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***Abstract* -- This paper presents the system integration and hierarchical control implementation in an inverter-based microgrid research laboratory (MGRL) in Aalborg University, Denmark. MGRL aims to provide a flexible experimental platform for comprehensive studies of microgrids. The structure of the laboratory, including the facilities, configurations and communication network, is first introduced. The complete control system is based on a generic hierarchical control scheme including primary, secondary and tertiary control. Primary control loops are developed and implemented in digital control platform, while system supervision, advanced secondary and tertiary management are realized in a microgrid central controller. The software and hardware schemes are described. Several example case studies are introduced and performed in order to achieve power quality regulation, energy management and flywheel energy storage system control. Experimental results are presented to show the performance of the whole system.**

***Index Terms*-microgrid, system integration, hierarchical control, microgrid central controller, energy management**

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.

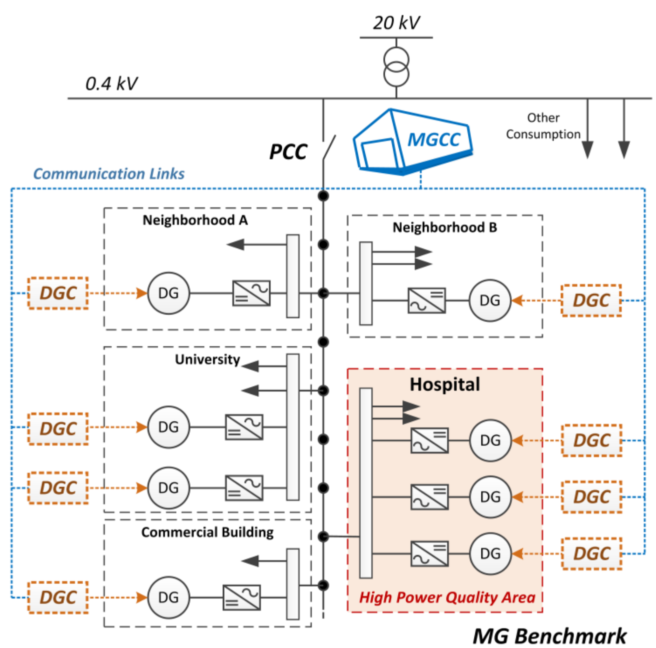

Fig. 1. Benchmark microgrid system.

However, the perfect ideal comes with challenges for the overall system control and management, such as power sharing, power quality, system stability and sustainability, as well as 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.

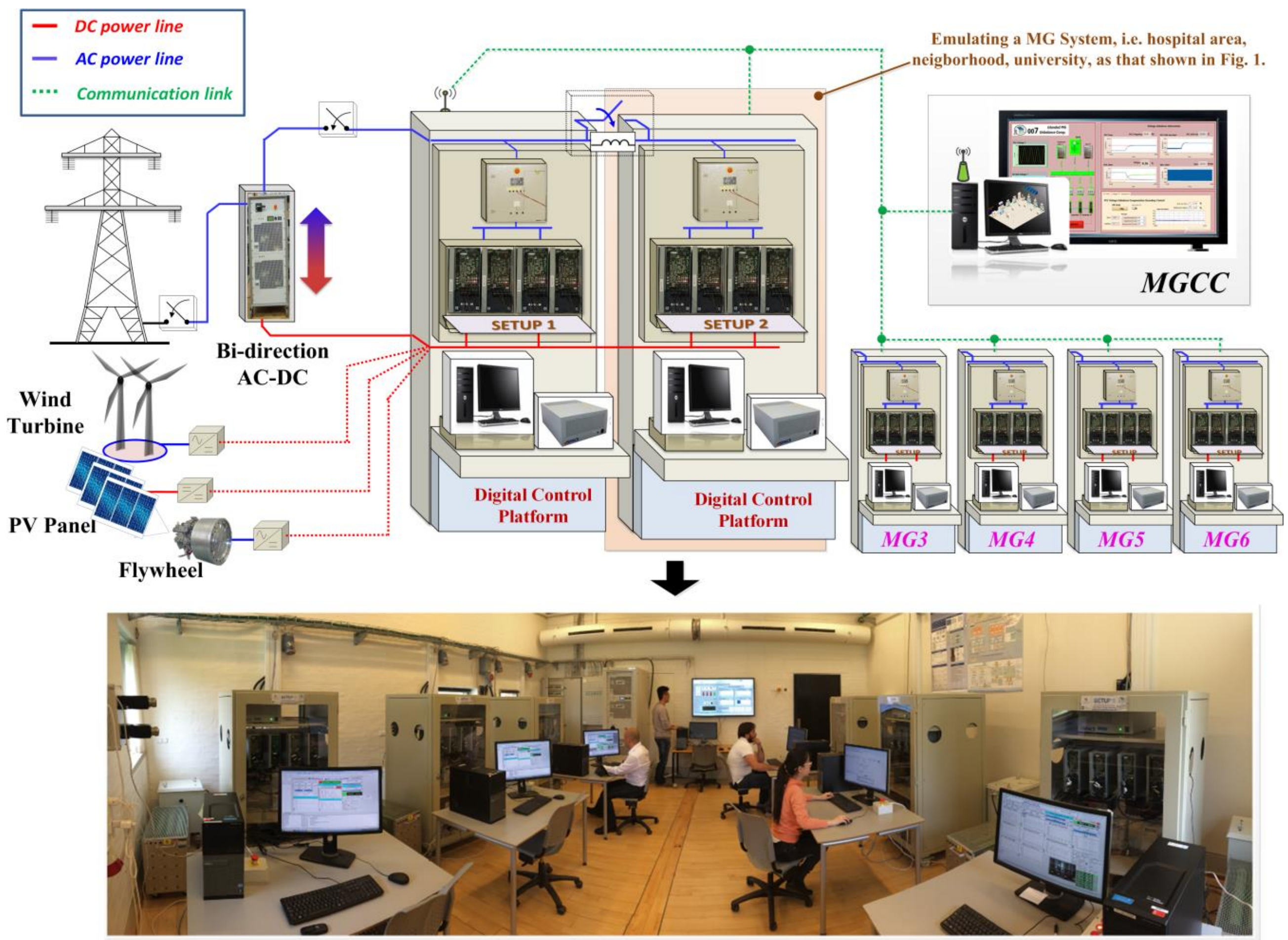

Fig. 2. Overview of microgrid research laboratory facilities.

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]–[4], as it was proposed for manufacturing [5], power systems [6], [7], process systems [8], and in general terms, for large complex systems [9]. 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 (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 [10]–[12] and achieve accurate power sharing [13], [14], 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 [12], [15]–[18]. 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 [19], 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, these control levels are mostly implemented in MGCC [10]–[18], [20]–[25]. 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 [26].

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, a microgrid research laboratory (MGRL) is established in the department of energy technology in Aalborg University [27], [28], which is introduced in detail in Section II. The generic hierarchical control scheme is presented in Section III. A study case is formulated in Section IV and implemented in the system. Section V presents another study case regarding energy management system. Section VI summarizes some distributed/decentralized applications in MGRL. The conclusion and future plan are given in Section VII.

II. Laboratory Configuration and Facilities

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

A. *Laboratory 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, low 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 real energy resources, such as photo-voltaic (PV) panels, wind turbines (WT), flywheel energy storage system (FESS), 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 which can be connected flexibly to measure local generation, local consumption or power exchange with external grid. 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

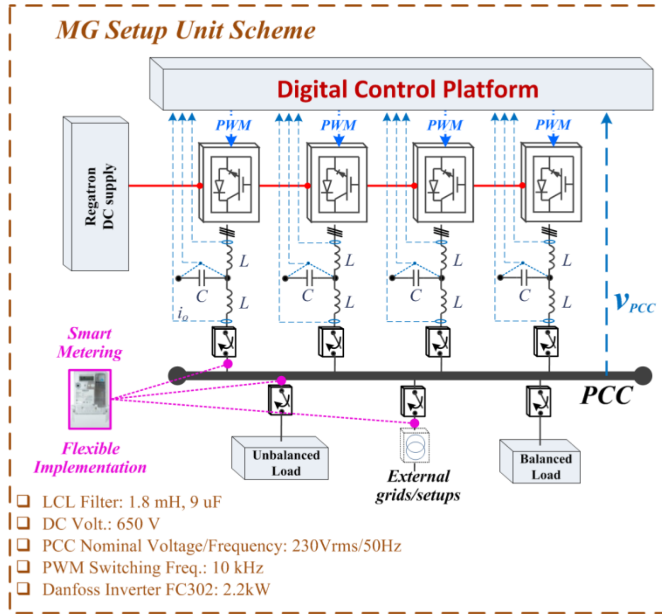

Fig. 3. Experimental setup details.

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 MGRL 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 to execute comprehensive MG studies.

B. *Generic System Architecture and Implementation*

The generic system architecture and information flow are shown in Fig. 4. The architecture shows the hierarchy of the control and management for a MG system.

The local controller directly measures and acts on the MG plant components, such as DGs, inverters, switches and loads. It also transmits essential information to MGCC and receives references/commands from MGCC. In MGCC, a database is required for storing and providing critical information, which can be used for periodical record, data analysis, prediction and short-/long term scheduling purposes. A powerful solver, such as CONOPT and CPLEX, along with a proper algebraic

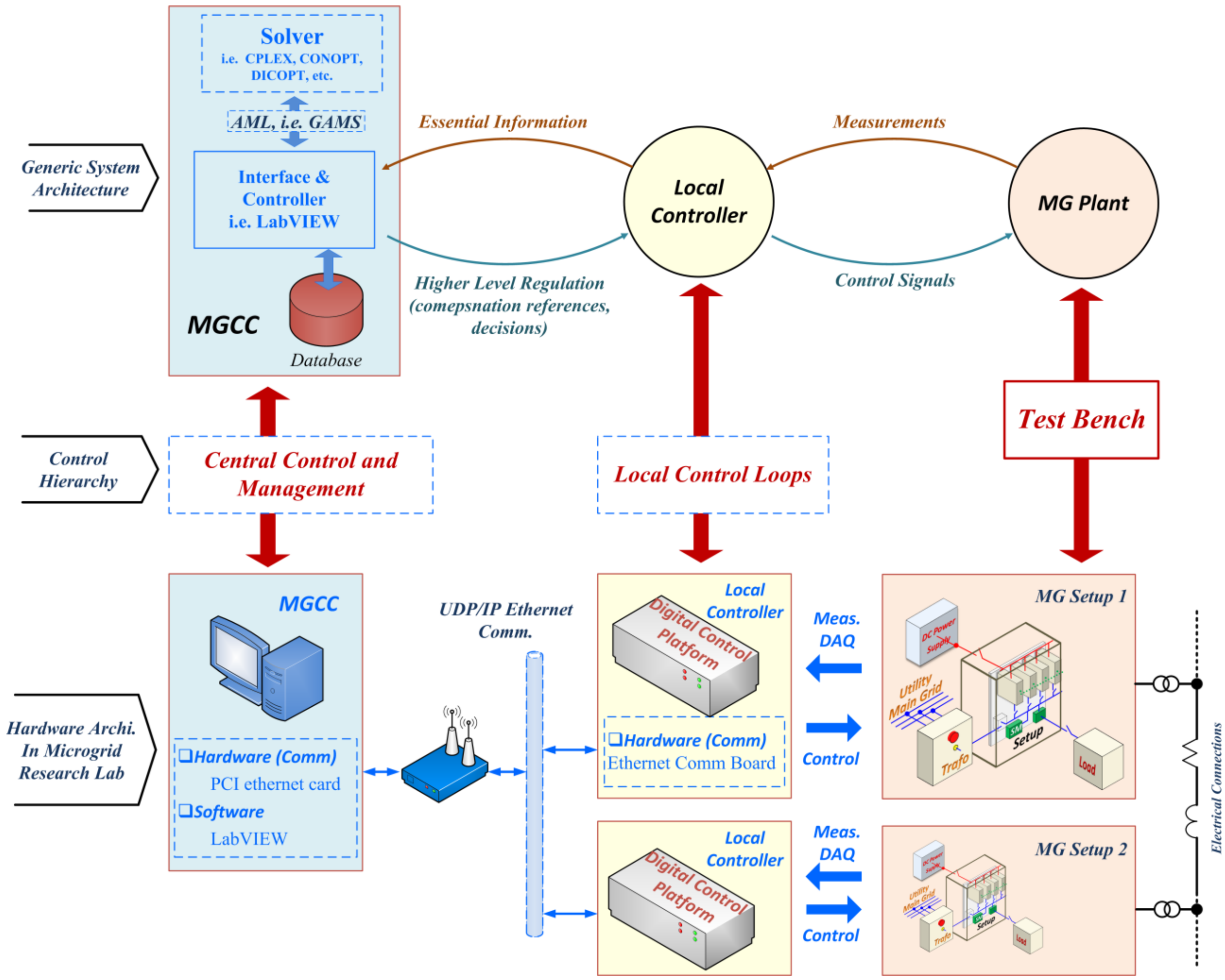

Fig. 4. Generic system architecture in MGRL.

modeling language, AML (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.

The corresponding hardware configuration is shown in the lower part of Fig. 4. The MG setup components, including the inverters and all the contactors, are controlled by a digital control platform, which acts as the local controller. 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 Pulse-Width Modulation signals from the local controller. The local controller functions, including the primary control loops, are developed using MATLAB/Simulink and implemented to the digital control platform 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, *UDP/IP* based Ethernet communication interface is established between MGCC and digital control platform. LabVIEW is used in MGCC, as an example, for developing user-interface as well as secondary and tertiary control functions.

C. *Smart Metering and Database*

The MGRL is also equipped with an Advanced Metering Infrastructure (AMI). The AMI substitute the manual collection of data, by a complex communication chain composed of data concentrators, hubs, and different control and central units. Furthermore, this AMI allows the integration of the metering of all energy systems in Denmark (electricity, district heating, gas, and water) in the same measuring infrastructure [29]. This feature is especially important in Denmark, where the 83% of the energy consumed in residential areas, is taken by the heating systems.

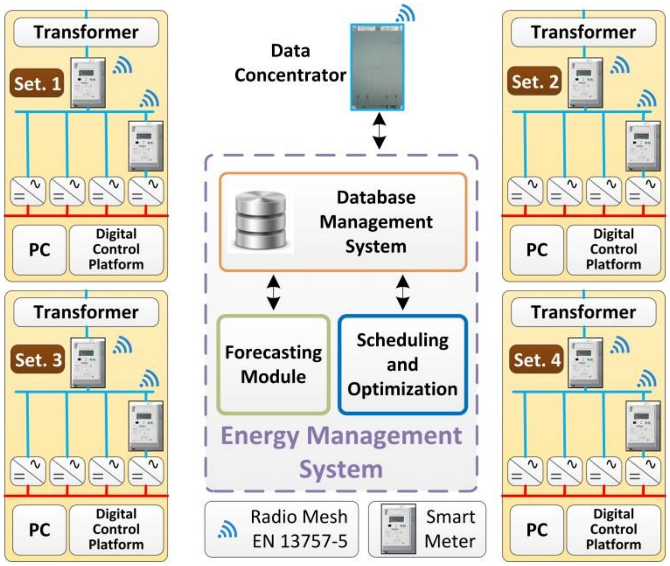

Fig. 5 Smart Metering Infrastructure and EMS in the MGRL.

The metering infrastructures have been always used for billing purposes by the utility company, however the Microgrid Research Group is working on how to use the information provided by the AMI for energy management purposes. The AMI is formed by smart meters, data concentrators, a database system, and software for user interface.

The electricity meters measure the energy in all four-quadrants, active positive and active negative, as well as, reactive positive and reactive negative energy. Furthermore they provide information regarding power quality, voltage, current and power measurements per phase, time stamp on power failures, registration of over-voltages and under-voltages, and detection of sags, swells, total harmonics distortion (THD), and supply voltages unbalances.

The electricity meters have been installed in the MGRL, as shown in Fig. 5, whereas the water, district heating and single-phase electricity meters are installed in the DC demonstration home [30]. Every experimental setup has two smart meters integrated, which allow the Microgrid research group to use the laboratory as a simulated smart grid platform.

The electricity meters communicate with each other and with the data concentrator by means of a radio mesh topology, based on the standard EN 13757-5. Regarding the security of the information transfer, the communication between the smart meters and the data concentrator is encrypted and protected against unauthorized monitoring by using AES-128.

The data concentrator receives all the information from the electricity meters, then, it transfers the information to a data system, using Ethernet, GPRS, or 3G, according to the DLMS/COSEM standard. The data concentrator is able to manage up to 500 Smart Meters, and is equipped with two different working modes, one for automatic meter readings

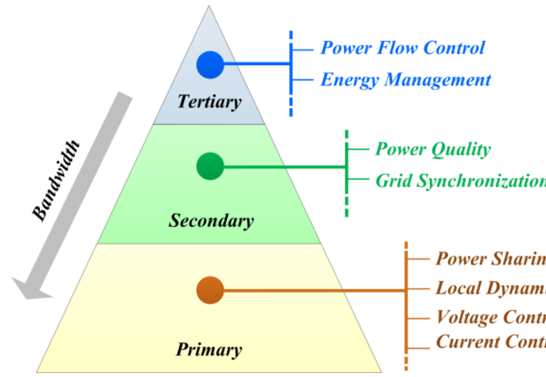

Fig. 6. General hierarchical control scheme.

(AMR), and a second one for on demand readings. Furthermore, the data concentrator transfers the information to the data base every 6 hours, using the AMR working mode. However, in case real-time information of the system is required, the user can request readings to the smart meters, using the on demand readings working mode. In addition when using the AMR working mode, a maximum of 5 minutes resolution between measurements can be achieved.

The information storage system is composed by a two level data system:

- Short-term database for the on demand readings, system events and wireless network optimization purposes.
- Long-term database for storing all the consumption profiles.

LabVIEW is used to develop the user interface, and for implementations of the EMS, scheduling, optimization, and forecasting modules.

Based on this laboratory configuration, microgrid oriented research work have been carried out, such as hierarchical control scheme, energy management, as well as distributed control methods.

III. Hierarchical Control Scheme

The control and management of microgrid systems are actually multi-objective tasks including the control of power electronic devices, regulation of power flow and power quality, management of different energy resources, etc. Accordingly, a generic hierarchical control scheme has been proposed for achieving proper overall control for microgrids, which includes primary, secondary and tertiary control levels, as that shown in Fig. 6 [2]–[4]:

- Primary control performs the control of local power, voltage and current. It is implemented in local controllers, following the setting points given by upper level controllers.
- Secondary control deals with power quality control, such as voltage/frequency restoration, voltage unbalance and harmonics compensation. Grid synchronization in AC MG is also within the scope of

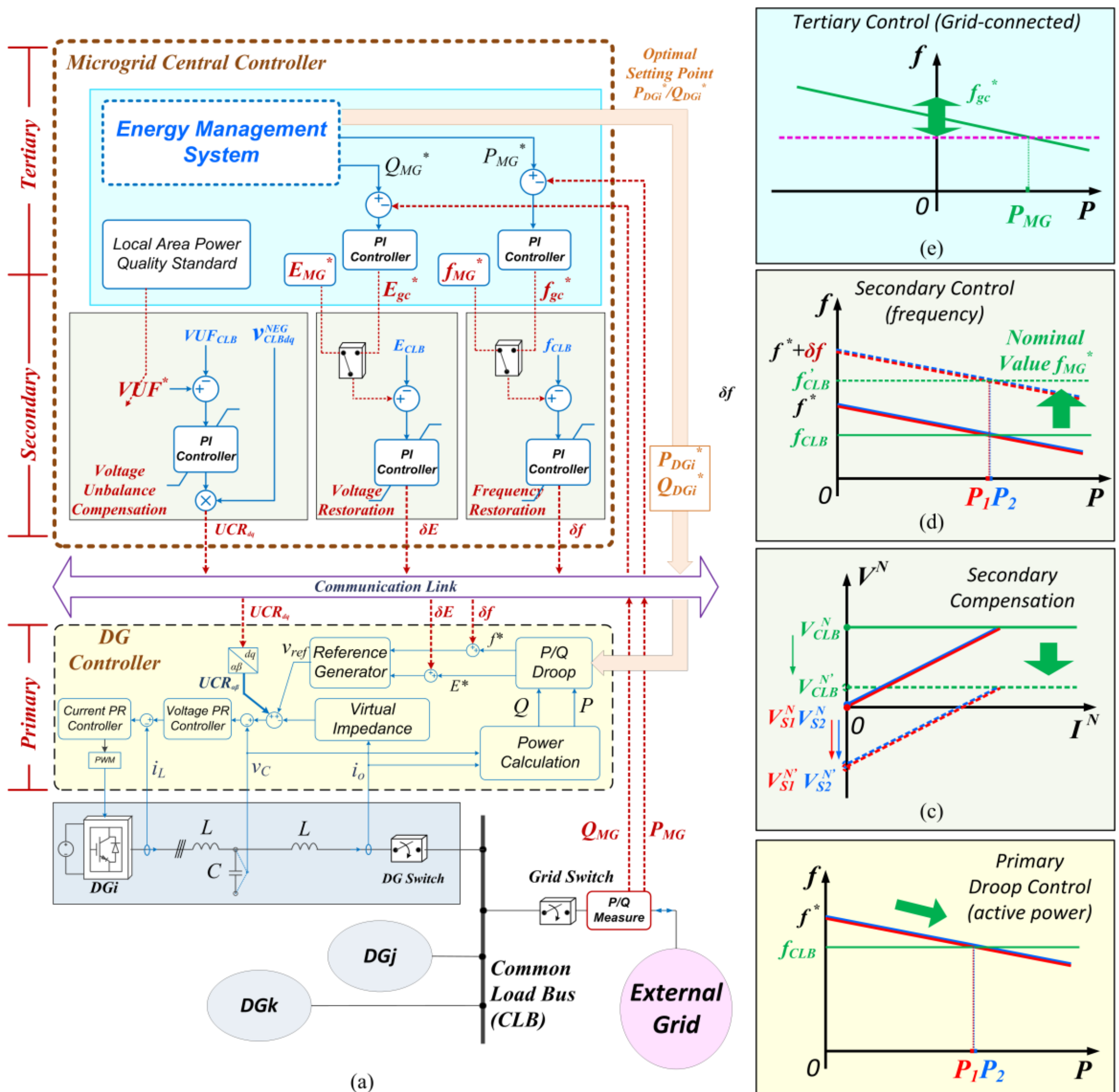

Fig. 7. Hierarchical control scheme of Example Case I.

secondary control.

- The objectives of tertiary control include power flow regulation and energy management function. The power flow regulation guarantees the accurate power sharing control among DG units, and the power exchange between MG and external grid. The energy management aims to introduce more intelligence to the system realizing economic operation.

With the increasing of the control level, the bandwidth is actually decreasing in order to decouple the dynamics of different levels. Generally, each higher control level needs to be approximately an order of magnitude slower than the down streaming level.

Based on the hierarchical control scheme and the laboratory configurations, several study cases are presented in the following sections, including the control, implementation and experimental results.

IV. Example Case I: Hierarchical Control for Voltage Quality in Islanded Microgrid

Considering the study case system shown in Fig. 1, in each local area, the DGs are connected to a common load bus (CLB). A high power quality area exists in the MG system, 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. Also, 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 interfacing inverters as distributed active power filters. An example study case for voltage unbalance compensation and *V/f* restoration is shown in this section, while similar approach has also been applied to harmonics compensation [31]. The hierarchical control scheme is shown in Fig. 7 (a), including primary control for basic power sharing, secondary control for power quality and tertiary control for power flow regulation.

A. Primary Control Loops

The primary control includes current and voltage control loops, active and reactive power droop control loops and virtual impedance loops. The output active and reactive power of the inverter is first calculated based on the instantaneous power theory [32]. 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 [10], [33]. A simplified plot of the active power droop is given as example in Fig. 7 (b), by assigning proper droop gains to the DG units, their power can be shared accordingly.

In addition to droop control, a virtual impedance loop [10], [33] 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 loops [10], [33]. More details about the primary control loops can be found in [10].

B. Secondary Control Loops

In MGCC, three secondary control functions are implemented: voltage unbalance compensation [10], voltage restoration and frequency restoration [2], [3]. Four essential information, voltage unbalance factor (VUF_{CLB}) [34], negative sequence voltage in dq reference (v_{CLBdq}^{NEG}), voltage amplitude (E_{CLB}) and frequency (f_{CLB}) are measured by remote sensor in CLB 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).

The functionality of voltage unbalance compensation is plotted in Fig. 7 (c). The idea behind the compensation is to reduce the negative sequence voltage on CLB (V_{CLB}^{N}) by adjusting the negative sequence voltage at the DG sides (V_S^N). The tuning of secondary control parameters and more details about this compensation process can be found in [10].

The functionality of frequency and voltage secondary control are similar. Taking frequency secondary control as an example, as that plotted in Fig. 7 (d), this process realizes the restoration of the frequency deviation caused by droop control. The frequency reference in the droop control is adjusted by secondary control (from f^* to $f^* + \delta f$) in order to keep the MG frequency at the nominal value.

C. Tertiary Control

On top of the MGCC, a tertiary controller can also be installed for adjusting the set-points in primary and secondary control. Depends on the operation mode (islanded or grid-connected) of the MG, the tertiary control can provide different functionalities.

In islanded mode, it keeps the constant nominal voltage/frequency reference (f_{MG}^* and E_{MG}^*) for secondary control loops and generates the power quality requirement (VUF^*) according to the local condition.

In grid-connected mode, it manages the power flow between the MG and external grid. The active and reactive power flow at the grid connection point are measured and compared with references (P_{MG}^* and Q_{MG}^*), frequency and voltage amplitude references (f_{gc}^* and E_{gc}^*) are then generated and given to secondary control loops. In this way the MG is managed as an entity, MGCC works as the agent between MG and external grid, exchange information with other systems or distribution system operators. The functionality of tertiary power flow control in grid-connected mode is shown in Fig. 7 (e) as an example. The f_{gc}^* can be adjusted to change the active power flow (P_{MG}) between MG and external grid.

In both grid-connected mode and islanded mode, the tertiary energy management can optimize the utilization of different energy resources, such as sustainable energy, conventional energy and energy storage systems, aiming to achieve economic operation of the MG. A decision making procedure can be deployed to decide the optimal setting points for lower level controllers, such as the cases studied in [12], [17]. An example case about energy management in a renewable energy based microgrid is given in Section V.

D. Demonstration Results

To conduct the experimental study, the proposed control loops are implemented in MGRL. The primary control loops are developed in Simulink and load to digital control platform executing the DGC function. The secondary and tertiary control loops are developed in LabVIEW in MGCC. Information exchange between DGC and MGCC are realized by using Ethernet connection. The electrical system parameters are shown in Fig. 3. Detailed parameters of the inner control loops and primary control loops can be found in [10]. The secondary control is implemented in LabVIEW by using the PID control virtual instrument. The PID loop is defined as:

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

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. 8. 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,

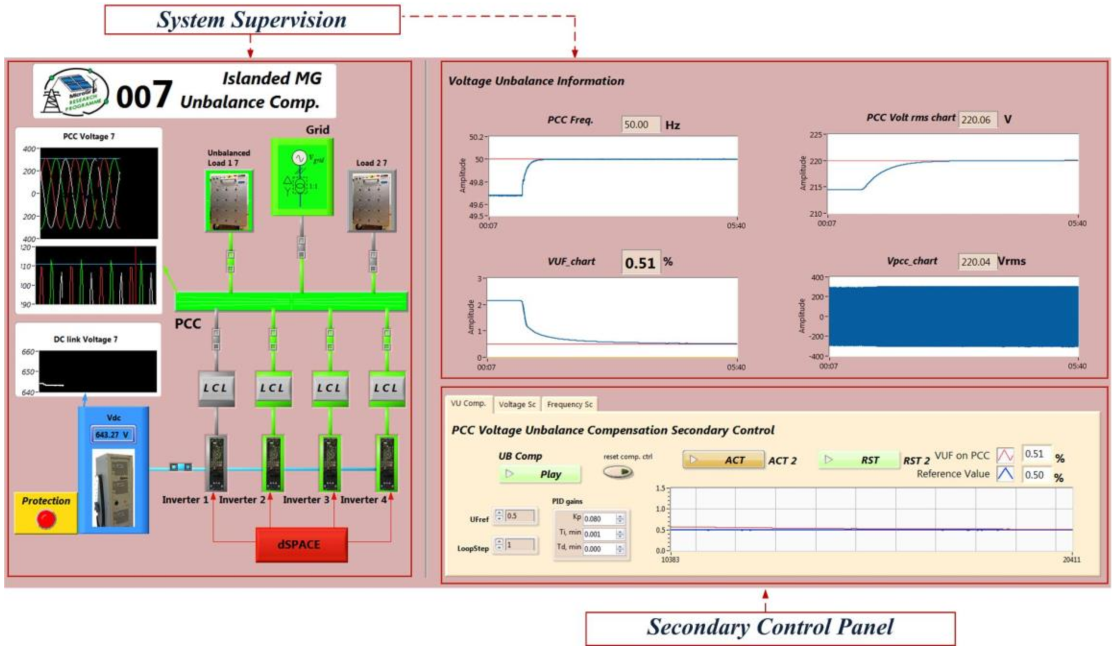

Fig. 8. Supervision system interface.

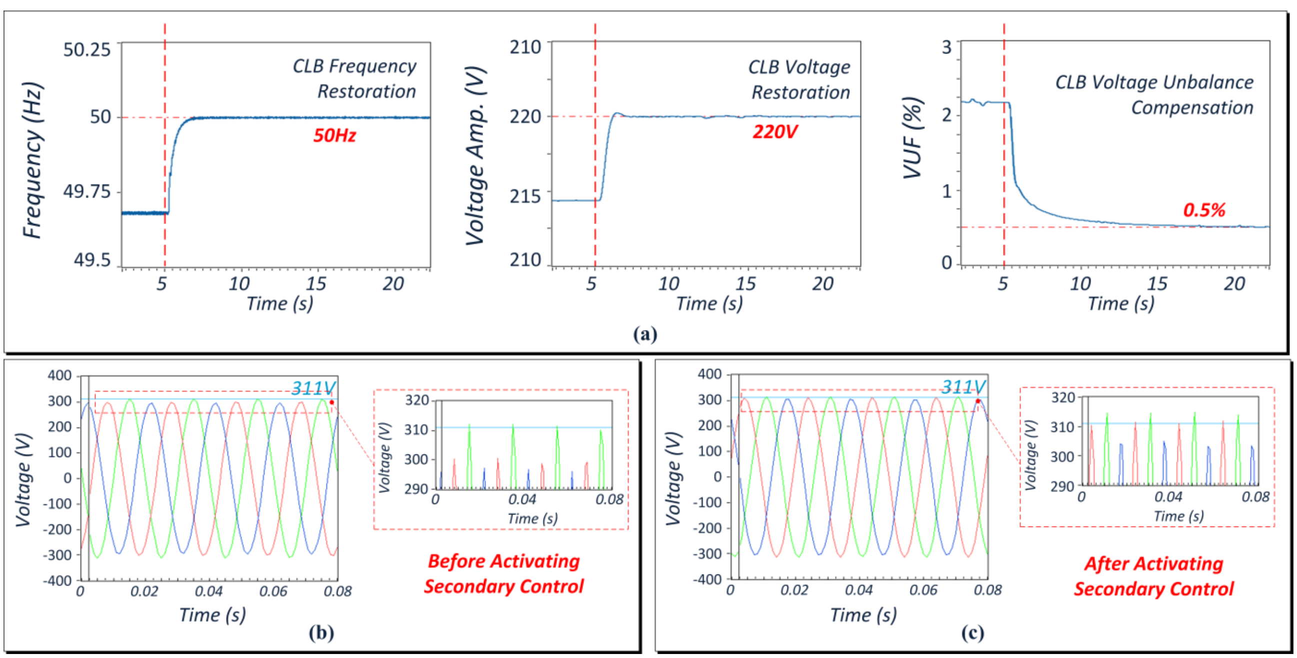

Fig. 9. Experimental results of *V/f* restoration and voltage unbalance compensation.

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 control parameters.

The experimental results showing the performance of secondary control are given in Fig. 9. 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. 9 (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. 9 (b) and (c), which demonstrate the effectiveness of the system.

To test the system response under fault conditions,

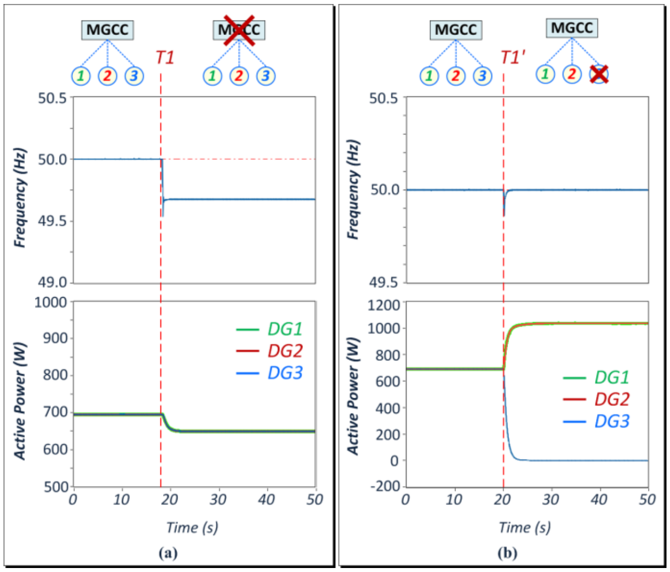

Fig. 10. System response under fault conditions.

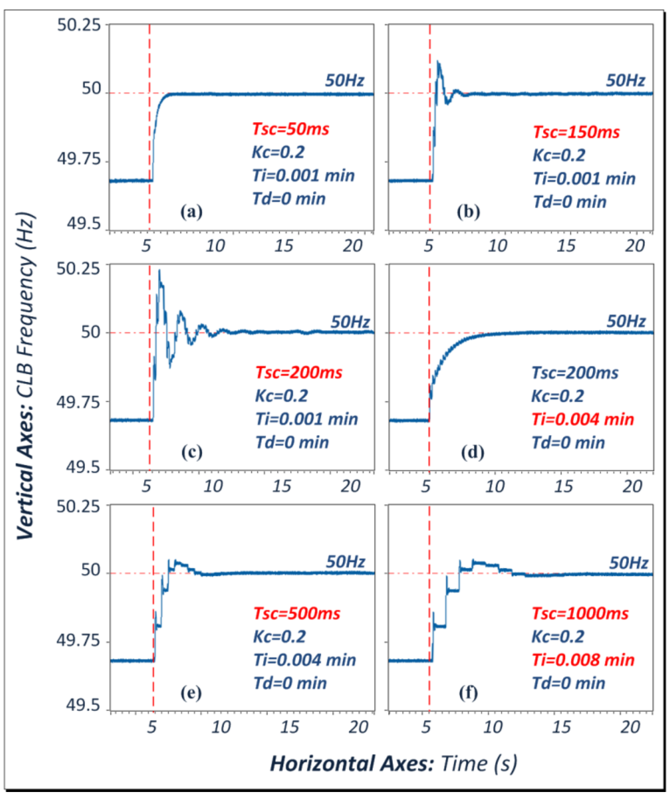

Fig. 11. Secondary frequency restoration dynamics under different communication sampling times and parameters.

experimental results are shown in Fig. 10 (frequency control loop is given here as example). Fig. 10 (a) shows the system frequency and active power under MGCC fault or loss of all the communication link condition. At *T1*, a failure occurs in MGCC causing the loss of secondary control functions. The frequency drops to 49.7Hz, but the power sharing is still

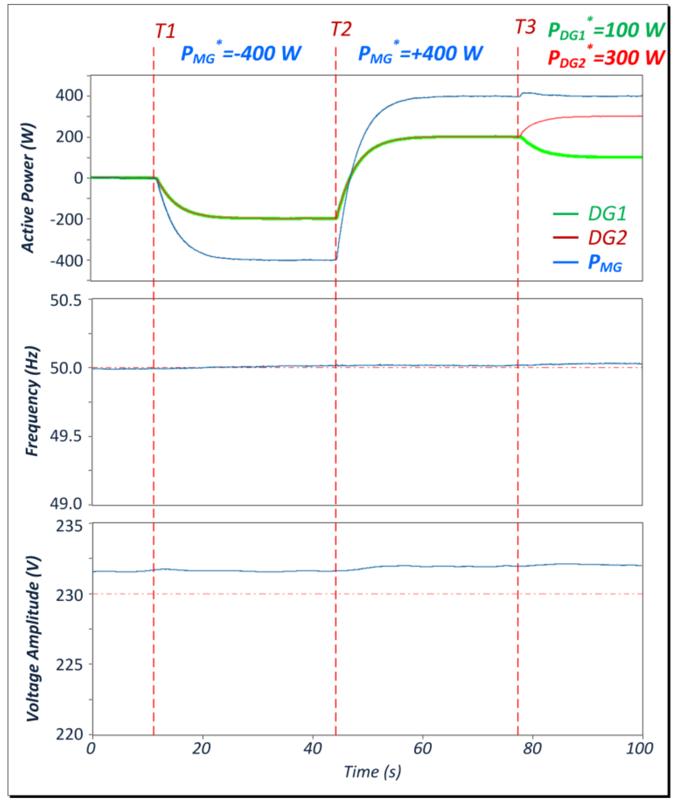

Fig. 12. Tertiary control of power flow.

guaranteed because of using of droop control. Fig. 10 (b) shows the system response under loss of a communication link or one DG unit fault condition. It can be seen that, at *T1'*, a fault happens to DG3 or the communication link between DG3 and MGCC is lost, DG3 stops sharing the total load power, but DG1 and DG2 are able to support the system and keep the frequency at nominal value.

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 plotted in Fig. 11 (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. 11 (d), resulting in slower but more damped system behavior. In Fig. 11 (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. 10 (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.

The above results show the system performance under islanded operation mode. In grid-connected mode, tertiary control regulates the power flow between MG and external grid, as that was shown in Fig. 7 (a) and (e). Also the power dispatching among DGs can be controlled by tertiary level. Taking active power as an example, the experimental results of power flow control during grid-connected mode is shown in Fig. 12. The blue curve (P_{MG}) shows the active power exported from MG to the grid. The green and red curves are the active power generated by DG1 and DG2 respectively. At *T1*, P_{MG}^* is set to -400W, the MG starts to import power from the grid in order to supply local load or charge the energy storage system. In this case as no local load is connected, DG1 and DG2 are equally sharing the power from main grid. At *T2*, P_{MG}^* is set to +400W, the MG starts to export power to the grid. At *T3*, instead of making DG1 and DG2 equally share the power consumption, different power references are given to DG1 and DG2. The power generation of DG1 and DG2 are consequently changed, but the total power exported to the main grid is kept at the reference value 400W. It also can be seen that during this process, the MG voltage and frequency are fixed by the stiff power grid.

V. EXAMPLE CASE II: ENERGY MANAGEMENT IN GRID-CONNECTED MICROGRID

Based on the results presented in the previous sections related to grid-connected operation mode, a study case microgrid composed of two renewable energy resources (a photovoltaic array and a wind turbine), a battery and a load has been deployed in one MG setup unit while the EMS is implemented in the MGCC as shown in Fig. 13. The distributed energy resources with their local controllers are developed in the digital control platform. In this case, all the inverters are working in current control mode (CCM), acting as grid following units [35]. The power flow between MG and external grid is conducted by the tertiary control whereas the energy management function is the responsible to decide the optimal operation of the DG units and other MG components, aiming to minimize the operation cost of the MG considering variant electricity price.

A. *Description of the EMS*

Regarding the EMS, the structure is integrated by three components: scheduling and optimization module, supervisory system interface and data storage. As can be seen, the communication between the MG and the EMS is performed by means of the supervisory system interface. This module is implemented in LabVIEW and is the responsible of gathering and displaying the current measurements and giving the references to the MG. The measurements come from either the real-time measurement or the AMI that includes the smart meters, data concentrator and communication devices.

The data collected by the supervisory system interface is stored in the data storage and, in the same way the references that the EMS sends to the MG are read by the supervisory system from the data storage. In fact, the data storage is a collection of files that is accessible by the supervisory system or by the scheduling and optimization module and it provides them with the required information to perform specific tasks.

And finally, the scheduling and optimization module is a system that includes a suitable algorithm to get optimal references for the distributed energy resources in the MG. Currently, the optimization model is been included in an AML and the results have been processed and sent to the database by means of MATLAB.

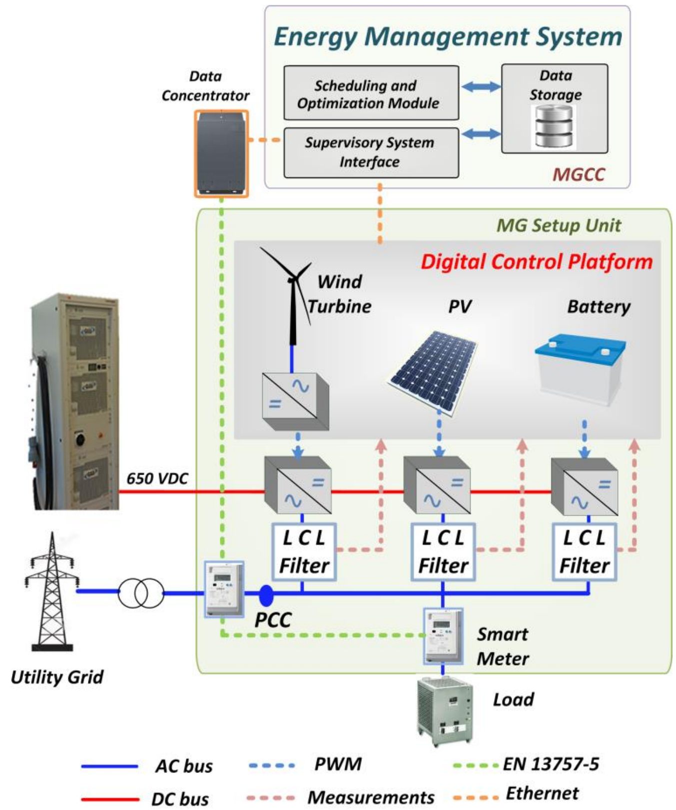

Fig. 13. Energy management study case and implementation.

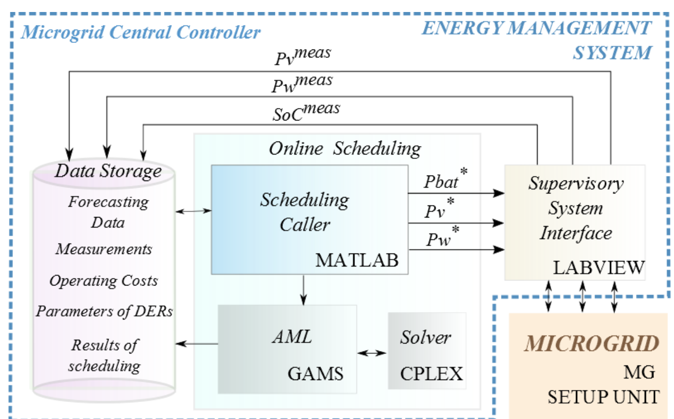

Fig. 14. Data flow in the EMS.

B. Implemented Online Scheduling

The aforementioned EMS scheme can be used to perform online scheduling as shown in Fig. 14. The scheduling model is included in an AML called GAMS and it is using the solver CPLEX to solve the optimization problem. On top of that, the block *Scheduling Caller*, deployed in MATLAB, is implemented to process the input/output data for the scheduling process and call GAMS in each iteration.

In this specific study case, the measured variables in the microgrid are P_v^{meas}, P_w^{meas} and SoC^{meas}, and correspond to the average power of the PV, WT and the current state-of-charge (SoC) of the battery and the scheduled references, set by the energy management system, are the power references for the DER, P_v^*, P_w^* and P_{bat}^*. The *Supervisory System Interface* receives the measurements from MG plant, visualizes them and sends them to the *Data Storage*. At the same time, it receives the references from the *Online Scheduling* and sends them to the MG. Measurements collected by the AMI can be considered in future works, as well as additional functions of the supervisory control.

Moreover, the *Scheduling Caller* reads, collects and processes the relevant parameters contained in the *Data Storage*. This process is executed every 15min with a time horizon of 4 hours and time slots of 1 hour. The detailed formulation of the optimization problem and description of the processing data can be found in [36].

C. Demonstration Results

To illustrate the performance of the EMS, the real simulation of one day is presented by reducing the time of the generation profiles and the capacity of the battery to obtained 24 h simulation (1440 min) in 24 min (1440 s). Additionally, the operation region of the SoC of the battery is established in the range [50%, 100%] and its initial condition as 40% so that it can be appreciated the capability of the system to restore the value of the SoC to a safe region. Moreover, the load is set as a constant value of 600 W.

The results are presented in Fig. 15. The first two figures correspond to the profile of power of each RES while the third figure shows the scheduled power profile of the battery The forth figure presents the power absorbed from the main grid in order to keep the energy balance in the MG. After that, the fifth figure corresponds to the SoC of the battery. And finally, the last figure show the accumulative cost duritng the day assuming that the elementary cost is 2 DKK/kWh.

It is possible to see that during the first interval (interval ***I*** in Fig. 15), the algorithm schedules the charge of the battery until the SoC reaches the minimum value in the defined operation range.

After that, in the second interval (interval ***II*** in Fig. 15), the power provided from the RESs are still not enough to supply the load, thus, it is requested to absorb power from the main grid whereas the power of the battery is set as zero.

When the power provided by the RESs increases (interval ***III*** in Fig. 15), it is no longer needed to absorb more energy

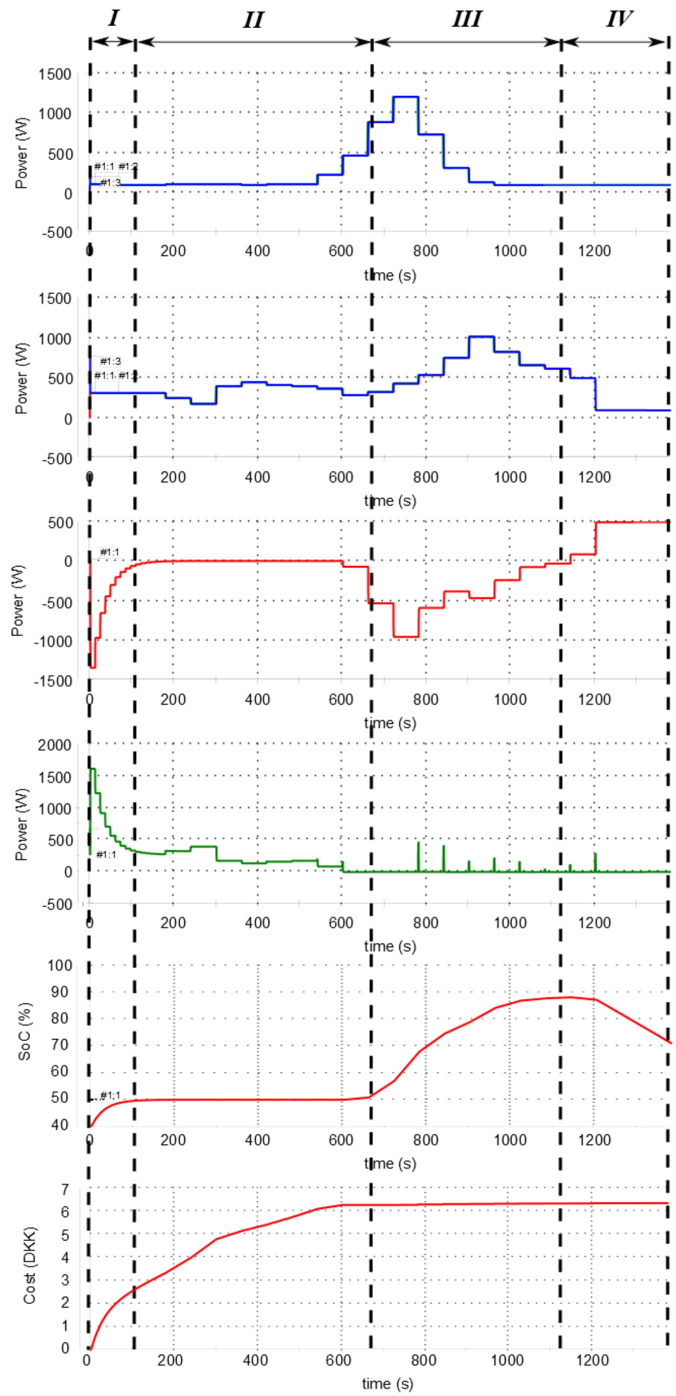

Fig. 15. Results obtained using EMS. Top to bottom: PV power, WT power, battery power, power absorbed from the main grid, SoC of the battery

from the grid and instead, part of the energy is used to feed the load, another part is sold to the main grid (in this case the PV generation can be sold) and the surplus of energy is stored in the battery. Consequently, the using of energy from the main grid stops increasing to reduce overall operation cost.

At the end of the day (interval ***IV*** in Fig. 15), part of the stored energy is used to supply the load without need of using the main grid, and consequently, reducing costs.

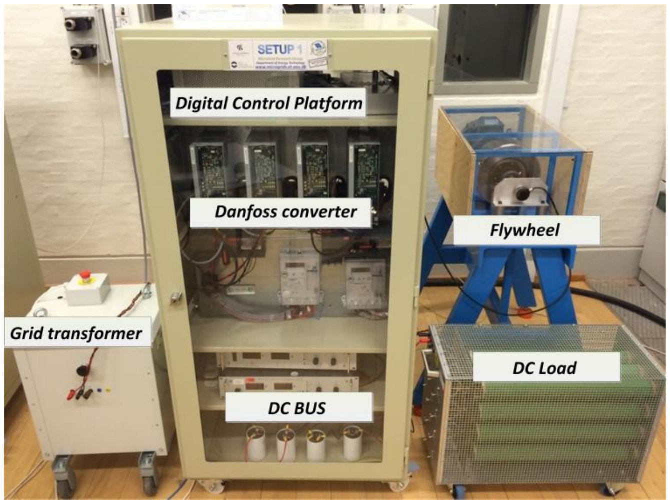

Fig. 16. Flywheel energy storage system.

It is worthy to notice that the SoC is kept in safety region with a smooth behavior during the whole day.

VI. Distributed and Decentralized Applications

In centralized infrastructure, such as the cases presented above, all the relevant data is transferred to one unique centralized controller via digital communication links (DCLs). Centralized controller then processes data and send commands back to units. While with the increasing penetration of distributed generation, the distributed and decentralized control/management methods are becoming increasingly attractive, as they offer higher flexibility and lower implementation cost. There is a clear distinction between decentralized, centralized and distributed control. Decentralized control refers to situation where there is no DCLs between the units. On the other hand, distributed control refers to situation where DCLs are installed only among the units and there is no centralized process of commands.

The authors of [37] have classified the distributed control techniques into four categories: Distributed Model Predictive Control-Based Techniques, Consensus-Based Techniques, Multi Agent-Based Techniques, Decomposition-Based Techniques. Taking consensus-based technique as an example, the same study case considered in Section III is managed in a distributed way by using dynamic consensus algorithm [38]. The complete control scheme has been implemented in MGRL. The DG controllers communicate only with their direct neighbors providing each other essential information. Distributed secondary and primary control loops are implemented in each DGC achieving the same control goals as in Example Case I, but in a distributed fashion without involving a MGCC.

In addition, the inclusion of consensus algorithm into control loops certainly affects the dynamics of the system which requires proper modeling and analysis. A simulation work has been done in [39] in order to provide a theoretical approach for evaluating the influence of communication delay and transmission rate on system dynamics.

Apart from that, decentralized methods, such as bus signaling [40], can realize control and coordination functions without involving either a central controller or DCLs. Taking bus signaling as an example, it uses the dc bus itself as the communication link to exchange essential information. An application of bus signaling method has been implemented in a fast charging station (FCS) upgraded with flywheel energy storage system (FESS) in MGRL, as that shown in Fig. 16 [41]. The system consists of a pair of ac/dc converters connected with grid and flywheel energy storage system and several loads emulating the PEV loads. Each component is coupled around a common dc bus around 650V in the system. The bus signaling strategy coordinates control of the grid and FESS converters in the local controllers and each controller adjust its operation by observing the change of dc bus voltage. Bus signaling method is also commonly applied in ac and dc microgrids which contain several renewable energy sources (RES) and energy storage system (ESS) [42], [43]. RES and ESS controllers adjust their operation modes according to dc or ac bus condition in order to reach power balancing between each component.

VII. Conclusion and Future Plan

This paper introduces the system integration in the MG research laboratory 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, an energy management study case is also presented. Based on the existing structure, future plan includes the more advanced utilization of smart meters AMI techniques. Different types of communication technologies, such as WiFi and Zigbee, and sorts of distributed algorithms are also planned to be implemented and tested, to achieve a complete MG emulation system with the flexibility of equipping a centralized, distributed or hybrid control/management architecture. Also the modeling and evaluation of system dynamic with different communication features are necessary. Considering the variant communication rates, adaptive control based on different communication performance and inclusion of network control system can be promising future study topics.

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