Preparation for demonstration sites

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1. Introduction

The m2M-Grid project focuses on the interface of grid-connected micro-grids, which have been defined as clusters of distributed resources (generation, storage, flexible loads) and customers (non-flexible load). The micro-grids are considered as entities, which are separate from the main grid, since they can operate based on their own strategies and aims and manage their resources to supply their customers in the most secure, efficient and economical way. If the micro-grid resources/loads can form a network structure or represent a single network component (act as one resource/load), then the micro-grids are called physical micro-grids. Otherwise, the clustering of the resources is driven by commercial purposes; this is the case of commercial micro-grids.

Three demonstration sites located in Sweden and France are being prepared to validate the solutions developed by the project for control and management of distributed energy resources (DER) using the micro-grid interfaces. The micro-grid interfaces can be classified into three categories: 1) *micro-grid control*, for control of the micro-grid resources/components by the micro-grid operator, 2) *micro-grid to distribution management system (DMS) coordination*, for control of micro-grid resources (and possibly main grid components) by coordination between the micro-grid operator and the distribution system operator (DSO), and 3) *micro-grid to micro-grid coordination* (for control of the micro-grid resources/components after interaction between the micro-grids (e.g. energy trading, load sharing).

1.1 Purpose of tests and assessment metrics

The purpose of the site tests is to evaluate the benefits of the proposed solutions for the various stakeholders (e.g. resource aggregator, micro-grid operator, distribution system operator). The benefits are associated with technical and economic efficiency, optimal scheduling of the micro-grid resources as well as increased utilization of renewable energy sources (RES). The main objectives of the physical site demonstrations are:

- To reduce the micro-grid energy cost.
- To increase the self-supplying capability of the micro-grid and the integration of renewables.
- To decrease the curtailment of active power generation by RES.
- To avoid or reduce the duration of the violation of the grid technical limits.

The evaluation will consider the costs/revenues, the self-consumption capability (duration) and the technical violations (incidents, duration) of the applied solutions. The assessment metrics associated with the physical site tests are:

- Cost of energy.
- Revenue of the micro-grid.
- Self-consumption.
- Curtailed active power.
- Voltage violations.
- Power import/transfer violations.

1.2 Preparation process

For a physical site demonstration, the preparation of the facilities must ensure the interoperability of the five Smart Grid Architecture Model (SGAM) layers, which are: 1) the *component layer*, 2) the *communication layer*, 3) the *information layer*, 4) the *function layer*, and 5) the *business layer* [1]. Candidate micro-grids, i.e. network sections or cluster of resources that could form a micro-grid, were first identified to be used in simulation models. Following this, demonstration cases were proposed to be implemented with these micro-grids. The developed solutions for micro-grid control and operation form the *function layer*, while the *business layer* includes the operation/economic targets that these solutions aim to achieve. The preparation process of the facilities is associated with the first three layers of SGAM and can be described in the following steps:

- Examination of available resources/assets and control/communication possibilities.
- Increase of remote controllability and monitoring capabilities.
- Set-up of communication interface.
- Preliminary tests of the communication/control set-up.

2. Description of physical test sites

2.1 Distribution network of Chalmers

The 12kV distribution network of Chalmers has a total of electrical load demand that varies between 2.5 and 6 MW [2]. Four areas of the distribution network have been proposed for the micro-grid implementation (Figure 1) with the aim to test at least one. These network areas contain DER (solar panels and/or batteries) and there is also the possibility of utilizing some controllable loads (cooling appliances, boilers). The batteries have been identified as the most important micro-grid resource at the site. The energy storage systems (ESS) are the most controllable units that can offer multiple services for the micro-grid (e.g. peak reduction, self-consumption) and since they have just been installed at Chalmers, they have a modern power electronic (PE) interface that offers many solutions for control implemented by the user (system operator). The ESS inverters as well as most of the PV inverters can be interfaced with communication protocols that enable connection through Transmission Control Protocol/Internet Protocol (TCP/IP).

2.1.1 Energy storage systems

Two energy storage systems (ESS) with batteries have been installed at two locations on the Chalmers campus. A 200 kWh ESS has been installed in a newly built building, which is called A Working Lab (AWL). This building will also host solar panels with a total capacity of 288 kWp. The solar panels and ESS make this part of the network capable for self-consumption and therefore very attractive for micro-grid implementation. In another location in the network a 100 kWh ESS will be combined with a smart EV charger. The battery technology that is used has an energy storage capacity to power capacity ratio of two hours.

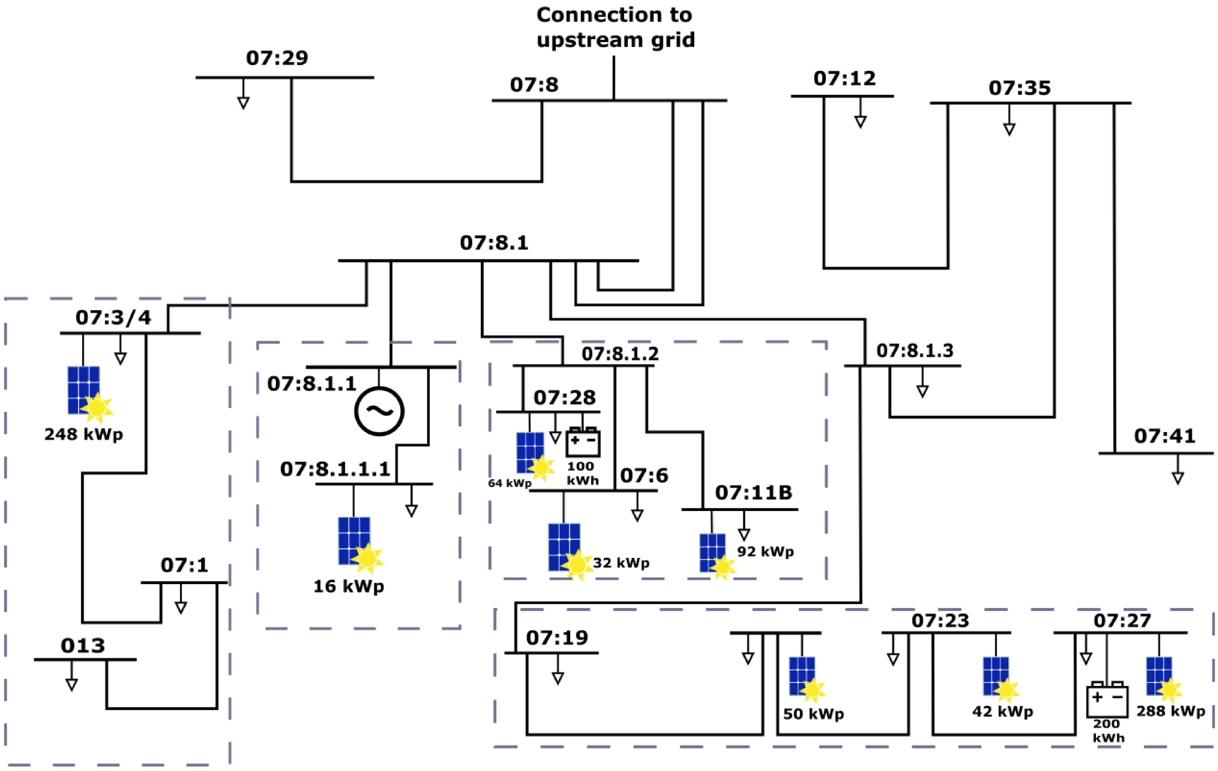

Figure 1 : The areas which are candidate for micro-grid implementation at the distribution network of Chalmers campus.

2.1.2 Photovoltaic systems

New solar panels (Figure 2) have recently been installed on rooftops of the Chalmers campus buildings adding to a total PV capacity of 831 kWp. Their inverters are provided by different manufacturers e.g. SUNGROW for the new photovoltaic systems as well as ABB and SMA for the old photovoltaic systems (Figure 3).

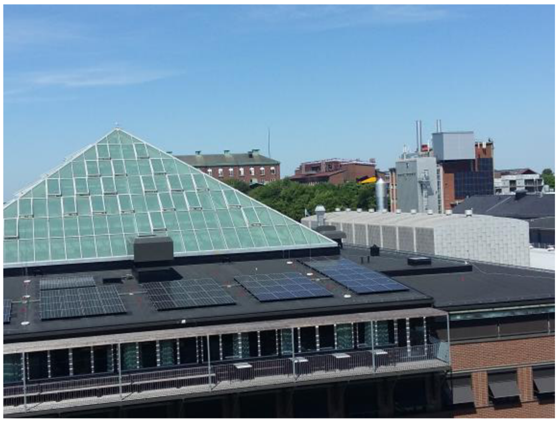

Figure 2 : Solar panels mounted on the roof of the Architecture building and on the wall of the building, where the CHP plant is located.

Figure 3 : PV inverters at Chalmers.

2.1.3 Combined heat and power plant

The combined heat and power (CHP) plant (Figure 4) consists of a boiler of 6000 kW heating capacity and a second boiler of 3000 kW heating capacity, which is combined with a steam turbine of 1000 kW. The maximum operational electric output depends on the choice of fuel and drops down to 500 kW, when wood pellets are used [3].

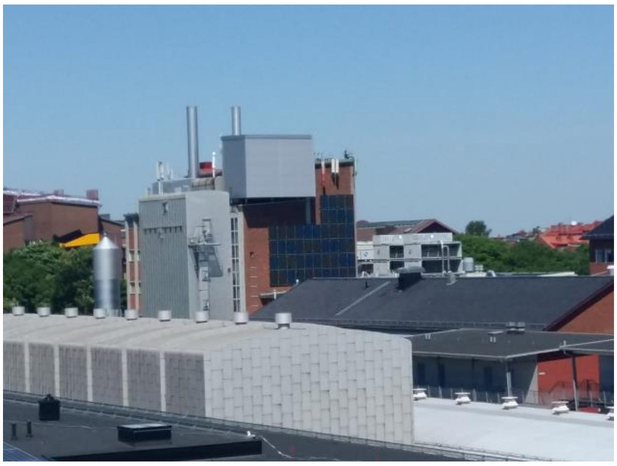

Figure 4 : The CHP plant at Chalmers campus.

2.1.4 Building controllable devices

The deployed building controllers enable the building operator to control the heating, cooling, and ventilation system by changing the settings of temperature, air flow etc. The graphical interface with the functionalities of one of these controllers is shown in Figure 5.

Figure 5 : The graphical interface and the functionalities of a builiding controller located at one of the buildings on Chalmers campus.

2.2 Brf Viva buildings

The Brf Viva is a housing association of six buildings comprising 132 residences. These are located in Guldheden, an area close to the Chalmers campus. A multi-disciplinary research project associated with the construction of the six Brf Viva buildings is led by the property manager Riksbyggen in cooperation with partners from academia and industry. Gothenburg's DSO, Göteborg Energi, as well as Volvo are collaborating partners in this project, which is called Positive Footprint Housing and has been running since 2011. The main aim of Positive Footprint Housing is to find new ways to sustainably construct and maintain residential housing. One of the goals with Brf Viva is to have a yearly excess of 5 MWh in generated energy due to the production of cooling energy and electric energy from solar panels [4]. Another project that involves Brf Viva and concerns smart optimisation and control aims to provide a better understanding of how the energy system in the housing association can be optimised from a residential housing perspective and as part of the larger energy system in Gothenburg.

The yearly aggregated electricity demand of each of the six Riksbyggen Brf Viva buildings is estimated to be around 450 MWh. For the local electric energy production solar panels with peak power of 170.8 kWp have been installed. Specifically, they are a total 589 solar cells, 290 W each, with a tilt angle of 17° with respect to the roof. Moreover, second-life Li-ion batteries taken from old electric buses (provided by Volvo Buses) have been installed (Figure 6 and Figure 7). The energy storage capacity is 159.6 kWh and the power charge/discharge limit is 84 kW. The solar panels and the batteries form a DC grid, which is connected to the upstream AC grid (400 V) via a converter provided by Ferroamp company. The converter (capacity of 168 kVA) is called EnergyHub [5]. It is a multi-level converter with bi-directional operation, since the solar energy and the battery stored energy can be exported to the upstream AC grid and, in addition, the batteries can be charged through the upstream AC grid.

Figure 6 : The second life Li-ion batteries of Brf Viva.

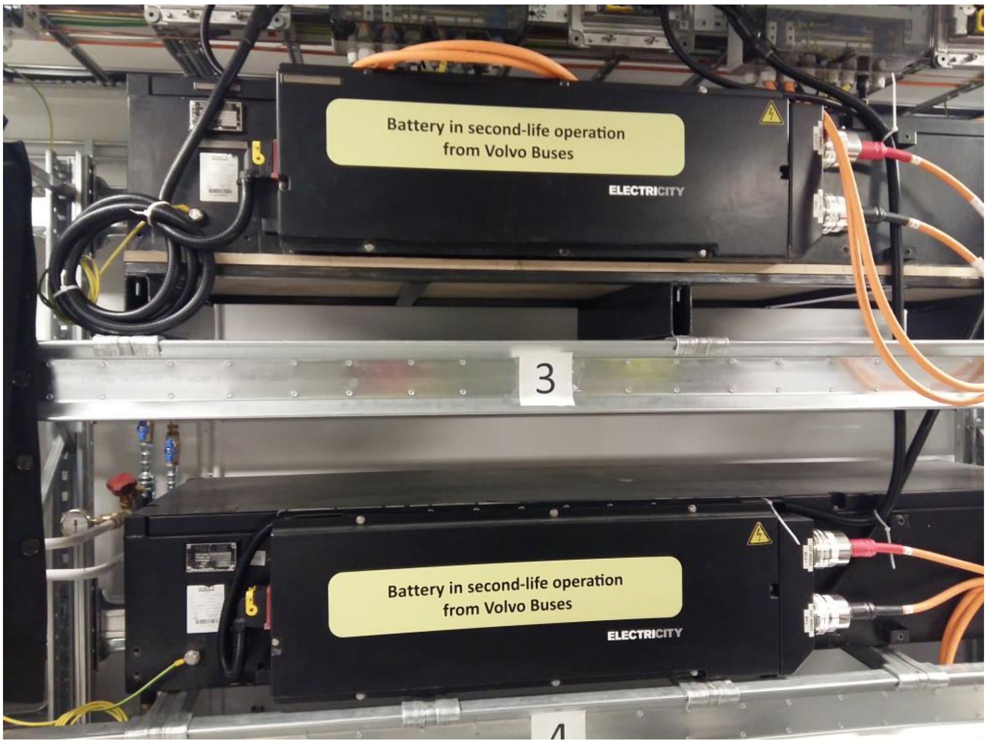

Figure 7 : Second life Li-ion batteries of Brf Viva.

2.3 Distribution network of SOREA

The demonstration sites in France are owned and operated by SOREA. The site is part of a 20kV network at Saint Julien Montdenis (Figure 8). This MV network hosts two solar PV plants (at Villarclement and Ruaz D'en Haut) each of which has an installed capacity of 250 kWp. The network also consists of a 3.2 MW hydroelectric power plant. In this part of the grid, there are 28 substations HV/LV that supply industrial, residential and commercial clients.

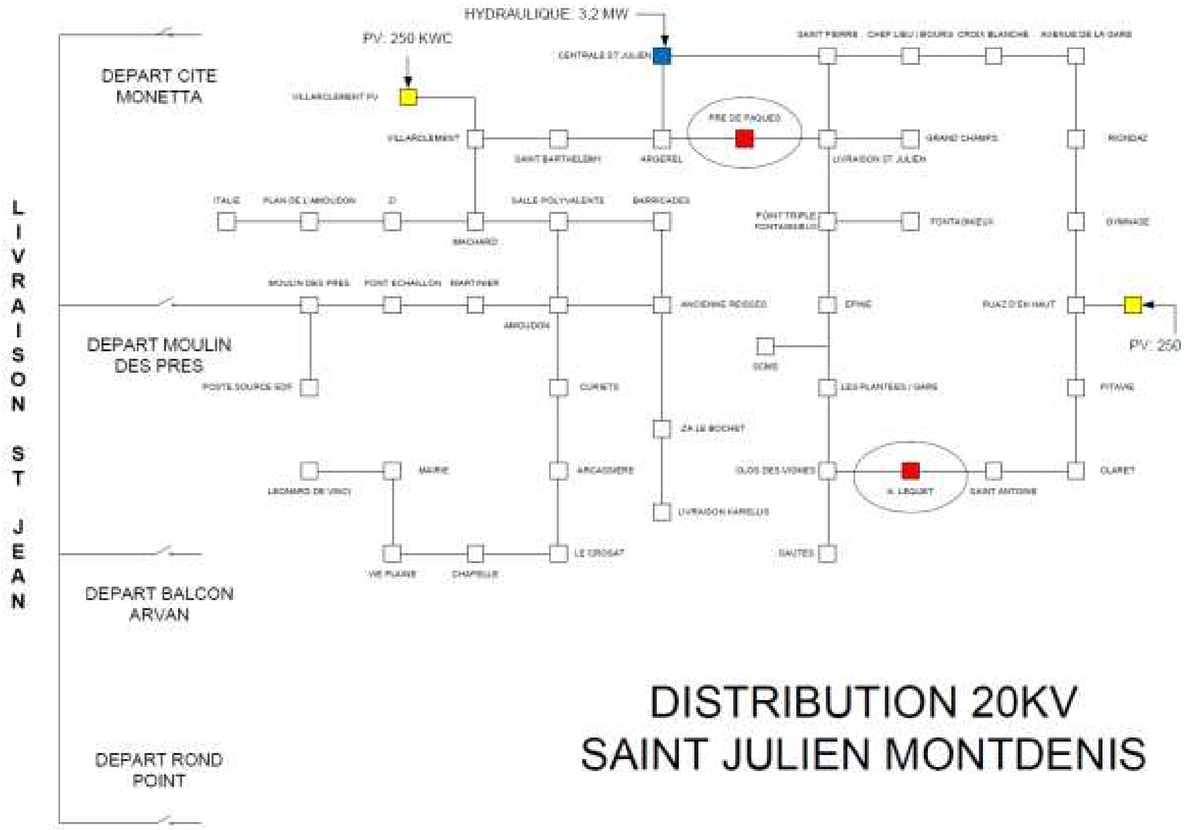

Figure 8: Demonstration site of SOREA.

The tests planned at SOREA ditribution network will be implemented in one of the three physical micro-grids, i.e. at the three LV networks located at Pre de Paques, A Lequet and Gymnase. The installed capacity of DER in these LV networks are described below.

- Pre de Paques: This network consists of two PV plants with PV canopies of 89kWp and rooftop solar panels of 72 kWp. The total installed capacity of PV systems in this network is 161 kWp (Figure 9).
- A Lequet: In this network, only rooftop solar panels have been installed, which are randomly distributed in the network using single-phase inverters. The total installed capacity is 43.36 kWp (Figure 10).
- Gymanse: This network supplies a sport complex. A rooftop PV system with the installed capacity of 234 kWp operates in combination with a lead-acid battery system of 36 kWh/18 kW capacity (Figure 11).

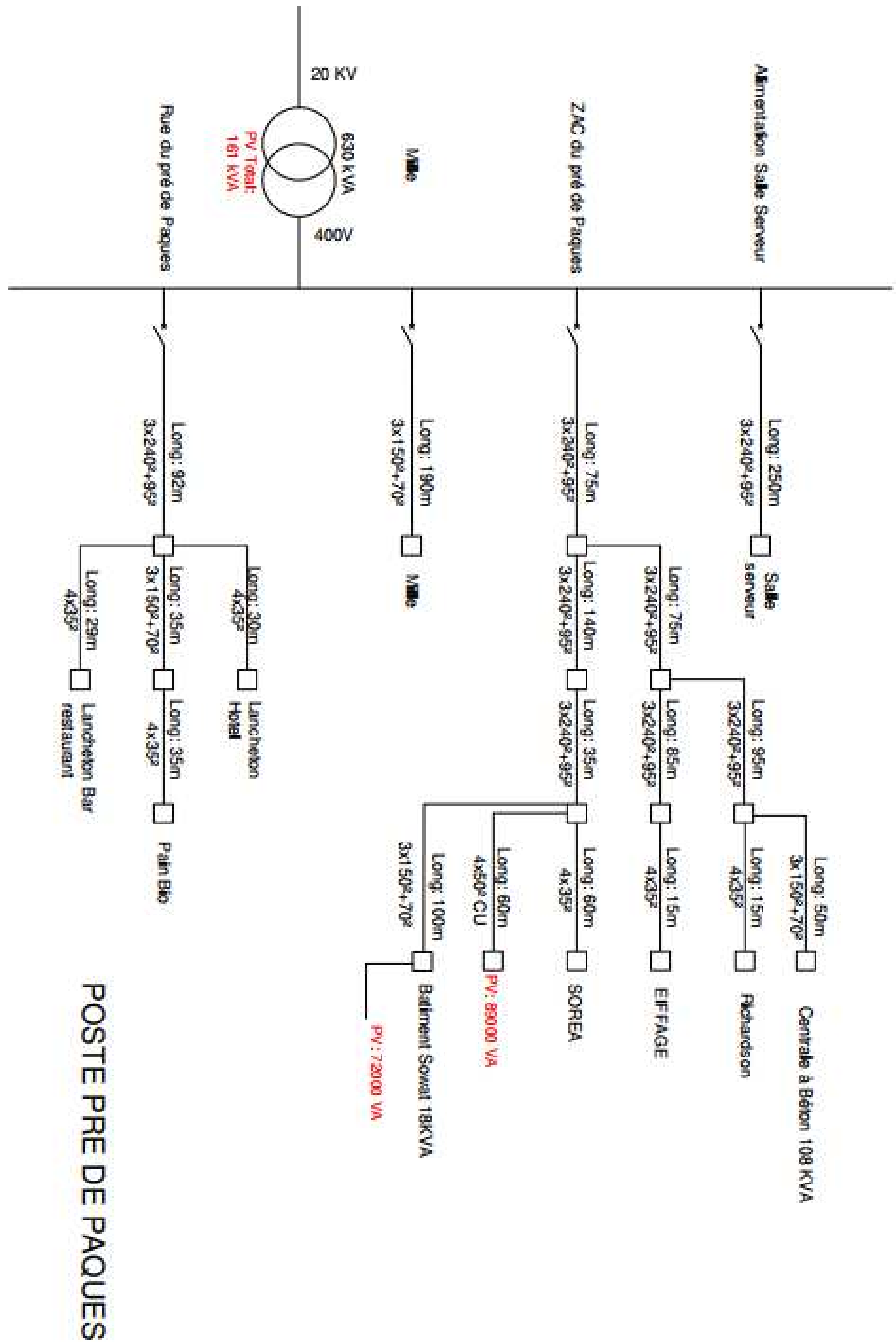

Figure 9: SOREA micro-grid at Pre de Paques.

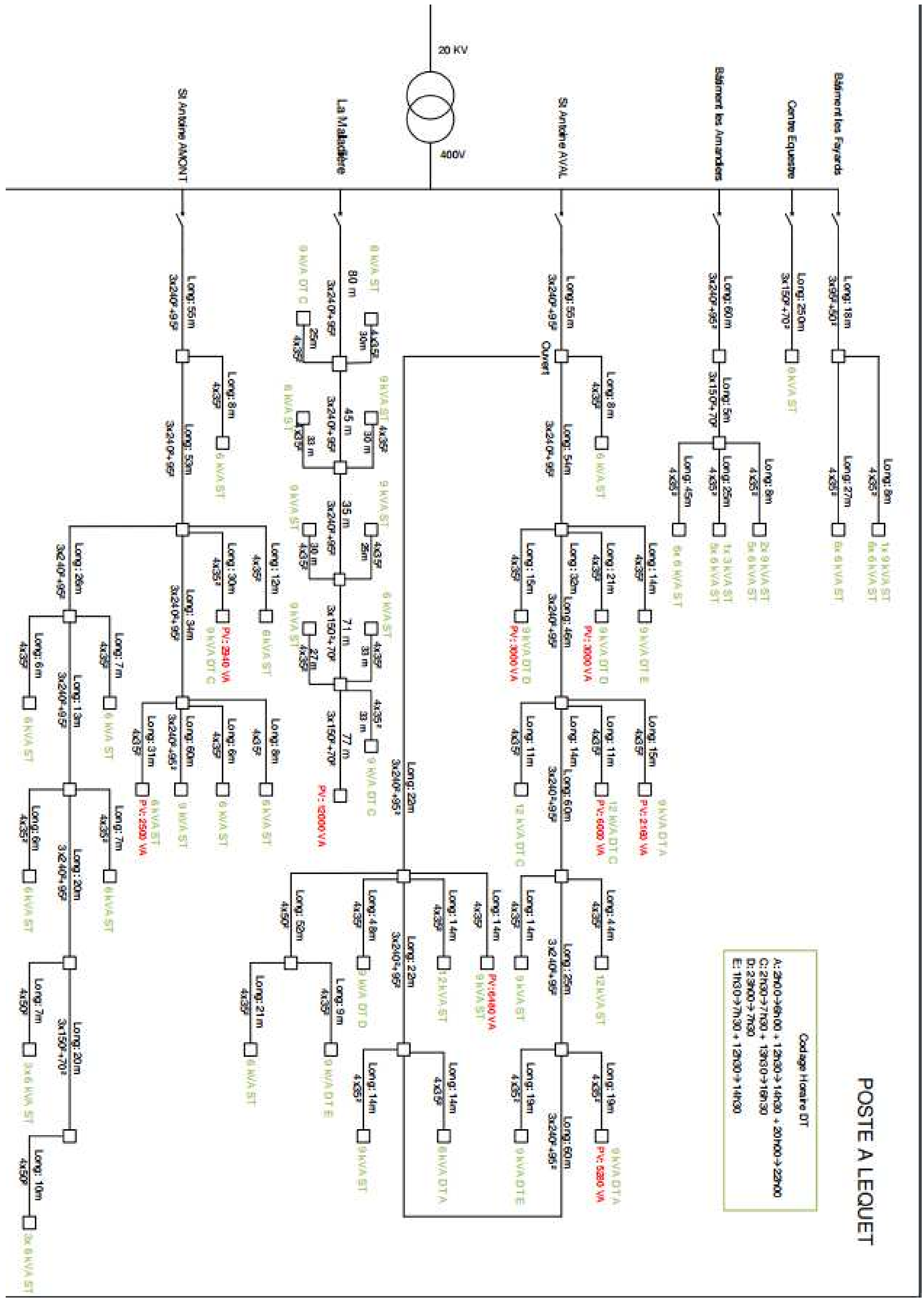

Figure 10: SOREA micro-grid at A Lequet.

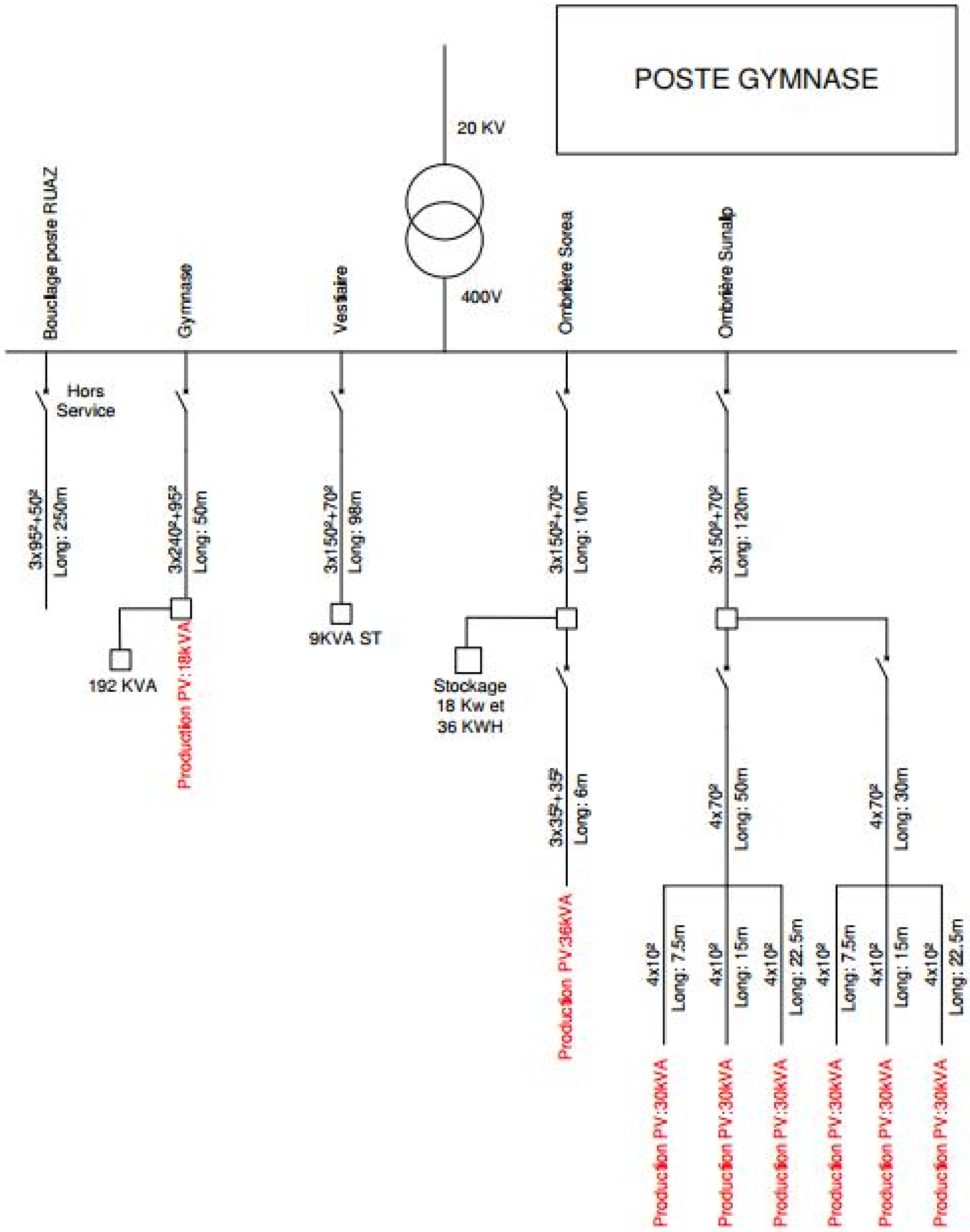

Figure 11: SOREA micro-grid at A Lequet.

3. Requirements and preparation for the tests

This section describes the test-related requirements to implement the developed interfaces (software layer) in the three physical test sites of the project and the preparations, which might be generic or specific to the individual test sites, to set-up the communication and control interfaces (middleware and hardware layer).

3.1 Micro-grid control

3.1.1 Micro-grid energy management system (MG-EMS) for optimal energy scheduling of micro-grid resources (Chalmers, Brf Viva)

The micro-grid energy management systems in Chalmers and Brf Viva will be implemented virtually, i.e. in a software where an optimization model will be developed for the optimal energy scheduling of the micro-grid resources. The energy scheduling model needs to interact with the controllable resources on site and dispatch them according to the operational targets. To implement the MG-EMS there were three requirements:

1. To identify the DER at the demonstration sites, their installed capacity and the technical limits of their operation.
2. To investigate about their external communication capabilities, their monitoring/controlling options provided by embedded sensors/controllers and the update rates of the measurements they can provide.
3. To establish a remote connection from the micro-grid resources to the dedicated server, where the developed models will run. This means that the data acquisition, the simulations and the execution of control commands can be performed automatically during the demonstration, as it would be done by a real EMS.

The options of utilizing other measuring equipment (e.g. smart meters) or data provided from energy portals were also investigated.

3.1.2 Voltage control prototype of PV inverters for solving voltage violation problems in micro-grid (SOREA)

The aim of this test is to apply coordinated voltage control within a micro-grid by utilizing reactive power control and active power curtailment of PV inverters. For this purpose, a voltage control prototype will be used at the distribution network of SOREA's demonstration site to interact with the deployed PV inverters. This prototype consists of a control algorithm, physical hardware, and interface components. It will operate as an external controller that has communication interface with a PV inverter at the demonstration site. The operational data measured at the demonstration site will be provided as input to the voltage control prototype, which produces a control signal and sends this signal to the PV inverters. Before the set-up of the voltage control prototype there are certain requirements that need to be taken into consideration during the preparation for this test:

- The voltage control prototype developed by TU/e will be tested in the laboratory environment prior to the implementation at SOREA network. An open-source electronic platform named Arduino board is used to build the voltage control prototype. The proposed control algorithm is then programmed into the voltage prototype. This platform is capable of reading inputs – the real-time measured data of the PV – and executing the control algorithm to generate outputs, i.e. the control signals sent to the PV inverter. This technology is open-source and the hardware is extensible, therefore, this platform is appropriate for building up a low-cost scientific instrument and, at the same time, it is flexible enough for advanced users. In addition, this voltage control prototype is in a compact size which makes it easy to install at a physical site. Figure 12 shows the voltage control prototype which is developed by TU/e and will be tested at SOREA network.

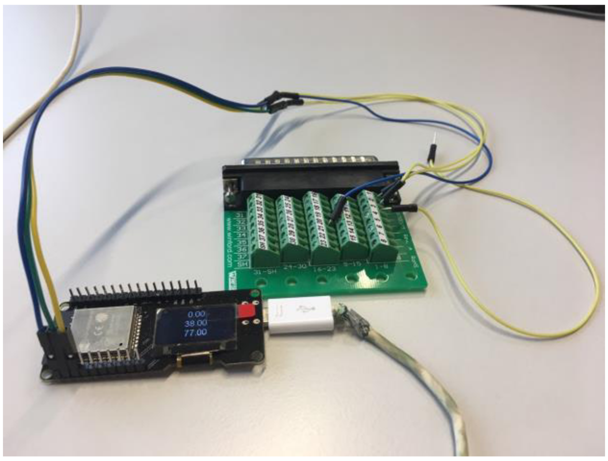

Figure 12: Voltage control prototype.

- The PV inverters must be capable of following the power set-points to adjust active power and reactive power outputs. In addition, the PV inverters should be equipped with communication capability, so that they can receive the power set-points in an on-line manner. To prepare the test performance, the specifications of PV inverters, e.g, P, Q controllability and communication protocol need to be known in advance, including but not limited to:
  - Available operating modes: e.g., MPP peak, voltage constant, power limitation.
  - Communication capability and protocol: e.g., ethernet cable, power line communication (PLC), Wi-Fi bridges.
  - Monitoring capability and interface.
  - Controllability: e.g., active power control, reactive power control, power factor control. An example of settings for active power control and reactive power control in response to voltage level is illustrated in Figure 13.

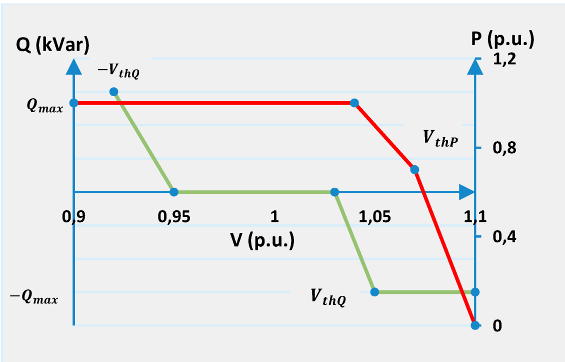

Figure 13: Active power and reactive power control of PV inverter for voltage regulation.

- Real-time measurements of the PV systems are required. These measurements can be derived from the operational data measurement system which is embedded in the PV inverters or from an external measurement system. This means that the knowledge of whether the PV inverters have a monitoring function or not is necessary. If not, additional measurement devices will be installed at the demonstration site. TU/e developed a real-time measurement platform that can be used for the test at the SOREA network as the additional measurement of PV systems. More details of the proposed real-time measurement are reported in Section 4.

- The PV system owners must agree for the installation and demonstration of the voltage control prototype because the prototype will operate in parallel with the PV inverters. Technicians will come to the PV inverter sites to implement the test. Thus, the PV system owners must be aware and agree with these works.

3.2 Micro-grid to DMS coordination

In this case, the optimal scheduling of the MG-EMS will consider support to the DSO in order to evaluate the benefits that the micro-grids could provide to the DSO or the restrictions to the grid-connected micro-grid operation imposed by the DSO. An additional requirement to the preparations for the MG-EMS set-up is to monitor the upstream network or the part of the network that is of interest. This will follow a different implementation for the Chalmers and the Brf Viva site:

- Chalmers: On Chalmers campus, there are smart meters that measure electric power consumption of each building (or groups of buildings). An aggregation of the measurements from these smart meters has been done, so that the values for the state estimation of the Chalmers network can be derived from each set of measurements. These values will be obtained through remote connection to the smart meters and will be used as input to the developed model of the distribution network to simulate its operation.

- Brf Viva: Due to the difficulties in integrating the monitoring of the large-scale upstream network to the demonstration tests, the physical behaviour of the upstream distribution network will be simulated by a digital real-time simulator (DRTS). Similar set-ups have been presented in [6]–[8] with the latest trend being the integration of Internet-of-Things (IoT) technology to the real-time simulation [7]–[8].

3.3 Micro-grid to micro-grid coordination

The micro-grid to micro-grid interactions could be tested between two MG-EMS in Chalmers (micro-grids located under the same transformer) or between the Brf Viva MG-EMS and a Chalmers MG-EMS (micro-grids located under different transformers). In any case, remote connections should be established:

1. Between the micro-grid resources (which could even be located at different test sites) and the dedicated server (where both MG-EMS will be simulated).

2. Between two servers, each of which will simulate one MG-EMS, remotely connected to the resources at one site (as described in Section 3.1.1).

4. Communication and control set-ups

4.1 Web API solutions for the demo sites in Sweden

4.1.1 Brf Viva interface

The implementation of the MG-EMS in Brf Viva will be achieved by using the bi-directional converter EnergyHub (E-Hub). The solar panels and the batteries will be monitored by sensors in the E-Hub. Data such as solar power generation, charging/discharging power and state-of-charge (SOC) of the batteries as well as power exchange at the point of connection can be read directly on the screen of E-Hub as well as in a web portal. The access to the web portal is provided by a cloud-based application programming interface (API). An external API, called extAPI also allows the remote connection to the converter via

TCP/IP and enables monitoring through either the Modbus or the message queuing telemetry transport (MQTT) protocol. The AC load consumption in the buildings will be monitored in real-time by separate meters and their data will be available at a monitoring and control centre called Styrportalen, which is owned by Riksbyggen.

The E-Hub can also control the batteries (charging/discharging power). The converter controller implements a battery scheduling algorithm, where a peak power and a low load threshold trigger the charge/discharge of the batteries. However, there is the option to override this automatic control and dispatch the batteries under a different scheduling model. This option is available with the remote connection by the extAPI.

Since the E-Hub provides the external communication capability through the MQTT protocol, it was decided that this protocol will be used for the control of the inverter by the developed models. It is superior to Modbus because it offers advanced security and moreover the connection with the MQTT protocol allows for continuous exchange of messages, whereas Modbus requires data polling. The MQTT protocol is an IoT messaging protocol based on a publish/subscribe architecture that is used for connection of devices over the wireless network and it runs over TCP/IP sockets or Websockets [9]. It is an extremely lightweight (very low overhead) protocol that works especially well with power-constrained devices or cases when intermittent connectivity is an issue, since it optimally utilizes the bandwidth. An MQTT client can be built in a software to publish/subscribe, i.e to exchange messages with the connected device (E-Hub). The software will interface the developed energy scheduling algorithms for the MG-EMS implementation. The client subscribes to the E-HUB, which acts as the broker, to read json formatted data that are provided by the E-Hub. Control commands can also be sent to the E-Hub by publishing. The communication interface set-up can be seen in Figure 14.

A Web API can be developed to run queries and update the data (input to the MG-EMS algorithm and dispatch commands to the batteries of the E-Hub).

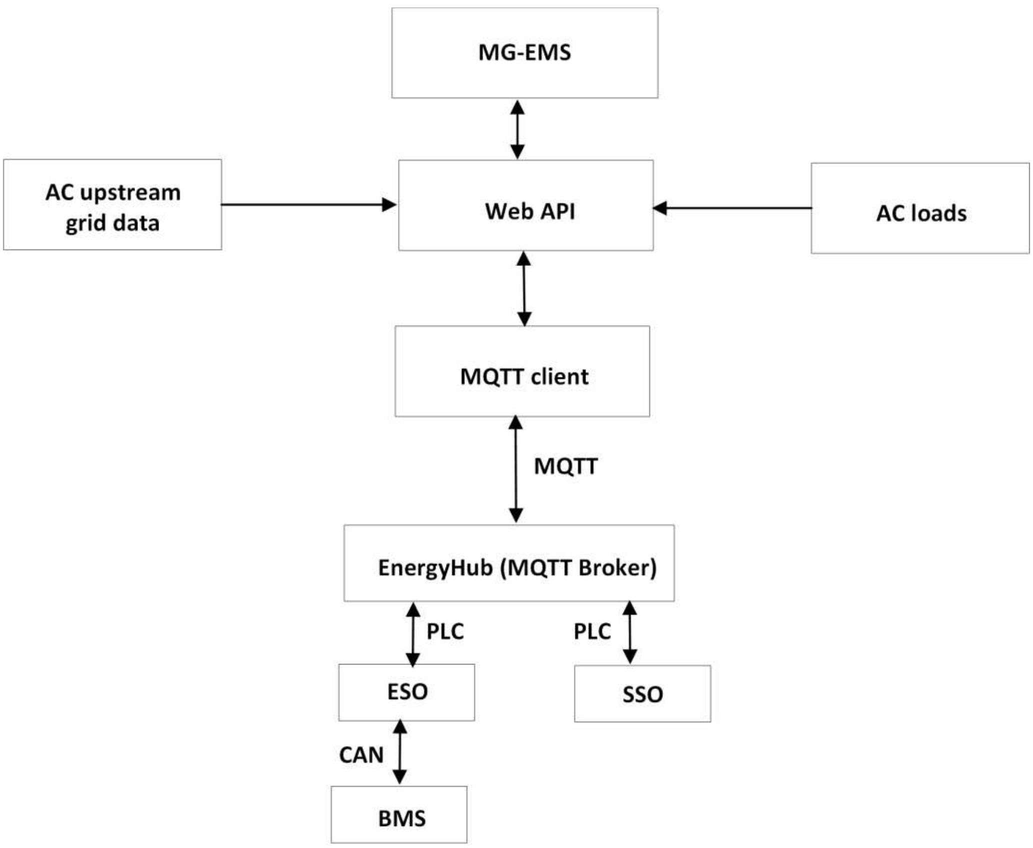

Figure 14: The communication interface set-up for the MG-EMS in Brf Viva.

4.1.2 Chalmers interface

Historic data and real-time measurements from the point of connection of the resources (battery converters, PV inverters, curtailable loads) as well as other locations in the network (in the case of the micro-grid/DMS interface) will be entered as input to the MG-EMS models. The dispatch set-points (decided by the optimization model) will be sent individually to the resources through the Webport HMI/SCADA [10], which will also provide the real-time measurements. The task of the Webport HMI/SCADA is to collect measurements from various meters/sensors and change parameter settings of control devices deployed at the campus buildings. The converter-embedded controllers (PVs, ESS) are integrated in Webport through Modbus protocol and the smart meters through the M-bus protocol. The building controllers are also integrated in Webport. The data exchange with the SCADA system is enabled through web requests and the Webport messages are formatted in json, so a Web API could be used here as well to read and write json formatted data, i.e. update the input and output of the MG-EMS (see Figure 15).

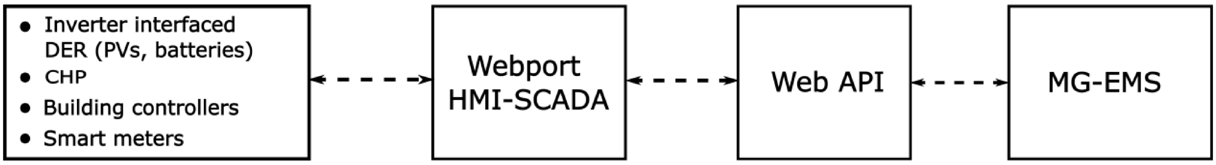

Figure 15 : Communication interface set-up for the micro-grid interfaces in Chalmers.

4.1.3 Micro-grid to micro-grid interface

As described in Sections 4.1.1-4.1.2, Web APIs will be developed for the micro-grid interfaces in Chalmers and Brf Viva. The APIs will be the interface between the resources (remotely connected through Wi-Fi) and the developed models that will provide the dispatch set-points to them. If one dedicated server is used for the models, the web APIs and the database (where the measurements/parameter settings will be stored), a communication set-up for the micro-grid to micro-grid interface could also be developed as presented in Figure 16:

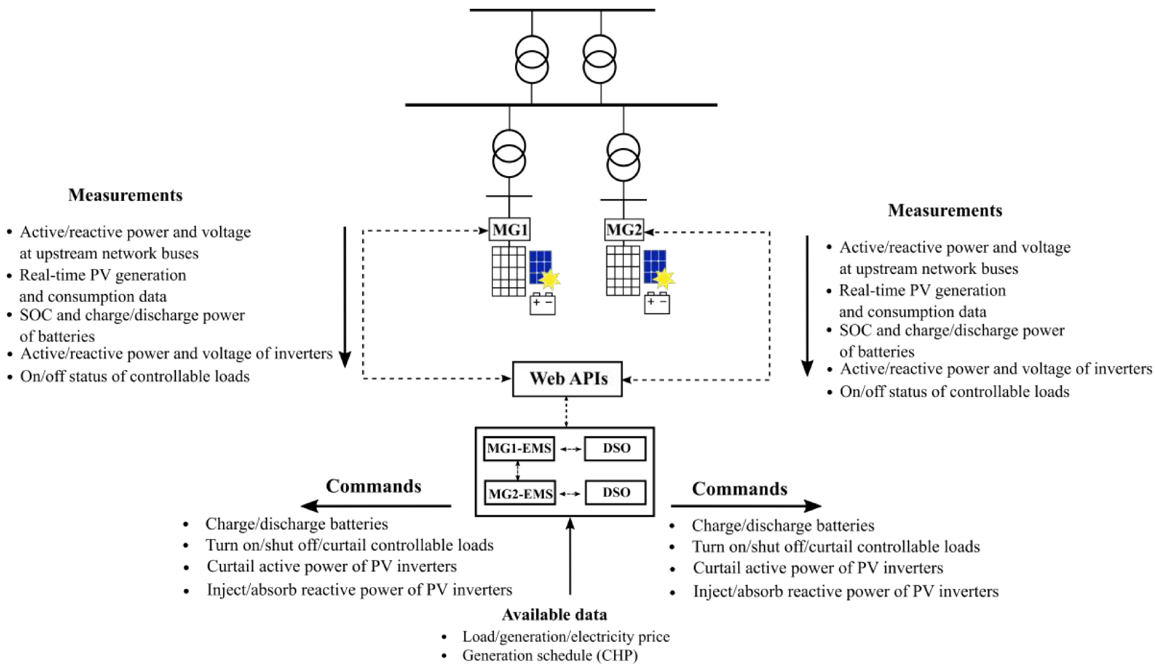

Figure 16 : Communication interface set-up for the micro-grid to micro-grid interface.

4.2 Real-time simulator set-up in Sweden

The data exchange between metering devices deployed at MV network and sensors/smart devices at LV network and even at end-user level is hard to achieve. However, it is a requirement for the DMS and MG-EMS interface. To overcome this obstacle for the physical site test digital real-time simulation can be used for a specific part of the network, if the near real-time monitoring of that part is not available. That is the case with the Brf Viva MG-EMS and therefore the upstream MV network owned by Göteborg Energi will be simulated using an DRTS. The network consists of 26 nodes (secondary transformers) and one of these nodes of the simulated network (the transformer that will supply Brf Viva) will exchange data with the E-HUB controller. The DRTS must be connected to the server of the simulated MG-EMS as shown in Figure 17.

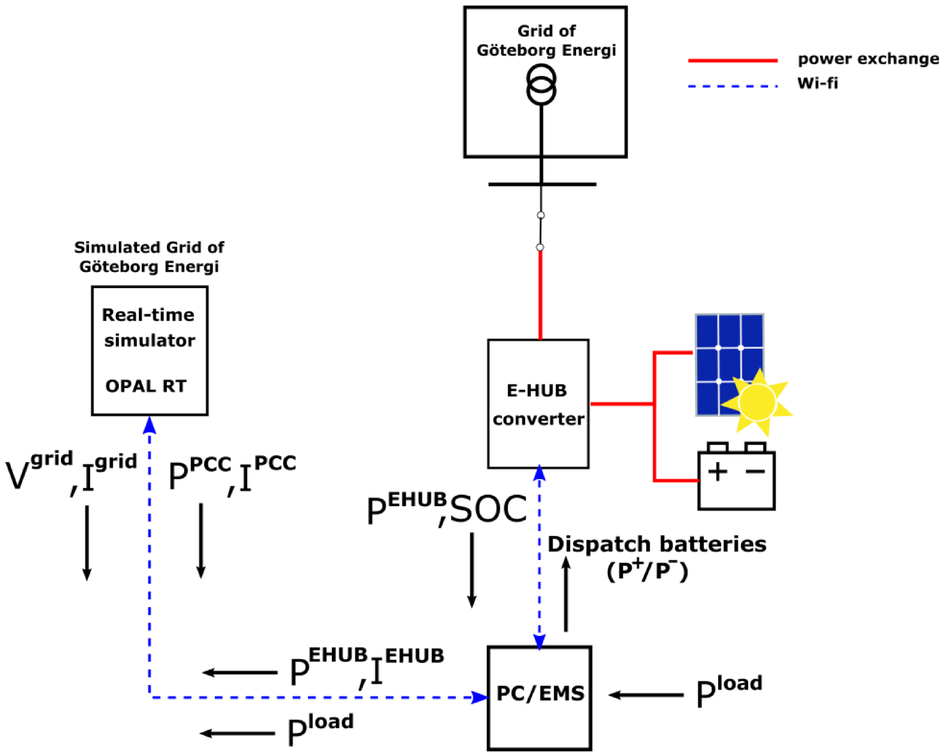

Figure 17 : Set-up with real-time simulator for the micro-grid to DMS coordination at Brf Viva test site.

4.3 Communication/control set-up at SOREA

Figure 18 shows the location of the pilot points, which represent the global grid. For coordinated voltage control at the MV network (20 kV), the voltage magnitude in the pilot points must be kept in the desired deadband by sending a reactive power set point to the controllable PV and hydroelectric power plant. The steps that will set-up the test to validate the voltage control at the 20 kV network are:

- Step 1: Identify the existing measurements at the MV network of SOREA and specify the configuration of the network.
- Step 2: Test the controllability of the PV inverters and the hydroelectric power plant to ensure that reactive power set-points can be sent to them.
- Step 3: Enable the communication between the control center and the PV inverters (test the interoperability of the ICT infrastructure).
- Step 4: Validate the control algorithm by evaluating the real-time measurements of voltage, active and reactive power at the point of connection (POC) of the PV inverters.

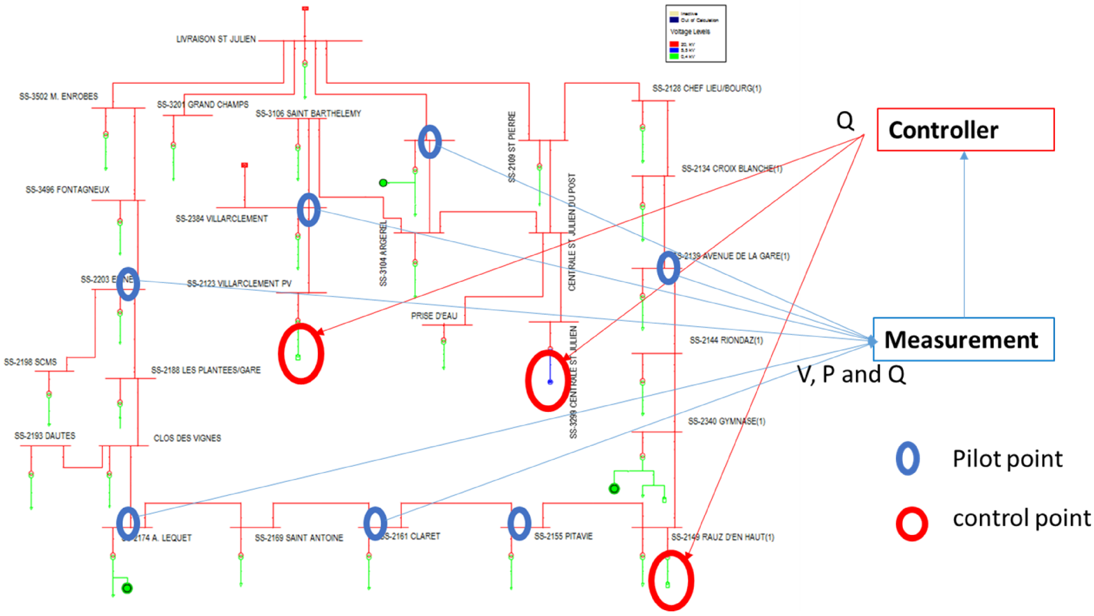

Figure 18: Pilot points and controllable plant in the single line diagram.

The purpose of Step 2 is to enhance the communication capability of local controllers and make the PV inverters remotely dispatchable, while, during Step 4, local real-time measurements at the POC will be gathered for evaluation of the associated metrics. The above are also requirements for the application of the local voltage control of a micro-grid (LV network) and therefore they are in alignment with the preparation for the test case described in Section 3.1.2.

Figure 19 shows the real-time measurement platform that can be used for testing the voltage control prototype developed by TU/e at the demonstration site. This platform will be used to gather the real-time measurements of the PV inverter in order to generate the inputs for the voltage control prototype if the PV inverter has no embedded monitoring function.

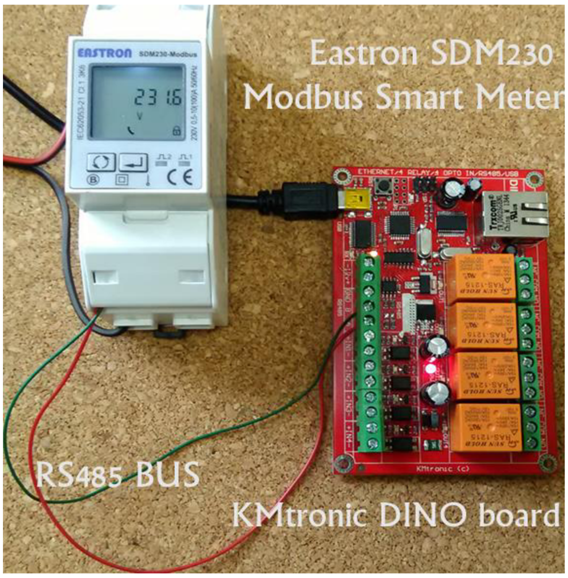

Figure 19: Proposed real-time measurement platform.

This real-time measurement system consists of a smart meter and an Arduino board. A smart meter will be installed at the POC of the PV system, where the voltage levels and the power delivery from the PV inverter to the grid will be measured. The smart meter will transmit the measured data using the Modbus communication protocol. An Arduino board - an open-source electronic platform – is used to build a device that interconnects with the smart meter. This Arduino board acquires the measured data from the smart meter and transmits the data to the voltage control prototype of PV inverters through Wi-Fi and using the RS485 communication protocol. The proposed real-time measurement solution is flexible and low-cost as well as easy to install and use at the demonstration site.

One more advantage of using the proposed real-time measurement is that it can enhance the real-time monitoring capability of PV systems in the network. Figure 20 shows the monitoring system that can be applied for the PV systems of the network.

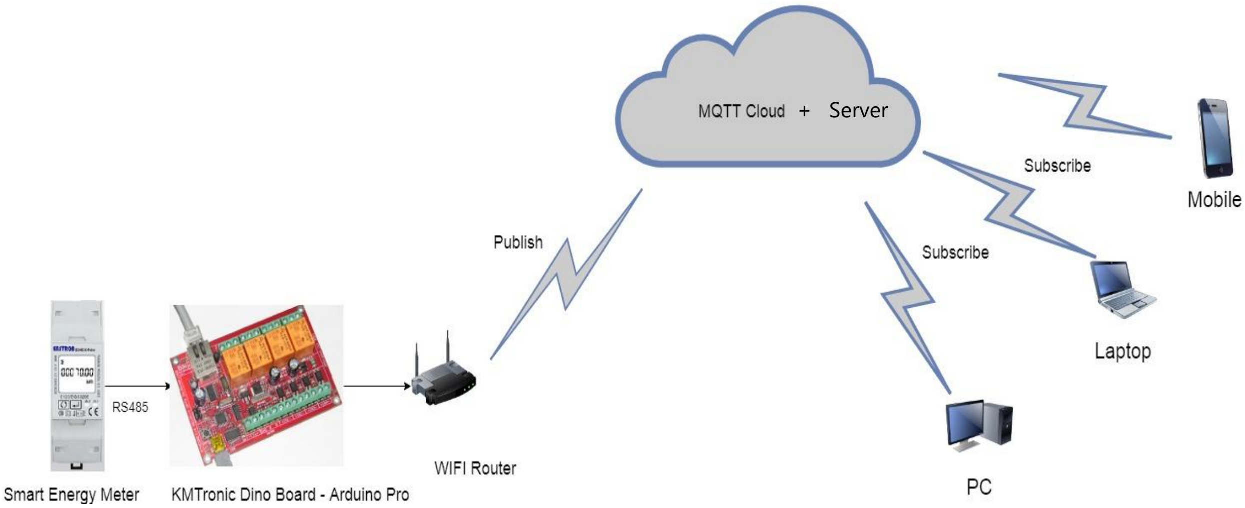

Figure 20: Example of monitoring system applied to PV

Connecting to Wi-Fi, the aforementioned real-time measurement platform is capable of transferring the measured data to MQTT cloud services in the Internet. The MQTT protocol is used to publish the measured data from the real-time measurement platform to the MQTT cloud, which receives the data, while Node-red is used for visualizing the received data. To develop a database for later use, for example analysis of historical data, a server can be built to connect with Node-red for storing data. By accessing the MQTT cloud and the server via computers or smart phones, the users are able to observe the PV performance in distances.

4.4 Interoperability challenges

The Web APIs promote scalability as the integration of new controllable devices/inverters is straightforward, once they can be interfaced via TCP/IP (either directly or preferably through the middle layer of a SCADA system). Very often not all functionalities (especially control settings) are directly available to the user that connects via TCP/IP and therefore additional interfacing devices might have to be used. Devices that can be accessed through MQTT protocol (which works on top of TCP/IP) and provide json formatted data are easier to integrate and work well with web-based solutions. The difficulties regarding interoperability and scalability at the test sites in Sweden have mostly been associated with the integration of Modbus-interfaced PV inverter controllers to the Webport SCADA. For this purpose, the Solar-Log™ [11] is used as an interface to enable the communication between the inverter-embedded device and the SCADA system.

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