Development, Modeling, and Testing of a Unified Controller for Prosumers Connected to 0.4 kV Voltage Level Grids. Part I: Modeling and Test Bench Assembly

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***Abstract* — The increasing use of distributed generation and energy storage units calls for changing the control methods for distribution grids. It is known that uncoordinated control of multiple "prosumers" (power grid consumers who can also generate power) can lead to unacceptable grid operating conditions. In the present two-part study we present the concept of a unified controller (UC) for prosumers at a 0.4 kV voltage level grids that can prevent the grid entering into undesired operating conditions. In the first part of the study, we present a problem statement with illustrative examples and then proceed to describe the principles of operation of the unified controller (UC). We then describe the laboratory test bench that was assembled specifically to validate the controller performance under real-life conditions. We describe the general arrangement of the test bench and the measurement system required to perform the corresponding controller testing.**

***Index Terms*: prosumers, inverters, distribution grids, control of multiple energy sources.**

I. Introduction

Conventional distribution grids have been "passive" parts of power systems: those distribution feeders always served a purpose of conducting a one-way power flow from substations to loads. However, the recent trends of increasing penetration of distributed generation and energy storage units have dramatically changed the behavior patterns of loads [1]. Now being able to both consume and generate power (and change the operating conditions in an automated way), the loads become the so-called prosumers – active participants of distribution grid operation. Typical examples of load types are households with either PV panels or storage units or electric vehicles, or with any combination of those.

Prosumers are typically controlled locally according to their own goals, although it is possible to implicitly influence their operation, for instance by sending some electricity price signals [2, 3]. Until the number of prosumers connected to a distribution feeder remains small, there is no significant impact from their side on the distribution grid operation. However, once prosumers' contribution to total power flow becomes considerable, their uncoordinated actions (either according to their own control logics, or in response to some grid parameters) might lead to unacceptable grid operating conditions. One of the most prominent examples illustrative of such a behavior is the uncoordinated charging of a set of electric vehicles on a distribution feeder. The problem of coordinated charging of a set of EV's connected to the same distribution feeder has already become well-established one in power engineering, attracting a lot of research [4–7].

Another classical example is a distribution feeder with high penetration of renewable sources (typically, PV panels). It is well known, that under high generating conditions, the voltage level on certain buses can become unacceptably high [8]. There have been a vast number of papers on voltage control by PV panels, with most of the results revolving around some reactive power control schemes [9–11]. Interestingly, it was recognized early enough, that due to considerable R/X ratios in distribution grids, constant voltage profile and minimization of losses in the grid cannot be simultaneously achieved. This is contrary to the transmission grids case, where two problems are almost equivalent. Therefore, for distribution grids, there exists a trade-off between voltage control goals (e.g., achieving a flat voltage profile or regulating voltage on certain buses) and reduction of power losses (or limiting

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the power flow through the feeding transformer) [12].

The problem of prosumers control has been one of the most widely addressed in the literature during the last decade. There is a vast amount of findings for both coordinated and uncoordinated control, as well as comparison of those two approaches and discussion of possible trade-offs. As a general rule, with the increasing share of prosumers connected to a distribution grid, the advantage of coordinated control over uncoordinated one grows, and after a certain point, uncoordinated control proves inefficient, due to excessive constraints needed to guarantee stable grid operation under a wide range of the system parameters. Most of the available results in literature are mainly control approaches and algorithms, which are tested by simulations, with the vast majority of methods dedicated to optimal real and reactive power dispatch. In such studies, power flow problem is solved, and prosumers are represented as ideal power sources or loads (for both active and reactive power). Details of control of power electronics devices are rarely taken into account, which is justified in most cases.

In the present two-part study we present a model of a new unified controller for prosumers in a distribution grid. The goal of the controller is to perform a coordinated control of a number of prosumers in order to guarantee stable and secure grid operation under different conditions. The motivation behind the controller development is the fact that prosumers are becoming more widespread in today's power grids, and very soon their uncoordinated control (or absence of control) will lead to reduction of the grid security. We also present the results of laboratory testing of the proposed controller on a realistic test bench representing a distribution feeder. The controller operation is tested on a system with two "passive" (although controllable) loads, and three prosumers, represented by inverters capable of operation in 4 quadrants, which are also developed and assembled in our laboratory. Compared to commercially available ones, our inverters have "open control architecture" – the control system is fully accessible to us, which is required to test a number of scenarios of the unified controller operation. In this first part of the study we present a background of the prosumers' control problem, propose the model of the unified controller, and provide a description of the laboratory test bench, including upgrades in the measurement system that were done specifically to perform the controller testing.

The rest of the study is structured as follows. In Section II we provide a problem statement and give an illustrative example where uncoordinated control of prosumers can cause unacceptable grid operating conditions. In Section III we provide a description of the unified controller and present its general scheme. Section IV is dedicated to a description of the laboratory test bench that is used for controller validation, together with the description or the measurement system that was installed specifically to perform the testing.

II. Problem statement and an illustrative example

In this section we provide a description of the general problem statement of the unified controller. In order to demonstrate the practical significance of the problem we also provide a motivational example of a distribution feeder that can potentially run into unacceptable operating conditions when prosumers adjust their controllers independently.

In order to illustrate the problem of uncontrolled (or controlled in an uncoordinated way) prosumer behavior, let us consider a simple two-bus system shown in Fig. 1. Such a system can be used to represent a distribution grid where all the loads are aggregated as a single load bus. This is reasonable if one is mostly interested in the effect of the prosumers' control on the total current drawn from the grid. We use this aggregate system to derive some closed-form expressions that can illustrate the type of controls that prosumers can execute and that can lead to an unacceptable operating point of a distribution grid. The voltage difference ΔV between the infinite bus and the load bus, i.e., $\Delta V = V - V_0$ in its linear approximation (which is rather accurate for distribution grids) is:

$$\Delta V = -\frac{1}{3}\frac{RP + XQ}{V_0}, \tag{1}$$

where P and Q are the aggregate active and reactive power loads, and R and X are the resistance and inductance of the line connecting the substation and the aggregate load. We note that the formula (1) represents the linear approximation and is very convenient for control design. However, we also note that unless the feeder is very long, formula (1) can be remarkably accurate over a wide range of loading levels.

From the formula (1) it can be inferred that if a prosumer is injecting to the grid certain active power P_g (on top of its regular loading level), then an additional control can be executed to consume the corresponding amount of reactive power equal to $Q_c = RP/X$ in order to compensate for any voltage deviation on the prosumer bus as caused by its active power injection. This can be arranged either directly by setting the prosumer power setpoints to satisfy this ratio or by setting certain voltage-reactive power droop characteristics with a steep enough response. In either case, the injection of the active power by prosumer leads to its increased consumption of reactive power, which is done intentionally in order to improve the voltage profile in the feeder [12].

Suppose that the system of Fig. 1 corresponds to 5 loads of the overall power consumption of P = 75 kW (15 kW each) and Q = 37.5 kVAr. This corresponds to 15 kW of active power per load and the Q/P ratio of 0.5, which is a rather realistic assumption. Let us also assume that the aggregate load is connected to a substation by a 200 m long line with the *A*-35 type wires with active resistance of R = 0.78 Ω/km, and reactance of X = 0.27 Ω/km – which is again, a realistic assumption. In this case,

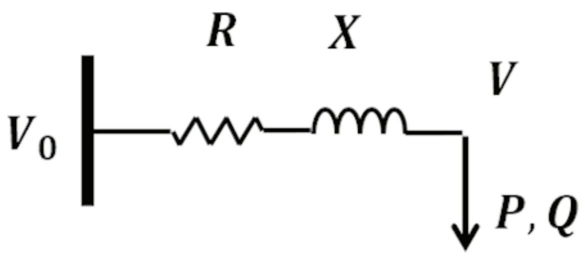

Fig. 1. A simple two-bus systems.

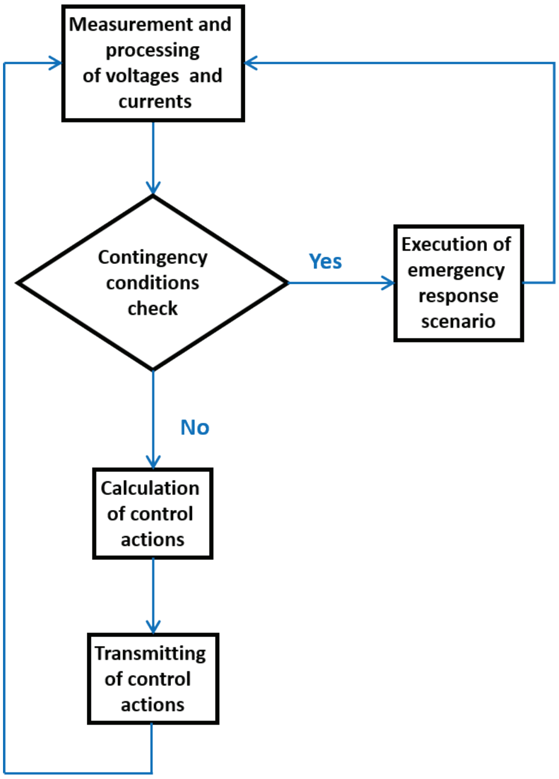

Fig. 2. Flowchart illustrating the operation of the unified controller for prosumers.

the phase-to-ground RMS voltage drop at the load bus is approximately $\Delta V \approx 20V$ which is on the boundary of the acceptable voltage deviation value. The RMS value of the current running through each phase is then 139.8 A, which is well within the limit of 172 A for the given type of wires.

Suppose now that two out of the five loads are prosumers that additionally inject 15 kW of active power each, i.e., effectively cancelling their active power consumption. In this case, if the simultaneous reactive power control is activated, each prosumer has to additionally consume 45 kVAr of reactive power in order to keep the voltage profile nearly the same as it was before the active power injection. This will lead the substation RMS phase-to-ground current to grow to nearly 224 A, which is well above the allowed limit of 172 A.

Such an example, although somewhat exaggerated, clearly demonstrates how the uncoordinated control of prosumers can lead to unacceptable distribution grid operating conditions. In the example above we assumed that only two out of five loads become prosumers, and it is obvious that even at this rather low level of penetration of prosumers the problem can become quite acute when there is no interference from a distribution grid operator.

There are a number of options to cope with the potential problems caused by uncoordinated prosumer controls that were illustrated above. One option is to set certain limits to prosumer active and reactive power generation; however, these limits will become overly conservative with the increasing share of prosumers in the grid. This will lead to severely sub-optimal operation states for the distribution grid. Another possibility is to introduce a certain level of coordination in controlling prosumers, which will be executed using additional knowledge about the grid parameters and also using the measurement data. Such a centralized control is not necessarily realized in the form of fixed setpoints specified for every prosumer but can also be executed by updating the limits on power outputs for every prosumer based on the existing grid conditions. In either case, a certain centralized controller is required that can leverage the information about the grid parameters and operating conditions in order to make decisions on the allowed prosumer setpoints.

III. Unified controller for prosumers

In this section we present the structure and operating principles of our unified controller for prosumers at 0.4 kV distributions grids. The controller is intended to execute coordinated actions over a set of prosumers in order to guarantee the secure and optimal operation of the distribution grid. As was illustrated in the previous section, fully decentralized control of prosumers cannot guarantee the secure grid operation under all scenarios, therefore the unified controller needs to perform the calculations over the grid model and update the control actions in order to satisfy all the constraints. Of course, many implementations of such a controller are possible depending on the available measurements, computational resources, communications system, etc. In this study we present a controller with a comprehensive set of possible functions ranging from a simple power setpoints update to fast real-time reassignment of the control modes for prosumers' inverters, allowing for seamless transition from grid-connected to islanded operation and back.

The flowchart describing the unified controller operating scheme is given in Fig. *2*. The controller collects the measurements of the voltages and currents from all the grid nodes (where measurements are available) and first checks whether the grid is in a contingent state. If there is no contingency, then the calculation of control actions for all the prosumers is executed and transmitted to the prosumers that are connected to the controller. The procedure is run continuously, with a certain time resolution, which is 50 μs (corresponding to the 20 kHz refresh rate) in the case of this study. We note that such

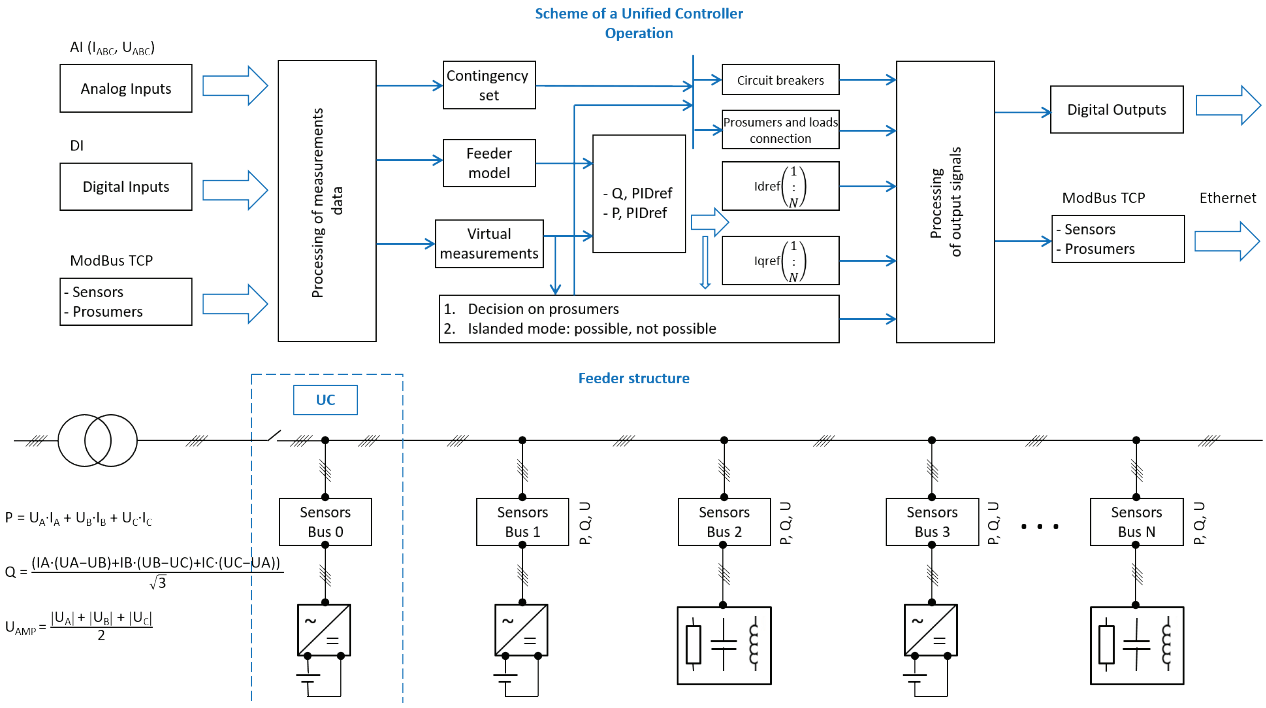

Fig. 3. Flow diagram of a unified controller operation and the controller placement in a distribution feeder.

a fine resolution is not a mandatory requirement, and it is possible to implement the controller operation at a lower resolution. However, execution of certain functions, such as a seamless transition of the grid to islanded operation, cannot be performed using controller with low time resolution. In the present study, our aim is to demonstrate a wide range of controller capabilities, so we use the high resolution of 20 kHz. Development of controllers meeting less strict requirements, or even a controller with some elaborate scheme where different time-steps are used for different purposes is a subject of further research.

Fig. *3* represents the structure of the unified controller (UC) and its place in the feeder. The controller can receive both analog and digital signals from measurements across the feeder: any possible combination of measurements can be used and the number of input channels should be adjusted depending on a particular feeder. The controller also has the input channels to accept signals over the ModBus communications protocol. In our case, most of the feeder buses were sending the measurements over this protocol. All the input data are then processed and readjusted for a set of measurements having the same time resolution. The measurements are then fed into a feeder model that runs in real-time – in our case we used the OPAL-RT module, however, different options are possible, depending on the purpose of the controller. Likewise, different levels of modeling details can be realized depending on the control goals. Since our goals in the present work were to perform a broad range of controller functions, we used rather detailed models of inverters for our controller. Contingency set check is also run in order to verify the feeder operation state: if a contingency is detected, then the control actions are selected from a dedicated set. In the absence of contingency, the controller is making decisions for prosumers' setpoints on a continuous basis and sends the corresponding signals to every prosumer under control.

After the input data is processed and fed to the feeder model, the decisions are made on the control actions: in our case the time resolution is 50 μs, which corresponds to the frequency of 20 kHz. The control actions include both continuous and integer variables. The former are the power setpoints for prosumers, while the latter are the on/off decisions as well of the grid-forming/grid-following decisions. Once the output signals are generated, they are sent to the prosumers over the ModBus communications protocol, however, other options are also possible. The controller is supposed to be placed at the feeding substation, with certain communications infrastructure available to transfer the measurements from the feeder buses to the controller. The bottom part of Fig. *3* represents the flow diagram of a feeder with the controller placed at the substation and sensors located at each prosumer and load bus, however, we note that flow diagrams with sensors only at some of the buses are also possible.

In order to test the controller operation under different scenarios, we have assembled a dedicated test bench with high-resolution measurement system and a number of inverters that represent prosumers. The next section describes the test bench in detail.

IV. Test bench assembly

In what follows we provide a description of the comprehensive laboratory test bench developed by us to experimentally validate the operation of our unified

Fig. 4. A smart grid test bench at the laboratory of energy systems at Skoltech. Every rack contains a load (either linear or nonlinear) or generator (of different types).

controller. We first describe the existing facilities: a "smart grid" test bench available at the Skoltech laboratory, and then provide a description of additional measurement systems that were installed for extensive testing with power electronics components.

A. Smart grid laboratory test bench

The smart grid test bench represents a physical model of a distribution grid with the possibility of connection of up to 3 individual loads, 3 individual generation sources (namely, storage, PV, and wind), and a possibility to change the effective resistance and reactance between the grid buses. The effective lines are represented by 3 segments with the corresponding resistance and reactance of 0.5 and 0.314 Ω, 1.0 and 0.314 Ω, and 1.0 and 0.628 Ω, respectively, that can be combined in arbitrary arrangements. An image of the test bench is presented in Fig. **4** where only a part of the bench is shown, and every rack corresponds to either a load or generator.

The test bench measurement and control system is a SCADA system that collects measurement of RMS voltage and current from every bus of the test bench with a time resolution of 1 Hz. The output of such a system is presented in Fig. **5**. Likewise, any control actions, such as load change, are also executed with a resolution of 1 Hz. Such a slow monitoring and control system is not adequate for controlling fast power electronics devices, therefore, for this purpose the test bench needs to be upgraded with a much faster measurement and control system. On the other hand, a certain trade-off is needed between the measurement system speed and its resiliency and cost. Thus, having very fast measurement system at every bus not only proves expensive but is also demanding in terms of the computational resources. For our specific purposes of a unified controller operation, at least one point in the grid (connection to the feeding substation) should be equipped with the high resolution (20 kHz) measurement system.

B. Measurement system

In order to collect the measurements of voltage and current and execute control actions at a sufficiently fast rate, the smart grid test bench was significantly upgraded by adding a fast-acting measurement system. The measurement system contains two types of measurement devices: measurement boards with fast current and voltage sensors that measure phase voltages and line currents at the 20 kHz resolution, and Power Quality Analyzers that provide the measurements of RMS of voltage and currents with the resolution from 5 to 50 Hz.

Fig. 6 shows the single-line diagram of our test bench with

Fig. 5. A screen capture from the SCADA system of the test bench. It is clear that only the RMS values of voltages and currents can be seen.

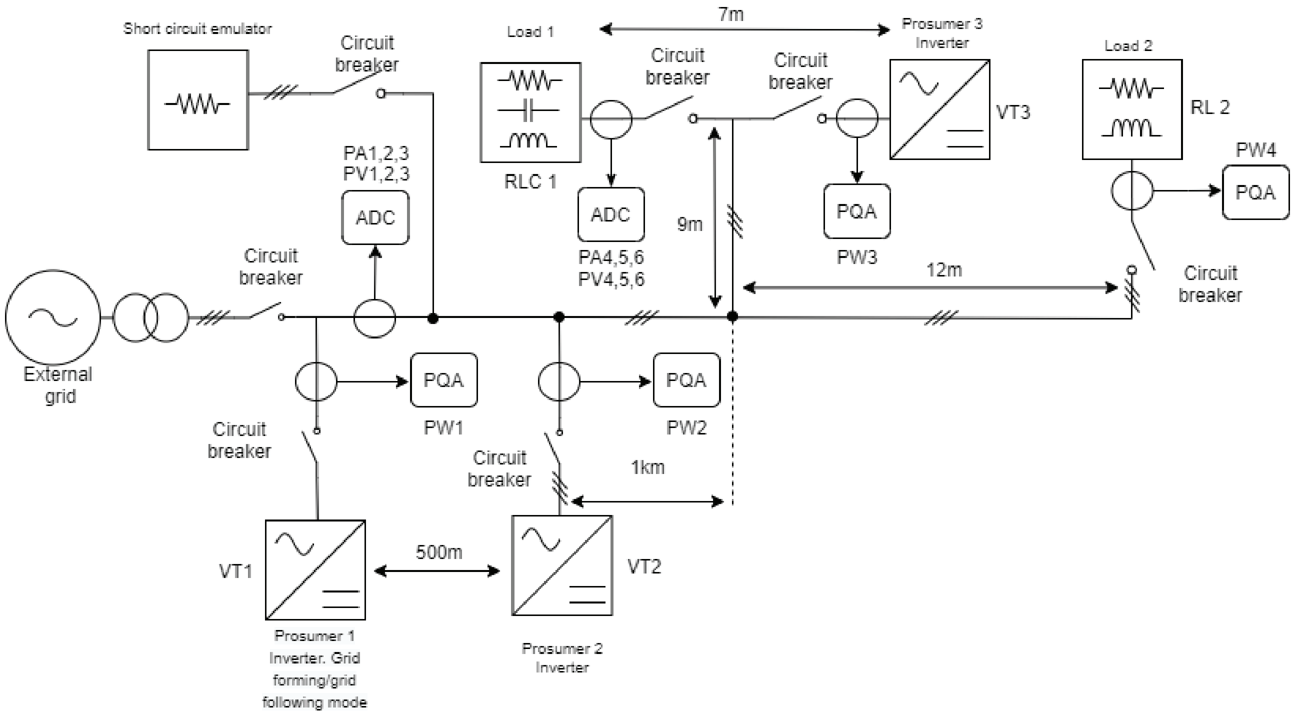

Fig. 6. Single-line diagram of the test bench with loads, prosumers, and the measurement system mounted.

Fig. 7. High resolution sensors mounted on a rack and plugged-in to the smart grid test bench.

connected loads, prosumers, and the measurement system. There are two constant impedance loads connected to the system, and three prosumers, each of which is represented by an inverter of our own design and assembly. Each inverter can operate in 4 quadrants and is also capable of operating in both grid-following and grid-forming modes. The fast (20 kHz) measurement units are installed at two points – at the feeder entrance and at the point of connection of Load 1. These units are denoted as "ADC" (analog-to-digital converter) in the diagram of Fig. 6. We note that the analog signals from these sensors go directly to the OPAL-RT real-time machine. Each unit is equipped with

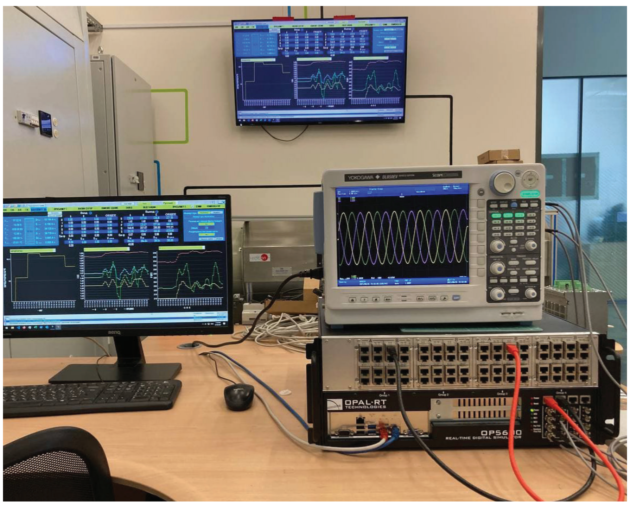

Fig. 8. Oscillograms of an AC-voltage signal from the operation of the test bench collected using the high-resolution measurement system.

4 LEM LV 25-P voltage sensors and 4 Honeywell CKSR 15-NP current sensors. Thus, there is a total of 16 analog signals going to the OPAL-RT machine. Fig. 7 shows the fast measurement unit connected to the test bench.

Another set of measurements is denoted as "PQA" (power quality analyzer) in the diagram (Fig. 6), they measure RMS voltage and current with a resolution of 5–50 Hz, which are processed by an OPC Modbus Server that also sends the (digital) signals to the OPAL-RT machine every 10 ms. Taking into account that the time resolution of the PQA units can be as low as 5 Hz, the overall accuracy of the measurements from the corresponding points is also limited by this number, which is still significantly better than the initial 1 Hz resolution of the SCADA system. Together with the fast measurement units described above, this system of measurements is sufficient for the purposes of validation of the algorithms of the unified controller for prosumers. Fig. 8 shows an example of oscillograms measured at the test bench feeding line.

V. Conclusion

In this first part of our two-part study we have presented a description of a unified controller for prosumers and a laboratory test bench that was assembled for experimental validation of the controller operation. We have also presented an example of a distribution grid operation without a coordinated control that can lead to unacceptable operating conditions, thus the motivation for development of a unified controller was demonstrated. Our controller setup is developed for execution of a broad range of actions, therefore, in our particular case the controller is rather demanding in terms of computational power and measurements resolution. We note, however, that less demanding controller setups are also possible, although at the expense of the controller capabilities and performance. The practical choice of controller capabilities will be a subject to some optimization over the required capital expenditures for measurement and communications infrastructure and the particular needs of the feeder. In the second part of this two-part study we will present the results of the extensive testing of the performance or our unified controller.

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