A Survey of Control Strategies Applied in Worldwide Microgrid Projects

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Abstract – A growing amount of distributed energy resources are integrated into the medium and low voltage level. This does not only bring a series of benefits, but also causes severe problems in power systems. The technologies of microgrids, including their architecture, distributed generation, storage, and control schemes, are widely researched across the globe, because of the increasing requirement of power quality and reliability and security of energy systems. This paper, focused on the technologies of operation systems and available control approaches, illustrates the review of diverse research projects and activities of microgrids around the world. It presents existing microgrid projects in Europe, America and Asia. It also illustrates the current state of control strategies and the correlation between volatile distributed generation and storage systems, and between loads and storage systems.

1. Introduction

To improve the reliability and security of electrical power systems and the power quality, as well as to decrease greenhouse gas emissions, the concept of microgrids (MG) has been introduced. The MG is a decentralized electricity network comprising distributed generators (DG), such as wind, photovoltaic (PV), biomass and diesel generation, local loads, and energy storage systems that can operate in grid-connected or island mode.

The most compelling characteristic of a MG is that it has the possibility to separate itself from the utility network when faults occur either in the overall grid or in the local network, and when the fault is cleared, the MG can reconnect to the utility grid. Distributed power generators are typically located closer to the side of consumers than centralized power plants. The energy then can be generated and stored near the consumption points, which can improve the stability and reduce the losses caused by large power lines [1].

2. State-of-the-art

While an increasing amount of distributed energy resources (DERs), i.e. decentralized generation capacity and decentralized energy storage, are integrated into overall grids, it is important to develop a safe and efficient control technique for the MGs operation. The control strategies of MGs face a series of challenges. This section introduces some existing control strategies.

2.1 Centralized control

A hierarchical control structure consists of a MG central controller (MGCC), which controls all the components of the MG, and local controllers (LC). The local controllers provide the locally measured data to the MGCC and receive instructions from the MGCC, such as setting points of voltage, active and reactive power. This centralized control concept was applied in large utility power systems for years to control the frequency of a large-area electrical network and has been applied to MGs for voltage and frequency restoration in the recent years [2]. An example of hierarchical control architecture is shown on the upper-left side in Figure 1.

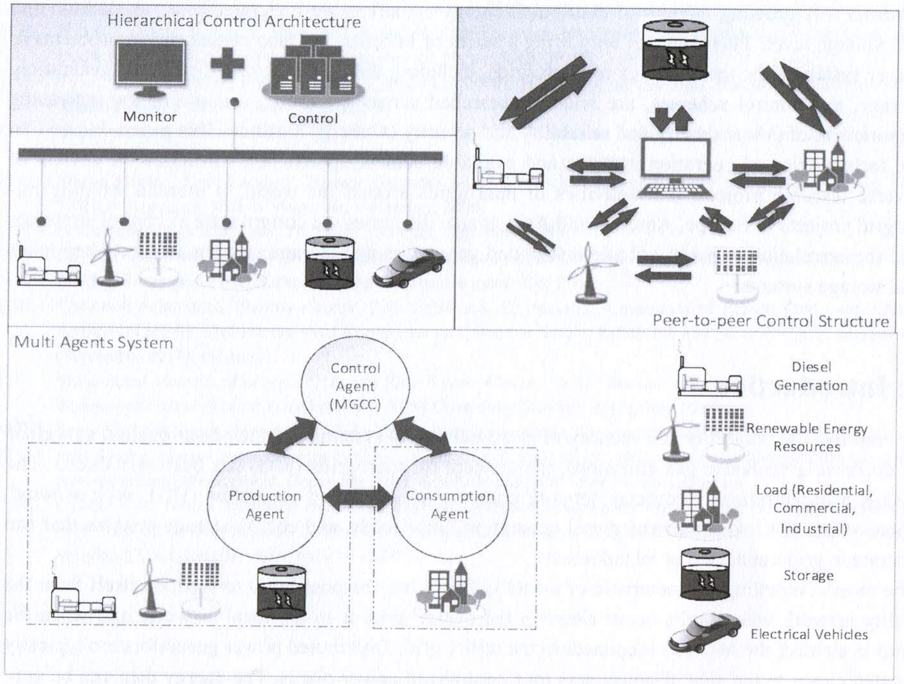

Figure 1. Hierarchical Architecture (Upper Left), Decentralized Control Structure (Upper Right) and the MAS (Bottom)

2.2 Decentralized control

Peer-to-peer control architecture was proposed by Piagi and Lasseter in [3] for the "plug and play" MG. In decentralized control, each microsource is equivalent, and no single component, such as the central controller or the central storage unit, is essential for the operation of the MG. A central controller may exist for the purpose of monitoring the system, but its presence is not necessary for the peer devices to operate. The MG can continue operating while any generator is connected or disconnected, if the energy requirements are still satisfied [4]. The upper-right picture in Figure 1 shows a peer-to-peer control structure.

2.3 Multi agents System (MAS)

A multi agents system [5] is a compromised structure between the centralized control and entirely decentralized control structure. To some extent, agents, which can make decisions and commands without the MGCC, have autonomy, and they are able to communicate with each other to exchange information. Also, there is an agent acting as the MGCC in the MAS, coordinating local tasks and recording power exchanges between the agents periodically. The structure of the MAS is shown at the bottom in Figure 1.

3. Overview of Microgrid Projects

With growing interest in MGs, plenty of projects regarding the operation of MGs have been carried out worldwide. In this section, some surveyed MG projects are presented, and some of their characteristic features are compared.

3.1 Microgrid Projects in EU

3.1.1 Isle of Eigg, Scotland

The Isle of Eigg near the Scottish coast, with a population of about 100, was without grid electricity before 2008. In 2004, a hybrid renewable energy system was proposed and completed in 2008. The MG system comprises a 30 kWp PV system, hydro plants of 112kW, four 6kW wind turbines, and diesel backup capacity of 160 kW. It now provides power limited to 5 kW for households and 10 kW of electricity for businesses 24 hours each day. The decentralized control approach is applied in the system. The whole system can be automatically controlled by means of calculating the state of charge (SOC) of the batteries and controlling the power via the grid frequency [6]. This MG is an example of a MG that is constantly operated in the island mode without any external grid.

3.1.2 CESI RICERCA DER test microgrid, Italy

The pilot microgrid is connected to the medium voltage (MV) grid through an 800 kVA transformer. It includes various DG sources, energy storage systems, and several controllable loads. A Supervision and Data Acquisition System (SCADA), which provides remote monitoring and control of all the DERs and the controllable loads, is used for centralized control. [7]. This MG structure is an example of a MG test bed featuring several DER technologies.

3.1.3 The virtual microgrid in Eberstalzell

The virtual MG in Eberstalzell, a municipality located in Upper Austria, is investigated in the ongoing research project "SORGLOS" led by the Institute of Energy System and Electrical Drives, TU

Wien. While the project "SORGLOS" investigates the possibility and requirements of MG operation, it is currently not planned to actually operate the grid in island mode.
Eberstalzell is a municipality located in Upper Austria. The MG is connected to a 20 kV MV grid via one 630 kVA transformer. PV systems with total peak output of nearly 300 kWp are installed in the network. Due to the high volatility of PV systems in the virtual MG system, therefore a backup diesel generator and storage would be required. The maximum load demand is about 450 kW, and the annual energy consumption of this region is approximately 1,350 MWh. The MAS will be implemented in the virtual MG system. Technologies, like Power Line Communication (PLC), radio and cable & wireless communication, are considered to be used for the communication system.

3.1.4 Other projects in EU

Diverse MG projects for control optimization of operation are under development in EU, for instance, the commercial feeder of LABEIN located in Spain [8] with a certain level of ability to reconfigure will be used to test out both centralized and decentralized control schemes. MG systems with central battery storage systems, like flywheel, normally use centralized control architecture, for example, the University of Manchester Microgrid/Flywheel energy storage laboratory prototype, DeMoTec Microgrid, Germany [9], the MG in Bronsbergen Holiday Park, Zutphen, Netherlands [7], and a benchmark low voltage (LV) microgrid network [10]. There are also a large size MG on Bornholm island [11, 12] and EDP Frielas feeder, Portugal, only operating one microturbine with a capacity in excess of the maximum load demand [13] utilizing the centralized control strategy.
In medium and large MG systems, like the residential MG, with a ring configuration, of Am Steinweg in Stutensee, Germany [7], decentralized control approach was planned.
The MAS is implemented in a residential MG in Mannheim-Wallstadt, Germany [14, 15], for controlling the loads, monitoring the production and storage systems, as well as in the laboratory-scale test microgrid in the National Technical University of Athens, Greece [7], and the rural off-grid on Kythnos Island, Greece [16].

3.2 Microgrid Projects in America

3.2.1 Santa Rita Jail CERTS Microgrid Demonstration, USA

Santa Rita Jail is the fifth largest county jail of the USA, requiring around 3 MW of reliable and secure electricity 24 hours each day. The MG system, with high penetration of DGs, a storage system, and a power factor correcting capacitor bank, is a demonstration of CERTS microgrid concepts. In this MG system, a localized control scheme is implemented for each component [17]. Another demonstration of the CERTS testbed is CERTS American Electrical Power. [18].

3.2.2 Joint Base Pearl Harbor Hickam, USA

The MG system of Joint Base Pearl Harbor Hickam, USA, is developed for military application. The most important characteristic of a military MG, unlike other applications, is the energy security in comparison to the economical aspect and energy efficiency. This MG, includes two electrically isolated generators, which ensures that the system can be operated without renewable resources, serves critical loads. A cyber-secure control system is used to achieve the seamless transition from or to the utility network. More military microgrid projects can also be found in [19, 20].

3.2.3 Other projects in the USA

The MG project of Allegheny Power, West Virginia Super Circuit intends to demonstrate the reliability benefits of the dynamic feeder reconfiguration across two adjacent feeders. The MAS and advanced wireless communication will be applied in the system [21].
Likewise in Europe, MG projects in the USA with battery energy storage systems at substations, such as the microgrid in the University of California, San Diego [22], SDG&E Borrego Springs Microgrid Demonstration Project [23] and Maui Smart Grid Project, Hawaii [24], and the Illinois Institute of Technology Perfect Power System Prototype equipped with Uninterruptible Power Supply (UPS) flywheels and batteries [25] use the centralized control architecture.

3.2.4 Research Projects in Canada

The MG projects in Canada are focused on the MV level and mostly implement hydro generation. The Hydro Boston Bar MG system and Hydro-Québec distribution system are prepared for planned islanding operation. Centralized control is used in the system [26]. The MG in the village of Hartley Bay, British Columbia, is an off-grid MG utilizing the centralized control technology [27].

3.3 Microgrid Projects in Asia

3.3.1 MG projects in Japan

Japan is the leader in MG demonstration projects. The New Energy & Industrial Technology Development Organization (NEDO) has started four demonstrations in 2003, namely, Hachinohe MG, Aichi MG, Kyotango MG and Sendai MG [7]. NEDO projects have a control target to maintain the operation of network between production and consumption over a certain period when errors occur. Meanwhile, many private MG projects, like Shimizu Corporation MG, Tokyo Gas Yokohama Techno Station MG, and Roppongi Hills, are carried out. From 2010, NEDO supported their first overseas Los Alamos MG project, and Albuquerque Building MG conducted in the USA [28] to research advanced technologies of DERs and energy security. All the listed MG projects in Japan with high penetration of DERs and a big amount of energy storage systems utilize the centralized control approach.

3.3.2 MG projects in China

The research of MGs in China, focusing on bulk DERs interconnection with the power system and the influence on the utility network, started around 2004. The MG research includes from laboratory-scale MG, like Microgrid testbed in Hefei University of Technology (HFUT), to medium and large scale MG, such as Tianjin eco-city Smart Grid Demonstration [29] and Turpan New District Sustainable Development City Project [30]. Since the foundation of microgrid technology in China is weak, it needs a long process to realize commercial operation, especially cooperating with national policies, laws and regulations.

4. Comparison of MG projects

The comparison between the power of maximum load demand and total installed capacity of DG sources in logarithm is presented on the left side in Figure 2. The surveyed MGs can be classified into three groups according to the maximum load demand as the following.

- Small Scale Microgrids: 1W < P_{load} < 30 kW
- Medium Scale Microgrids: 30 kW < P_{load} < 1 MW
- Large Scale Microgrids: P_{load} > 1 MW

From the picture, the majority of MGs have enough installed capacity of DGs for islanding without load shedding and the rest needs to be supported by the utility network for covering the full load. Among all the investigated MG projects, the installed capacity of the DG sources cooperated with the backup diesel generation and batteries are sufficient for the demand of consumers in the off-grid MG projects. Most of on-grid projects are able to use the DG sources to support their local loads, and some exceptions need to get the energy supply from the utility grid.

Existing control techniques have offered a lot of possibilities for the operation of MGs. Parameters like power quality and stability, installed storage capacity, requirement of a communication infrastructure, and types of installed distributed generators affect the choice of control strategies. The right picture in Figure 2 shows the percentage of the utilization of applied control strategies in the surveyed MG projects.

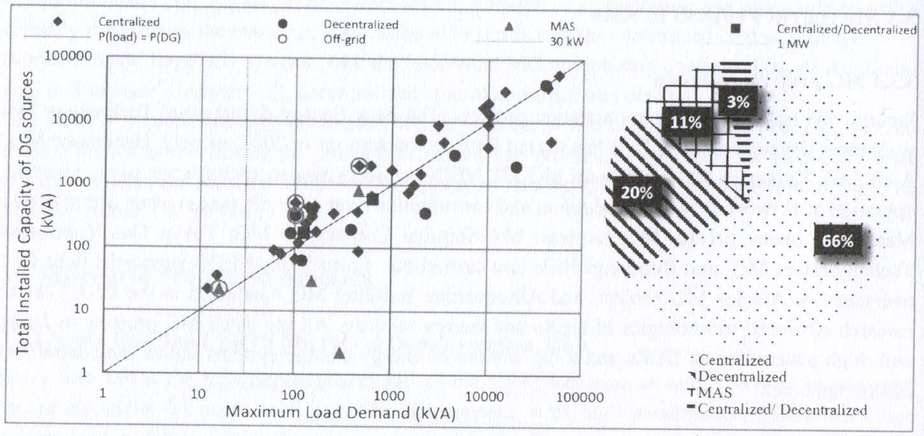

Figure 2. Comparison between the power of maximum load demand and total installed capacity of DG sources in logarithm (Left) and applied control strategies in the surveyed MG projects (Right) [Self-created]

The centralized control approach is widely adopted, when there is a central storage system in the MG, from the small scale MGs to the large scale MGs. The MAS is implemented mostly in the small and medium scale MGs, as long as there are controllable loads and controllable generation. The decentralized control technology is applied in medium and large MGs. For medium and large systems with complex grid structure, utilizing the decentralized control strategy is easy to achieve the plug-and-play function of MGs and would not influence architecture and the communication structure of energy systems. There are also test fields, which have the ability to reconfigure, allowing to test out both centralized and decentralized control strategies for their systems.

The analysis of the correlation between volatile DG sources, like PV and wind power plants, and the storage capacity is also made based on the available data of the survey. The more volatile DG sources are installed, the larger the capacities of the storage systems are used, as it can be seen in Figure 3. Most storage can be fully charged within 6 hours and provide energy to the customers for at least one hour. In case of failure during the period, which is lack of volatile DG sources, those MGs would only last for a blackout of several hours, but surely not days.

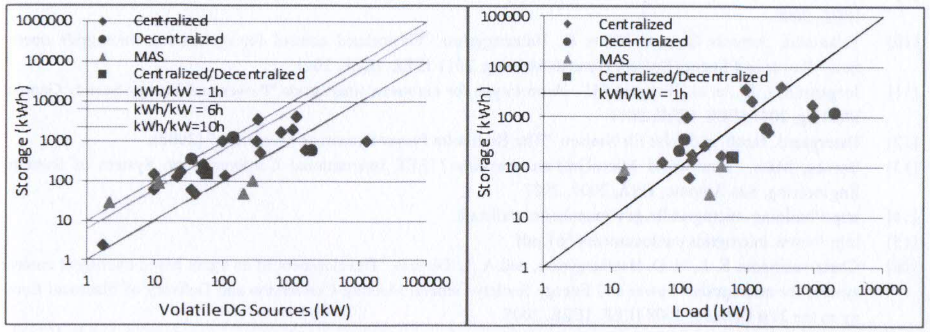

Figure 3. The correlation between capacity of installed volatile DG sources and storage (Left), the correlation between load demand and storage (Right) [Self-created]

5. Conclusions and Findings

Although there are differences among microgrid control structures, they all intend to ensure the reliability and security of networks when a plenty of DGs are integrated into utility grids. According to the surveyed MG projects, centralized control is currently dominant. In off-grid MGs, total installed capacity of DG sources usually exceeds maximum load demand, while in around 38% of on-grid MGs, load shedding would be necessary at a situation of reaching maximum load demand and depleted storage. Storage capacity rating related to installed volatile DG sources is usually between 1 and 10 kWh/kW. The data of MGs is collected and made into a summary table and is allowed for further research applications. Due to the page limit, it cannot be shown in the paper.

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