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Distributed Energy Resources in Grid Interactive AC Microgrids

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Abstract—Increased penetration of distributed energy resources (DER) and large-scale deployment of renewable energy sources are challenging the entire architecture of traditional power system. Microgrid, featuring higher flexibility and reliability, becomes an attractive candidate for the configuration of future electrical power system. This paper gives an overview of DER units in the grid interactive ac microgrid. The options in structures and control methods of power electronics interfaced DER units are described. Instantaneous load sharing strategies among DER units in the islanded microgrid operations are discussed pointing out the importance of closed loop system output impedance for the power electronics interfaced DER units.

Index Terms—AC microgrids, electronically-coupled DER unit, instantaneous load sharing

I. INTRODUCTION

Liberalized electricity market, environmental concerns with greenhouse gas emissions, energy efficiency, and diversified energy sources constitute the most important driving forces for the proliferation of distributed energy resource (DER) units in the electricity system. With the growing deployment of DER units, especially small-scale combined heat and power (CHP) plants and renewable energy sources (RES) based distributed generation (DG) units, distribution grids can no longer be considered as passive networks. The architecture of the future electric power system must be redesigned to undertake the increasingly complex operation. Three conceptual models are envisioned: Microgrids, Active Networks supported by ICT and the ‘Internet’ model [1], [2].

Microgrids paradigm connects multiple customers to multiple DER units including DG and distributed storage (DS) units, and can form an intentional or non-intentional energetic island in the distribution network. Within the microgrid, customers and DERs not only can operate in parallel with the mains grid, but also requires a smooth transition to the intentional or non-intentional islanding mode during abnormal conditions. In contrast to the conventional distribution network, this kind of grid structure has much more flexibilities on the control of DER units, consequently offer potential benefits of higher power supply efficiency through integrating combined heat and power (CHP) plants, better power quality, higher reliability of the electric service, and dispatchable local power. The extensive research on microgrids and the number of worldwide demonstration projects, e.g. CERTS microgrid in USA, EU More microgrid in

Europe, NEDO microgrid in Japan, and Hydro-Quebec microgrid in Canada, have shown problems and solutions in the microgrid field [3]–[5].

In recent years, power electronics technology has undergone a rapid evolution due to the fast development of power semiconductors, improving the transient response of the power stage, and digital signal processors (DSP) decreasing the processing time, being able to increase the complexity of the control algorithms. The intensive use of power electronics converters not only offers cost effective and flexible DER interfaces to the network but also enable the microgrid to properly control and manage the power and energy flows [6], [7].

This paper starts with an overview of miscellaneous system topologies of DER units. This is followed by a description of the operating conditions and corresponding control schemes for the power electronics interfaced DER units. Then a discussion of instantaneous load sharing strategies among DER units is provided. Finally the conclusions are presented.

II. SYSTEM TOPOLOGIES OF DER Units

Fig.1 illustrates the configuration of a grid interactive ac microgrid. Generally speaking, a microgrid consists of a static transfer switch (STS), single or multiple DER units, distributed critical and noncritical loads, a power management system, and protection devices. In the microgrids, DER units can be distinguished by their interface characteristic as the conventional rotary DER units and electronically-coupled DER units [8].

A. Conventional Rotary DER Units

Conventional rotary DER units are interfaced directly through the rotating generators, which comprises fixed speed wind turbines, reciprocating machines, and small hydro engines. Fig. 2 shows the structure of the “Danish Concept” fixed speed wind turbine system, which is widely used for power ratings up to 2.3 MW. It consists of a squirrel-cage induction generator (SCIG), connected via a transformer to the grid [6].

B. Electronically-Coupled DER Units

In contrast, the electronically-coupled DER units utilize the power electronics converters to match their characteristics and the requirements of grid conditions. The electronically-coupled DER units mainly involve the variable speed wind turbines and other RES based DG units, microturbines, internal combustion engines (ICE), and DS units. Fig. 3 shows the structure of variable speed

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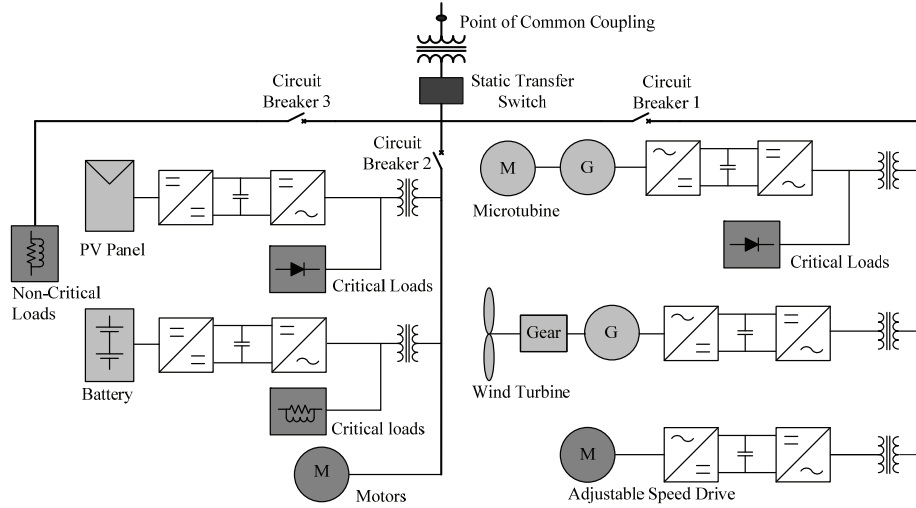


Fig. 1. The configuration of a grid interactive ac microgrid system.

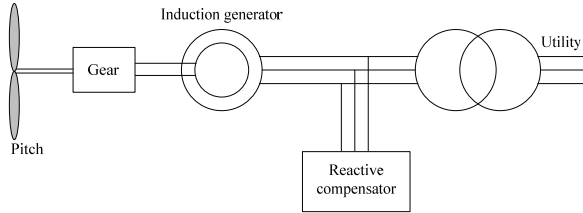


Fig. 2. The structure of fixed speed wind turbine system.

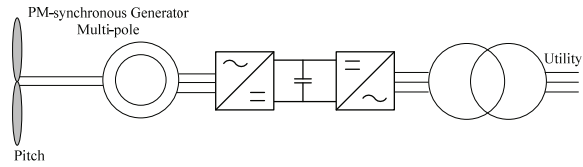


Fig. 3. The structure of variable speed wind turbine system.

multi-pole permanent magnet synchronous generator (PMSG) wind turbine system [11].

C. Topologies of Electronically-Coupled DER units

Since the prime energy sources can produce either dc or ac voltages, the general topologies of electronically-coupled DER units consequently fall into two categories. For wind turbine, ICE, and microturbine generation systems the output is either high frequency ac or line frequency ac voltages, whereas the photovoltaic (PV) and fuel cell (FC) power systems produce dc voltages. The output voltages from those energy resources are then converted by means of a power electronics converter to the voltages that are compatible to the microgrid. Hence, the types of output power from the prime energy sources determine the topologies of power electronics interfaces.

Furthermore, the expected operational scenario of a microgrid also imposes limitations when choosing the appropriate power stage topology. For example, in the CERTS microgrid, the plug-and-play feature requires that all of DG units have a unified dynamic performance regardless of prime energy source type [9]. This implies that an energy storage module with a bidirectional converter must be included within each DG unit. Fig. 4 shows a wind turbine integrated with a battery energy

storage system. The bidirectional converter controls the operation of the storage unit based on the dynamics of the prime energy source [10]. Therefore the structures of electronically-coupled DER units are not only determined by the types of prime energy sources but also dependent on the load requirements, microgrid configurations and the expected operations.

A wide variety of power converter topologies have been proposed for DER units. These power converters are classified into different categories with respect to the use of isolation transformers, the number of power processing stages, and utility connection [11]-[19].

For PV and FC power systems, a single-stage power conversion system features the simplest configuration, whereas is compromised by the bulky and expensive low frequency transformer. Fig. 5 shows a three-stage single-stage power conversion system [12]. Recently proposed Z-source converters [13] and the popular neutral point clamped (NPC) multilevel converters [14] offer alternative solutions for the transformerless single-stage power conversion system. On the other hand, multiple-stage power conversion system is widely used. Fig. 6 shows the commonly used two-stage topology. It consists of a dc-dc converter with or without a high frequency galvanic isolation transformer and a dc-ac converter. The dc-dc converter performs maximum power point tracking (MPPT) functionality to capture the maximum power from the energy sources, while the dc-ac converter is controlled to follow grid requirements [12]. In addition, another two-stage topology that can be used for FC system is a high frequency link direct dc-ac converter, as shown in Fig. 7 [15]. This approach provides high power conversion efficiency. However, it is mainly used in single-phase topologies due to a large number of devices used by the three-phase cycloconverters.

For battery or supercapacitor energy storage system, the commonly used power electronics topology is also a two-stage power conversion system [16], [17]. It consists of a bidirectional dc-dc converter with a high frequency galvanic isolation and a dc-ac converter.

Power electronics systems for wind turbines have been presented in [6], [11]. Similar to wind turbine system, the

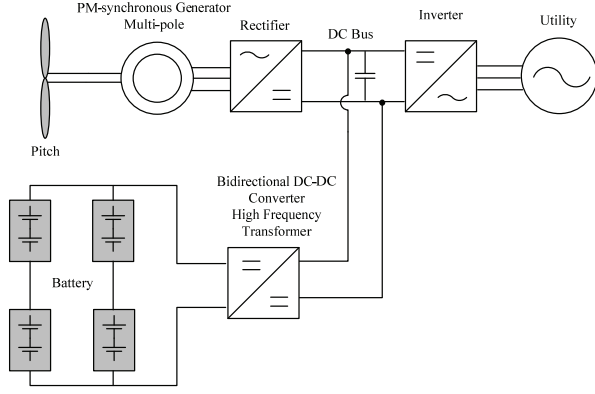


Fig. 4. The structure of a wind turbine integrated with a battery system.

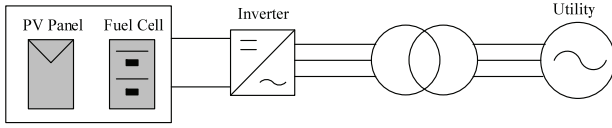


Fig. 5. The single-stage power conversion system for PV or FC.

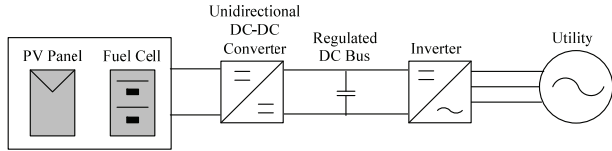


Fig. 6. The two-stage power conversion system for PV or FC.

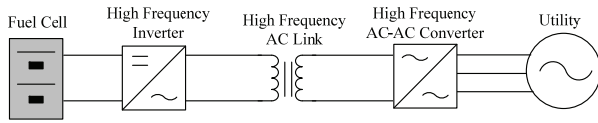


Fig. 7. High frequency link direct dc-ac power converter for FC.

most commonly used power converter for microturbine and ICE systems is generally a two-stage back-to-back power conversion system [18], [19]. It comprises an ac-dc converter which can be a passive diode bridge rectifier or an active bidirectional rectifier, along with a dc-ac converter to interface the network.

III. CONTROL METHODS FOR ELECTRONICALLY-COUPLED DER UNITS

As aforementioned in the Section I, the grid interactive ac microgrids can operate in the grid-connected and the intentional or non-intentional islanding modes, as well as smooth transitions between both modes are also desired. The complex behavior of such a microgrid challenges its control and power management strategies. However the massive use of power electronics interfaces introduces new control issues and possibilities for the DER units in the ac microgrids. The control methods for electronically-coupled DER units are therefore discussed following.

In general the controls of DER units are designed on the basis of the desired functions and possible operating conditions. In grid interactive ac microgrids, DER units can operate in the three different conditions. They are termed as *grid-forming units*, *grid-feeding units* and *grid-*

supporting units. Table I presents the control methods for DER units in accordance with their different operating conditions.

A. Grid-Forming Units

Grid-forming units regulate the system voltage and frequency through balancing the generation power and load demands when the microgrid operates in the islanded mode [8], [20]. However, in the grid-connected operation mode, as there are voltage and frequency references from the main grid, the grid-forming units are changed to operate as grid-feeding units. Hence the control methods for grid-forming units should be suitable for both microgrid operation modes, so as to ensure the smooth transients during the microgrid operation mode changes.

By using the conventional control method [21], [22], there are two control modes: voltage-controlled mode and current-controlled mode, corresponding to the islanded operations and grid-connected operations of microgrid, respectively. The transitions between one and the other mode may bring voltage stability problems during the delay time caused by islanding detection, in case of non-intentional islanded mode. To cope with this problem, indirect current control algorithms, and ac voltage control loops have been widely implemented [23], [24]. Fig. 8 shows a diagram of the power control method through ac voltage regulation [24]. Moreover, in the case where two or more DER units operate as grid-forming units, the load demand sharing among them complicates more the control methods. In this sense, voltage and frequency droop-based method [24]–[26] and active current sharing techniques [27] were developed, as will be discussed in Section V.

TABLE I
CONTROL SCHEMES AND FUNCTIONS FOR DER UNITS IN DIFFERENT OPERATING CONDITIONS

Operating Conditions	Functions	Control Methods
Grid-forming units	Voltage and frequency control	Hybrid ac voltage and current control, indirect current control, and ac voltage control
	Load sharing	Voltage and frequency droop-based control and active current sharing
Grid-feeding units	Power dispatch	Current control and ac voltage control, VOC and VFOC, direct power control
	Active/reactive power support	Unity power factor control, positive sequence control, and constant active and reactive power control
Grid-supporting units	Maximum active power output	MPPT
	Reactive power support	AC voltage control

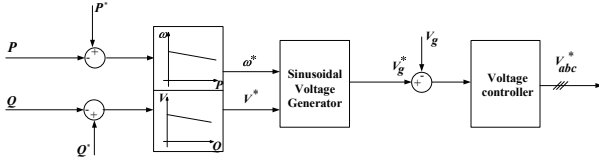


Fig. 8. Block diagram of the droop-based power control method.

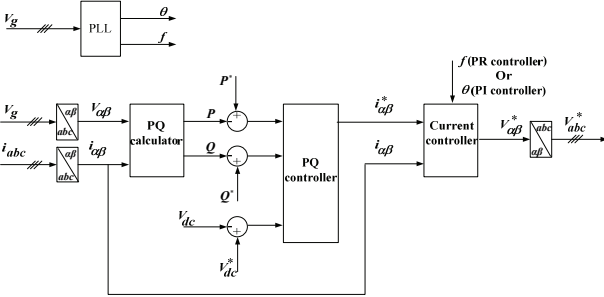


Fig. 9. Block diagram of the VOC based current control system.

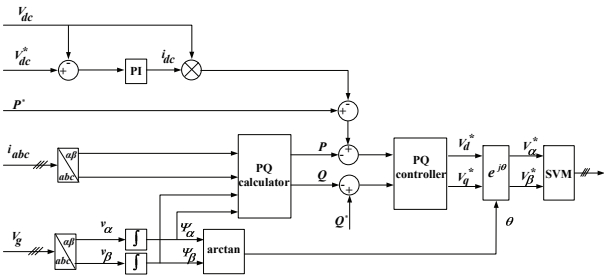


Fig. 10. Block diagram of the VFOC based direct power control system.

B. Grid-Feeding Units

Grid-feeding units adjust the output active and reactive power (P and Q) based on the power dispatch strategies or the frequency and voltage variation of the load or the feeder. Grid-feeding units are operated by the current-controlled mode as normal grid-connected DER units. Many current control methods for grid-connected DER units have been presented in [28], [29]. In addition to the wide variety of current controllers, the power control methods can also be distinguished as voltage oriented control (VOC) and virtual flux oriented control (VFOC) [30]. These control methods try to mimic the power electronic converter as a synchronous machine. Fig. 9 gives a general diagram of VOC current control system. Three types of reference frame control strategies based on PI or proportional plus resonant (PR) controllers that can be used for VOC control purposes [28]. Instead of synchronizing with the grid voltage, the VFOC method makes the power control synchronized with the integral of voltage which can be viewed as a filtered grid voltage. In addition, the power control can also be performed together with the direct power control method [30]. Fig. 10 shows the structure of direct power control based on the virtual flux.

In order to maintain a stable power system with the high penetration of DER units, grid-feeding units are required not only to comply with the grid requirements but also to ride through short grid disturbances [29]. On

the other hand, in an islanded microgrid, switching of loads can also cause high voltage transients which require all DERs to support this disturbance [31]. To meet these requirements, the fault conditions in the utility grid and microgrid should be identified. A detailed description about unbalanced grid faults was presented in [32]. The appearance of negative-sequence component in the grid voltage causes the second harmonic oscillation in the system of DER units. The control methods for DER units under grid fault conditions, in terms of requirements, were categorized as four groups in [29]. In such cases, the power calculation algorithm to generate the required current reference significantly influences the performance of control system. In this sense, several current reference generation methods for the active power control have been investigated in [33].

C. Grid-Supporting Units

Grid-supporting units here are different from grid parallel units defined in [20]. They are controlled to extract maximum active power from their primary energy source and the required reactive power to support grid voltage sags and local demands of reactive current. The control method for a small PV system with power quality conditioner has been reported recently in [34]. The ac voltage control method with a repetitive control loop to compensate selected harmonics was applied, along with a modified MPPT algorithm.

IV. INSTANTANEOUS LOAD SHARING STRATEGIES

Grid interactive ac microgrids involve significantly lot of issues somewhat different than in conventional distribution networks. A number of power electronics interfaces, inherently without inertias, and the intentional or non-intentional islanding operation modes challenge the control design of a grid interactive ac microgrid and its power management system.

Instantaneous load following and sharing capability for DER units, among other microgrid control tasks, plays a vital role in stabilizing microgrid frequency and voltage during the intentional islanding and non-intentional islanding operation mode. To achieve the instantaneous load following, the load controller integrated with load shedding strategy is essential for a microgrid without distributed storage (DS) units [35]. The inertialess power electronics interfaces result in a challenge when pursuing the load following capability for electronically-coupled DER units, but do offer the possibility of a more flexible control for load sharing. While many control strategies have been proposed for the parallel operation of inverters [36], their applicability for load sharing among multiple electronically-coupled DER units needs to be further investigated. Two main groups of strategies are available for load sharing depends on the use of critical communication links, which are active load (current/power) sharing [27] and voltage and frequency droop-based control [26].

A. Active Load Sharing

Active load (current/power) sharing methods comprise

the master-slave approach and the current limitation control [36]. In this kind of control strategy, the DER unit acting as the grid-forming (master) unit regulates the system voltage and frequency, whereas the rest of DER (slave) units receive the current references through communication links from either the master unit or the previous slave unit. Any DER unit in the microgrid can be the master. The most obvious drawback of this control method is that the limited communication bandwidth leads the master to take up most of nonlinear and unbalance loads in the microgrid [27].

B. Voltage and Frequency Droop-Based Controls

Voltage and frequency droop-based controls are based on the well-known active power-frequency ($P-\omega$) and reactive power-voltage ($Q-V$) droop characteristics in the synchronous generator operations, as shown in Fig. 11 [26], [34]-[50]. The conventional droop control method can be simply applied by introducing the following $P-\omega$ and $Q-V$ droop concept into the power controller of DER units, as shown in Fig. 8.

$$\omega = \omega^* - m(P - P^*) \quad (1)$$

$$V = V^* - n(Q - Q^*) \quad (2)$$

where ω^* and V^* are the nominal system voltage frequency and amplitude, m and n are the droop frequency and amplitude coefficients, respectively. P^* and Q^* are the nominal output active and reactive power. The controller gains m and n are chosen as a function of the P^* and Q^* , and the allowed maximum deviations in the system frequency and voltage amplitude.

Instead of using communication links, the droop-based control methods enable each DER unit in the microgrid to automatically share the total load through locally sensing its output voltage and current, thereby achieving higher reliability and flexibility. Droop-based control methods can be further split into two types, i.e. single master control and multi-master control [35]. Single master control is the composite use of the master-slave control and the droop method, which requires one DER unit to act as the grid-forming unit (master), and the other slave units adjust the output active and reactive power based on the voltage and frequency droop characteristics. On the other hand, multi-master control is applied for the case that several DER units operate as grid-forming units.

In grid interactive ac microgrids, due to the low X/R line impedance ratio of distribution feeders, conventional $P-\omega$ and $Q-V$ droop characteristics cannot be directly applied for sharing loads and are very sensitive to the line impedance unbalances. Taking such effects into account, the droop control method in general form are described as follows

$$\omega = \omega^* - m(P \sin \theta - Q \cos \theta) \quad (3)$$

$$V = V^* - n(P \cos \theta + Q \sin \theta) \quad (4)$$

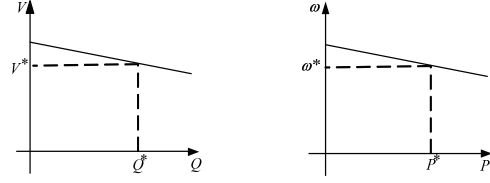


Fig. 11. Conventional $Q-V$ and $P-\omega$ Droop characteristic.

where θ is the phase angle of the output impedance and the line impedance. Notice that this general droop method can be easily derived from the well-known Park transformation [37].

It can be observed from the general form of droop control method that the output impedance of DER units has large impact on the load sharing performance. The phase angle of the output impedance and line impedance determines the droop control law for decoupling the active and reactive power flows of DER units. Proper design of the output impedance can reduce the effect of line impedance unbalance. In view of this, several control methods are developed to decouple the active and reactive power flows. In [41] the interface inductors were introduced between the DER units and the distribution feeder, but they are heavy and bulky. Recently, decoupled control of virtual active and reactive power through frame transformation was proposed, but it cannot share the actual active and reactive power among the DER units in the islanded microgrid operations [42]. There are also some control methods that fix the output impedance of the units by emulating lossless resistors or reactors to provide alternative solutions [43], [44]. Nevertheless the effect of line impedance was not considered in those control methods. To overcome this problem, injecting high-frequency signals through the power lines [45] and adding external data communication signals [46] were developed. Unfortunately such communication among DER units increases complexity and reduces reliability.

It is important to note that the output impedance of a DER unit can be altered by the feedback control. This provides a new control variable for the load sharing performance. Based on the design of output impedance, adaptive output impedance method is proposed which allows a good reactive power sharing with low sensitivity to the line-impedance [38]. Alternatively, an adaptive $Q-V$ droop control algorithm based on a virtual inductance is presented to achieve the reactive power sharing [40].

Furthermore, due to the appearances of nonlinear and/or unbalanced loads in ac microgrids, compensating the harmonic and/or unbalanced power is another challenging issue for the load sharing control. To cope with the nonlinear load sharing, in [47], a controller was proposed to share nonlinear loads by adjusting the output voltage bandwidth with the delivered harmonic power. But this method has two main limitations: the harmonic current sharing is achieved at the expense of reducing the stability of the system, and high-frequency signals injection limits the power rating of inverters. In another approach [48], every single term of the harmonic current is used to produce a proportional droop in the

corresponding harmonic voltage term, which is added to the output-voltage reference. However, those solutions have an inherent tradeoff between voltage regulation and power sharing. In this sense, the controllable closed loop system output impedance provides several alternative solutions. The resistive behavior of output impedance for high-order current harmonics presented an effective way to share nonlinear loads [39]. Instantaneous power theory based output impedance design methods were recently proposed to offer another approach to sharing nonlinear and unbalanced loads [49], [50].

It can be concluded that the proper design of the closed loop system output impedance is essential to achieve the instantaneous load sharing capability of DER units in grid interactive ac microgrids. Nevertheless, the load sharing strategies based on the design of output impedance have an inherent tradeoff between the distorted load sharing and the sinusoidal output voltage regulation. In addition, the design of output impedance can merely reduce the unbalanced line impedance effect.

V. CONCLUSIONS

This paper gives an overview of distributed energy resources in grid interactive ac microgrids. The options in structures of DER units were described. The local control schemes for DER units in accordance with the possible operating conditions and required functions were presented. In addition, instantaneous load following and sharing strategies and the importance of closed loop output impedance design on the load sharing performance were discussed.

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