An Enhanced Hierarchical Control Strategy for the Internet of Things-based Home Scale Microgrid

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***Abstract*— As the intelligent control and detection technology improving, more and more smart devices/sensors can be used to increase the living standard. In order to integrate the Internet of Things (IoT) with microgrid (MG), an enhanced hierarchical control strategy for IoT-based home scale MG is proposed in this paper. Physical smart devices/sensors and inverters are defined at the primary level. Electrical and environmental variables deviation restoration loops are adopted at the secondary level. Power flow management and optimization algorithms with different objectives are deployed at the tertiary level. In this sense, the IoT infrastructure can be smoothly integrated with the original MG hierarchical Control theory. The proposed structure will be implemented in an IoT MG laboratory in line with VICINITY project at Aalborg University, Denmark.**

***Keywords*—Internet of Things, microgrid, hierarchical control, voltage controlled inverters.**

I. INTRODUCTION

Global warming problem has drawn considerable concerns all over the world because of the increasing greenhouse gas emissions from burning fossil fuels and vehicles [1]-[2]. For mitigating this issue, the renewable distributed generation systems (DG) based microgrid (MG) is considered as one of the promising piece of decentralized architecture [3]. Meanwhile, as the increasing deployments of various Internet of Things (IoT) networks for sensing, measuring, controlling and business process optimization purposes, the integration of MG and information technology based-IoT will bring the system more possibilities to accomplish advanced objectives [4].

A Kalman filter based MG state estimation and control was proposed in [5], the fifth generation network based IoT was used for transferring information between renewable DERs and control center. Nevertheless, different infrastructures are mostly acting as isolated islands in the global IoT landscape while inter-connection of these islands might bring significant value added. Exploitation of these benefits is inhibited by various interoperability barriers including the lack of IoT protocol interoperability and privacy issues induced by the interconnected smart objects of different owners. Therefore, a software enabled framework to address the fragmentation challenge was proposed in [6]. Flexible communication agents were adopted as gateway to adapt various devices communication with different data formats and protocol. Security and scalability aspects were also investigated.

Given that almost everything can be part of IoT when smart sensors are adopted, diverse services can be achieved. Therefore, advanced infrastructure and sophisticated mechanism are required by resources management, service creation, service management, service discovery, data storage, and power management, etc. Integration of IoT with cloud computing, termed as Cloud of Things (CoT) was discussed in [7]. An architecture of smart gateway with fog computing was presented with data trimming technology to decrease pressure of communication network. Another issue for using IoT technology in applications is the increasing requirement of real-time data, which will bring the information storage and accessing more difficult and challenging. A semantic data model was proposed in [8] to store and interpret IoT data, and then a resource-based data accessing method (UDA-IoT) was designed to acquire and process IoT data ubiquitously to improve the accessibility to IoT data resources for emergency medical services.

The integration of IoT with energy system has also been investigated to deliver various intelligent services to the energy market. Three-layer architecture of IoT enabled smart grid was discussed in [9]. Economic performance of energy system can be improved by adopted IoT with conventional energy management system (EMS). The appliance and activity recognition mechanism for IoT-based EMS was investigated in [10] and a management service layer was presented for the recognition of current household appliances. However, the distributed energy resources were not taken into consideration.

In this paper, an enhanced hierarchical control strategy of IoT based home scale MG is proposed. Compared with the original MG hierarchical control strategy, inverters and physical smart devices/sensors for E-health and home security are defined at the primary level. The deviation restoration control loops of electrical and environmental variables are implemented at the secondary level according to its response time scale. The tertiary control is responsible for power flow management between the MG and the utility grid. Furthermore, economical, efficient and comfort optimizations are also considered. In this sense, IoT can be smoothly integrated with original hierarchical controlled MG. The proposed structure will be implemented in an IoT MG laboratory in line with VICINITY project at Aalborg University, Denmark.

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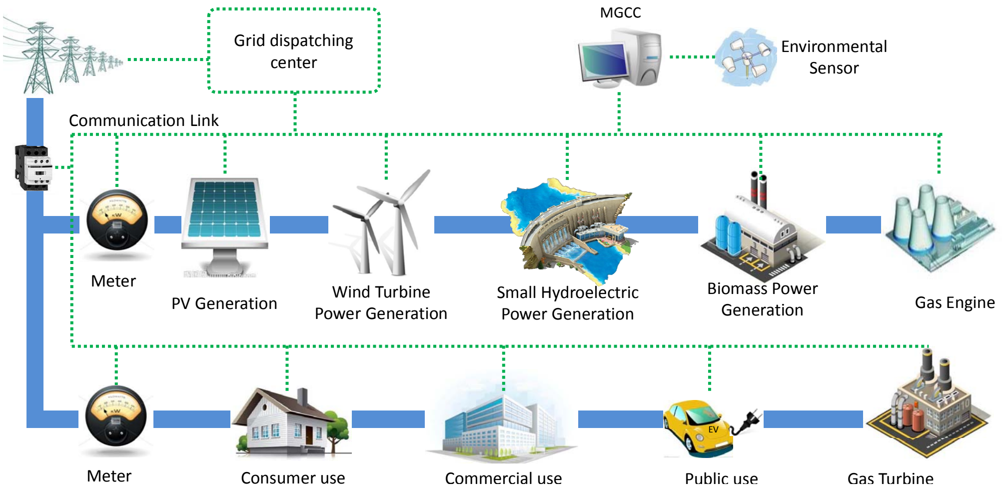


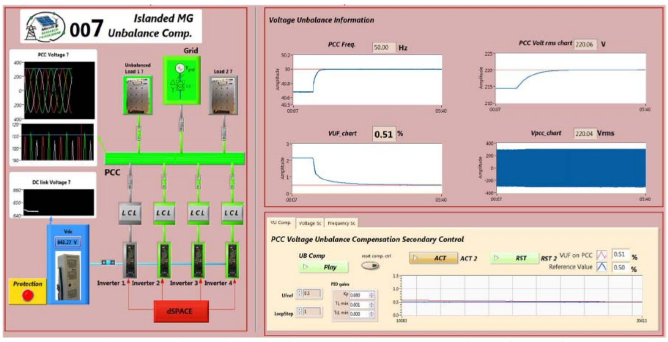
Fig. 1. A typical configuration of a MG with conventional MGCC.

II. CONVENTIONAL MICROGRID CENTRAL CONTROLLER

A typical configuration of an MG with microgrid central controller (MGCC) is shown in Fig. 1, which integrates power transmission lines, various energy sources, DG facilities and communication links. The power converters with PV or wind turbine are all connected to the common AC bus, and then connected to the utility grid through Static Transfer Switch (STS). A number of communication links including RS-485, Controller area network (CAN) and industrial Ethernet are usually adopted to connect MGCC with DGs, STS and grid dispatching central. Besides electrical variables, a cluster of environmental sensors, such as ambient and PV penal temperature, humidity, wind speed, and solar irradiance will supply necessary information for MGCC to achieve MG coordinated and optimized operation. Three typical functions of conventional MGCC will be discussed in details.

A. *Operation monitoring and remote control*

Given that the DG units in a MG are usually located dispersedly in practice, the remote monitoring and control are most useful functions of MGCC, such as DG operation modes transfer, STS on and off, controllable loads, operation status monitoring, system failure detection, and state-of-charge (SoC) estimation for energy storage systems (ESSs). A LabVIEW-based typical supervision system interface of MGCC is shown in Fig. 2 [11]. In addition, Supervisory Control And Data Acquisition (SCADA), mass data storage system and burst buffer technology will be also involved and considered for MGCC as the communication nodes or DGs units increased.



PCC Freq. 50.00 Hz

PCC Volt rms chart 220.06 V

VUF_chart 0.51 %

Vpcc_chart 220.04 Vrms

Vdc 843.27 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. 2. A LabVIEW-based typical supervision system interface of MGCC.

Because a MG usually has the capability to operate at grid-connecting mode when the grid utility is available, instead to transfer to the islanded mode in case of grid fault, the fault detection and seamless transition are necessary which not only depend on the control strategy, but also require the reliable communication links for the information exchange between STS and MGCC. Moreover, some advanced coordination control algorithms for power flow management can be also adopted by MGCC.

B. *Prediction and optimization*

Another indispensable function of MGCC is to optimize the MG operation point in order to increase economic benefits, improve system efficiency and to achieve more reliable and sustainable power supply. The time-varying parameters including wind speed, solar irradiance and electricity price can be used as the inputs of the optimization model. Moreover, in order to achieve global optimum solution, different time scale prediction algorithms should be considered. Given that the support vector machine (SVM) which has similar roots with neural networks will construct a hyperplane or set of hyperplanes in a high- or infinite-dimensional space, it can be used for regression and prediction [12]. Therefore, SVM is suitable for short term forecasting of different variables in MGCC, as shown in Fig. 3(a). It can be seen that the predicted one sample point ahead of PV power output exactly matches the practical PV power output.

The peak shaving performance will be achieved at the cost of increasing control complexity, because the ESSs are included and the SoC of ESSs need to be considered to prevent deep-discharge and over-charge. Together with time-varying electricity price, a multi-objective rolling optimization can be realized based on Particle Swarm Optimization (PSO) algorithm, in which the SoC limitation and profit are used as constrain and penalty function respectively. The weights of different factors can be adjusted to achieve different objective [13]. The optimized SoC is shown in Fig. 3(b). It means that ESS will be charged and discharged following the results of PSO.

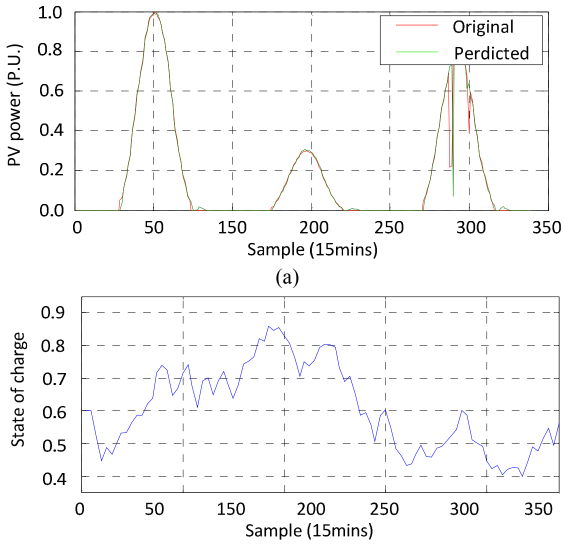


Fig. 3. Simulation results of prediction and optimization for a MG, (a) PV power prediction base on SVM, (b) Optimization results of SoC.

C. *Power quality management*

The power quality management (PQM) of MGCC can be categorized into two cases according to the MG operation mode. In the islanded mode, given that the high power quality is usually required by local sensitive loads, voltage magnitude and frequency restoration control loops are usually adopted in MGCC, by which the voltage magnitude and frequency deviations generated by droop controller at the primary level can be restored to the nominal values. Moreover, some advanced control strategies for such as reactive power sharing, and non-linear load sharing are implemented [14].

On the other hand, when a MG is connected to a distorted utility grid, PQM of MGCC can be used for improving the power quality of grid-connecting current through adopting an additional compensator in MGCC, as shown in Fig. 4. A voltage offset generated by the compensator is sent to DGs at the primary level to decrease the harmonic voltage difference between the MG output voltage and grid voltage, thereby the grid-connecting current of MG is purified, as shown in Fig. 5.

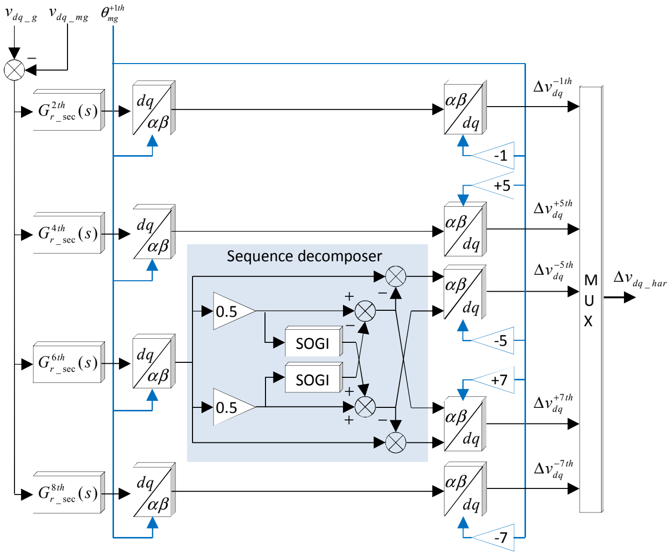


Fig. 4. Power quality compensator for grid-connecting current in secondary control of MGCC.

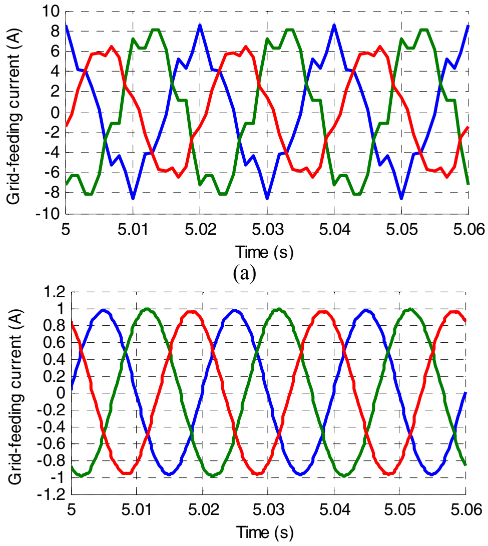


Fig. 5. Simulation results of grid-connecting current of a MG, (a) Current waveforms without compensator, (b) Current waveforms with a compensator.

III. INTEGRATION OF A HOME SCALE MG WITH INTERNET OF THING

The integration of IoT with a neighborhood or home-scaled MG involves the installation of smart sensors, smart meters, controllable switches/valves, communication links, gateways, etc. The data flow is collected from smart devices and smart meters in physical layer and then sent to up control layer to ensure appropriate central control. Therefore, one reasonable way for integrating IoT with a MG is to reorganize the original functions of MGCC according to IoT enabled capabilities. Therefore, an enhanced hierarchical control theory is proposed to facilitate system integration as shown in Fig. 6.

A. *Integration at the primary level*

Besides the original voltage/frequency establishment and power sharing function of VCIs, the integration at the primary level is more associated with connecting smart devices with different communication protocols. During the last decade, different standardization bodies have made many attempts to provide comprehensive solutions starting in different application-driven domains, including industrial production systems, smart homes, smart building solutions, eHealth applications. Therefore, the intermediate data structures and protocols have been proposed. For example, the Common Industrial Protocol (CIP), which can be adopted in several industrial networks includs Ethernet/IP, DeviceNet, CompoNet and ControlNet. CIP, supported by the Open DeviceNet Vendors Association (ODVA), is a media independent, connection-based, object-oriented protocol designed for automation applications. The abstract object model of CIP supports interoperability at the application level by its

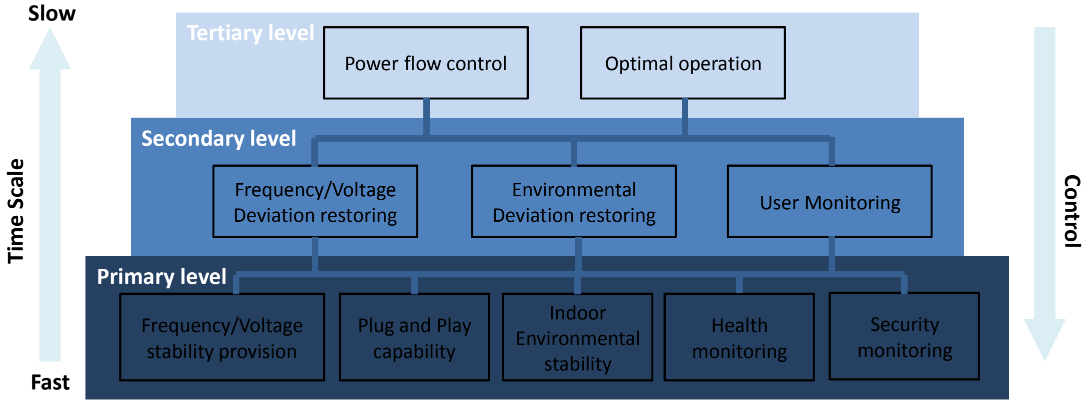


Fig. 6. Hierarchical control structure of IoT enabled home scale MG.

specification of classes, instances, and data types as defined in standard IEC 61131-3.

B. *Integration at the secondary level*

Since one of the objectives of IoT-enabled neighborhood and home scaled MG is to improve the users' experiences, comfort level and efficiency, indoor environmental deviation restoration controllers for temperature, humidity, ventilation and light lumen can be included in the original secondary control of MGCC. Its dynamic response time scale is from second to minute level which is similar to the frequency and voltage restoration loop [15]. At the same time, the environmental controller will regulate the indoor environment according to the commands sent from the optimization algorithm in the tertiary controller.

The health monitoring system aims to observe the measurements of users' biometric average data based on E-health sensors deployed at the primary level, including oxygen in blood (SpO2), airflow (breathing), body temperature, electrocardiogram (ECG), glucometer, galvanic skin response (GSR-sweating), blood pressure (sphygmomanometer). The collected data will be sent to the tertiary level for the further optimization operation.

C. *Integration at the tertiary level*

The control principle of active and reactive power flow management is similar to the original function in MGCC, which means the grid-connecting current is still controlled by the MGCC according to the commands sent from the up-layer dispatching center. In the IoT-renewable energy integrated home scaled system, the comfort level, outdoor weather, residents' habit, and real-time electricity price are needed to be taken into account to achieve the global optimal operation for efficiency enhancement and cost savings. This will increase the complexity of optimization algorithm. A reasonable solution is to establish a complete scenario list according to weather and time, in which the comfort and economic weight factors may alter in order to find the sub-global optimal operation point in each specific scenario with predicted data and electricity price real-timely. The controllable household appliances need to be scheduled in line with MGCC to fulfill demand response.

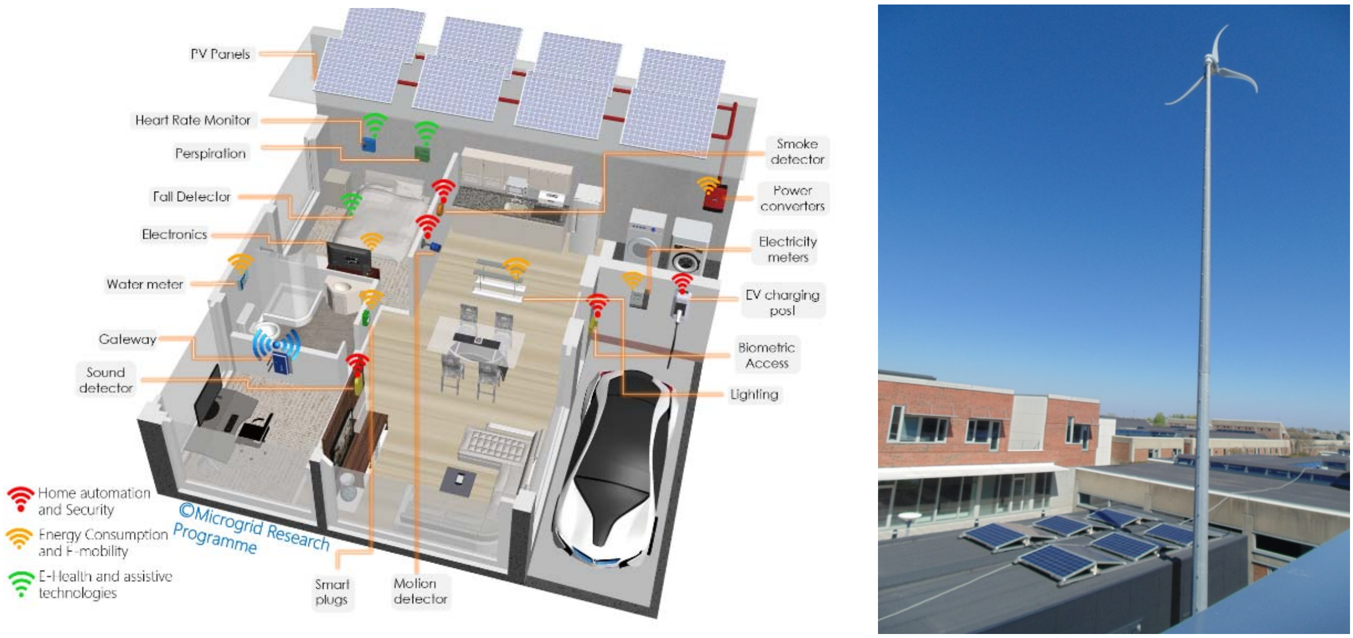
Furthermore, the value to a utility goes far beyond basic operational enhancements or efficiency, ultimately leading to major change to the business value for the utility, typically reflected in the form of new products and services that are outside of the traditional utility model and offering more value-added services to consumers.

IV. IOT MG DEMONSTRATION LABORATORY OF AAU

An IoT MG demonstration home laboratory is building in line with VICINITY project at Aalborg University, Denmark. The VICINITY project will build and demonstrate a platform linking various ecosystems providing "interoperability as a service" for infrastructures in the IoT. The approach is bottom-up, decentralized, user-centric and standards-based without relying on a single standard. The test laboratory aims to test and evaluate the technical feasibility and performance, thereby improving and increase safety, comfort, flexibility and efficiency.

The EMS in addition with the smart devices will allow the users to have full-access to the system´s information, and also provides the users the option to remotely control the system, as shown in Fig.7. Smart devices will work and provide valuable information to the EMS. The EMS monitors the generation and consumption, receives all the data from the appliances and applies the developed control strategies to fulfill the user requirements, while optimizing system performance. The configuration of IoT MG laboratory is shown in Fig.8 (a).

Fig.7. Smart home devices and EMS.



(a) (b)

Fig. 8. Configuration of IoT MG laboratory. (a) IoT MG laboratory Concept, (b) Installation of a Wind turbine and PV panels.

Fig. 9. Household appliances for testing in the IoT MG laboratory

Now, around 2 kWp PV panels and a 2 kW wind turbine are installed on the roof of IoT MG laboratory, as shown in Fig.8 (b). Electronic appliances, like laptops, cellphones, LED lights, home entertainment systems and white goods are already placed in the living area and kitchen area of the laboratory, as shown in Fig.9.

The project intends to integrate different types of renewable energy sources, energy storage systems and controllable loads. The power architecture will be properly designed and constructed to facilitate the integration of controllable devices and equipment. The lab will also incorporate with the district floor heating system and electrical heating system.

It is expected that the EMS together with the smart products will enhance the overall system performance and users experience, reaching new levels of flexibility, controllability, comfort and efficiency.

V. CONCLUSION

Different functions of conventional MG hierarchical control strategy is briefly reviewed in this paper, and then an enhanced hierarchical control strategy of IoT enabled home scale MG with renewable energy resources is proposed to facilitate the proper design and smooth integration of IoT with MG EMS system. Different functions are defined for control levels according to the response time scale. An IoT MG demonstration laboratory in AAU is introduced.

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