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Abstract—**Smart meters are the cornerstone in the new conception of the electrical network or Smart Grid (SG), providing detailed information about users' energy consumption and allowing the suppliers to remotely collect data for billing. Nevertheless, their features are not only useful for the energy suppliers, but they can also play a big role in the control of the Microgrid since the recorded power and energy profiles can be integrated in energy management systems (EMS). In addition, basic power quality (PQ) disturbances can be detected and reported by some advanced metering systems. Thus, this paper will expose an example of Smart Meters integration in a Microgrid scenario, which is the Intelligent Microgrid Lab of Aalborg Univeristy (AAU). To do this, first the installation available in the Microgrid Lab will be introduced. Then, three different test scenarios and their respective results will be presented, regarding the capabilities of this system and the advantages of integrating the Smart Meters information in the Microgrid control.**

Index Terms—**Advanced metering infrastructure, smart meter, microgrid, energy management system, power quality**

I. Introduction

The concept of Smart Grid (SG) has completely changed the conception of the electrical network, where the classical chain of centralize energy production, transmission, and end users' consumption has been substituted by a bi-directional power flow, with distributed generation (DG) and consumption, and new emerging types of energy resources. In this context the Smart Meters play a main role, not only giving the suppliers access to accurate data for billing, but also collecting information of the end users, and establishing a two-ways communication [1].

This new approach has been possible due to the implementation of new communication protocols and a complex metering infrastructure. In consequence, the direct manual billing has been substituted by a metering network composed of communication hubs, data concentrators, central system units and different control centers, defining a new Grid architecture [2].

In the beginning, these protocols were mainly proprietary and the development of an advanced measuring network had to face a wide range of issues. Nevertheless, a standardization process has been promoted to assure the interconnection

between different Smart Meter units. In this context, protocols such as DLMS/COSEM (IEC 62056-53 [3] and IEC 62056-62 [4]), SML (IEC 62056-58 [5]), M-Bus (EN 13757 [6]) or IEC 61850 [7], are today ones of the most common implemented standard for Smart Meters and substations data collection [8].

This standardization process has implied significant benefits from the point of view of system integration and control in Microgrid networks. A Microgrid can be described as an electrical system where a bi-directional flow of energy exits. It is usually composed of many DG units (renewable or not) and the whole system can be either isolated or connected to the main grid [9]. Therefore, to control this shared energy flow, a well-developed communication infrastructure is an essential part of the Microgrid conception [10].

Likewise, another important feature of the Microgrid networks is the usage of a hierarchical control strategy. The primary control is focused in the inner control of each DG unit (droop control), the secondary control is supposed to restore frequency and voltage amplitude deviations due to the inertias. The tertiary control regulates the power flows between the Microgrid [11], [12].

The reported frequency of the Smart Meters measures is usually slow, 5 to 15 minutes, to be integrated into the primary or secondary control. However, they can be employed in a higher level for matching production and demand in the Microgrid network. Thus, it is in the so-called tertiary control level of the Microgrid where the Smart Meters can provide measures for the EMS, allowing the implementation of demand response (DR) techniques [13], [14].

In addition, some advanced Smart Meter systems report not only information about energy consumption, but also basic power quality (PQ) indices, with increasing importance due to the proliferation of non-linear loads. These PQ measures can range from voltage profile measurement to harmonic distortion calculations [15], [16].

In this paper, the benefits of the Smart Meter systems for the Microgrid will be addressed, showing a real example in a lab-scale Microgrid. For this aim, the structure of this paper is as following: in Section II the installation available in Aalborg University Microgrid Lab for emulating a Microgrid network is presented. Section III will provide different test scenarios defined to evaluate the operation of the Smart Meters and the obtained results will be commented. In Section IV, future

works in the Microgrid Lab are described. Finally, Section V is dedicated to the conclusions about the systems and tests.

II. SYSTEM OVERVIEW

The Smart Meter system is integrated into the Aalborg University (AAU) Intelligent Microgrid Lab [17]. The whole system is composed of 6 workstations that can be supplied using a central DC source of up to 80 kW, PV panels, Wind Turbines or flywheel storage. The general schema of the Lab can be observed in Fig. 1. Each set-up includes four DC-AC three phase converters with LCL output filters, monitored switches for load operation and two Smart Meters from Kamstrup Company.
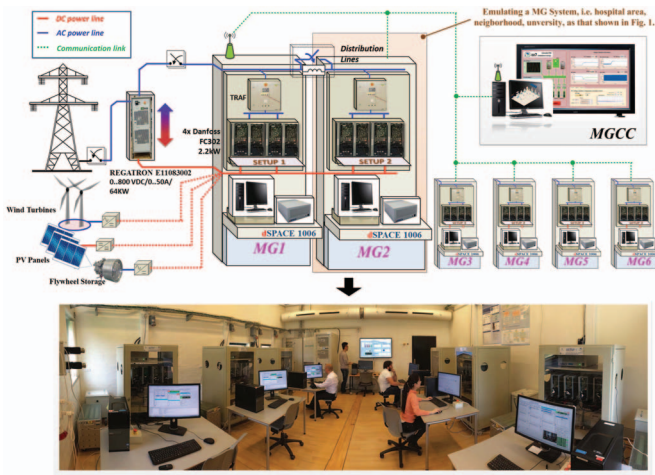

Fig. 1. Overview of the Intelligent Microgrid Lab facilities

The four three phase converters can be individually controlled using a dSPACE real-control platform managed from a desktop PC. In addition, the different switches on the system can be operated from this PC, enabling the remote control of the whole system, that can be connected to a wide range of load types.

A. Smart Meters

As mentioned before, each workstation contains two Kamstrup Smart Meter, each one with a different purpose. The industrial Smart Meter 351B is used to measure the energy flow of the whole workstation, so it can measure DG, whilst the other model the 382L is attached to the load consumption, and therefore it can be regarded as an individual consumer.

Both models of Smart Meters are for three-phase measurements. They measure active positive energy (EN 50470-1 and EN 50470-3 [18]), reactive energy, and active negative energy (IEC 62052-11 [19], IEC 62053-21 and IEC 62053-23 [20]). In addition, average and maximum power values during the billing period and different tariffs can be configured in the Smart Meter, recording individual information in each tariff period.

Along with these basic features, as can be desirable in any Smart Meter, additional characteristic are provided by these models. The two employed Smart Meters have a built-in

EEPROM memory where the load profile information can be stored. The amount of data that can be recorded depends on the number of energy variables and integration period selected for the energy. Thus, the number of days range from 450 days when only the positive active energy is recorded every 60 minutes, down to 17 days, when positive and negative active and reactive energy is monitored with 5 minutes of integration period.

Another common feature of the two models is the measurement of the voltage quality. The Smart Meter is able to record deviations in the nominal voltage within a given range and during a defined period of time. The default characteristic of this function is minimum $\pm10\%$ voltage deviation detection for events longer than 10 minutes.

Finally, an additional characteristic only available in the 382L model is the possibility of defining a customized analysis logger. This logger can register up to 16 different variables with sampling periods of 5, 15, 45 or 60 minutes. Depending on the number of variables and the selected resolution, the logger's depth can range from 2 days up to 520 days. Therefore, in this model, not only the load profile is available, but also the average voltage, current, power, etc. can be recorded in different intervals [21].

B. Communication

Another important feature of the Smart Meters is the implemented communication protocol. The Kamstrup meters installed in the Microgrid Lab are compliance with the IEC 62056 standard [3], which is the International Standard version of the DLMS/COSEM specification (Device Language Message Specification/Companion Specification for Energy Metering). In particular, these Smart Meters support the DLMS/COSEM specification over TCP/IP, GSM or over a serial communication through an optical port.

From these three options, the communication procedure implemented in the Lab is the TCP/IP connection since it provides a scalable solution, where all the Smart Meters installed in the Lab can be accessed using the TCP/IP protocol over the same network structure. In addition, a ZigBee Communication is implemented between the 382L Smart Meter and an In-Home display only for global energy monitoring. However, since the goal of the experiments is to study the real detailed measures of the Smart Meters it has not been used.

III. TEST SCENARIOS AND RESULTS

In order to test the capabilities of the installed Smart Meters, a simulated scenario was developed using one of the workstations in the Microgrid Lab of Aalborg University. As it can be observed in Fig. 2, the test set-up was composed of one of the four three-phase DC-AC converters working as a Voltage Source Inverter (VSI). This converter was supplying two different loads (in both sides of the cabinet) connected in parallel throw two individual monitored switches. In addition, two system Smart Meters were monitoring the energy flow between the converter and the two loads. Finally, all the system was controlled from the desktop PC and the dSPACE,

whereas the Smart Meters data were collected using a TCP/IP communication and over an Ethernet connection.
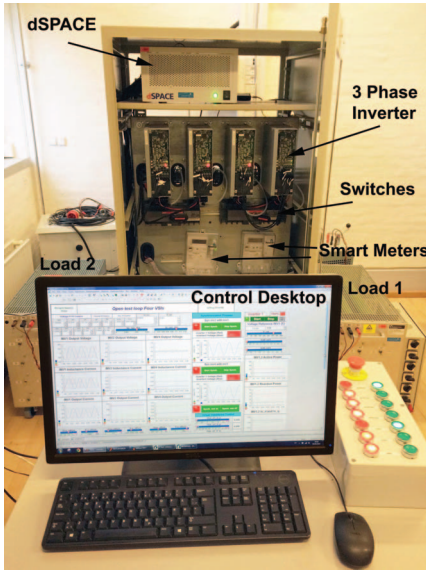

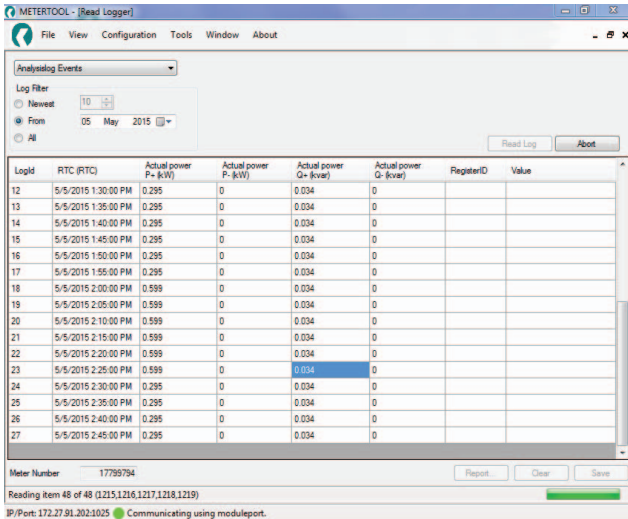Fig. 2. Workstation configuration for the tests

Fig. 3. Screenshot of Kamstrup MeterTool software.

Using this configuration, three different test scenarios were analyzed. First, the possibilities of the Smart Meters to record the power and energy demand profile were studied by means of switching the two loads on and off. Secondly, the capability of these Smart Meters to detect voltage quality events was tested by changing the voltage reference of the three-phase converter. Finally, the possibility to detect changes in the network parameters due to the droop control strategy was tested.

To obtain the data recorded by the Smart Meters, the MeterTool software, provided by Kamstrup, was used. A screenshot of the application is shown in Fig. 3. This screenshot corresponds to the Analysis logger of the Smart Meter where each column corresponds to a monitored variable.

In addition, these data can be exported in a wide range of format. For the performed tests, the data were exported as CSV files (Comma Separated Values) in order to build the different graphs that will be subsequently shown.

A. Load Profile Measurement

The first scenario aims to simulate a power demand variation, to test the capability of the Smart Meters for measuring and recording the load profile of the system. For this purpose, two different load were used, named as Load 1 and Load 2. Load 1 was an inductive load with 460 Ω and 50 mH per phase, whereas Load 2 was a pure resistive load with 460 Ω per phase.

Using the two loads with different characteristic a simulated power demand change was forced in the system. The VSI was started together with Load 1 and after a defined period of time, Load 2 was turned on. Finally, after 30 minutes, Load 2 was switched off again.

The obtained results were recorded by the Smart Meter using the load profile memory and were extracted in CSV format using the MetorTool Kamstrup Software. The load profile logger recorded four variables: active positive and negative energy, and reactive positive and negative energy. However, since the energy is only sunk by the loads the active and reactive negative energy do not present any variation, so they are not represented in Fig. 4. It should also denote that the energy is an aggregated variable and therefore, the initial value at the beginning of the experiment was not zero due to the previous usage of the Smart Meter. Another important consideration is that all the results will be represented as a line-scatter plot where the real values of the Smart Meter correspond to the points, whilst the line is just a linear interpolation between adjacent measures.
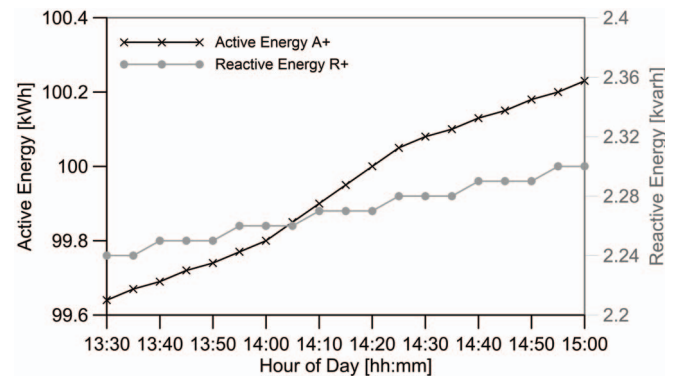
Fig. 4. Scenario 1. Active and Reactive Energy during a Load Disturbance

As it can be seen in Fig. 4, the active energy (solid black line with cross symbols) at the start of the test had a value of 99.7 kWh (left Y-Axis), whereas the reactive energy (solid grey line with point symbols) equals to 2.24 kvarh (right Y-Axis). Three different zones can be observed in the active energy profile, characterized by a different slope. One from 13:30 h to 14:00 h, the second one from 14:00 h to 14:25 h and the third one from 14:25 h until the end of the experiment. In

contrast, the reactive energy profile seems to have an average constant slope.

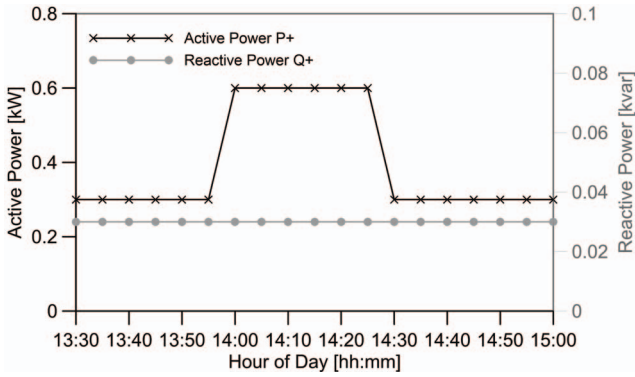
Fig. 5. Scenario 1. Active and Reactive Power during a Load Disturbance

These three zones clearly correspond with three different power intensities in the active power consumption. This power can be easily obtained from the energy profile since the integration period is known (5 minutes). However, due to the existence of an analysis logger in the 382L Smart Meter, the system was configured to store the average active and reactive power during each integration period. The different measures obtained by the Smart Meter are graphically represented in Fig. 5.

Now, the load variation can be observed in terms of power consumption. As it was expected, after switch on the Load 2, the active power measured by the Smart Meter rose up from 0.295 kW to 0.599 kW, whereas the reactive power kept a constant value, since Load 2 was pure resistive. The opposite happened between 14:25-14:30 h when Load 2 was turned off.

B. Voltage Quality Events Detection

The second test scenario was focused in the detection of voltage quality events using the Smart Meter system. For this aim, the DC-AC three phase converter was operated again as a VSI, but changing now the voltage reference value for the control loop. With this configuration two perturbations in the voltage were generated, firstly an undervoltage and secondly an overvoltage.

The detection of voltage quality events is recorded in a logger inside both 351B and 382L Smart Meters. This logger stores not only the deviations of the supplied voltage outside the normal operation range, but it also detects and notice the power cut off and the switch on events of the meter system. In order to illustrate this behavior, a screenshot of the voltage quality logger of one of the Smart Meters during the Test is shown in Table. I.

The previously presented test and this second one were carried out approximately from 13:30 h to 16:20 h. Before this time, the Smart Meters were off and after the two scenarios the system was again turned off. This can be perfectly seen in the report of the voltage quality logger, where a power enabled event was detected at 13:28 and a power cut off at 16:19.

Nevertheless, two additional events were also recorded in between. One of the lines of the system seems to have

TABLE I
SMART METER VOLTAGE QUALITY EVENTS LOGGER

RTC (RTC)	Hour counter (h)	Voltage extremity (V)	Voltage event
5/5/2015 1:28:42 PM	66	0	System L1,L2,L3: Power enabled - above cutoff threshold
5/5/2015 3:12:14 PM	68	0	System L3: Voltage below limits
5/5/2015 3:41:51 PM	68	91	System L3: Voltage within limits from minimum
5/5/2015 4:19:25 PM	69	0	System L1,L2,L3: Power cut off

a undervoltage during approximately 30 minutes. Thus, to validate the occurrence of the event, before the start of the simulation the 382L Smart Meter Analysis logger was also configured to store the voltage in the 3 lines of the system.

Fig. 6 illustrates the evolution of the three phase voltages during the test period where the voltage perturbation was introduced. Again the real measured data are shown as different points, whereas the line is just an interpolation. In addition, two dashed lines have been represented to indicate the maximum and minimum thresholds of the system, which for these case were ±10% of the nominal voltage (230 V).
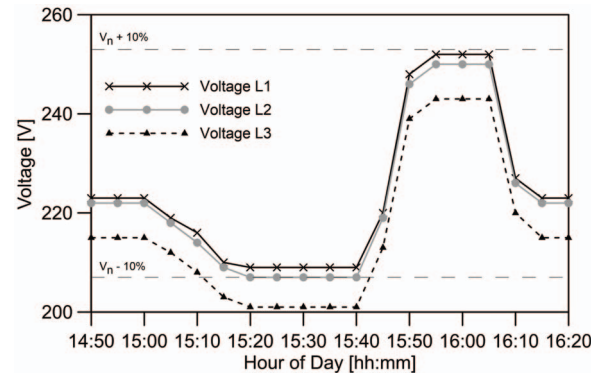

Fig. 6. Scenario 2. Voltage per phase during a variation in the reference voltage of the VSI.

Fig. 6 shows that at the start of the test, the voltages of the three phases of the system are within the admissible range. Furthermore, a small unbalance can be observed between three-phase, that can be justified since the real resistance and inductance values of the load are not perfectly similar for all the phases.

After approximately 10 minutes, the voltage of the system was slowly decreased. This operation promoted that the voltage in line 3 reached a value outside the nominal range. The first sampled value outside range was reported to be 203 V at 13:15 h. However, regarding Fig. I and Fig. 6it can be noticed that the event occurs before the refresh of the register. This depicts an important fact in the behavior of the system. In spite of updating the measuring registers after the integration period (5 minutes), the instantaneous values of voltage and current are measured to calculate power and energy, otherwise it would have been impossible to have reported the undervoltage event with a precision of seconds.

The undervoltage situation is maintained during approximately 30 minutes. After this time, the voltage is restored to the nominal value. As it was illustrated in

Fig. I, the system is also able to detect and record the instant when the voltage is again between the limits.

Subsequently, an overvoltage situation is forced. However, in this case, the voltage was selected so that it was still within the limits to prove the behavior of the system tolerance for voltage quality event detection. As it can be observed in Fig. 6, the voltage in line 1 reached a value near to the maximum threshold. The value of this voltage is equal 252 V, a figure which is inside the limits since 230+10% is 253 V. Thus, as it was expected no voltage quality event is reported in Fig. I during this period.

C. Monitoring of Droop Control

The third and final scenario was focused in the detection of deviations in the system parameters, due to the control operations of the Microgrid, specifically the droop control. This control strategy is employed to regulate the active and reactive energy power flow by means of changing the frequency and voltage of the DGs respectively, a behavior that can be clearly observed in the Microgrid when it is working in islanded mode, which means without connection to the main grid, and no voltage and frequency restoration strategy (secondary control) are implemented.

The operation mode of the droop control is summarized by the equations (1) and (2), where ω is the angular frequency of the DG, E is the voltage, and P and Q are the active and reactive power exchanged with the Microgrid. In the other hand, k_p and k_v are the droop coefficients, which determines the slope of the control strategy and, therefore, the frequency and voltage deviation for achieving a determined power exchange.

$$\Delta \omega = -k_p \cdot P \qquad (1)$$

$$\Delta E = -k_v \cdot Q \qquad (2)$$

Since the Smart Meters installed in the Lab are not able to measure frequency, only the droop control strategy for reactive power exchange was tested. For this aim, the same loads of the Scenario 1 were used, but activating now the droop control in the DC-AC converter, which works as a VSI emulating a DG unit. In addition, the switch on sequence was inverted, so now the Load 2 (pure resistive load) is first turned on, and subsequently Load 1 (inductive load) is activated to cause a change in the demanded reactive power.

The obtained results are shown in Fig. 7, where the three-phase voltages are represented together with the demanded reactive power. As it can be seen, from 12:50 h to 13:05 h, only Load 2 is activate, so no reactive power consumption is observed, and therefore the voltage of all the lines is around the reference, which was set to be 220 V.

However, Load 1 is activated between 13:05-13:10 h, so the DG needs to supply now reactive energy. Since the droop control is activated, the system starts to decrease the nominal voltage in order to fulfill the requirements of the load.

The voltage deviation can be observed in Fig. 7(b), where a screenshot of the analysis logger of the MeterTool software is shown. The average deviation in all the phases was observed
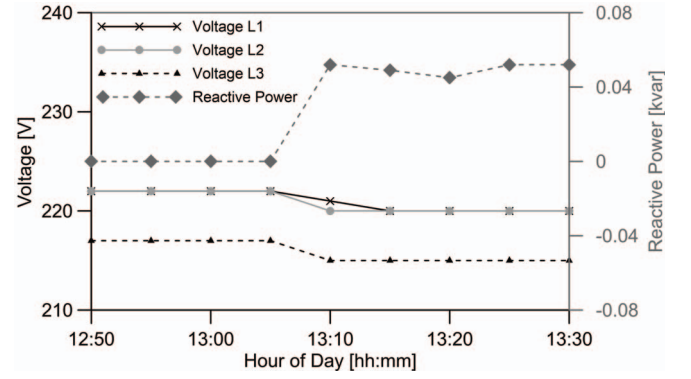
(a) Voltage and Reactive Power Profiles

RTC (RTC)	Actual power P+ (kW)	Actual power Q+ (kvar)	Average Voltage L1 (V)	Average Voltage L2 (V)	Average Voltage L3 (V)
5/11/2015 12:50:00 PM	0.306	0	222	222	217
5/11/2015 12:55:00 PM	0.306	0	222	222	217
5/11/2015 1:00:00 PM	0.306	0	222	222	217
5/11/2015 1:05:00 PM	0.306	0	222	222	217
5/11/2015 1:10:00 PM	0.596	0.052	221	220	215
5/11/2015 1:15:00 PM	0.596	0.049	220	220	215
5/11/2015 1:20:00 PM	0.596	0.045	220	220	215
5/11/2015 1:25:00 PM	0.596	0.052	220	220	215
5/11/2015 1:30:00 PM	0.596	0.052	220	220	215

(b) MeterTool Analysis Logger Screenshot

Fig. 7. Scenario 3. Voltage and Reactive Power during a load disturbance, using droop control.

to be 2 V, whereas the average change in the reactive power demand was 50 var. Thus, the theoretical droop coefficient k_v, that was selected to be equal to -0.05, can be compared with the measured value. This is illustrated in (3).

$$k_v = \frac{\Delta E}{\Delta Q} = \frac{-2}{50} = -0.04 \qquad (3)$$

As it can be seen this value is very near to the theoretical one, and the observed error might be due to the resolution of the measures of the Smart Meter. Therefore, the Smart Meters have demonstrated to be able to detect not only load disturbance and voltage quality issues, but they can also notice the influence of the different control strategies employed in the Microgrid context, when neither frequency nor voltage restoration strategy is implemented, and the Microgrid is working in islanded mode.

IV. FUTURE WORK

The presented metering infrastructure inside the Microgrid Lab will be soon substituted by a more advanced and powerful system which will be based on the OMNIA Suite of Kamstrup. OMNIA Suite is an advanced metering infrastructure (AMI) which includes Smart Meter units, data concentrators, network communication and data management and storage, so the Lab will be able to emulate a SG [21].

As it is shown in Fig. 8, all the Smart Meters within the system will be connected using the Wireless standard (EN 13757-5 [6]) using the radio mesh communication version. In addition, others Smart Meter systems regarding district heating and water will be implemented, using Wireless M-Bus Standard (EN 13757-4 [6]), to have a complete simulation of a real system.
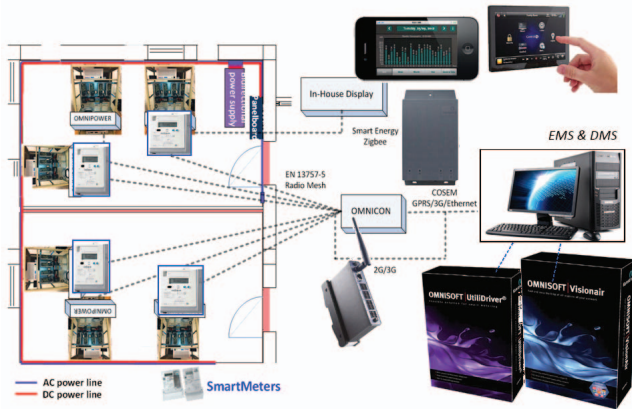
Fig. 8. Conceptual schema of the future Smart Metering Infrastructure in the Microgrid Lab of Aalborg University.

The data from the Smart Meter will be collected in a data concentrator using the radio mesh communication. As well, this data concentrator will be connected to a PC using Ethernet, GPRS or 3G, and the DLMS/COSEM standard. Inside the PC a software called UtiliDriver® will be responsible for integrating the data from the Smart Meter with the rest of the system.

This central software will not store any data, but it will allow the intercommunication with the Smart Meters using an Open Web Service API (Application Protocol Interface). Thus, the protocol complexity is simplified, so the Smart Meter measurements can be integrated into others systems with a relatively low complexity.

V. CONCLUSIONS

The work has presented the benefits of integrating Smart Metering systems inside the electrical grid and specifically in Microgrids. A real application of the Smart Meters to monitor a workstation in the Aalborg University Microgrid Lab was commented, showing three test scenarios for studying the load profile measurement, the voltage quality events detection, and the droop control strategy, and having discussing their respective results.

The Smart Meters have demonstrated their capability to report in the most basic case at least the energy consumption profile and in other more advanced systems the power, voltage and current, too. All of this is due to the wide range of communication possibilities offered by the Smart Meter, which have allowed us to monitor the system from a central PC.

In addition, the report frequency for these energy and power measurements has been observed to range between 5 minutes and 1 hour integration interval, a period that can be fast enough for implementing EMS and DR strategies in a tertiary control level without additional equipment and investment.

The system has also shown the possibility of detect voltage quality events with a resolution of 1 second. This depicts that the real sampling frequency of the system to measure current and voltage is much faster. Therefore, the Smart Metering system can be seen as the most suitable part of the system

to implements not only power and energy monitoring but also to detect some basic PQ issues.

Furthermore, although the measures from the Smart Meters cannot be directly used for the inner control loops, the system has shown to be able to detect voltage deviations due to the operations strategies of the Microgrid, such as the Droop control for the regulation of reactive power flow.

Regarding these ideas, the future implementation that will be carried out in the Microgrid Lab has been exposed. This new Smart Metering system will provide a centralized communication and data collection, more advanced PQ measurement and the integration with other systems.

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