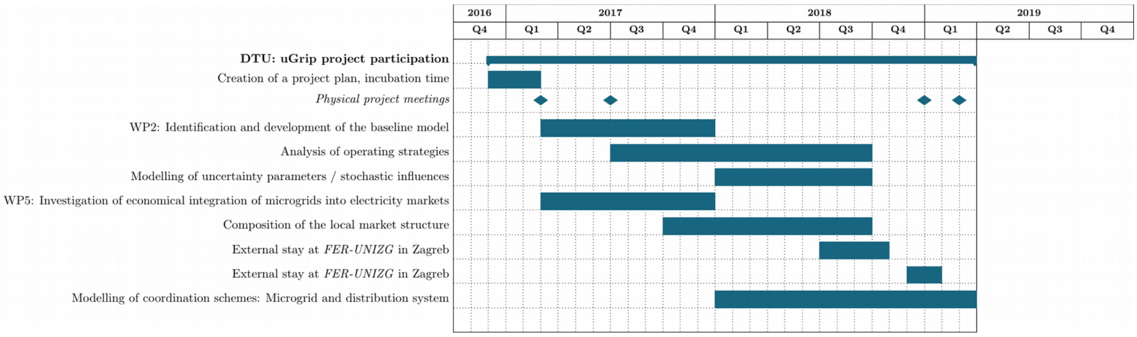

Figure 4.2.1: Project overview gantt–chart.

4.2.1 Risks

Already during the preparation of the proposal, the project team identified risk factors and developed a risk-prevention-and-mitigation plan to guarantee maximum benefit from the project activities. Two types of risk factors have been identified, namely *Management and financial risk* and *Technical risk*.

Management and financial risk, including:

- Unawareness of existing advanced techniques to solve similar problems (severity: medium; probability: low). Proposed risk-mitigation measure: all the partners are leading experts in the area and continuously monitor progresses in the state-of-the-art to incorporate them in the different project activities.
- Partners fail to deliver reports, financial statements, preliminary software solutions, etc. in time (severity: medium; probability: medium). Proposed risk-mitigation measure: Internal deadlines will be set prior to the official ones to make room for possible delays, with reminders to the relevant person(s). If failure to comply with internal deadlines persists, the project coordinator will take action in accordance with the grant and consortium agreement.
- A partner goes into financial problems or bankruptcy (severity: high; probability: very low). Proposed risk-mitigation measure: All the partners have a strong financial position for the time being. In case such a rare event occurs, an agreement will be reached to redistribute the work and the funds.
- A partner leave the project (severity: high; probability: low). Proposed risk-mitigation measure: the work to be carried out by the affected partner will redistributed among the remaining partners, and/or the affected task(s) will be removed in case that the requiring competences cannot be covered by the rest of the project members.
- Lack of a project vision and direction (severity: medium; probability: low). Proposed risk-mitigation measure. Phone/conference meetings will be organized on a regular, e.g. monthly basis, among the WP leaders, where they will report on the progress, next steps, coordination activities, intermediate goals, etc.
- Delays in finding good candidates for PhD positions (severity: medium; probability: low). Proposed risk-mitigation measure: DTU and the University of Zagreb count on admisnitrative staff, standard procedures and services to assist the project team in attracting high-quality students. The project team already participates in the

supervision of MSc. students that shape up as good candidates for the planned PhD projects.

Technical risk, including:

- Problems with testing the developed microgrid operation models and market architecture in the lab (severity: medium; probability: medium). Proposed risk-mitigation measure: the lab testing facility already exists and is owned by the project coordinator. Mathematical models will be tailored to the existing facilities (feeders, CHP unit, PV panels, batteries, loads …) in the lab and will be flexible enough to accommodate potential changes and/or the installation of new elements.
- Problems with interfacing the ICT software for the implementation of operational models and market solutions with the lab equipment (severity: medium; probability: medium). Proposed risk-mitigation measure: OFFIS has long experience with the manufacturing of middleware solutions to connect different software platforms in similar environments. Some of their customers include AIT Vienna, KTH Stocholm, OPAL-RT Technologies, and others. Team members from OFFIS and KONþAR have already established a collaboration within the IEC 61850 work group. On top of this, the PhD students from FER-UNIZG will spend time studying the mosaic software, which is open source, which additionally reduces this technical risk.
- Problems with equipment installation and microgrid operation at FER-UNIZG laboratory (severity: high; probability: medium). Proposed risk mitigation measure: Koncar is the leading supplier of *SCADA* systems, especially in Croatia, and has been included in the setting up the laboratory for many years. The laboratory documentation is complete and Prof. Tomiša from FER-UNIZG team has been developing this laboratory for many years. This means that the equipment installation and microgrid operation does not depend on a single person, and not even a single project partner.

5. Project results and dissemination of results

5.1 Project realization

Integration of distributed generation, energy storage and flexible loads schemes virtually increases the network capacity, particularly when these resources are co–optimized within a microgrid. Demand response can be used to defer or entirely eliminate investments in lines, because of the reduced congestion, and peak generating capacity, because of the peak shaving feature. [ERA-NetSmartGridsPlusMicrogridPositioninguGrip2015]

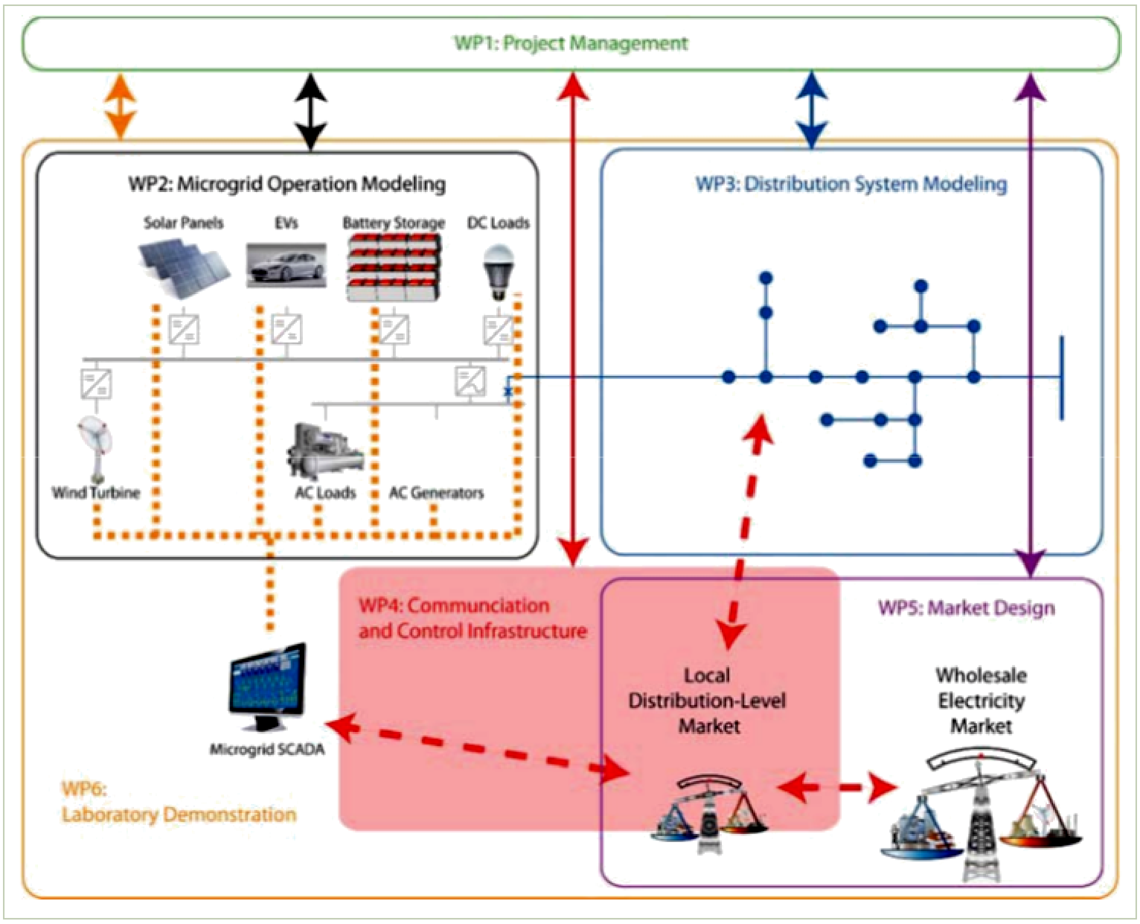

Figure 5.1.1: Work–package overview.

5.1.1 Work package 1: Project Management

This work package has been considered by *FER-UNIZG*.

5.1.2 Work package 2: Microgrid Operation Modeling

We utilize a hierarchy of control routines where each level in the hierarchy is tailored to specific requirements with regards to the problem to be solved. Long–term predictions of uncertain processes are incorporated at the highest level using Stochastic Programming techniques. Model Predictive Control (MPC) approaches are used for optimization of the real–time system using dynamic system models at the lower levels. All levels retain degrees of freedom with respect to the objective at a given level, such that system resilience is improved. The modular nature of this approach facilitates replication and ability to scale. In this setting, a broad range of grid compositions can be operated by adjusting parameters of the control hierarchy.

- Stochastic Programming implementations:

  Two stochastic programs have been covered throughout the project:

  - The 'Baseline Microgrid Simulation Model': outlined in milestone report M2.1, this implementation covers the plant models listed below. This model is utilized for the laboratory tests as the *Energy Management System* in order to yield reference trajectories u_{EMS}.
    - Thermal Generator(s)
    - Wind Turbine(s)
    - Photovoltaic collector(s)
    - Storage(s)
    - Demand Response

    - 'Optimal Coordinated bidding of a profit-maximizing EV aggregator under uncertainty': based on the publication [VardanyanOptimalcoordinatedbidding2018], this implementation allows for the derivation of a bidding curve in day–ahead and balancing markets utilizing a group of electric vehicles. This model is utilized for a journal contribution which focuses on the combination of the solution of this problem and real–time system operation including Indirect Control.

  These two models are implemented in both *GAMS* and *python*.

- Active power regulation / Frequency stabilization:

  In [BanisUtilizingflexibilityMicrogrids2018] (*Paper A*) we present a novel load–frequency (*LFC*) controller that is prepared for disturbance rejection, input reference tracking, system constraint satisfaction and inclusion of predictions. The implementation is following the approaches outlined in [pannocchia_disturbance_2003,PannocchiaCombinedDesignDisturbance2007]. In comparison with discussed alternative approaches to this control problem, the implementation focuses on:

    - Splitting of the problem with respect to complexity
        - Frequency stabilization as fast control problem should be treated with a controller that can be sampled sufficiently fast. Several papers discussed in this publication consider a Stochastic Program or similarly (computationally) heavy optimization approach that cannot be sampled sufficiently fast.
    - Optimization around a stationary point
        - This implementation allows for achievement of offset-free control (with respect to frequency) as well as balanced gains in the input space (the control actions).
    - Input reference tracking
        - u_{EMS} given by the Energy Management System

  This controller is tested in the laboratory at FER-UNIZG. *Paper C* is a follow–up journal contribution where we develop the hierarchy of controllers further in order to account for uncertainty during real–time system operation.

- Reactive power regulation / Voltage level stabilization:

  Paper D is a focus on integrating reactive power regulation into the control hierarchy. We combine a RLS–MPC (*Recursive Least–Squares Model Predictive Controller*) with a classical AC–OPF (*Alternating Current Optimal Power Flow*) such that we split the problem with respect to complexity (dynamics) whilst retaining sufficient degrees of precision. The utilized model in this controller is derived using system identification approaches carried out at the laboratory at FER-UNIZG.

  The implementation focuses on:

    - Review of related applicable control approaches
        - In particular, we review and implement a controller outlined in [DongActivedisturbancerejection2018] which is able to stabilize voltage for a single plant–bus system.
    - Generalized Predictive Controller (*GPC*)
        - In order to include predictive capabilities, we develop the approach further and combine it with the mentioned RLS algorithm. This online–system model correction is useful in order to account for the non–linearity and dynamics of this control problem.
    - Regular Model Predictive Controller
        - Based on the GPC, we add system constraints and input reference tracking such that this controller can take the solution of an AC–OPF into account.

- Indirect Control / Demand Response integration:

Paper B considers a group of electric vehicles for the support in times of stressed system conditions.

The implementation focuses on:

- Augmenting the control hierarchy with both indirect control and re–dispatch routines
- System Identification and temporal clustering algorithm

5.1.3 Work package 3: Distribution system modeling

This work package has been considered by *FER-UNIZG*.

5.1.4 Work package 4: Communication and control infrastructure

This work package has been considered by *OFFIS*.

5.1.5 Work package 5: Market design

This work package has been considered by *FER-UNIZG*.

5.1.6 Work package 6: Laboratory demonstration

In the laboratory at FER-UNIZG several components have been considered:

- (Pumped) Hydraulic Power Plant
- Bank of controllable loads (DC–side)
- Solar panels (DC–side)
- Feeders
- …

In the carried out tests, the focus was on the hydraulic power plant as main microgrid actor: System identification experiments have been used to derive models used in the Model Predictive Controllers (MPCs). Within the project, project partners at FER–UNIZG derived an MPC solely for the hydraulic power plant (paper published), whereas DTU focused on aggregated system MPCs that co–optimize several components within the grid. Hereby both frequency related aspects and voltage related aspects have been considered.

An important consideration with regards to the laboratory work was the combination of various software products: SCADA, NEPLAN, Python, GAMS and other libraries have had to be interfaced and orchestrated. The co–simulation library MOSAIK[10] has been used; throughout the project the partners *OFFIS* developed several interfaces for the listed software products.

An example of a simulation test can be seen in Figure ref:fig:scenario_00: Here the system has been operated in grid–connected mode with input references provided by the GAMS layer.

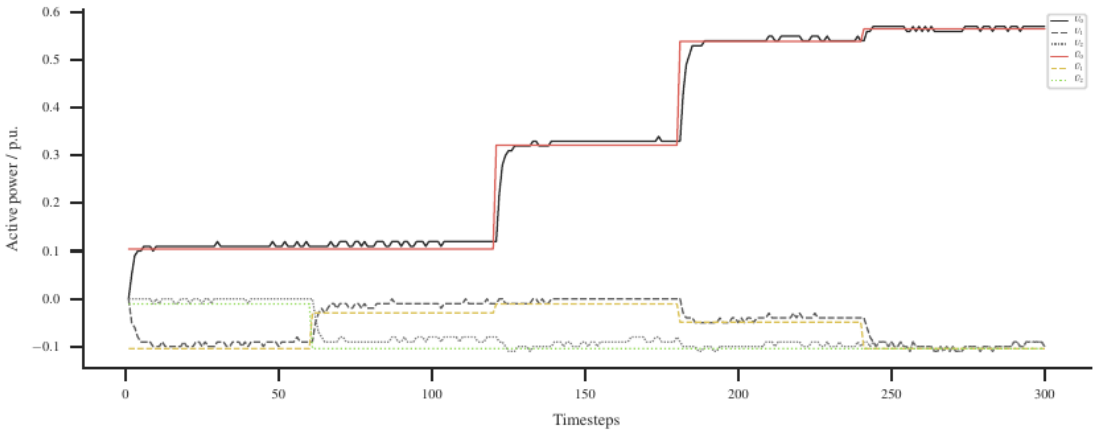

Figure 5.1.2: Input reference tracking example. Frequency is within a narrow band around nominal, deviations from input references are to some degree result of either too low measured/filtered frequency or too high measured/filtered frequency.

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[10] See https://mosaik.offis.de/.

Input reference bounds and input deviation capacity bounds have been considered in order to introduce additional tuning capability for the controller for different modes.

5.2 External benefits

So far the project did not result in increased turnover or exports. It is however expected that improved control approaches allow for optimized economical operation of the system and as such lead to monetary benefit.

5.3 Dissemination

The project has been participating in the *ERA-NET*[11] knowledge community program and related meetings and activities. As such the uGrip project members took part in conferences, online–meetings and the *expera* platform organized by ERA-NET[12].

Several workshops and seminars in relation to the uGrip project have been organized by the Croatian partner *FER*:

- Workshop *Mathematical Modeling in Power Systems (2016)*
- Seminar *Integration of Renewable Energy Sources (2017)*
- Workshop *HO-CIRED and IEEE PES Croatia (2017)*
- Workshop *Demand Response and Energy Storage Modeling (2018)*
- Workshop *ETIP SNET (2019, Zagreb)*

FER also presented the project to Croatian governmental organizations and media:

- uGrip project presentation to the Croatian Power Utility
- Article in the Croatian daily news on the uGrip project
- Article on *Energetika-net* about "Projects that will induce development of the Croatian industry" including the uGrip project

The uGrip project has furthermore been presented at the following conferences:

- ERA-NET SG+ project meeting in Bucharest during June 2017
- 12th SDEWES Conference during October 2017
- Presentation at the European Parliament 28/11/2017
- Knowledge Community Meeting and Co-Creation "Regional Value Chains" Malmo
- ERA-NET SES project event at the Fraunhofer Institute for Factory Operation and Automation IFF (Magdeburg/Germany)

6. Utilization of project results

6.1 Economical aspects

Operating a Microgrid with high penetration of renewable energy sources (*RES*) involves taking measures to increase system resilience — or system flexibility — either by physical means or by operational means. Physical means hereby refers to investments in system infrastructure, operational means refers to improved control strategies. Compared to the former case, the latter is considered to be characterized by

increased *OPEX* and lower *CAPEX* for incentivizing DER services

The concept of microgrids is a means to integrate larger amounts of Distributed Energy Resources (*DER*). A microgrid, which incorporates dynamic processes optimization, treatment of uncertainty, inclusion of predictions and other means of improved decision making, allows for larger penetration of Renewable Energy Sources (*RES*). *Larger* hereby refers to an equal microgrid without optimized operative measures or other considerable investments into improved system resilience. Alternative approaches that allow for larger penetration of RES are structural improvements. Via the concept of aggregation and the related market entity — the aggregator — DER are enabled to enter electricity markets.

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[11] See https://www.eranet-smartenergysystems.eu/.

[12] See Knowledge Community Overview (link shortened).

6.1.1 Utilization of results

The knowledge of operating an optimized Microgrid obtained by running of the laboratory experiments can be utilized for other applied projects. Given the relevance of the concept of Microgrids for the facilitation of higher penetration of RES, new projects developing the approaches further are expected to take place.

- Which commercial activities and marketing results do you plan for?

  I do not know of planned commercial activities or marketing results that are currently planned.

6.2 Future context

6.2.1 Market potential and competition

As mentioned earlier, DER are enabled to enter electricity markets via the *Aggregator* market entity (see Section Executive summary).

6.2.2 Patents

No patents have been registered from DTU's side of the project.

6.2.3 Energy policy objectives

uGrip project members from FER–UNIZG discussed the legislative aspects with respect to the points below at ERA–NET events:

- How legislation has to be adapted for the adaptation of the *aggregator* entity?
- How legislation has to be adapted for the facilitated DER and RES integration?
- How can dependency on legislation be avoided?

It has also been discussed how prosumers can participate in this new market environment.

6.2.4 Result transferal

Results have not been transferred to other institutions.

6.2.5 PhD: Usage of results in teaching and other dissemination activities

The project has been part of one *PhD* project. Throughout the uGrip project, the PhD student took part in various courses at DTU and partly at summer schools. The student participated in various ERA–NET related meetings, project meetings (uGrip project) and the MedPower conference 2018. Project results from DTU's contributions alongside results from other project members have been consequently used as learning ground for the PhD student.

- The PhD student presented his results at various meetings within the uGrip project scope.
- Collaborative work in between project member institutions lead to an exchange of knowledge within the several PhD students working within uGrip.
  - An external stay in Zagreb for the duration of several months allowed for a focus on the partly validation and implementation of derived control strategies at the laboratory in Zagreb
- Part of the results have been utilized in a *special course* at DTU Compute focusing on Model Predictive Control for the operation of Microgrids.

7. Project conclusion and perspective

This project focuses on microgrid related aspects which ultimately aim for facilitating the integration of Renewable Energy Sources (*RES*) in the electrical system.
Market structures that allow for informing the optimized decision making in this context have been examined. Legal improvements supporting these adaptions have been proposed.
A laboratory platform has been build throughout the course of the project. This laboratory can serve as test–bed for microgrid related control approaches.
Models and optimization routines have been developed that can help to improve the operation of microgrids in both operational and economical means.

Aspects of the uGrip project will be continued in the *CITIES* project[13]: The CITIES project, amongst others, focuses on energy systems integration and management, modeling,

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[13] See http://smart-cities-centre.org/.

forecasting and control. In particular, work package 5 (forecasting and control) is considered here.

8. Annex

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Vardanyan, Y., F. Banis, S. A. Pourmousavi, and H. Madsen. 2018. “Optimal Coordinated Bidding of a Profit-Maximizing EV Aggregator Under Uncertainty.” In 2018 IEEE International Energy Conference (ENERGYCON), 1–6. https://doi.org/10.1109/ENERGYCON.2018.8398821.

Table 8.1: Paper contributions in the uGrip project (Technical University of Denmark). - denotes undecided content.

Label	Title	Description (Abstract)	Conference / Journal	Year
Paper A	Utilizing flexibility in Microgrids using Model Predictive Control	We derive a control strategy for the operation of Microgrids (*MGs*) with high shares of Renewable Energy Sources involving Model Predictive Control (*MPC*). By combining the MPC with an Energy Management System (*EMS*) utilizing stochastic programming techniques and a sufficiently large temporal optimization window we improve the point of operation of the system regarding both short and long-term operational aspects. We aim for a system operation that allows for the utilization of the MG as a Virtual Power Plant. In this work we focus on the predictive controller design and the incorporation of information derived in the EMS layer.	MedPower (Conference)	2018
Paper B	Supporting power balance in Microgrids with uncertain production	In Microgrids with uncertain production storages are valuable assets	CSGRES (Conference)	2019

Label	Title	Description (Abstract)	Conference / Journal	Year
	using Electric Vehicles and Indirect Control	to facilitate system stabilization. Consequently, electric vehicles (*EVs*) are promising for providing prosumer services. EVs as assets driven by human behavior and related objectives can rarely be directly controlled. However, indirect control approaches are considered promising regarding their integration into system control. In this paper we consider a hierarchy of advanced system controls including Indirect Control approaches in order to leverage flexibility potential associated with EVs. We aim to activate up-regulation and down-regulation capabilities of EVs in order to support the Aggregators market commitments.		
Paper C	A Model Predictive Regulator formulation for the frequency stabilization in	-	IET RPG (Journal)	2019

Label	Title	Description (Abstract)	Conference / Journal	Year
	Microgrids			
Paper D	Voltage control approaches for Microgrids	We work towards a voltage controller optimized for Microgrids with considerable penetration of stochastic production units. Building on a gain based controller described in [DongActivedisturbancerejection2018] we derive a Generalized Predictive Controller with Recursive Least–Squares online system model estimation. We extend this controller with a sensitivity model capturing the sensitivity of the grid topology and utilize the solution of an AC–OPF implementation as reference for real–time decisions.	SEST (Conference)	2019
Paper E	-	Laboratory paper	-	2019
Paper F	-	Collaboration with Yelena Vardanyan: Combination of indirect control approaches and the optimal bidding routine outlined in the publication "Vardanyan, Y.,	-	2019

Label	Title	Description (Abstract)	Conference / Journal	Year
		Banis, F., Pourmousavi, S. A., & Madsen, H., Optimal coordinated bidding of a profit-maximizing EV aggregator under uncertainty, In , 2018 IEEE International Energy Conference (ENERGYCON) (pp. 1–6) (2018)" ([VardanyanOptimalcoordinatedbidding2018])		

Table 8.2: Links to external resources

Link	Description	Link
uGrip homepage		http://www.ugrip.eu/
– "" --	List of publications	http://www.ugrip.eu/

8.1 Project objectives and goals

- Assessment of the role of storage and the price responsiveness on the consumer side. Proactive consumers, i.e. prosumers, may exploit their own flexibility or operate their distributed generation and storage units in a peak-shaving way to reduce their electricity bills. The entire economics of such an investment will be assessed and impact on distribution/transmission grids will be analyzed.

- Assessment of microgrid business cases for different countries, i.e. Croatia, Denmark and Germany, based on their respective grid codes and incentive policies.

- Development of a robust framework that optimizes the scheduling process of a microgrid while actively participating in electricity markets. This scheduling process includes uncertainty management.

- Development and definition of standardized communication protocols between the microgrid elements and the central computer in charge of the microgrid operation, as well as the microgrid and local (distribution level) electricity markets.

- Development of a microgrid at the FER-UNIZG laboratory. This laboratory already includes a hydro generating unit, a wind turbine, a CHP unit, a set of photovoltaic panels, a series of line models with circuit breakers and feeder disconnectors simulating high voltage power system network, a transformer substation fully equipped with circuit breakers, feeder disconnectors, current and voltage transformers, protection devices and control circuits. This equipment will be upgraded with energy storage units and flexible loads. Since the microgrid can be synchronized to the power grid or run in an isolated mode, we will perform different tests on a fully functional microgrid. We emphasize that the proposed research is directed towards the microgrid operation in parallel to the power system, and not the island operation.

- Design and development of a local market to manage the microgrid at the FER-UNIZG laboratory. This local market will drive the operation of the microgrid based on the physical features and cost structure of the microgrid components and the wholesale market price (at the transmission level). To this end, market-clearing procedures to dispatch a distributed power system will be developed, simulated and tested in cooperation with KONCAR-KET, who will also perform the real-world testing of the equipment, e.g. protocol gateway and SCADA systems, in order to gain competitive advantage over similar solutions.
- Developing and executing simulation scenarios integrating the available hardware components and software models with the co-simulation framework mosaik. These simulations are the first validation step before testing the new approaches in the real grid.