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Recent advancements on the development of microgrids

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Abstract With high penetration of distributed energy resources (DERs) into power systems, microgrid has showed great advantages of enabling efficient and reliable operation of distribution grids with high flexibilities and robustness. This paper discusses the recent advancements of microgrid development with particular focus on different dispatch, and control schemes using distributed communication technologies, load management technology, and protection strategies applied in a microgrid environment. It also describes typical R&D activities and projects worldwide in e.g. European Union (EU), Japan and the United States (US). Based on comprehensive review, it is convinced to conclude that microgrids could provide electricity supply with higher efficiency, reliability and quality to regional customers and will make contributions to smart grids development at large.

Keywords Microgrids, Microgrid structure, Multi-agent, UFLS, Controllable load, Protection

1 Introduction

As both energy demand and environment concern increase dramatically in the past decade, centralized electricity supply through long transmission distance at a high voltage level may not be the optimal solution to fulfill the need of further development, particularly for remote areas without access to main grids. With renewable energy sources such as wind power and solar energy integrated into power system that appears mostly as distributed generation systems (DGs) [1], the operation reliability of power grid has become an outstanding issue. DGs rely on small scale of generation units to meet local demand and to support economic operation of main grid, which promotes renewable and clean electricity while reducing transmission loss.

In order to ensure seamless integration of DGs into power system and improve reliability and efficiency of power delivery, the concept of microgrids is proposed. Microgrids are small scale of power grids operating at a low voltage level formed by local generations, storage device and controllable loads [2]. Energy transformation in microgrids relies on power electronic devices with essential control functions, providing electricity and thermal energy to local regions. Microgrids can be in grid-connected or islanded modes. Under normal conditions, they are connected to medium voltage grid and could exchange power with the main grid. In case of grid maintenance or severe disturbances occurring in the upstream networks, they should be capable of disconnecting from the main grid and remain self-sufficient operation [3].

Microgrids are expected to achieve economic and environmental benefits through utilizing automation technologies and renewable energies. Moreover, they may promote the security and sustainability for regional electricity supply through flexible islanding operation in events of grid disturbances or main grid maintenance based on many DGs [4].

Driven by the environmental problem and energy crisis, different kinds of renewable energies have gained development in power systems and provide great opportunities

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to the rapid expansion of microgrids. Although there exist many challenges, such as establishing standards for microgrids design and construction, great R&D efforts have been made in the US, EU and around world. Examples of the project are initiated by US department of energy [5].

Microgrid is a power grid of small scale which may make power system a revolutionary architecture. Many recent events of catastrophic blackouts in main power grid have raised concerns for more robust and reliable structures like microgrids integrated into main system, which could guarantee reliable and economic power supply to local regions. In addition, the potential of facilitating quick restoration after system blackouts through microgrids is also worthy of further investigation. New technology like price-responsive load control makes it possible for consumers to participate in competitive market, which will reduce energy cost and obtain economic benefits.

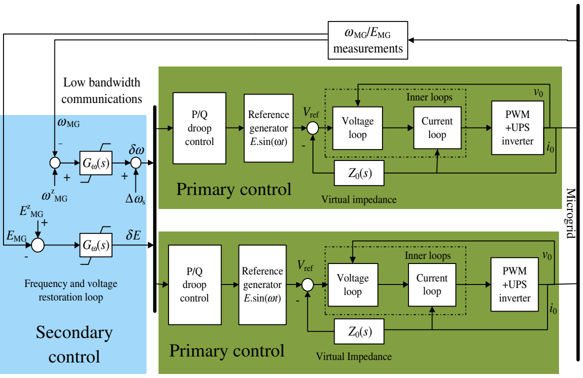
In this paper, we first discuss different control and dispatch schemes, load response technology, and protection strategies for microgrid applications; Secondly, the latest R&D activities in EU, Japan and America are presented.

2 Technologies and applications in microgrids

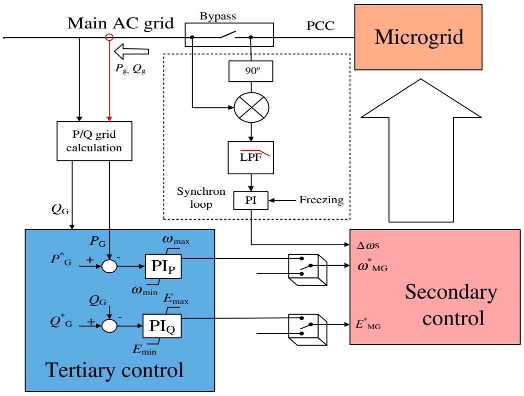
2.1 Control and dispatch strategies in microgrids

The integration of diverse DERs into power grid boosted development of microgrids. There are various control schemes which have been studied in the past decades, including centralized, decentralized and hierarchical structures [6–8]. The control schemes should guarantee flexible and secure transition between grid-connected and autonomous modes. A control center in centralized scheme plays a key role in managing all the local controllers, but once it breaks down, the consequence may be the loss of controllability to the entire microgrid. On the contrary, no control center is needed in the decentralized scheme, in which various local control techniques have been applied. The hierarchical scheme combines the above two types, which would function more effectively due to bi-directional power flow between microgrids and main power grid.

Figure 1(a) and (b) [9] show that hierarchical scheme consists of three control levels. The key issues for the control of microgrid include control of frequency and voltage, which is usually implemented into a cascaded manner with three levels. The primary control focuses on the parts of local inverter control, deploying frequency and voltage droop control method, which is the inner control of DG units. The secondary control aims at restoring synchronies implemented by centralized control center in microgrid, to eliminate the deviation of frequency and voltage value caused by virtual impedance which shares the fundamental and harmonic elements of load current among distributed generators in the primary control. The deviations can be caused by e.g. changes of load or generation in practice. In order to keep microgrid stay in grid-connected mode, the frequency and voltage reference value for secondary control should be synchronized with that of the connected main grid. The tertiary control can be designed to regulate active and reactive power flow with adjusting frequency and voltage respectively after microgrid is staying synchronized with main power grid in gird-connected mode [9]. As hierarchical scheme is more effective and workable, researchers have developed many advanced techniques and methods under such scheme [10, 11], e.g. multi-agent techniques for the implementation of the secondary control [11].



(a) Primary and secondary control level in hierarchical scheme of microgrid



(b) Secondary and tertiary control level in hierarchical scheme of microgrid

Fig. 1 Hierarchical Structure of microgrid

Based on the hierarchical control scheme, a centralized load frequency control that is used to maintain the frequency value at reference point and an economic dispatch algorithm deployed to obtain power set-point according to economic criteria have been integrated into the second control level in [12]. With this approach, optimal dispatch

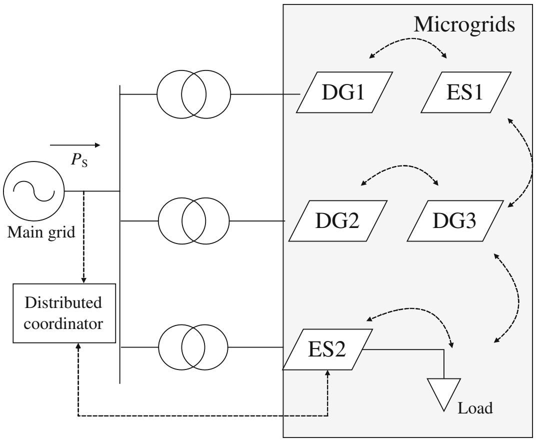


Fig. 2 Distributed dispatch scheme of microgrid

solution can be obtained adaptively and the operation reliability of power grid would be enhanced.

In above hierarchical structure, it is necessary to have a center to accomplish optimal dispatch. However, after various distributed generation (DG) and storage devices are merged in microgrid, it is difficult and uneconomical for the dispatch and control center to collect the information from every DG and storage device. In order to make the dispatch more flexible and economic, a new distributed scheme for microgrid optimal dispatch is proposed in [13]. In Fig. 2, based on primal-dual sub-gradient algorithm and multi-agent system (MAS) model, each DER as a decision-making agent only needs to exchange limited information with its adjacent ones without directly sharing its information with dispatch center. Each separate agent in MAS can respond to the change of current status and has the ability to schedule its own activities to fulfill local goals [14]. Although the dispatch center is no longer needed, neighborhood communication could not realize the overall optimal goal. Thus, the coordinator showed in Fig. 2 is employed to organize the information from the nearest DG and the joint of microgrid with power system, enabling the optimization for the whole system. Utilization of MAS through neighborhood communications makes it possible to leave out dispatch center and to realize plug-and-play function which is robust and flexible. Any DG or energy storage suffering from sudden breakout will not affect normal operation of the rest parts of a microgrid, thus enhancing the reliability of electricity supply to local regions.

2.2 Load management in microgrids

Traditional methods of balancing supply and demand are limited to the regulation of generator output in response to the change of load. Due to the fact that most DERs could not be dispatched, microgrids with high penetration of DERs have to employ different techniques from the traditional ones. They are easily subjected to frequency deflections especially when disconnected from the main power grid. Due to severe imbalance between generation and consumption, microgrids may be confronted with collapse. Therefore, load participation in regulation can greatly improve the reliability. Under-frequency load shedding scheme (UFLS) could play an important role via shedding some selected load in maintaining operation and security. Most UFLS is applied on the basis of initial rate of change of frequency or changes of voltage and frequency [15, 16]. One important procedure of UFLS is to determine which load to shed. Two approaches including Dynamic Time Warping and Hidden Markor Models are compared in [17]. Subsequently, as technologies in communication improve, a centralized decision-making and distributed revising UFLS is proposed in [18] using information sharing technology, making up for the weakness of accuracy in load shedding.

The controllable load research in microgrid by Electric Reliability Technology Solutions (CERTS) indicates a high possibility to treat the load as a resource [19]. In summer 2006, CERTS initially demonstrated that making use of controllable demand as spinning reserve could improve system reliability. Later studies further indicate responsive loads as spinning reserves meet requirements of power system operation [20, 21]. CERTS also researched into Price-Responsive Load Program that enabled customers to participate in the competitive price market. Demand side management involved in electricity market can reduce the peak consumption and increase economic benefits [22], which has significant impact on electricity market operation.

2.3 Protection strategies in microgrids

The flexibility to transfer between grid-connected and islanded modes enables microgrids to provide high reliability and power quality. However, it brings about challenges in protection issues. In conventional power grid overcurrent protection might be an effective strategy by detecting large fault current. But microgrids are integrated with mostly inverter interfaced DGs whose fault currents are limited especially when they disconnect from main power grid. Therefore it is necessary to deploy different strategies in two operating conditions.

Protection schemes should have ability to detect whether fault occurs in main power grid or microgrids when in the grid-connected mode. If overcurrent protection scheme is adopted, high selectivity and sensitivity could be important requirements for this scheme improvement [23]. Calculation of impedance of system and microgrid by means of voltage and current fault component in an automatic overcurrent protection algorithm is proposed in [24].

In the islanded mode, two important voltage protection approaches are suggested in [25]. Abc-dq transformation protection makes use of reflected disturbed dq values to track the information of fault. And another approach is to detect the terminal voltage threshold of converters under harmonic distortions. But voltage protection schemes are recommended to be used as back-up ones because sometimes dynamic loads would fail the accuracy of voltage detection. An effective protection scheme for islanded mode deploys digital relays based on differential protection [26], which could also be implemented in grid-connected condition.

3 Research and development activities of microgrid

Since microgrid system is more flexible and controllable than conventional distribution networks, it is gaining increasing attention and has vast potential of further development in the future. Thus, various research and development activities are taking place around world.

3.1 Microgrids project in EU

With great advantage in renewable energy sources, EU has carried out two major projects on microgrids, including Microgrids Project and More Microgrids Project, in order to enhance the penetration of micro-sources and to extend more valuable design for microgrids improvement.

One pilot 1-phase microgrid in Greece is Kythnos Microgrid constructed on the Kythnos island, providing electricity power to 12 houses in a small valley [27]. This microgrid is designed to connect with other part grid of the island. An integrated solar-storage generation consisting of 10 kWp of photovoltaic, 53 kWh battery banks and a diesel Genset with 5 kVA output make up the generation system. Three Sunny-island battery inverters which could operate in both droop mode and isochronous are connected in parallel to form single-phase. This project aims at research and tests on centralized and decentralized control schemes. Moreover, communication protocols as one important part for effective operation are studied as well. Other new attempts such as integration of AC wind turbine and utilization of load management are reported to be involved, which would make the system operate more strongly.

As a low-voltage microgrid which is connected to a medium-voltage grid via an 800 kVA transformer, CESI RICERCA DER Test Facility (DER-TF) is another typical engineering demonstration. Formed by various types of generation including conventional and renewable ones, controllable loads and storage devices, DER-TF could deliver up to 350 kW power to the main power system. The construction of DER-TF targets on one hand at getting diverse grid topologies by changing the configuration of DERs in microgrid. On the other hand, it is an effective platform as Europe Union has put an emphasis on the implementation of new communication technologies in the microgrid operation.

3.2 Microgrids activity in Japan

Located on the campus of Tohoku Fukushi University in Sendai City in Tohoku district in Japan to supply power to the facilities, Sendai Microgrid was implemented by New Energy and Industrial Technology Development Organization between 2004 and 2008. It contains several sources formed by a photovoltaic array, a phosphoric acid fuel cell and two gas engines, in order to be able to supply different levels of power quality. This microgrid project showed its effectiveness especially in the destructive earthquake in Tohoku district on March 11, 2011. A three-day outage occurred in the area surrounding the Sendai Microgrid while the microgrid could still operate to supply power to its service, which had proved advantage in stability and robustness of microgrid construction in severe cases.

3.3 Microgrids project in America

US Department of Energy has engaged in various research activities in microgrids. CERTS represent their endeavor to promote an intelligent network which can operate automatically. CERTS Microgrid concept is built on the peer-to-peer and plug-and-play strategies, which could be demonstrated in test bed with American Electric Power. Figure 3 illustrates the Schematic of the CERTS Microgrid [29].

The test bed is designed consisting of three sources motivated by natural gas based on converters, different type of loads and surge module as storage device. It is under

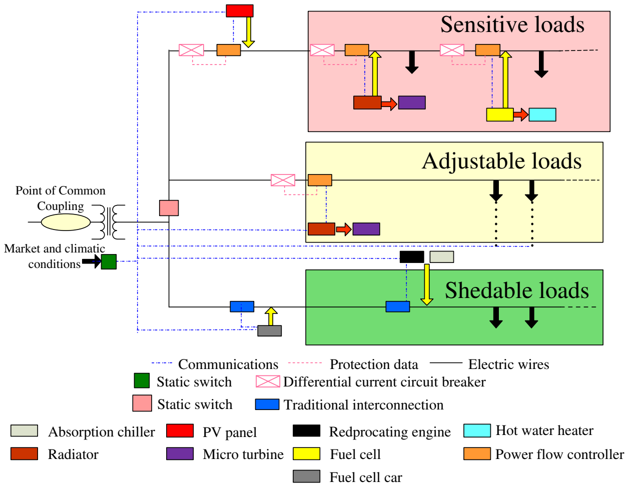


Fig. 3 Schematic of the CERTS Microgrid

automatic control. The concept tested aims at three goals [28]: first to find out a way to achieve seamless transition between grid-connected and autonomous conditions; second to get a method for protection without dependence on high fault currents; third to obtain an approach to guarantee frequency and voltage stability under autonomous mode without requirement of high-speed communication.

Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS), a three-phase multi-agency project, is designed to lower the risks of power outages with supplying more robust and secure power to critical loads. It deploys Sandia’s Energy Surety Microgrid methodology. The SPIDERS contains three separate microgrid installations: the first one is the circuit-level microgrid on Hickam Air Force Base in Hawaii; then the second is larger which incorporate a large photovoltaic system and vehicle to power grid storage at Fort Carson in Colorado; the last one supplies power with significant renewable energy and storage to Camp Smith in Hawaii [30].

4 Conclusion

With power electronic technologies and other advanced techniques, DERs have possibilities to be integrated into power systems via implementation of microgrids.

In order to obtain comprehensive understanding of microgrid operation and to suggest improvements in the future work, this article has discussed about control and dispatch strategies, load management, and protection schemes in microgrids. It also gives descriptions of R&D activities in the EU, Japan and America in this field. It has been clear that microgrids will have great potentials in changing the way to cope with demand increase and to improve flexibility and reliability of power system operation.

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