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CSGriP Project Deliverable: TUD Report 1

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

Delft University of Technology

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Contents

Executive Summary

This first set of two deliverable report series presents an overview of the major outcomes, modelling developments, and scientific contributions 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 five MSc theses, which were performed at TUD within CSGriP project. The table below introduces the thesis titles of five MSc students at TUD.

	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.
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."

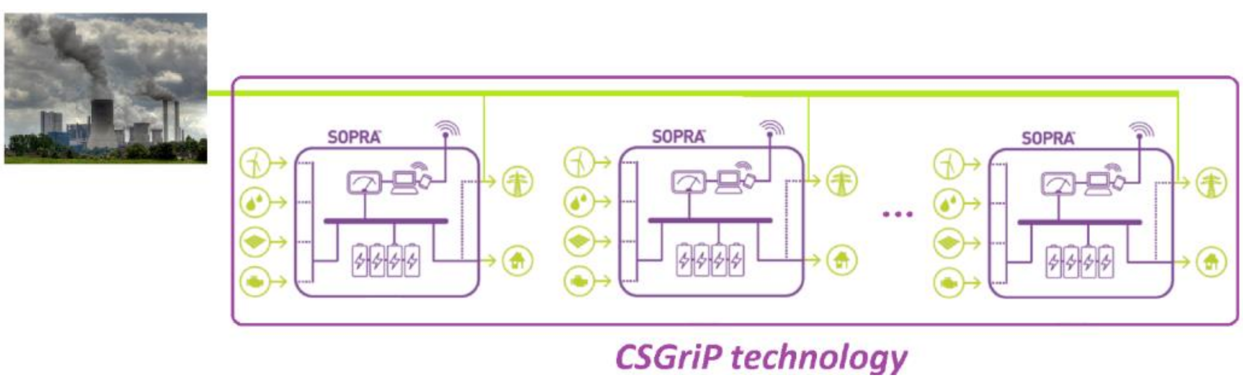

Figure 1. CSGriP technology including several SOPRA cells, which can be connected either to the backbone or the main grid.

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. Next, we describe in detail these five MSc theses at TUD. Finally, we draw some important conclusions on this first set of two deliverable report series of TUD for the CSGriP project.

2. Performance Evaluation Of Multiple CSGriP Cells At TUD

Figure 2 presents the evaluation analyses performed at TUD so far for the CSGriP project. 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 last one year and a half, two MSc students at TUD (i.e., TUD.1.A & TUD.1.B) worked on the medium and long term analysis of multiple CSGriP cells, while three other MSc students (i.e., TUD.1.C, TUD.1.D, & TUD.1.E) mainly focused on the short term dynamic analysis of CSGriP. These five MSc theses, which accompany this document, are as follows:

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

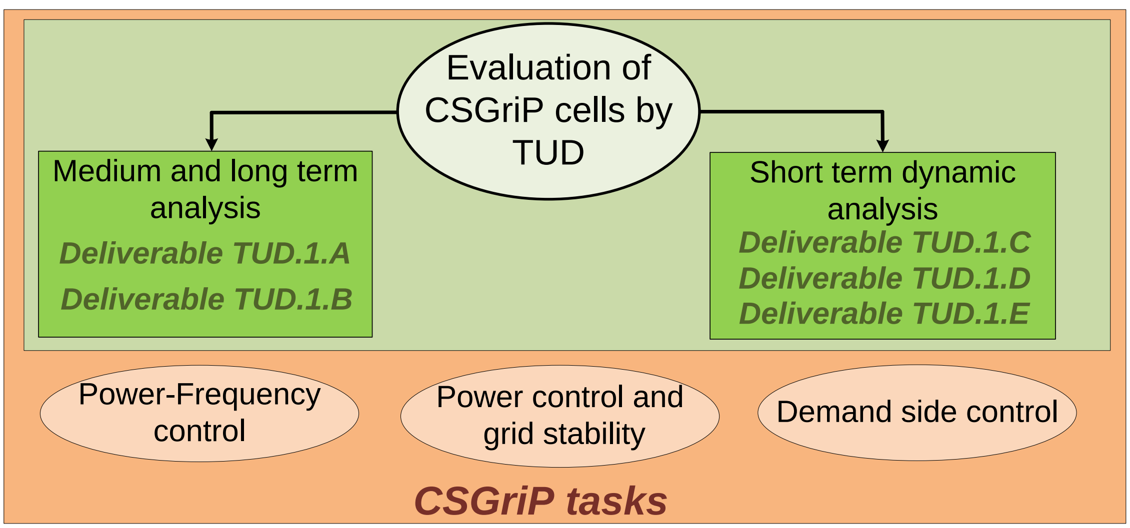

Figure 2. Evaluation analysis of CSGriP cells by TUD considering various project tasks.

Also, Figure 2 shows three major tasks of TUD within CSGriP project that were covered and addressed in five MSc theses 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 students, i.e., TUD.1.A, TUD.1.B, TUD.1.C, TUD.1.D, & TUD.1.E (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 various MSc students at TUD, i.e., TUD.1.A, TUD.1.B, and TUD.1.D.
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 MSc students at TUD, i.e., TUD.1.A, TUD.1.C, TUD.1.D, & TUD.1.E.

2.1 Medium & long term analysis (TUD.1.A & TUD.1.B)

Figure 3 presents the medium and long term analysis of CSGriP cells by TUD.1.A & TUD.1.B considering various project tasks. TUD.1.A has addressed all three tasks mainly through dynamic simulations in DIgSILENT power factory, while TUD.1.B has focused on two tasks, i.e., power-frequency control and demand side control schemes, mainly from an optimization point of view using GAMS software.

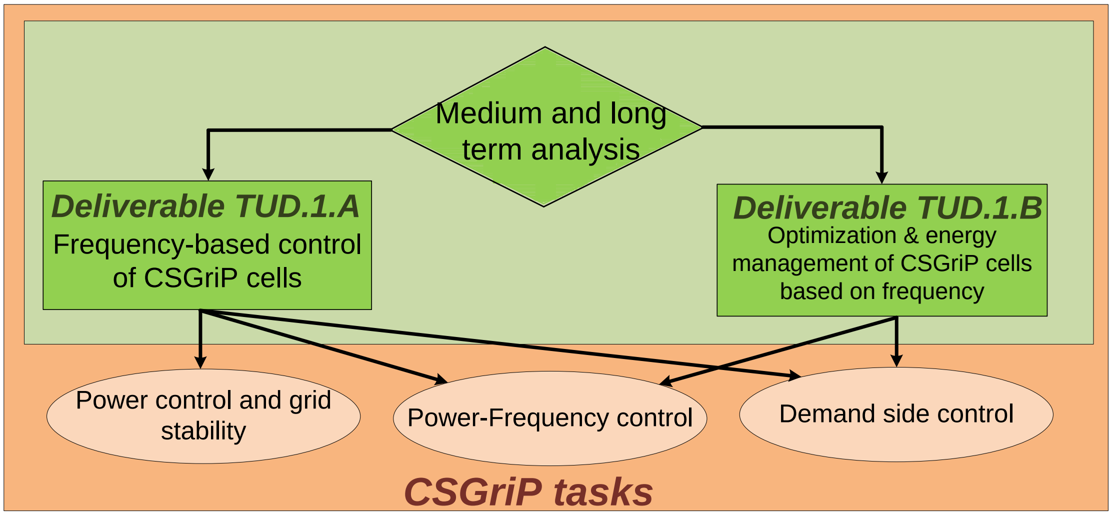

Figure 3. Medium and long term analysis of CSGriP cells by TUD.1.A & TUD.1.B considering various project tasks.

Deliverable TUD.1.A (see Appendix A)

The main goal of TUD.1.A was to test and validate the concept of ICT-less frequency-controlled based scheme of CSGriP project through technical dynamic simulations. TUD.1.A showed that multiple CSGriP cells can be safely and reliably operated for a wide range of operating conditions over a long period of time, while they use the frequency as the only mean of communication. As shown in Figure 3, all three above-mentioned tasks were conducted and covered as follows:

1. **Power-Frequency control:** To successfully enable ICT-less frequency-controlled based scheme, a novel controller was proposed and implemented in power-frequency droop controller of battery energy storage system. First of all, one CSGriP cell was modelled in DIgSILENT power factory and then its stand-alone operation was evaluated where a BESS fully controlled the voltage and frequency of the cell. Second, a frequency-based control scheme was designed in such a way that the frequency of the backbone is selected according to the state of charge (SOC) of all CSGriP cells. If the BESS in a cell had low value of SOC, then the frequency of the backbone was set below the nominal value. Afterwards, other cells measure and detect the low set point of the frequency and then started to connect to the backbone. This way, the cells became able to communicate through the frequency signal and exchange the required amount of energy. On top of this, the amount of power exchanged between the cells was adjusted according to different frequency-power droop curves. Importantly, the proposed controller showed excellent performance in two different contexts, i.e., rural villages in Burundi and urban cities in the Netherlands, for different types of loads, e.g., capacitive, inductive, and resistive.
2. **Demand side control:** In order to further improve the performance of multiple CSGriP cells, an autonomous demand side and supply side management system was developed. On the one hand, various types of loads (e.g., budget or comfort) with different under frequency load shedding characteristics were defined and compared. On the other hand, different power curtailment schemes were implemented in renewable energy sources for SSM. The proposed DSM and SSM schemes were successfully tested and evaluated in multiple CSGriP cell environment.

3. **Power control and stability issues:** When the power-frequency control strategy was developed, it was observed that the value of droop controllers has a large impact on the stability of multiple CSGriP cells. Therefore, it became necessary to well-design the controller gain perfuming an stability analysis, i.e., small signal stability. In particular in multiple CSGriP cells, where the inertia has a very low value, there is a very strong trade-off between the frequency stability and performance. On the one hand, if the controller gain has a low value, then a stable operating point might not be obtained within the maximum/minimum power limits of BESSs. On the other hand, if the controller gain has a large value, then the CSGriP cells might have high-amplitude high-frequency oscillations or even become unstable. Finally, the controller was well designed taking into account a wide range of the frequency set points for the maximum and minimum limits of SOC as well as the active power.

Deliverable TUD.1.B (see Appendix B)

TUD.1.B proposed an energy management system (EMS) whose main objective was to optimally operate a CSGriP cell using frequency as the only communication signal. The EMS controls the BESS and solves the optimization problem, which determines the optimal frequency of the system. The rest of the system components react according to the optimal frequency by following their specific frequency-power response curves. In this way, an optimal planning and operation of the CSGriP cells sought in order to minimize operational costs and consequently increase the use of RESs, reduce GHG emissions, perform a smart charge of the BESS and optimally operate the diesel generator. The optimal operation of CSGriP cells may have four major benefits as follows:

- Increase the use of energy produced by renewable energy sources
- Smart charging of battery energy storage system
- Optimal operation of a network, which does not rely on the ICT infrastructure
- Reduce carbon dioxide emissions which are mainly produced by diesel engines.

Finally, the performance of the proposed EMS was validated through simulation results for different scenarios using real numerical data from an existing CSGriP cell, comparing the results against the traditional control system.

As shown in Figure 3, two tasks were conducted and covered by TUD.1.B as follows:

1. **Power-Frequency control:** This research developed an energy management system which aims to provide optimal scheduling and operation of a CSGriP cell by minimizing the total operational costs of the system. To tackle this problem, a Mixed-Integer Linear Programming (MILP) was formulated using optimization software GAMS, where different constraints and non-convexities of a CSGriP cell (e.g., power-frequency droop curves) were taken into account. It was shown that the optimal operation of CSGriP cells could be achieved using frequency as the only communication signal.
2. **Demand side control:** A demand side control was implemented in the energy management system in order to manage the controllable load in an efficient way. The aim of DSM was to define the optimal level of load shedding through which the power and energy balance between supply and demand is obtained. To further balance the power between generation and demand, RES curtailment (supply side management) was implemented through the application of a version of an available standard, which ensured the security of a grid with high penetration rate of RESs.

2.2 Short term dynamic analysis (TUD.1.C, TUD.1.D, & TUD.1.E)

Figure 4 presents the short term dynamic analysis of CSGriP cells performed by TUD.1.B, TUD.1.C, & TUD.1.E considering various project tasks. Since CSGriP cells generally has zero or very low values of inertial response, TUD.1.C developed new control schemes to emulate the inertial using BESSs. TUD.1.D evaluated and compared the seamless transfer of multiple CSGriP cells from backbone interconnected to islanded modes. TUD.1.E focused on the seamless transitions between grid connected and stand-alone modes of multiple CSGriP cells. It is worth mentioning that TUD.1.C and TUD.1.E initially created and simulated their models in Matlab/Simulink, while TUD.1.D carried out the analysis in DIgSILENT power factory from the very beginning. Anyways, those Matlab/Simulink models created by TUD.1.C and TUD.1.E were later re-produced in DIgSILENT power factory by another MSc student.

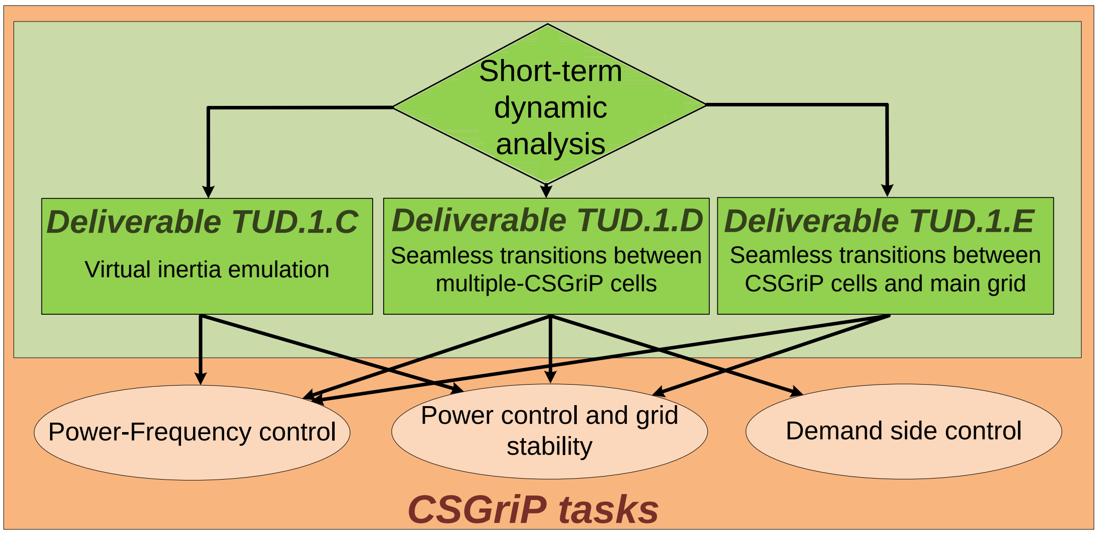

Figure 4. Short term dynamic analysis of CSGriP cells by TUD.1.C, TUD.1.D, & TUD.1.E considering various project tasks.

Deliverable TUD.1.C (see Appendix C)

The main goal of TUD.1.C was to increase the inertial response in multiple CSGriP cells by emulating the inertia using BESSs. To this end, the CSGriP cells with and without diesel were modelled and built in Matlab/Simulink environment. While the BESS in the CSGriP cell without diesel was modelled as a voltage source, the BESS in the CSGriP cell with diesel engine was represented by a current source.

As shown in Figure 4, two tasks were conducted and covered by TUD.1.B as follows:

1. **Power-Frequency control:** In order to enable CSGriP cells to emulate the inertia, it was required to enhance the conventional droop control loops. In this research, several control schemes was proposed to increase the inertial response for both CSGriP cells with and without diesel engines. On the one hand, if the diesel engine was connected to the cell, then a BESS based on current control scheme was modelled and used. On the other hand, if the diesel engine was not connected to the grid, then the BESS was the main responsible to control both voltage and frequency using a voltage source scheme. For both CSGriP cells with and without diesel engines, a number of control methods (e.g., swing equation method, low pass filters, adjustable rate

limiters) were developed and compared to emulate the inertia response. Finally, it was shown that the proposed control schemes are able to successfully emulate the inertia, therefore the rate of change of frequency (ROCOF) can be greatly improved in both networks.

2. **Power control and stability issues:** Undoubtedly, the absence of inertia in CSGriP cells could result in high-frequency high-amplitude oscillations or even frequency instabilities. To improve the stability of BESS based on voltage source scheme, the virtual inertia loop (i.e., swing equation block), filters, and rate-limiters were used to slow down the abrupt frequency deviations. To emulate the inertia using BESS based on current source scheme, an additional control loop was designed and used to react to the fast rate of change of frequency. It was shown that the frequency stability in both networks can be largely improved using the proposed control schemes.

Deliverable TUD.1.D (see Appendix D)

The main goal of TUD.1.D was to enable the seamless transfer of multiple CSGriP cells between the backbone interconnected and islanded operating modes, using frequency as the main communication signal.

As shown in Figure 4, all three tasks were conducted and covered by TUD.1.D as follows:

1. **Power-Frequency control:** TUD.1.D proposed novel control schemes to enable the seamless transitions of multiple CSGriP cells from backbone interconnected to islanded modes, and vice versa. During the transition from islanded to backbone connected modes, a control scheme was developed to prepare the CSGriP for its connection. To this end, the voltages of the cell and backbone were represented in the *dq* reference frame, and then it was ensured that during the connection, both amplitude and phase of both voltages have a very similar values. Also, as the cell was prepared in such a way that its frequency has been adjusted according to the frequency of the backbone. Moreover, another control scheme was implemented to ensure the seamless disconnection of a CSGriP cell from the backbone. To this end, it was ensured that the active and reactive power exchanged by the backbone has the minimum possible value. Finally, the performance of the proposed controllers was tested and evaluated through dynamic simulations for both intentional and unintentional disconnection of a CSGriP cell.
2. **Demand side control:** In this research, a simple demand side control scheme was used that helped improve the frequency and voltage profiles during the transitions between islanded and backbone connected modes.
3. **Power control and stability issues:** Undoubtedly, the seamless transfer between backbone interconnected and islanded modes require a fairly stable and reliable networks. In particular, during the transition from the backbone interconnected to islanded mode, the CSGriP cells shall be able to stabilize and operate in an islanded mode for a long period of time. Thanks to the proposed control schemes, a stable transition between two different operating modes were obtained in various operating conditions.

Deliverable TUD.1.E (see Appendix E)

The main goal of TUD.1.E was to enable the seamless transfer of a CSGriP cell between the grid connected and islanded operating modes.

As shown in Figure 4, the following two tasks were conducted and covered by TUD.1.E as follows:

1. **Power-Frequency control:** TUD.1.E used power frequency droop controllers to enable a smooth transition between one CSGriP cells and the main grid. However, the ICT was partly used where the information on the status of the circuit breaker was sent to the control system of BESS.
2. **Power control and stability issues:** Undoubtedly, the seamless transfer between grid connected and islanded modes require a fairly stable and reliable network. In particular, during the transition from the grid connected to islanded mode, the CSGriP cells shall be able to stabilize and operate in an islanded mode for a long period of time.

3. Conclusion And Future Work

The aforementioned five MSc theses conducted at TUD successfully analyzed and provided solutions to the main operational and planning challenges of the CSGriP project. In particular, three MSc theses focused on the short term dynamic issues of multiple CSGriP cells, while two MSc theses mainly focused on the medium and long term optimal operation of CSGriP cells including renewable energy sources.

- TUD.1.A, entitled " Frequency based cellular microgrid control", successfully demonstrated that the key concept of ICT-less frequency-control based cell could be implemented while the stability of the system is ensured and guaranteed. Moreover, demand side and supply side management techniques were proposed to further improve the operational aspects of multiple CSGriP cells.
- TUD.1.B, entitled " Optimization & energy management of a microgrid based on frequency communications", devised a novel MILP optimization problem using GAMS software in order to optimally operate a CSGriP cell over a long period of time. Not only the main constraints of a CSGriP cell was fully formulated but also non-convexities associated with frequency-power droop curves, demand side management, supply side management, and diesel engine were successfully incorporated into the optimization problem.
- TUD.1.C, entitled "Virtual inertia emulation in islanded microgrids with energy storage system", enhanced the dynamic response of CSGriP cells by emulating the inertia using BESS. Different sets of methods were developed and evaluated in CSGriP cells with and without diesel engine. It was concluded that BESS unit using additional control loops has a great potential to increase the inertial response of CSGriP cells.
- TUD.1.D, entitled "Seamless transitions of multiple midrogrids between the backbone interconnected and the islanded operational modes", proposed novel control schemes to enable the seamless transitions from backbone interconnected to islanded modes, and vice versa. It was shown that a CSGriP cell can be successfully and seamlessly connected or disconnected from the backbone, while the frequency and voltage would remain within acceptable limits during the transitions.
- TUD.1.E, entitled " Seamless operation of a microgrid using BESS during transition between grid-connected and stand-alone modes", enabled the seamless transfer of a CSGriP cell from grid-connected to islanded mode. Similarly, it was shown that a CSGriP cell using the proposed control loops can be successfully and seamlessly connected or disconnected from the main grid.

The principal academic supervisors of aforementioned students were Prof. Bauer and Dr. Laura Ramirez-Elizondo at TU Delft. Also, over the last academic year, two postdoctoral fellow researchers at TUD, Germán Morales-España (daily-supervisor of Antía Varela Souto) and Mahdi Izadkhast (daily-supervisor of Thijs Vral, Yuguang Zheng, and Nikolaos Bilidis), were involved. In the coming academic year, as shown in table below, one MSc student will work on the experimental demonstration of a CSGriP cell during transitions between grid-connected and islanded modes. Another MSc student will work on the experimental demonstration of two CSGriP cells during their connection and disconnection. Next to the daily supervision of two mentioned MSc students, Mahdi Izadkhast will continue working on the frequency stability of multiple CSGriP cells including plug-in electric vehicles. This way, the final remaining task of TUD within CSGriP (i.e., electric vehicles) would be covered and accomplished.

	MSc thesis title	**Student**
TUD.2.A	Simulation-based and small lab-scale experimental studies of seamless transitions of two CSGriP cells	Seungyeon Kim
TUD.2.B	Simulation-based and large field-scale experimental studies of seamless transitions of a CSGriP cell and main grid	Ashil Thomas
TUD.2.C	Frequency stability analysis of multiple CSGriP cells including plug-in electric vehicles	Seyedmahdi Izadkhast

Appendices

Appendix A

T. Vral, "Frequency Based Cellular Microgrid Control," Master's thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Dec 2016]:
http://repository.tudelft.nl/islandora/object/uuid%3A584cc65f-72ab-4fb8-bf11-3659867f3eec?collection=education

Appendix B

A. Varela-Souto, "Optimization & energy management of a microgrid based on frequency communications," Master's thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Dec 2016]:
http://repository.tudelft.nl/islandora/object/uuid%3A31002d86-b88d-46e2-9462-6c214a552543?collection=education

Appendix C

Y. Zheng, "Virtual inertia emulation in islanded microgrids with energy storage system," Master's thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Dec 2016]:
http://repository.tudelft.nl/islandora/object/uuid%3A51849a15-2f89-447b-8661-ac5d12b44edb?collection=education

Appendix D

N. Bilidis, "Seamless transitions of multiple micro-grids between the backbone interconnected and the islanded operational modes", Master's thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Dec 2016]:
http://repository.tudelft.nl/islandora/object/uuid%3A3d74c4f7-f2d0-4539-9a39-e1c3a03f2c37?collection=education

Appendix E

B. Naeinian, "Seamless Operation of a Microgrid Using BESS," Master's thesis, Delft University of Technology, 2016. Available [Online] [last consultation date: Dec 2016]:
http://repository.tudelft.nl/islandora/object/uuid%3A5655df88-9b44-4fca-8992-94951105524e?collection=education