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CSGriP Project Deliverable: TUD Report 2

Power-Frequency control
Demand side control
Power control and grid stability issues

Delft University of Technology

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Contents

TUDelft

Executive Summary

This second set of two deliverable report series presents an overview of the major outcomes, modelling developments, and experimental analysis conducted at the Delft University of Technology within the framework of *Cellular Smart Grid Platform* (CSGriP) project.

Herewith, three main tasks of TUD within CSGriP project are covered and addressed as follows:

- Power-Frequency control
- Demand side management
- Power control and stability issues

This document accompanies the research works of one postdoctoral researcher as well as two MSc theses, which were performed at TUD within CSGriP project in 2017 (& partly 2016) (see Table below).

	MSc thesis title	Student
TUD.2.A	A distributive approach of microgrid control based on system frequency	Ashil Thomas
TUD.2.B	Experimental verification for seamless mode transitions of multiple microgrids using fuzzy-based droop controller	Seungyeon Kim
	Research work title	**Postdoctoral Fellow**
TUD.2.C	Frequency stability analysis of multiple CSGriP cells including plug-in electric vehicles	Dr. Seyedmahdi Izadkhast

Note that the first set of two deliverables (submitted to CSGriP coordination on December 2016) presented the major outcomes, modelling developments, and scientific contributions of five MSc theses at TU Delft within CSGriP in 2016.

	MSc thesis title	Student
TUD.1.A	Frequency based cellular microgrid control	Thijs Vral
TUD.1.B	Optimization & energy management of a microgrid based on frequency communications	Antía Varela Souto
TUD.1.C	Virtual inertia emulation in islanded microgrids with energy storage system	Yuguang Zheng
TUD.1.D	Seamless transitions of multiple midrogrids between the backbone interconnected and the islanded operational modes	Nikolaos Bilidis
TUD.1.E	Seamless operation of a microgrid using BESS during transition between grid-connected and stand-alone modes	Behzad Naeinian

1. Introduction

To shortly introduce *Cellular Smart Grid Platform* (CSGriP) project, it is the successor of another project, namely *Sustainable Off-grid Power Plant for Rural Applications* (SOPRA) project. In the first step, SOPRA project aimed at developing a cost-effective, robust and reliable stand-alone power grid, which could provide electricity to remote areas, e.g., rural villages. A SOPRA cell consists of various essential equipment such as batter energy storage systems, photovoltaic solar cells, micro wind turbines, combined heat and power (CHP) units, electrical loads, and the grid connection. Over the course of SOPRA project, the performance of a SOPRA cell was independently evaluated during two essential operating modes as follows: 1) during the grid-connected mode, in which the grid dominantly controls the frequency and voltage of the cell, 2) during islanded mode, where the battery energy storage system within SOPRA cell is the main responsible for controlling both frequency and voltage.

In the next step, a new technology, the so-called CSGriP technology, was introduced, as shown in Figure 1. In particular, CSGriP technology consists of several SOPRA cells interconnected to a backbone that have the possibility to connect to the main electrical network. According to the CSGriP project description, CSGriP technology is determined as follows:

"Development and testing of a new technology, called CSGriP, to realize a local, intrinsic stable, self-sufficient, and self-regulating energy grid (level of a neighbourhood, a village or an industrial plant).
A control system will be developed, allowing an efficient exchange of energy between cells or between a cell and the backbone. A cellular network exists of the CSGriP system, coupled to the backbone (the MV grid) on one side, and to storage and a variety of energy generators and users, like PV, wind turbines, &CHPs, fuel cells, biofuel-CHPs, heat pumps, electrical vehicles (EVs).
One example is a communication standard which regulates how one CSGriP base station will communicate with the base station of another cell on the backbone. Advantage of the CSGriP concept is the redundancy of communication from a cell to individual consumers / prosumers and their appliances. This will have a great impact on the number of needed standards and communication protocols required for cooperation, and makes the basic functionalities of the system insensitive for loss of ICT equipment."

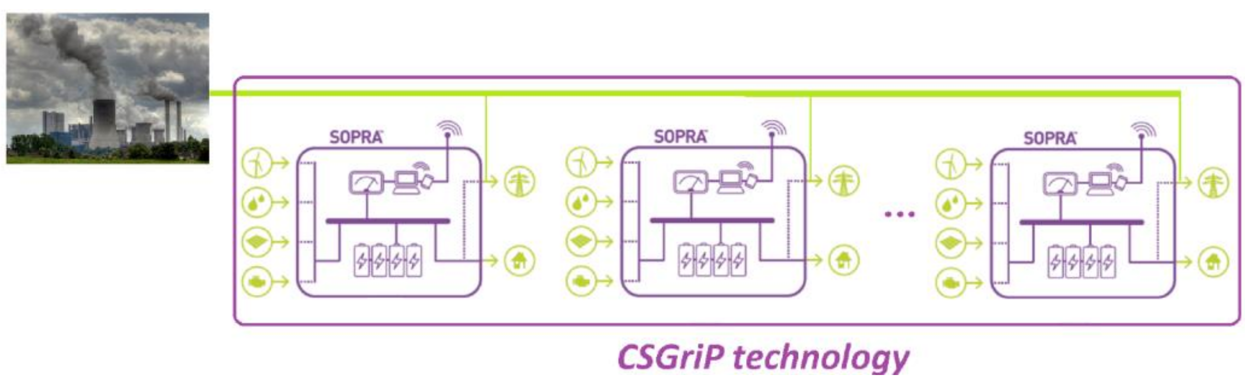

Figure 1. CSGriP technology including several SOPRA cells, which can be connected either to the backbone or the main grid.

The main goal of the project is to design and develop the CSGriP technology, which is highly stable, reliable, self-sufficient, and self-regulating.

The specific objectives of CSGriP project are as follows:

- Avoid the reliance on the information and communication technology (ICT) infrastructure: Generally speaking, both present-day electrical networks and future smart grids heavily depend on the ICT in many different ways. Therefore in the case of failures in ICT, electrical networks may experience serious operational problems or blackouts. Similarly, the failure of communication network in a number of SOPRA cells has a potential to put at risk their stability and performance. To avoid this problem, CSGriP proposed to use the frequency as the only reliable communication signal, by which several SOPRA technologies are able to communication.
- Develop frequency-controlled based communication: Frequency is a global reference signal in electrical network that could be potentially used for the communication purposes. In a large-scale power system, this concept may not be technically feasible due to many obvious reasons such as a massive number of units and controllers involved. As a result, little research works have been conducted on this concept in the past. However within a smaller scale electrical networks like microgrids in general and CSGriP in particular, frequency might be effectively used as a reliable communication signal. On the one hand, the control systems implemented in electrical networks try to minimize frequency deviations. On the other hand, if such frequency-based scheme is designed, there is a need for intentionally deviating the frequency set-points of CSGriP cells. Thus, to achieve a frequency-controlled based scheme, it is required to develop and implement new robust and optimal controllers in cells, which are interconnected through a backbone.
- Promote modularity and ensure seamless transitions in CSGriP technology: CSGriP cells shall be implemented in a fully modular and flexible way. Also, they must be stable and reliable in different essential operating modes, i.e., stand-alone mode, backbone interconnected more, and main grid connected mode. One of the main challenges of CSGriP is to ensure seamless transfer of cells between previously mentioned operating modes.
- Enhance inertial response in CSGriP: The inertial response plays a key role in electrical network to reduce the rate of change of frequency, mainly following the contingency events. Due to the lack of rotating masses of conventional generating units, CSGriP technology has a very low or zero value of inertia. In such cases, CSGriP cells may experience very oscillatory or unstable conditions. To increase the inertia, the electronically-interfaced units could be employed to emulate the inertial response. One of the challenges of the project is to develop appropriate control loops using which battery storage systems could enhance and emulate the inertial response.

Taking into account the aforementioned objectives, challenges and requirements, five highly-relevant MSc research topics were defined at the Delft University of Technology within the framework of CSGriP project in 2016 (see first set of two deliverable report series).

In 2017 (& partly 2016), two other MSc theses as well as one research work were defined to further develop and extend the previous five-MSc works. This second set of two deliverable report series intends to address these research works (including experimental results obtained at TU Delft) within CSGriP project.

TU Delft

2. Performance Evaluation Of Multiple CSGriP Cells At TUD

Figure 2 presents the evaluation analyses performed at TUD for the CSGriP project during the course of 2017 (& partly 2016). In general, the research works can be divided into two major parts according to the time scale of analyses:

1) Medium and long term analysis,

2) Short term dynamic analysis.

Over the course of 2017 (& partly 2016), two MSc students at TUD (i.e., TUD.2.A & TUD.2.B) as well as a postdoctoral researcher (i.e., TUD.2.C) worked on the short term analysis of multiple CSGriP cells (due to its high relevance and priority). Also, TUD.2.A partly focused on the medium and long term dynamic analysis of CSGriP. These research works, which accompany this document, are as follows:

- MSc thesis TUD.2.A, entitled "A distributive approach of microgrid control based on system frequency", by Ashil Thomas,
- MSc thesis TUD.2.B, entitled "Experimental verification for seamless mode transitions of multiple microgrids using fuzzy-based droop controller", by Seungyeon Kim,
- Research work TUD.2.C, entitled "Frequency stability analysis of multiple CSGriP cells including plug-in electric vehicles", by Dr. Seyedmahdi Izadkhast.

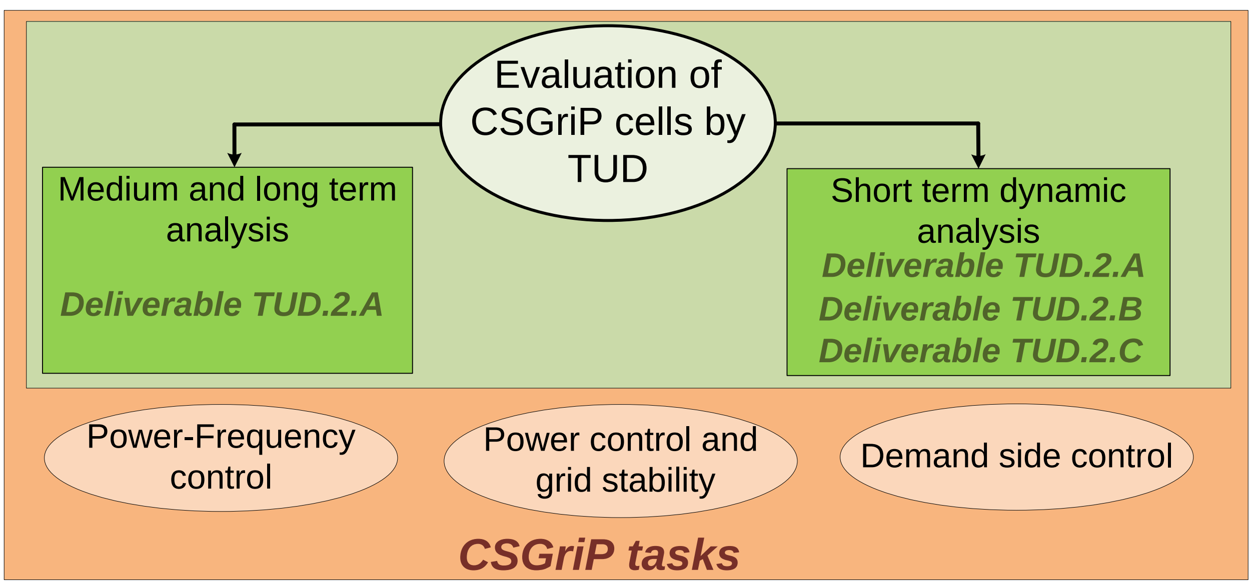

Figure 2. Evaluation analysis of CSGriP cells by TUD considering various project tasks.

Also, Figure 2 shows three major tasks of TUD within CSGriP project that were covered and addressed in two MSc theses + one research work as follows:

1. **Power-Frequency control:** An instantaneous balance between the active power production and consumption shall be always maintained under either normal operation (e.g., load power fluctuations or intermittent renewable power production causing a continuous active power mismatch over the day) or emergency conditions (e.g., connection/disconnection of other CSGriP cells, or sudden outages of generating units). As a result of the active power balance, the frequency is successfully kept within acceptable predefined limits. In the CSGriP technology, the battery energy storage system (BESS) is the main responsible to control the frequency using active power-frequency droop controllers. To achieve a ICT-less Frequency-based control scheme, the BESS is to be additionally equipped with advance power-frequency control schemes (e.g., enhanced droop curves, fuzzy, or adaptive controllers). From different points of view, this task was covered by all above-mentioned TUD works, i.e., TUD.2.A, TUD.2.B, & TUD.2.C (see sections 2.1 & 2.2).
2. **Demand side control:** One of the major tasks of CSGriP project is to enable various demand side control schemes in the CSGriP technology. This technology can benefit from the demand side control during both normal and emergency operating conditions. During normal operating conditions, demand side control facilitate to optimally manage and shift the demand, when needed. During the emergency conditions, when the frequency excessively deviates from its allowable range, some portion of the demand might be shed. Importantly, not only demand side management has a potential to improve the performance of multiple CSGriP cells, but also supply side management can play a crucial role. In particular, when the frequency goes to high values due to abundant availability of electrical energy by renewables, supply side control effectively curtails extra energy production. Note that both active demand and supply side control systems were covered and implemented by one MSc student at TUD, i.e., TUD.2.A.
3. **Power control and stability issues:** The power-frequency stability of CSGriP cells is one of the most challenging tasks of the project. Technically speaking, as stated before, CSGriP cells may face some serious stability issues due to the lack of inertia. In particular, during transitions between stand-alone, backbone connected, or grid-connected modes, the CSGriP cells shall remain stable and balanced. To properly address this problem, some innovative solutions have been proposed by various works at TUD, i.e., TUD.2.A, TUD.2.B, & TUD.2.C.

2.1 Medium & long term analysis (TUD.2.A)

Figure 3 presents the medium and long term analysis of CSGriP cells by TUD.2.A considering various project tasks. It is worth reminding that TUD.1.A & TUD.1.B had extensively evaluated the medium and long term analysis for the CSGriP project. As these works had recommended, there was still a need for an advanced control logic (decision making process) for the proper connection and disconnection of CSGriP cells based on the frequency signal. This is why, TUD.2.A focused on this new control logic, which covers two tasks (i.e., power-frequency control and demand side management) mainly through dynamic simulations in DIgSILENT power factory.

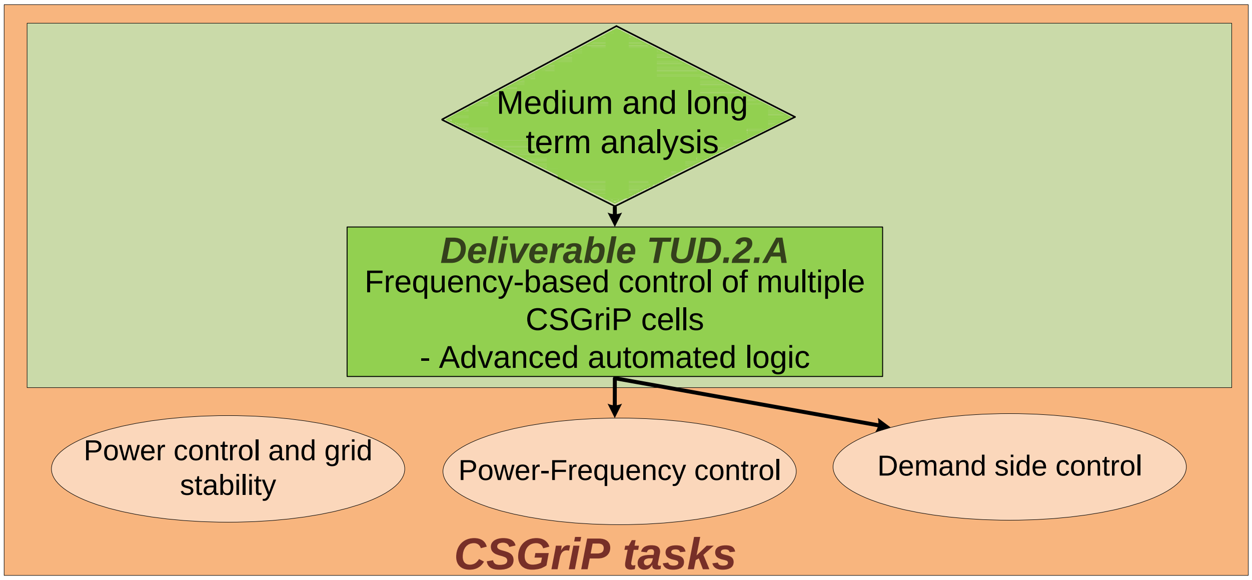

Figure 3. Medium and long term analysis of CSGriP cells by TUD.2.A considering various project tasks.

Deliverable TUD.2.A (see Appendix A)

The main goal of TUD.2.A for medium and long term analysis was to develop a new advanced automated control logic for multiple distributed CSGriP cells. This work showed that multiple CSGriP cells can be safely and reliably operated and help other needy cells using the automated logic control, while they use the frequency as the only mean of communication. As shown in Figure 3, the two above-mentioned tasks[1] were conducted and covered by TUD2.A as follows:

1. **Power-Frequency control:** To successfully enable ICT-less frequency-controlled based scheme, a novel automated control logic was developed. A decision-making algorithm is developed for an autonomous operation of Cells, that determines the switching instants between Stand-alone and Interconnected modes. The developed control strategy and automated decision-making algorithm was simulated in DIgSILENT PowerFactory software for varied scenarios to evaluate the performance and the overall stability of the system. The simulations show a seamless transition between different operating modes – Stand-alone, Interconnected and Grid-connected and the automated decision-making algorithm succeeded in achieving overall stability, increasing the reliability of power to end consumers. Experiments were performed on a standard converter to prove the practical implementation capability of the developed control scheme as an intermediate interface. The modular and distributed nature of the developed controls and algorithm, makes its advantageous to apply such Cells to electrify remote areas, which have limited or no access to power. The system can be easily scaled and expanded by adding more Cells, to build a strong and robust microgrid network.
2. **Demand side control:** This work employed the autonomous demand side and supply side management system by TUD.1.A. These control schemes were quite effective to keep the needy cell operational, particularly when other cells were not able to help the needy cell.

[1] Note that this MSc student TUD.2.A also covered the third task (i.e., power control and grid stability), however mainly for the short term analysis. The scientific contributions of TUD.2.A for the third task will be explained in detail in Section 2.2.

2.2 Short term dynamic analysis (TUD.2.A, TUD.2.B, & TUD.2.C)

Figure 4 presents the short term dynamic analysis of CSGriP cells performed by TUD.2.A, TUD.2.B, & TUD.2.C considering various project tasks. First of all, the seamless transfer of CSGriP cells between various operational modes were investigated by TUD.2.A and TUD.2.B. In short, TUD.2.A evaluated the seamless transfer of one CSGriP cell between grid-connected and islanded modes. To achieve this, TUD.2.A developed a control scheme with which the voltage source inverter remained operational and stable during the grid-connected mode. This way, the seamless transfer between grid-connected and islanded modes were guaranteed and evaluated through dynamic simulations in DIgSILENT power factory. On top of this, TUD.2.B focused on the seamless transfer of two-CSGriP cells, which are connected through a backbone (no grid-connection). TUD.2.B developed a new fuzzy controller which improved the transition performance during connection and disconnection of two cells. TUD.2.B validated the results for synchronization and islanding process via both simulations (in LabVIEW software) and experiments (via National Instruments FPGA board). Last but not least, TUD.2.C intended to evaluate the performance of CSGriP cells including plug-in electric vehicles (PEVs). In summary, he described a new control strategy to well-design the frequency droop controller of PEVs for frequency control analysis of CSGriP cells.

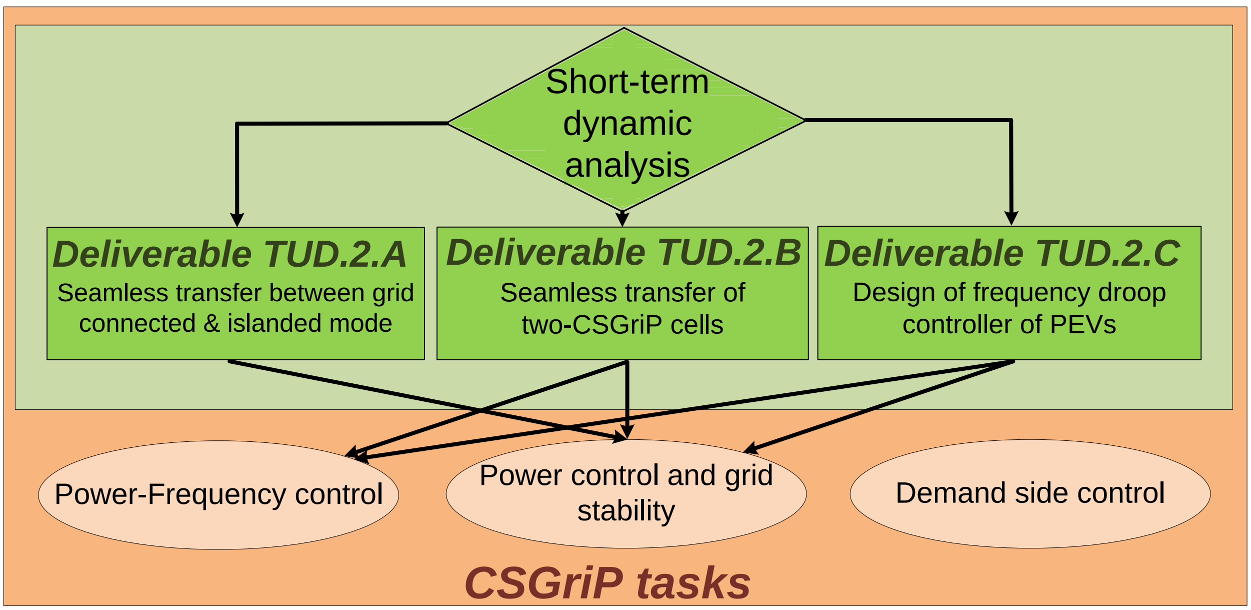

Figure 4. Short term dynamic analysis of CSGriP cells by TUD.2.A, TUD.2.B, & TUD.2.C considering various project tasks.

Deliverable TUD.2.A (see Appendix A)

TUD.2.A, not only worked on the medium and long term analysis of CSGriP cells, but also developed new short term controllers for voltage source inverters to enhance their performance during the seamless transitions between grid-connected and islanded operating modes.

As shown in Figure 4, for short term analysis, TUD.2.A covered the following task:

- **Power control and stability issues:** In 2016, the MSc student TUD.1.D (Nikolaos Bilidis) had worked on the seamless transition of multiple CSGriP cells, however the grid-connected mode had not been investigated. This is why, TUD.2.A extended the models of TUD.1.D in DIgSILENT to evaluate the seamless transfer of one CSGriP cell with the conventional upstream grid. To this end, TUD.2.A developed a new control scheme by which the inverter remains operational and stable in voltage source mode during both grid-connected and islanded operations. Therefore, the seamless transitions can be secured during the transition as well. Moreover, TUD.2.A improved the control loops for the synchronization of one cell to the grid, in such a way that it becomes much faster (e.g., synchronization time improvement from 20 to 3 s).

Deliverable TUD.2.B (see Appendix B)

The main goal of TUD.2.B was to validate and experimentally verify the disconnection and connection of two CSGriP cells to the backbone. Note that the detailed model of two CSgriP cells was first created and simulated in National Instruments™ LabVIEW software. Then, all the simulation results were validated and compared to the experimental results, obtained from the FPGA control board of National Instruments – General Purpose Inverter Controller (GPIC). As shown in Figure 4, the two following tasks were conducted and covered by TUD.2.B as follows:

1. **Power-Frequency control:** Due to several crucial drawbacks of constant droop controller (employed in previous research works), TUD.2.B worked on a newly-developed well-known controller, the so-called fuzzy controller, which notably improved the active power sharing among two CSGriP cells. The fuzzy controller dynamically changes and adjusts the droop coefficient based on both active power deviation and its derivative.
2. **Power control and stability issues:** TUD.2.B also worked on the experimental results of seamless transition of two CSGriP cell between different operational modes as follows:
    - **Connection to the backbone:** As mentioned above, several control loops were developed by two previous MSc students (i.e., TUD.1.D and TUD.2.A) to synchronize one CSGriP cell to either upstream grid or the backbone. Though the synchronization process was improved by TUD.2.A in DIgSILENT PowerFactory, still the performance was not very fast due to the limited access to the controller in the software. As TUD.2.B developed a new model in LabVIEW software, it provided a more flexible opportunity to further improve and accelerate the synchronization process. TUD.2.B proposed a new controller using synchronous reference frame phase-locked loop (SRF-PLL), which remarkably improved the time required for synchronization. This was validated and verified by both simulations and experiments.
    - **Islanding process (disconnection from the backbone)**
        - **Intentional (programmed) islanding:** When one CSGriP cell receives/ provides all the required energy from/to the backbone, then it shall be disconnected, but in a controlled way. To this end, the active and reactive power, exchanged between the cell and the backbone, is set to zero during a "preparation" process. TUD.2.B worked on a new process, which helps quickly prepare one cell for intentional islanding (disconnection). Also, the preparation time was also notably improved by the implementation of a newly-developed controller (i.e., fuzzy controller).
        - **Unintentional (un-programmed) islanding:** To improve the stability of two-CSGriP cell during unintentional islanding, TUD.2.B developed and adjusted the fuzzy controller, instead of the previous-used constant droop approach. Note

that it was shown that the implementation of constant droop (particularly with high gains) may lead to very oscillatory responses or even unstable conditions. However, the fuzzy controller dynamic adjusts the droop coefficient according to the power variation and its derivative in such a way that the response would become much more stable. Both simulation and experimental results confirmed the satisfactory performance of the fuzzy controller under a wide range of two-cell operational conditions.

Deliverable TUD.2.C (see Appendix C)

The main goal of TUD.1.E was to evaluate the impact of electric vehicles on the operation of a CSGriP cell (in the islanded mode). To achieve this goal, a strategy was described to well-design the frequency droop controller of electric vehicles for primary frequency control. The design was made in such a way that the frequency stability is maintained during all the operating conditions.
As shown in Figure 4, the following two tasks were conducted and covered by TUD.1.E as follows:

1. **Power-Frequency control:** This work implemented the power-frequency droop control for the electric vehicles, and then evaluated their performance in both large power system and islanded grid conditions. It was shown that if the droop controller of EVs is properly designed, then the maximum deviation of frequency following disturbance can be largely improved by EVs.
2. **Power control and stability issues:** It was shown that if the droop controller of electric vehicles has a very high gain, then the stability of the network might be put at risk. Therefore, we obtained the bode phase and magnitude diagrams (and accordingly the phase margins and crossover frequency) of a wide set of system parameters and then described a strategy to well design the droop controller of EVs for the PFC studies. To be able to properly compare the frequency response of control system with and without PEVs, the design is done to guarantee the same stability margin for both systems in the worst case scenario.

Besides, a method was proposed to evaluate the positive economic impact of PEV's participation in PFC. The method evaluates to what extent PEVs using well-designed droop are able avoid the costs associated with under frequency load shedding in the network. It took into account the value of lost load, duration of shed load, and the amount of shed load, in the case that the under frequency load shedding is activated.

3. Conclusion

The aforementioned two MSc theses as well as the research work in 2017 (& partly 2016)[2] conducted at TUD successfully analyzed and provided solutions to the main operational and planning challenges of the CSGriP project. In particular, during 2017 (& partly 2016), all of the above mentioned works focused on the short term dynamic issues of multiple CSGriP cells, while one MSc thesis focused on the medium and long term optimal operation of CSGriP cells including renewable energy sources. The effectiveness of the proposed control schemes and methods were not only evaluated through simulations (in DIgSILENT, LabVIEW, & Matlab/Simulink), but also partly validated and verified through experimental results (FPGA board of National Instruments GPIC).

[2] Note that in 2016, five other MSc theses had been developed at TUD for the CSGriP project, which were addressed in the first set of two deliverable report series.

Appendices

Appendix A

Ashil Thomas, “A distributive approach of microgrid control based on system frequency,” Master’s thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Aug 2017]:
https://repository.tudelft.nl/islandora/object/uuid%3Acf589588-87c1-4445-8df8-a20bff3105e7?collection=education

Appendix B

Seungyeon Kim, “Experimental verification for seamless mode transitions of multiple microgrids using fuzzy-based droop controller,” Master’s thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Oct 2017]:
https://repository.tudelft.nl/islandora/object/uuid%3A32231ac9-87c6-4873-bbf6-acdefd3f2d8c?collection=education

Appendix C

Dr. S. Izadkhast, “Frequency stability analysis of multiple CSGriP cells including plug-in electric vehicles,” Journal Paper: S. Izadkhast, P. Garcia-Gonzalez, P. Frías, and P. Bauer, “Design of plug-in electric vehicle’s frequency-droop controller for primary frequency control and performance assessment,” IEEE Transactions on Power Systems, vol. 32, no. 6, pp. 4241–4254. Nov 2017. Available [Online] [last consultation date: Nov 2017]:
http://ieeexplore.ieee.org/document/7836334/