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Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University

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***Abstract*—This paper presents the development of a microgrid central controller in an inverter-based intelligent microgrid (iMG) lab in Aalborg University, Denmark. The iMG lab aims to provide a flexible experimental platform for comprehensive studies of microgrids. The complete control system applied in this lab is based on the hierarchical control scheme for microgrids and includes primary, secondary and tertiary control. The structure of the lab, including the lab facilities, configurations and communication network, is first introduced. Primary control loops are developed in MATLAB/Simulink and compiled to dSPACEs for local control purposes. In order to realize system supervision and proper secondary and tertiary management, a LabVIEW-based microgrid central controller is also developed. The software and hardware schemes are described. An example case is introduced and tested in the iMG lab for voltage/frequency restoration and voltage unbalance compensation. Experimental results are presented to show the performance of the whole system.**

Keywords—microgrid central controller, secondary control, voltage unbalance compensation, intelligent microgrid lab

I. INTRODUCTION

The MicroGrid (MG) concept has been proposed for efficient and flexible utilization of distributed energy resources [1]. According to the US Department of Energy (DOE), as well as Electric Power Research Institute (EPRI), a MG is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It may connect or disconnect from such grid to enable it to operate in both grid-connected or "island" mode. In that way, it provides a more flexible and reliable energy system. The capability of integrating different kinds of distributed energy resources and generators (DGs), such as renewable energy, storage system and micro turbines, improves the sustainability and efficiency of the overall system.

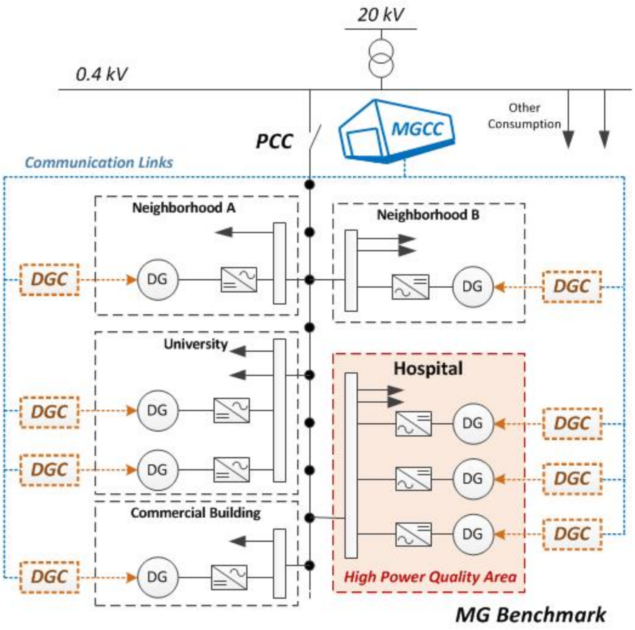

Fig. 1. Benchmark microgrid system.

However, the perfect ideal comes with challenges for the overall system control and management, such as power sharing, power quality, stability, environmental influence and economic issues. The realization of these objectives relies not only on the well planning and design of MG systems but also on efficient and intelligent operating of the MG components without ignoring the practicability considerations. With the development of power electronics, power converter interfaced DG units are able to provide reliable power supply to consumer side and enable the integration of advanced control algorithms.

The use of a hierarchical control scheme has been proposed for MGs in order to manage objectives in different time scales, technical fields and significances [2], [3], as it was proposed for manufacturing [4], power systems [5], [6], process systems [7], and in general terms, for large complex systems [8]. Dedicated control algorithms are placed in different layers with necessary information/signal exchange between them but with decoupled behaviors. Usually a three-level hierarchy is considered comprising primary, secondary and tertiary control levels. Primary control is implemented in local DG controllers

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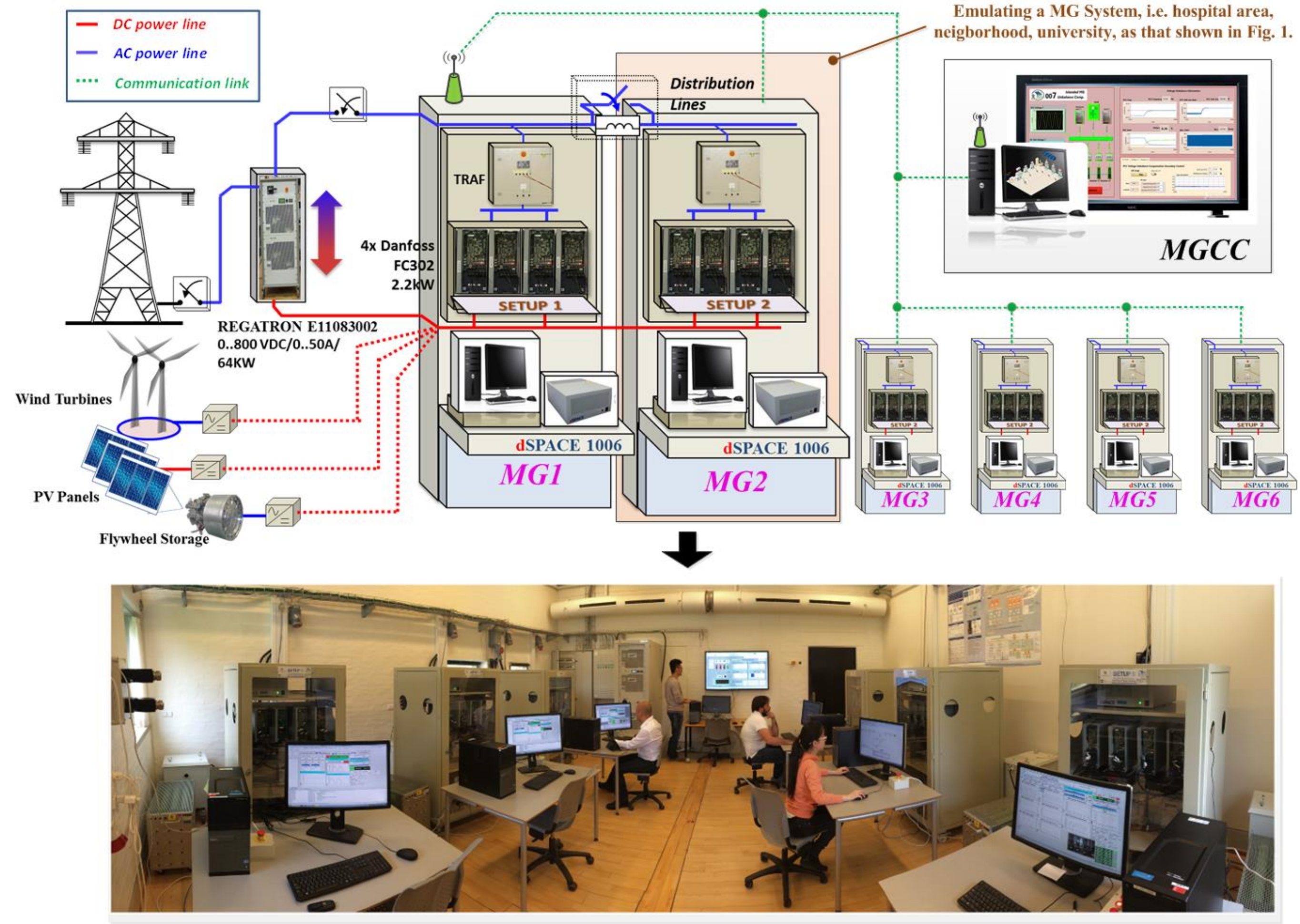


Fig. 2. Overview of iMG lab facilities.

(DGCs) including inner voltage/current control loops and power sharing control loops. It ensures the stable operation of the DGs and distributed power sharing among them. Moreover, in order to enhance the system power quality [9]–[11] and achieve accurate power sharing [12], [13], secondary control approaches can be developed which act over primary control loops by sending adjustment and compensation references. In the tertiary level, optimization and decision making functions can be applied which give optimal set-points to lower level controllers achieving intelligent and more efficient operation of the whole system [11], [14]–[17]. In addition, the synchronization and reconnection with external grids is based on the cooperation between secondary and tertiary levels. From primary, secondary levels to tertiary control level, the control bandwidths are decreased to achieve the decoupled behavior between layers, which also simplifies the implementation of higher-level controllers as well as the system stability analysis.

Thanks to the advances in information and communication technologies, the real world implementation of the above mentioned control levels can be actualized with centralized, distributed or hybrid fashions. Consider the benchmark MG shown in Fig. 1 [18], in which DGs are connected to the system in a distributed way supplying consumers, i.e. neighborhood, university, hospital, etc. A point of common coupling (PCC) usually exists where the MG is connected to external grids. Power converters are necessary interfaces between DGs and the MG system. DGCs are implemented to perform primary control functions. Typically, an MG central controller (MGCC) is also needed to coordinate the DGs and manage the overall MG as one integrated entity. As the performing of the secondary and tertiary control functions requires the global information collection, these control levels are mostly implemented in MGCC [9]–[17], [19]–[24]. Communication links are essentially needed between DGCs and the MGCC, while the type and bandwidth of the communication should be carefully designed according to the control requirements [25].

The test and verification of the control algorithms as well as measurements and communication infrastructure require rationally conducted laboratory experiments. Aiming at the comprehensive study for power converter based MG systems, an intelligent MG (iMG) lab is established in the department of energy technology in Aalborg University [26], [27], which is introduced in detail in Section II. A study case is established in Section III and implemented in the system. Section IV presents the experimental results with discussions over the system performance. Section V gives the conclusion and future plan.

II. LAB CONFIGURATION AND FACILITIES

The combination of hierarchical control structure with proper design of the hardware structure formulates a generalized and expandable experimental platform in iMG lab. The details of the lab are introduced in this section.

A. Lab Overview

With the prevalent utilization of power converters as interfacing devices, the control and operation of them become critical issues. Generally, sorts of DG units, such as wind turbine and photo-voltaic panels, are connected to the grid through grid inverters realizing not only the power conversion from DC input to AC output, but also the advanced capabilities like active/reactive power control, voltage ride-through, reactive power injection due to fault conditions, etc. Based on this scheme, a MG emulation setup is designed and established as shown in Fig. 2. Four *Danfoss* inverters (FC302, 2.2kW) are equipped in each setup working as the interfacing power converters between DGs and the utility side. The DC side of these inverters can be powered either by a real energy resource, such as photo-voltaic panels, wind turbines, flywheel energy storage system, etc., or by a bidirectional power supply, in this case an 80kVA unit, emulating sorts of resources. The AC sides of the inverters are connected to a common load bus through filters and contactors. Detailed electrical scheme of each setup is shown in Fig. 3. Smart meters are also implemented for total generation and consumption measurement as well as energy management functions.

Besides, as the ultimate objective of future power system is to realize flexible operation of the whole system with the capability of dividing each fraction into an independent MG system, several MG setups can be operated together to emulate different conditions and study cases. For example, several MG setups can be connected to the main grid while each MG pursues its own objectives; several setups can also be interconnected formulating a multi-zone islanded MG system, while each sub-MG has the flexibility to connect/disconnect to/from the system, such as the case shown in Fig. 1.

Moreover, when an MG is considered as an autonomous system, proper coordination between DGs is required. In this case, an MGCC can be deployed to introduce more ‘intelligence’ to the system by integrating advanced control methods and optimization algorithms. Essential information from each setup is collected and sent to MGCC for supervision and higher-level regulation. Communication links are needed. UDP/IP based wired and wireless Ethernet links are used now in iMG lab for the setup-to-setup and setup-to-MGCC information exchange. In addition, this architecture does not limit the application of this system into totally centralized cases, MGCC may also act as coordinator while transfer the ‘power’ to local side. In this way a distributed decision-making scheme, also named multi-agent system, can be adopted. Accordingly, the system is considered with high flexibility with potential to execute comprehensive MG studies.

B. Communication and Information Flow

The details about the system architecture and information flow are given in Fig. 4. The MG setup components, including the inverters and all the contactors, are controlled by the DGCs. It sends digital signals to inverters for enable and reset functions and to contactors for dis-/connecting components (inverters, transformer and loads). Inverters are also switched by the power width modulation (PWM) signals from the DGC. The DGC functions, including the primary control loops, are developed using MATLAB/Simulink and compiled into dSPACE for execution. Essential measurements are implemented by using voltage and current sensors for obtaining voltage and current curves. These signals are first used by primary control loops, some of them are also transmitted to MGCC for higher-level regulation purposes. For communication purpose, an Ethernet communication card (DS4121) is equipped in dSPACE. Peripheral Component Interconnect (PCI) Ethernet card is installed in MGCC and used for communicating with dSPACEs based on UDP/IP. LabVIEW software is used in MGCC, as an example, for developing user-interface as well as secondary and tertiary control functions.

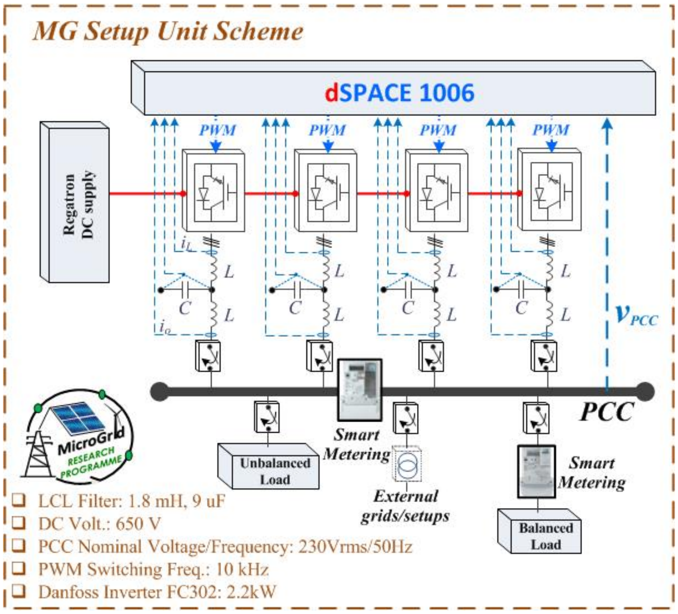


Fig. 3. iMG lab setup details.

A generalized MGCC architecture and information flow is also shown in Fig. 4. Basically, a database is required for storing and providing critical information, which can be used for daily record, data analysis, prediction and short-/long term scheduling purposes. A powerful solver, such as CONOPT and CPLEX, along with a proper algebraic modeling language (i.e. GAMS, AMPL, etc.) can be applied for solving a scheduling or optimization problem when needed. As the core of MGCC, an interfacing tool with capability of communicating with external world (human interface and inter-communication with other equipment) is needed. Sorts of programming languages, such as C language, C++, Python, MATLAB and LabVIEW, can be used to develop this part. Basic control functions can also be developed by using them. As an example, this paper deploys LabVIEW language to develop a user-interface and secondary control functions. The next Section is dedicated to the details about this example case.

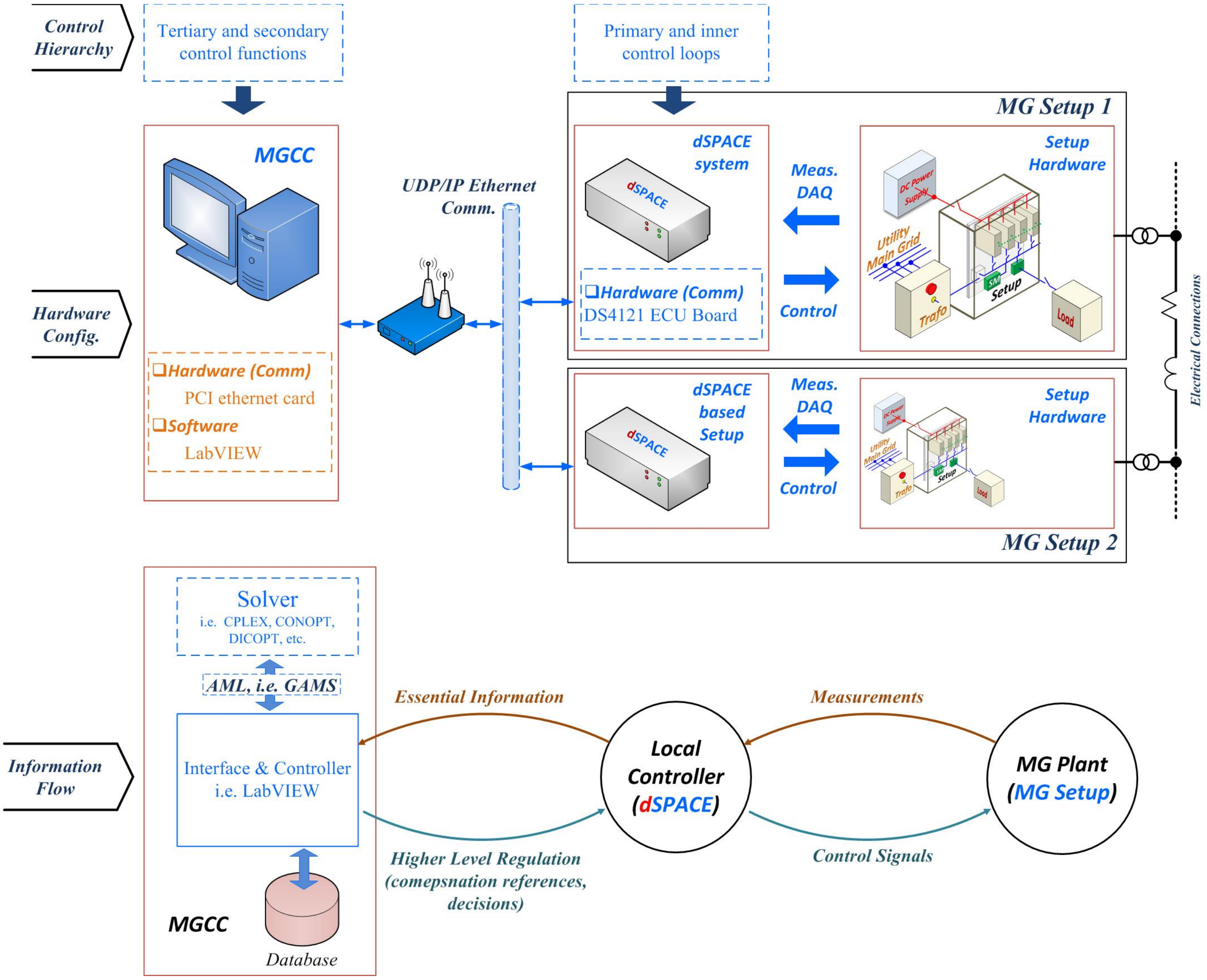


Fig. 4. Detailed architecture and information flow.

III. CASE STUDY AND HIERARCHICAL CONTROL SCHEME

A high power quality area is considered in the MG system shown in Fig. 1, e.g., the electric utilities used in the hospital require reliable power supply with desirable power quality. As droop control is applied in each DGC, voltage and frequency (*V/f*) deviations are inevitable. In addition, the presence of single-phase load causes voltage unbalances which may affect the performance of sensitive apparatus as well as the stability of the system. Instead of using additional compensation facilities, a hierarchical control scheme can be applied to employ DG units as distributed compensators for voltage unbalance compensation and *V/f* restoration. The hierarchical control scheme is shown in Fig. 5. In each local area, the DGs are connected to a common load bus (CLB) through LCL filters, and the inductor current (i_L), capacitor voltage (v_C) and output current (i_O) are measured by DGC. Several control loops are implemented in each DGC including voltage/current inner loop, droop control and virtual impedance loop, which form the primary control level. PWM signals are generated to control the DG interfacing inverter. The energy resources are modeled as DC voltage sources fed to the interfacing inverters.

A. Primary Control Loops

The primary control includes current and voltage control loops, active and reactive power droop control loops and virtual impedance loops. All the control loops are designed in $\alpha\beta$ frame. The output active and reactive power of the inverter is first calculated based on the instantaneous power theory [28]. Positive sequence active and reactive power (P^+ and Q^+) can be extracted by using *low pass filters* (LPF). The calculated P^+ and Q^+ are then used by droop controller for P^+/Q^+ sharing control, as defined in [9], [29].

In addition to droop control, a virtual impedance loop [9], [29] is implemented so as to ensure decoupling of P^+ and Q^+, and to make the system more damped without inducing additional losses.

In order to track non-dc variables, proportional-resonant (PR) controllers are used in the voltage and current control

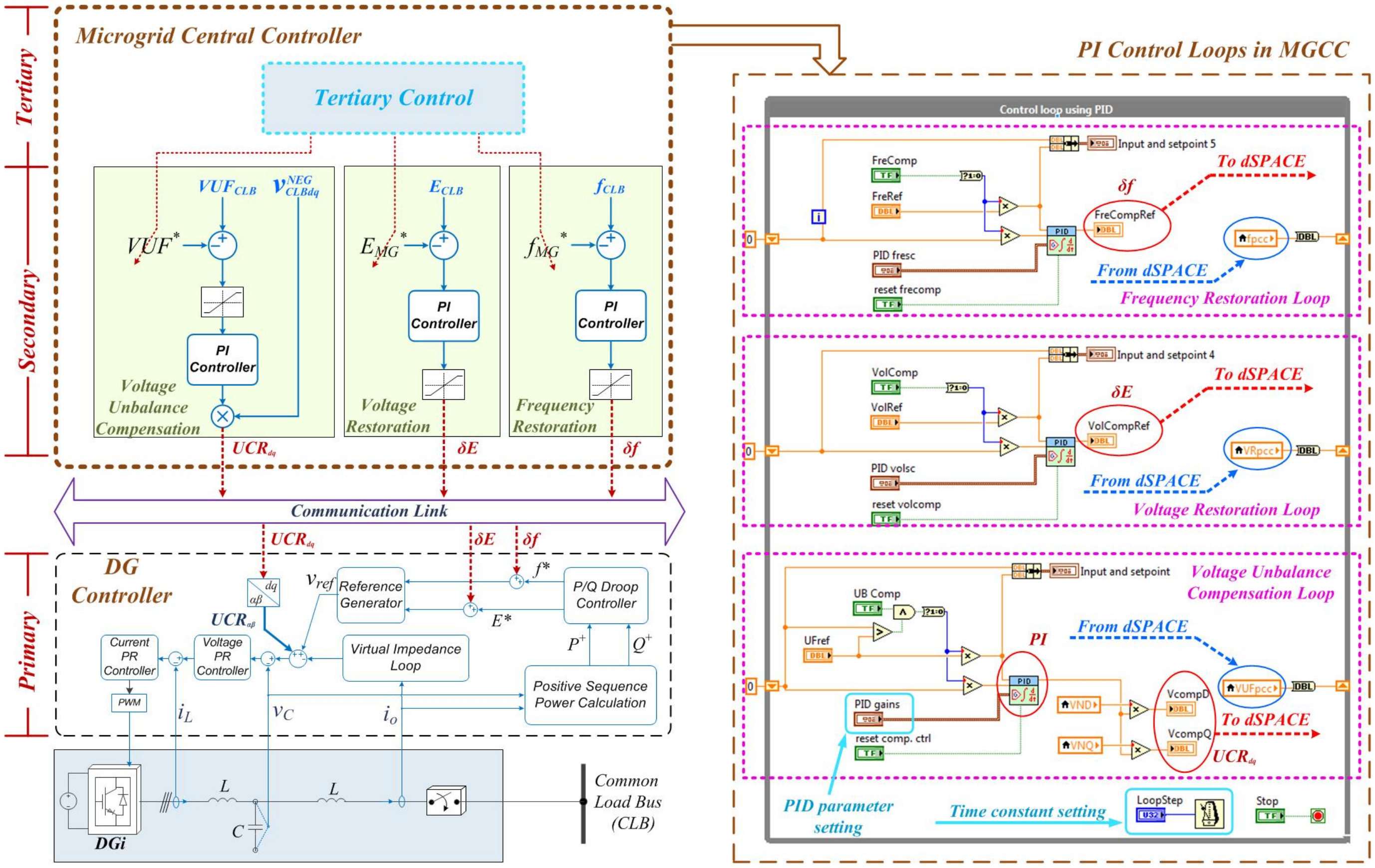


Fig. 5. Example case hierarchical control and its implementation.

loops [9], [29]. More details about the primary control loops can be found in [9].

B. Secondary Control Loops

In MGCC, three control functions are implemented: voltage unbalance compensation [9], voltage restoration and frequency restoration [2], [3]. Four essential information, voltage unbalance factor (VUF_{CLB}) [30], negative sequence voltage in dq reference (v_{CLBdq}^{NEG}), voltage amplitude (E_{CLB}) and frequency (f_{CLB}) are measured by remote sensor in PCC and sent to MGCC. They are then compared with desired/nominal values (VUF^*, $E_{MG}{}^*$, $f_{MG}{}^*$) and the differences are fed into proportional integral (PI) controllers to generate compensation references (UCR_{dq}, δE , δf).

In top of the MGCC, a tertiary controller can also be installed for adjusting the set-points in primary and secondary control, i.e. VUF^*, $E_{MG}{}^*$, $f_{MG}{}^*$. For the intelligent and economic operation, a decision making procedure can be deployed to decide the optimal setting points for lower level controllers, such as the cases studied in [11], [31].

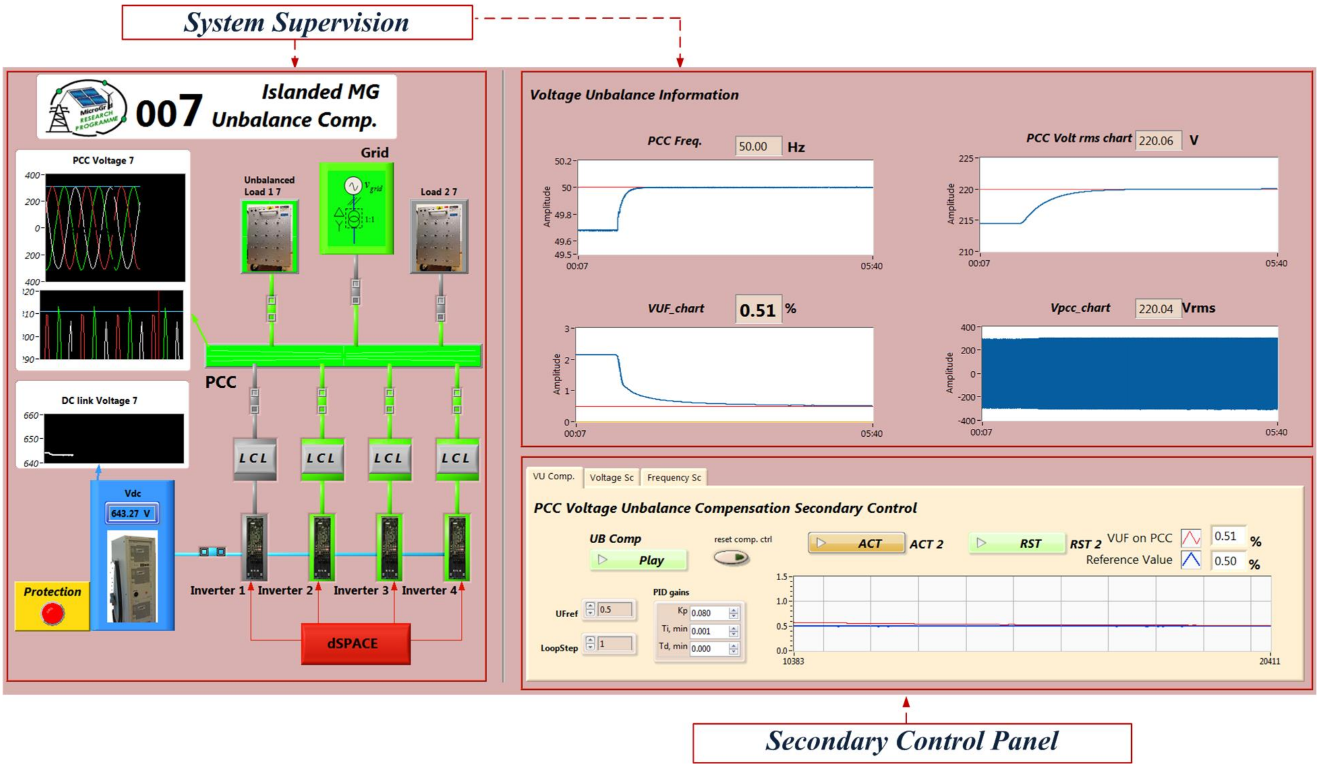
C. Implementation

The implementation of the three control loops has been done by using LabVIEW (Fig. 5). The control loop in LabVIEW is based on the PID virtual instrument (VI) with a *while loop* and its *shift registers*, which is suitable for basic PI control applications. Three dedicated loops are established for voltage/frequency restoration and voltage unbalance control. The measured frequency, voltage and VUF values are received from DGCs (dSPACE) through communication links, and stored in the *shift registers*. Then, the PID VI compares the measured value with reference value and sends adjustment references (UCR_{dq}, δE , δf) back to dSPACE. The lower level control loops in dSPACE follow these references and properly switch the inverters.

The time constant of the discrete-time *while loop* and the PID parameters can be adjusted in order to well tune the overall control system.

IV. DEMONSTRATIONS AND EXPERIMENTS

The study case and control algorithm introduced above are implemented in the MG setups to test the performance of the lab facilities and the hierarchical control scheme. The electrical system parameters are shown in Fig. 3. Detailed parameters of the inner control loops and primary control loops can be found in [11]. The secondary control is implemented in LabVIEW by using the *PID control* virtual instrument. The PID loop is defined as:



PCC Freq. 50.00 Hz

PCC Volt rms chart 220.06 V

VUF_chart 0.51 %

Vpcc_chart 220.04 Vrms

Vdc 643.27 V

VUF on PCC 0.51 %

Reference Value 0.50 %

UFref 0.5

LoopStep 1

Kp 0.080

Ti, min 0.001

Td, min 0.000

Fig. 6. Supervision system interface.

$$G_{PID}(s)=K_c\left[e(\tau)+\frac{1}{T_i}\int_0^t e(\tau)d\tau+T_d\frac{de(\tau)}{dt}\right] \qquad (1)$$

where K_c is the gain parameter, T_i and T_d are the integral and derivative time respectively. The detailed secondary control parameters are given in the next part.

The supervision interface in MGCC is shown in Fig. 6. Generally, it gives information of the MG setups, such as the operation status of the inverters, the power supply to the CLB or PCC, the connection status of the load and external grid, the CLB bus voltage curves, the *V/f* amplitude curves and VUF value in CLB. The secondary control panel offers access to activate the secondary controls and adjust the PID control parameters.

The experimental results showing the performance of secondary control are given in Fig. 7. The parameters are set to K_c=0.02, T_i=0.001min for all the three control loops and the sampling time of the secondary control in MGCC is set to 1ms. An unbalanced resistive load is connected to the system which causes unbalanced voltage in CLB as well as *V/f* deviations. At 5s, the secondary control for *V/f* restoration and voltage unbalance compensation are activated. It can be seen in Fig. 7 (a) that, the *V/f* deviations caused by droop control are recovered within 5s, and the VUF value in CLB is reduced from 2.2% to 0.5% within 10s. The detailed voltage curves are given in Fig. 7 (b) and (c), which demonstrate the effectiveness of the system.

Furthermore, consider that the real world communication has finite and different transmission rates, which may cause stability problems; the sampling time of the secondary control and communication interface (T_{sc}) is changed to test the performance of the system, as shown in Fig. 8. As depicted in Fig. 8 (a) to (c), the sampling time of MGCC is changed from 50ms to 200ms causing more and more oscillations to the frequency. In order to stabilize the system, the integral time (T_i) is changed from 0.001 to 0.004 min in Fig. 8 (d), resulting in slower but more damped system behavior. In Fig. 8 (e), T_{sc} is set to 500ms to emulate a low bandwidth communication condition while the increased T_i (0.004 min) can still keep the stable operation of the system. In Fig. 8 (f), T_{sc} is set to 1000ms, by increasing the T_i (0.008 min) the secondary control can be kept stable. The above results indicate the importance of control parameter tuning considering the communication transmission rate.

V. CONCLUSION AND FUTURE PLAN

This paper introduces the iMG lab in Aalborg University [26], [27] along with the hierarchical control implemented in this system. The combination of hardware/communication architecture and proper designed control hierarchy forms a flexible experimental platform for MG related study. A completed hierarchical control for voltage/frequency restoration and voltage unbalance compensation has been introduced and implemented in this system. Experimental results are presented to show the performance of the system. The research of this group started from basic control for inverter interfaced DGs, including inner control loops, primary and secondary control loops. Along with the progress of higher-level control and optimization algorithms study, the future work will put more efforts on the secondary control, tertiary optimization as well as energy management functions

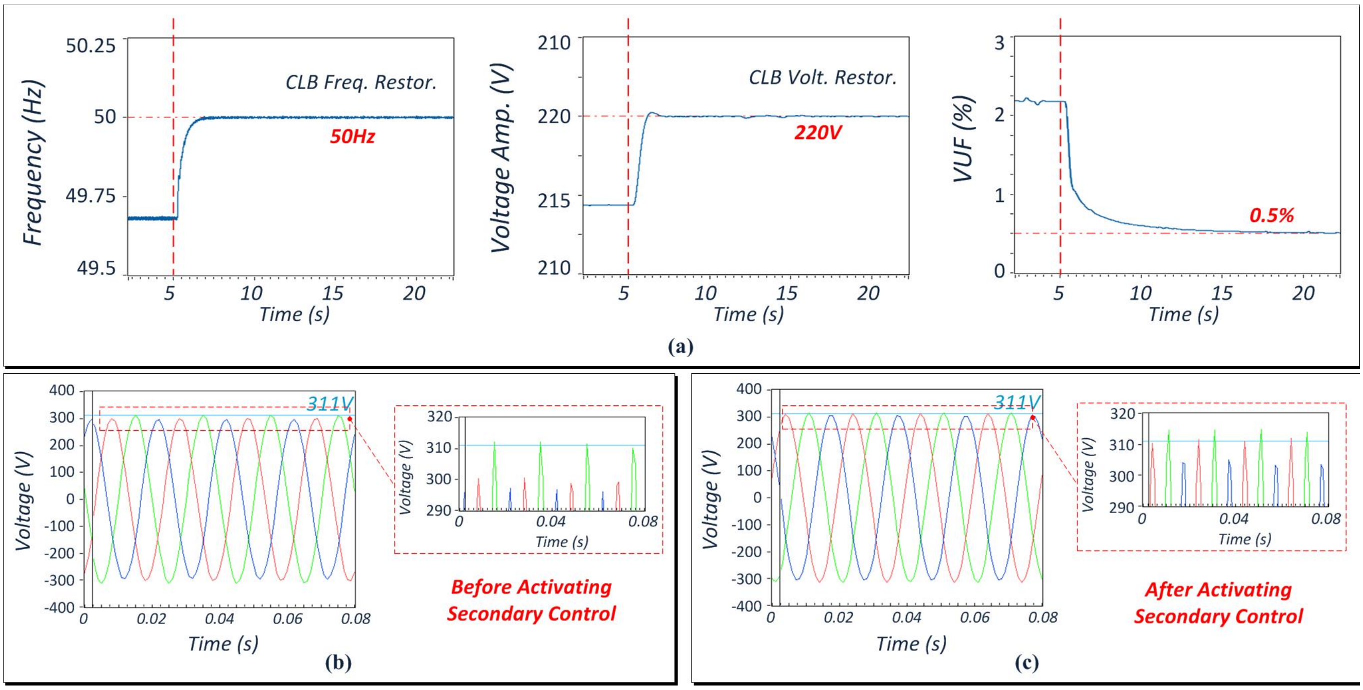


Fig. 7. Experimental results of *V/f* restoration and voltage unbalance compensation.

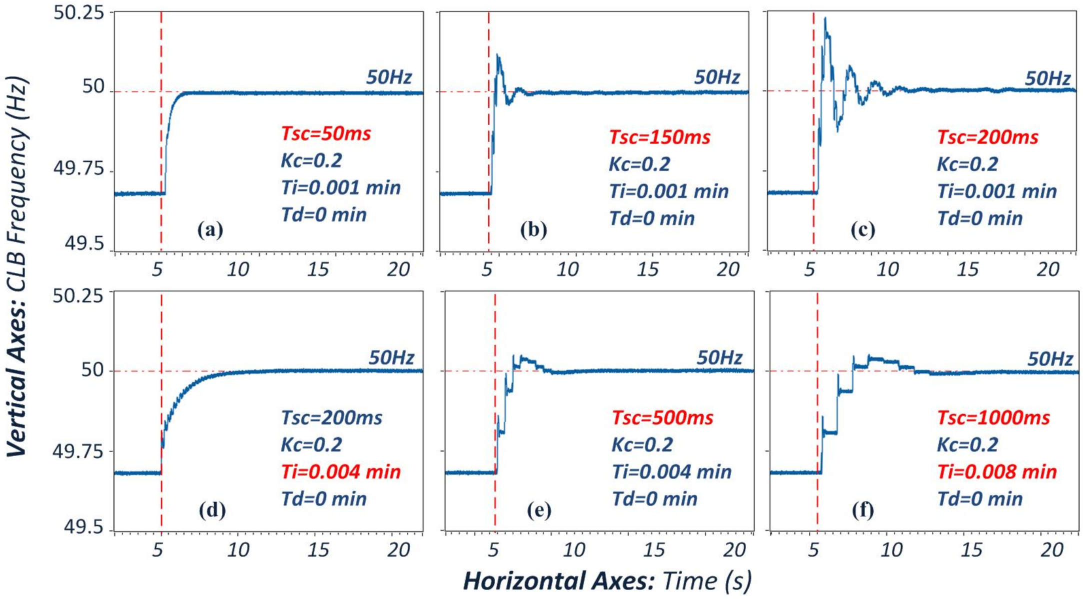


Fig. 8. Secondary frequency restoration dynamics under different communication sampling times and parameters.

and their implementation. Different types of communication technologies, such as WiFi and Zigbee, and sorts of distributed algorithms are also planned to be implemented and tested in this lab, to achieve a complete MG emulation system with the flexibility of equipping a centralized, distributed or hybrid control/management architecture.

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