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Distributed and Decentralized Control Architectures for Converter-Interfaced Microgrids

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Abstract: This paper gives a summary on recently available technologies for decentralized and distributed control of microgrids. They can be classified into two general categories: 1) power line communication based architectures and 2) multi-agent based architectures. The essential control methods and information sharing algorithms applied in these architectures are reviewed and examined in a hierarchical manner, in order to point out benefits they will bring to future microgrid applications. The paper is concluded with a summary on existing methods and a discussion on future development trends.

Keywords: Decentralized control, distributed bus signaling, distributed control, microgrids, multi-agent systems, power line communication.

1 Introduction

The growing pressure to increase the penetration of renewable energy sources (RES) results in the emergence of microgrid (MG) concept, which is considered as an appealing way to integrate distributed generators (DGs), energy storage systems (ESS) and loads into small power systems[1-3]. An MG has a clearly defined boundary and can be connected or isolated from the main grid[4]. The isolated operation of MG can ensure its power quality independency from utility mains especially under grid contingencies. Conversely, when connected to grid, it appears like a singular and flexible entity from the overhead power system perspective, which makes it a valuable building block in the future Smart Grid.

Motivated by those benefits, the academic community has therein found a particularly fertile research field and notable progress has been made in real-time operation and control of both AC- and DC-coupled MGs. Particular attention was devoted to elimination of problems that come with paralleling multiple power electronic converters in AC systems without the use of dedicated communication infrastructure. Largely finding inspiration in early works from Chandorkar, Tuladhar, and Coelho[5-7], initially reported solutions based on local droop control method showed promising performance for small and dense systems[8-10]. Nonetheless, limitations of classical droop control in practical applications have soon come to light: Its suitability only for dispatchable generators, inherent voltage/frequency deviations, and inter-dependence of control parameters with power sharing accuracy and stability, to name a few.

Low-bandwidth centralized communication system (CS) is the widely used solution that links DGs to go around these impediments and ensure proper operation[11-14]. However, CS is in direct contradiction with the new paradigm of DG based power grids, i.e. fully distributed and redundant control system that is easily expandable and entails "plug-and-play" feature for new units and that is not subject to a single point of failure. Thus, distributed computing and algorithms have been brought to the main research trend recently and receive increasing attention from researchers all over the world. This research could be categorized into following two groups:

(1) Conventional digital communication system is avoided and power lines are used as a communication medium, leading to two concepts; power line signaling (PLC)[15] and distributed bus signaling (DBS)[16-18].

(2) There exist conventional communication links, but rather than a centralized data aggregator, a multi-agent system(MAS) is used. This case opens the potential for a whole new range of added benefits, such as the "plug-and-play" capability, enhancement of redundancy and reliability, allocation of computational burden to more vendors, and reduction of communication costs[19-20].

It should be noted that in its standard form, PLC relies on dedicated technologies since the frequencies of practical communicating signals are at least several kHz and power converters on the market are normally not suitable for their processing. In addition, PLC is still an emerging technology that, due to slow development of generally accepted standards[15], today has only some restricted applications in utility power systems and possibilities of its deployment to MGs would require much more extensive examination than that permitted by the space available in this article.

Therefore, the remainder of this paper is focused exclusively on disclosing the features of DBS and MAS control methods.

Without the loss of generality, both of them could be also combined together to form hybrid arrangements. In any case, aspiration to adopt fully distributed management strategies can be identified as a fashionable and increasingly important trend in MG arena. The most relevant features of those strategies are disclosed, examined, and analyzed in order to point out benefits that they can bring to future industrial MGs and also to demonstrate that we are presently in a key moment where energy companies will try to transform recent theoretical developments into real and competitive products.

Today, the MG market is worth around $5 billion

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and accounts for more than 4 GW of installed capacity around the globe, with more and more new deployment projects being carried out[21]. It is interesting to note that some of those already embrace distributed control approaches in practical real world environments. Companies like Morningstar and SMA offer plug' and'play converters that can rapidly form AC or DC MGs using different bus signaling methods[22-24]. Due to user friendly interface and straightforward commissioning, many small-scale industrial MGs have been built relying on their basis. From larger-scale distributed deployments, a Cell pilot project in Denmark can be singled out as a good example. It is based on the idea of dividing low voltage distribution system to a number of distributed agents, i.e. utility-scale MGs, that communicate with each other through high speed fiber optic cables with respect to predetermined control hierarchy[25]. Another example is a multi-agent system based on intelligent local load control, assembled for MG of Kynthos island, Greece[26].

Relying on successes of these projects and with already firmly established theoretical background; it is natural to expect that leading companies will continue to show interest in deploying distributed solutions in order to maintain the competitive market position. In that sense, extension and standardization of existing bus signaling solutions, as well as breakthrough of distributed algorithms to higher control layers seem to be a next natural step in development of advanced MG technologies.

2 Fundamentals of a conventional control structure for microgrid

Stemming from the conventional control of large power systems, a hierarchical control structure has been defined with primary, secondary and tertiary levels differentiated[27]:

(1) Primary control is responsible for individual converter power, voltage and frequency regulation. Droop control and virtual impedance are often used on top of inner voltage and current loops.

(2) Secondary control's main function is to perform power quality regulations to manage voltage/frequency deviations, unbalances and harmonics. Optionally, it encompasses synchronization loop between the MG and external grid.

(3) Tertiary control is in charge of regulating power exchange with external grid or/and with other MGs. It can also include advanced functions related to efficiency and economic enhancements which constitute a higher management level, commonly referred to as the energy management system (EMS)[28-29].

Fig.1 shows the organization of the control layers within the MG. It can be seen that the bandwidth is gradually decreased when climbing up the hierarchy. Besides, unlike secondary and tertiary, all the functions of primary layer are by definition achieved without using digital communication technologies. Following sections cover one layer at a time and address the applications of advanced distributed control techniques to each of them.

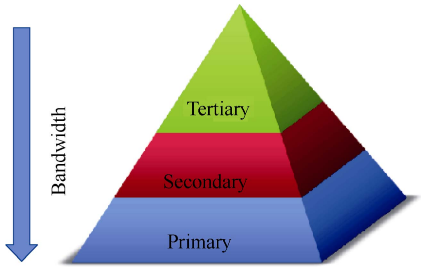


Fig.1 Hierarchical control concept for microgrids

3 Decentralized primary control of AC/DC microgrids

Primary control is the basic control level of a MG hierarchical control structure. It follows the operational command from upper levels and regulates the DG tie converters to realize the committed functions. Although centralized architectures can be used for primary control[30], decentralized and distributed control methods are gaining increasing attention for the sake of flexibility and plug-and-play functionality[27].

On the other hand, some system level regulation functions usually require the conventional digital communication infrastructure[31-34]. However, with the help of DBS concept, some of those functionalities may be realized locally, leading to distributed coordination of an MG system. Apart from increased flexibility and reliability, low implementation cost and inherent robustness of DBS make this kind of strategy very attractive for cost-sensitive industrial applications.

3.1 Primary control system and characterization of units

A typical MG configuration is shown in Fig.2, consisting of RES, ESS and distributed loads. The common challenge for such a system is the management of uncertain RES generation and load consumption. In order to make full use of renewable energy, RESs are usually operated at maximum power point (MPP) whenever possible[35-36]. In this regard, ESSs are indispensable components in order to achieve autonomous operation of MGs[37-38], while the limitation of ESS energy and power capacity require a reasonable regulation strategy to prevent over-charge or over-discharge. Reactive power flow and power quality issues are also of great importance and to be taken into account.

Depending on the nature of interconnecting power lines, active and reactive power can be more or less decoupled[39]. In inductively dominant lines, reactive power is related with voltages and cannot be accurately distributed due to differences in line impedances that lead to diverse voltage drops[40] (similar effect can also be found for current sharing in DC MGs[41]). With dominantly resistive lines, active power sharing would be more problematic. One way or another, droop control laws need to be appropriately tuned to achieve proper sharing[39]. Since the exact R/X ratio is not known in practical applications, virtual impedance (VI) control loop has been proposed to fix the impedance seen from the interfacing converter[10,42-45]. VI concept can also be employed to specify the impedance for selected harmonics, and to control the harmonic power flows in that way[46-47]. With this in mind, the sole focus of this section was to reveal the features of decentralized active power control based on coordination between ESS and RES with regard to the energy stored in ESS.

In addition, it should be noted that MG supplemented with ESS can provide a number of benefits to utility mains in grid-connected mode[48-49]. However, discussion in this section will remain focused exclusively on autonomous mode of operation due to the following two reasons: a) control is more challenging in islanded mode since there does not exist a stiff source, and b) although energy management priorities are typically different in the two modes, the same control concept can be used to achieve them in both cases.

Two critical conditions have to be carefully addressed: a) light load consumption with high RES generation may cause over-charge of ESS; b) heavy load consumption with low RES generation may cause over-discharge of ESS. Both conditions demand a proper coordination of the MG. To avoid building a costly digital communication network, power line based communication, such as DBS, can be utilized.

3.2 Distributed bus signaling (DBS)

DBS coordination control schemes can be generally classified into ESS-RES distributed generation control (DGC) and ESS-load demand side management (DSM). Both schemes can be utilized in either AC or DC MGs with a proper design and selection of bus signals. Frequency signal is commonly used for AC systems, whereas in DC systems the common bus voltage can be selected for DBS purpose. Since both AC and DC MGs share practically the same energy management priorities in the autonomous mode of operation[18], the following elaboration focuses on application of DBS method only to AC MGs without any loss of generality.

In both AC and DC MGs, the DBS strategy employs ESS as the master unit to regulate bus voltage frequency (in AC) or amplitude (in DC) based on its SoC condition. High SoC control and low SoC control are divided in the coordinated control algorithm for taking proper decision according to the practical condition. In high SoC condition, DGC dominates the control by managing the power from RES and ESS; in low SoC condition, DSM dominates the control by managing the load shedding. The detailed algorithms are discussed as mfollows, and AC MG is used as the exemplary syste

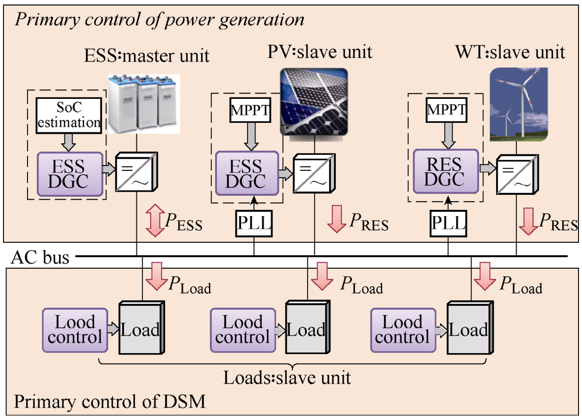


Fig.2 A configuration of decentralized primary control

3.2.1 Distributed generation control (DGC)

Fig.3 shows the DGC coordination algorithm for coordinating ESS and RES. When SoC is within the normal operation range (lower than the upper-threshold SoC_1), the ESS operates in stiff voltage control mode (VCM)[50] and keeps the MG frequency at the nominal value; in the meantime, each RES unit is under current control mode (CCM) using power references generated by MPPT[51-53]. This control mode guarantees that the RES power is fully utilized when the ESS is within the safe SoC range.

In high SoC conditions, the ESS unit is nearly fully charged so that the RES power needs to be curtailed in order to avoid over-charge condition. An autonomous operation is realized by DBS that the ESS increases the bus voltage frequency, RES regulates its power by monitoring the frequency signal and curtails its power when the frequency goes higher. Fig.3 indicates a frequency droop of RES during this range of operation, which is similar as synchronous generators with built-in inertia.

Ultimately, the charge power of ESS is reduced to a low level such that the bus frequency and system power flow are stabilized at an equilibrium point. In addition, if a system involves multiple ESS units operating in parallel, droop control is still compatible with the coordinated control scheme, and can be used between ESS units to realize decentralized power sharing control[44, 55]. In this way, all the ESS units are like a singular entity with a common SoC from the DBS perspective, and the MG coordination principle remains the same as for a single ESS.

3.2.2 Demand side management (DSM)

In low SoC condition while the RES has limited power generation, the only solution to keep continuous operation of an islanded MG is to perform DSM[58-59]. Similarly, ESS also acts as the master unit to manipulate the frequency when the SoC is lower than certain limit, as that shown in Fig.4. A load shedding process is the

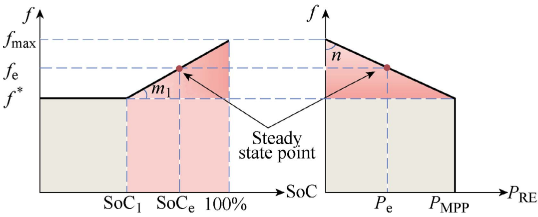


Fig.3 Principle of primary DGC control

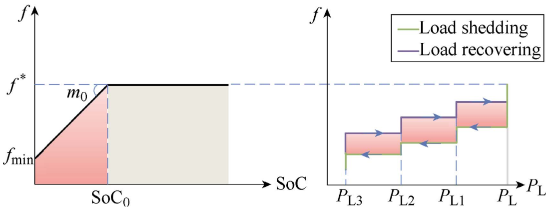


Fig.4 Principle of primary DSM control

consequence of reducing frequency so that the ESS discharge rate is also reduced, and finally an equilibrium point is reached when the power is balanced within the MG system.

Furthermore, the load shedding procedure also follows a prescribed pattern such that critical loads have uninterruptible supply while noncritical ones are also classified with certain priorities. The load recovering process is also based on the observation of frequency increase, for which a relay based control is necessary to avoid chattering behavior in the MG system.

In addition, instead of always applying a fixed frequency-SoC slope, adaptive slopes are also potential solutions for systems with special operational requirements on load tripping time and coordinated control sensitivity.

4 Secondary control

As elaborated in the previous sections, droop-regulated converters may be combined with other types of units such as RES (regulated by local MPPT algorithms or virtual inertia emulation) and distributed loads. The system voltage and frequency, however, are determined by droop characteristics and their steady-state deviations from their nominal values are inevitable[13-60]. In addition, accurate (active/reactive) power sharing cannot be achieved in the most common droop mechanisms[65-66]. Taking the idea from large power systems, secondary control is typically deployed to overcome the limitation of droop mechanism in droop-controlled DGs. Using digital communication, this control level is able to provide improved performance and global controllability for the MG. To achieve the global controllability of system, the secondary control must be implemented either centralized or distributed.

4.1 Centralized secondary control

Conventional secondary controller is unique for the whole MG, relies heavily on centralized communication infrastructure and is, among other functions, implemented within the MG central controller (MGCC)[60–62]. Some other strategies such as power flow control, and harmonic/voltage unbalance compensation have also been applied to the MGCC under the name “secondary”[45,63-65]. Fig.5 shows conventional secondary control architecture for a MG consisting of a number of DGs controlled by local primary control and one central secondary controller, which collects remotely measured variables transferred by means of a low bandwidth communication system. Those variables are compared with the references in order to calculate appropriate compensation signals by secondary controller, which sends them through dedicated communication channels back to primary control of each unit.

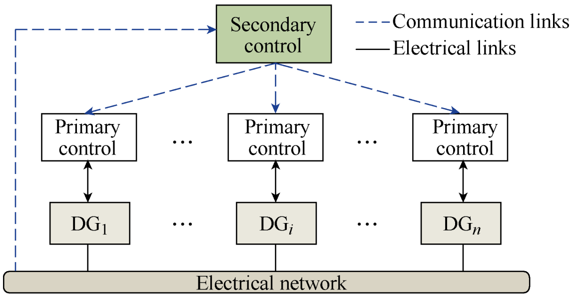


Fig.5 Scheme of centralized secondary control

The centralized approach requires point-to-point communication, which adds complexity to the system and compromises its reliability due to a single point of failure issue. Alternatively, distributed methods can be used. Due to their attractive features, they have recently drawn a lot of attention in MG research community[65-69].

4.2 Distributed secondary control

Distributed secondary control (DSC) as an alternative has recently gained popularity since it discharges duties of a central controller with less communication and computation costs, while improving the reliability of the control system. The idea is to merge primary and secondary control together into one local controller. However, for proper operation, these local controllers need to “talk” with their companions, as shown in Fig.6. Their conversation is typically processed through band-limited neighboring communication, resulting in a control system that is in literature generally referred to as distributed control[70-72]. Bearing in mind the abundance of applications that can arise from this kind of control structure, we limit our discussion here only to DSC of droop regulated converters, while some of more advanced functions are elaborated in the next section.

The basic working principle of DSC is to exchange the information through the neighboring communication, by utilizing a distributed protocol and achieving a consensus, e.g. the average value of measured voltages. As opposed to frequency, voltages are local variables, implying that their restoration can be done either in selected critical buses, or on the total average level. In the latter case, DSC can be exploited to generate a common signal which is compared with a reference and passed through a local PI controller, which produces appropriate control signal to be sent to

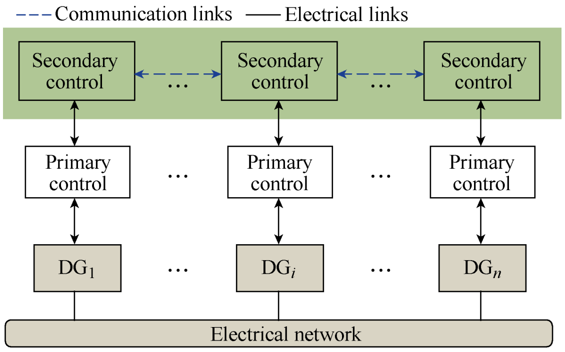


Fig.6 General scheme of distributed secondary control

the primary level for removing associated steady state errors. It should be noted that the type of protocol, which is essential for making the secondary control distributed, influences the feasibility and performance of DSC. The preliminary –so called– distributed secondary controllers were based on normal averaging principle[57,65,78]. In such works, communication between DGs has been identified as a key ingredient in achieving the control goals while avoiding a centralized control architecture. Several distributed control methods have been introduced in the literature out of which consensus-[73] and gossip-based[72] algorithms have recently received significant attention mostly because of their implicitness and robustness for distributed information exchange over networks.

4.2.1 Distributed algorithms

Among the introduced distributed protocols, consensus is the most used for secondary control of MGs. In consensus-based algorithms, all the nodes of the network get activated synchronously at each time step and update their current state with respect to local information and that gathered from their neighbors.

These algorithms have a long history in the field of computer science and distributed computation as well as in many applications involving multi-agent systems, where groups of agents need to agree upon certain quantities of interest[70-71]. They rely on principle of dynamic.

Averaging of certain signals between only neighboring agents. The usage of these algorithms for secondary control of both AC and DC MGs has been considered recently[66-69]. On the contrary, gossip algorithms are asynchronous, meaning that only one random node chooses another node (or more) to exchange their estimates and update them to the global information e.g. the average value at each time steps. Gossip algorithms are attractive because they are robust to unreliable wireless network conditions, and they have no bottleneck or single point of failure[74]. Application of these algorithms in MGs have been reported recently[20,75]. A gossip algorithm is presented in [20] for secondary voltage and frequency control of AC MGs which tightly couples the communication and control layers.

Applying these types of algorithms makes the secondary control fully distributed, meaning that it only requires a sparse communication network spanned across the MG. Furthermore, for scalability of secondary control, prior knowledge of the system is not needed for a new component entering the MG[66, 69].

4.3 Common functions of distributed secondary control

The main function of distributed secondary control is to shift/change the droop characteristics of associated inverters so as to perform the restoration of voltage (and frequency) levels to nominal values or values that ensure proper power sharing among DGs in the system.

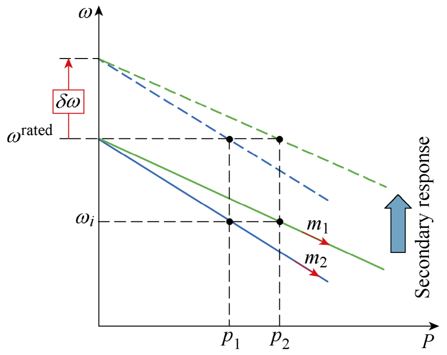
4.3.1 Frequency and voltage regulation

The concept of secondary control, under the name of automatic generation control (AGC) or load frequency control (LFC), has been used in large power systems to address the steady-state frequency drift caused by the droop mechanisms. It is conventionally implemented via a slow, centralized PI controller with low bandwidth communication[76]. Inspired by this idea, a centralized integral secondary controller is implemented in the MGCC in order to regulate the frequency of the MG[3,60]. Corresponding distributed approach is to use frequency control locally at selected MG units, so that their local controllers slowly add increments to the primary level until the network frequency deviation gets eliminated[20,66-68].

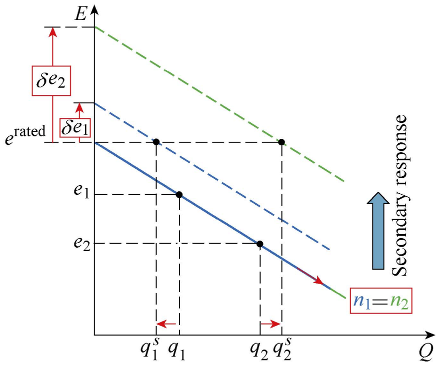
Since system frequency is a global variable across the microgrid, droop control itself can share the active power among sources. Frequency secondary control eliminates the frequency deviation caused by the droop control. However, this restoration process may inversely affect the proportional power sharing. To avoid this, the secondary controller must be designed such that all local droop controllers receive identical set-points[68]. Fig.7(a) shows the ω-P droop characteristics before and after the secondary control activated in a microgrid with two parallel sources with different power ratings. The secondary control output ($\delta\omega$) changes the voltage reference of local unit(s) by equally shifting the droop lines up (or down), regulating the frequency to the nominal value.

As opposed to the network frequency, voltage amplitude is not a global variable. Voltage values will normally be distinct at different connection points in the MG due to line impedances. In large power systems, voltages at generator stations are fixed by local automatic voltage regulators (AVR) which act on the excitation system[77]. In MG, this type of voltage regulation is inherently included into a definition of secondary control. Similar phenomena as the frequency secondary control has been defined for eliminating voltage deviations in microgrid using both centralized and distributed architectures[66,69]. This concept is illustrated in Fig.7(b), where the secondary control effort (δe_i) is added to the local droop controls to remove the voltage deviation.

For simplicity, a microgrid consists of two parallel sources with the same power rates are examined. As in practice, the lines connecting the inverters to the common bus are considered to have different impedances; it is assumed here that $X_1 > X_2$. As Fig.7(b) depicts, the primary control imposes different voltage levels at the inverters' terminals, i.e., $e_1 \neq e_2$. This is because of unequal reactive power injection ($q_1 < q_2$), due to the line impedance effect. It is shown that in the presence of non-negligible line impedances, terminal



(a) ω-P droop characteristics of a microgrid with two parallel sources with different rates ($m_1 < m_2$)



(b) E-Q droop characteristics of a microgrid consists of two parallel sources with the same power rates (inverter 1 (blue) and inverter 2 (green)), but different line impedance ($X_1 > X_2$)

Fig.7 Secondary control response vs primary control response before (solid lines) and after (dashed lines) applying voltage secondary control

voltages cannot be identical; hindering the reactive power sharing process provided by droop control. When the voltage secondary controller is applied, voltage magnitude at the inverters' terminals is restored to the rated voltage (e^{rated}). However, application of this controller for voltage regulation may deteriorate the sharing of reactive power between inverters, i.e., $q_2^s - q_1^s < q_2 - q_1$.

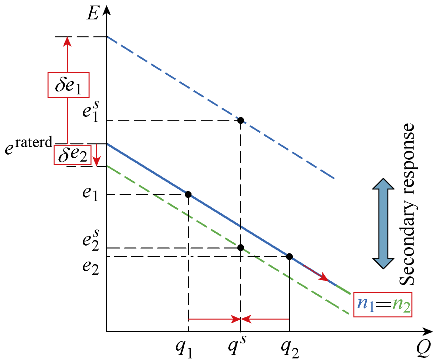
4.3.2 Load sharing

Reactive power sharing is typically not a major concern in large power systems due to capacitive compensation along the transmission lines and at load connection points[77]. On the contrary, it is an important issue in parallel converter driven MGs[63, 65-66, 69]. In a typical MG, as sources respond to more power demand, onboard droop controllers reduce their frequency/voltage to handle load sharing and prevent overload. In that sense, precise voltage and frequency measurements are essential to achieve the effectiveness of the droop mechanisms. Unlike frequency, which is a global variable, the voltage varies across the MG due to the distribution line impedances. As depicted in the previous subsection, these voltage mismatches incapacitate the droop mechanism and result in a poor voltage regulation and load sharing. Similar effect occurs when trying to proportionally share the active power of units using P-V droop in AC MGs with highly resistive lines. Moreover, in DC MGs current/power sharing follows the same phenomenon[57, 69, 78].

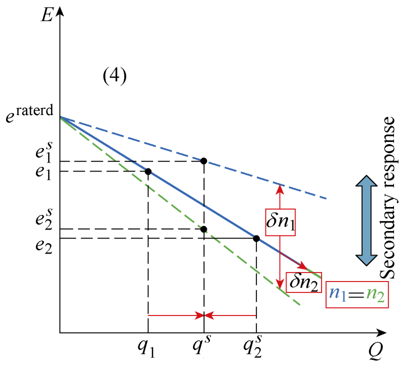
Distributed power sharing in the secondary control loop is a good alternative to share power between the MG units. This way, all the units reach a consensus according to their power rates and obtain the same reference. Proportional power sharing is achieved independently from voltage sensing mismatches or line impedances in the MG. To this end, one might add another secondary control loop[35, 38, 44] or a new term to the voltage control module[37,39], where a correction term, δe_i^q, is added to the droop mechanism (see Fig.8(a)).

As another solution, the reactive power module can be applied in a way that it changes the droop characteristic to manage the reactive power (see Fig.8(b)).

Fig.8 illustrates the E-Q droop characteristics before and after applying the reactive power secondary controllers. As seen, although the secondary control ensures proportional sharing of reactive power, q^s, it might inversely affect the voltage regulation. One can note that the voltage regulation procedure is in a direct conflict with sharing the reactive power among inverters. Therefore, a trade-off must be made between these two control objectives.



(a) Shifting the droop mechanism



(b) Changing the droop mechanism

Fig.8 E-Q droop characteristics of a microgrid consists of two parallel sources with the same power rates (inverter 1 (blue) and inverter 2 (green)), but different line impedance ($X_1 > X_2$) before (solid lines) and after (dashed lines) applying reactive power secondary control

5 Information-sharing-based distributed tertiary agent systems

Tertiary control is located at the top level of a MG hierarchical control system, as shown in Figure 9. It is envisioned to enhance the “smartness” of the system by offering more sophisticated functionalities such as real-time monitoring and supervision, power management, and energy scheduling, among others[13,79,80]. Typical enhancement targets are energy efficiency, power quality, system level safety/stability and economy[28,80-90]. Naturally, the self-awareness level and thus the intelligence of the whole system can be largely improved by implementing tertiary control. However, this property does not come for free. Centralized decision-making (DM) requires information collection from all the active units and other critical points, and, as a consequence, carries a lot of computational burden on itself. This kind of strategy becomes highly impractical in case of dispersed and large scale MGs and the possibility of distributing the computation to a number of local DM entities comes to mind as a natural alternative.

In particular, if one unit is to a certain extent aware of actions of other units and how their decision influences the system, the activity that brings the system closer to optimal state can be made locally. There are three technological challenges that need to be overcome in order to establish a distributed, multi-agent system (MAS) based tertiary control layer (seen in Fig.10): distributed information sharing, system modelling and design of DM procedure[91-95]. Each agent perceives its environment through low bandwidth communication links and sensors. Information sharing algorithms, such as consensus algorithm and diffusion strategy, can be applied to facilitate the global information discovery[73, 88-90, 96-100] based on which the tertiary DM procedure can perform optimization or scheduling functions[18,97-99]. System model is established at each unit locally for predicting the environment reaction and assisting the DM process. Finally, proper actions are taken to change the status of the environment. Controller layer works simply as an actuator between agent and environment.

Based on this scheme, conventional centralized DM functions can be performed in a distributed way so as to fit into the new paradigm of distributed generation and consumption in MGs.

As explained in previous section, the general purpose of information sharing algorithms is to allow a set of agents to reach an agreement on a quantity of interest by exchanging information through communication network[70]. While associated information is limited to only a few quantities in case of secondary control, tertiary agents may exchange a number of different signals with neighboring agents. Consensus algorithms, information diffusion strategy and distributed optimization algorithms are potential solutions in this circumstance. The following parts provide example applications in two typical categories: distributed tertiary control for power flow and voltage regulation; distributed optimization for optimal dispatch.

5.1 Distributed tertiary control

The applications of consensus algorithms along with existing DM procedures have been explored in MG related research perspective regarding coordination and restoration issues. The authors in [97] propose a fully distributed agent based load restoration algorithm. As consensus algorithm is used, the communication links

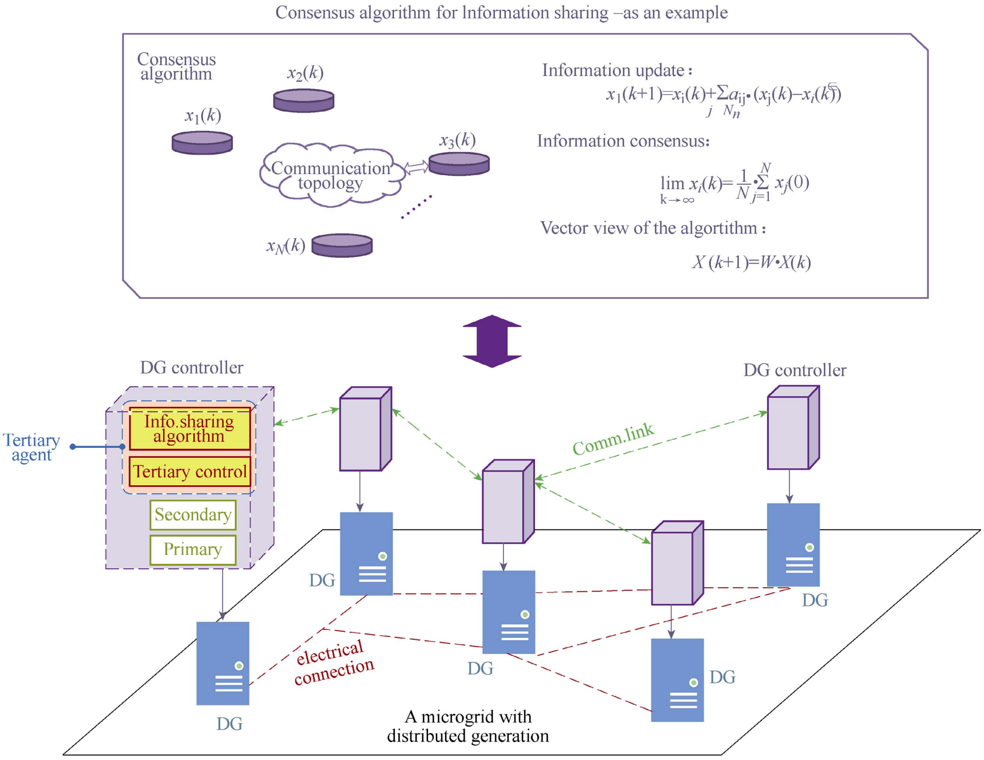


Fig.9 Distributed agent based hierarchical control system for microgrids

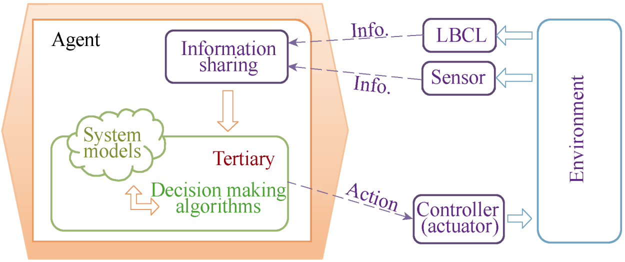


Fig.10 Tertiary agent system

are established only between neighboring nodes. The information state vector of each agent includes three parameters: the total net power, the indexes of the buses and the loads that are ready to be restored. The global information is discovered by each agent knowing the current state of the generation and consumption in all the buses. Local decision for loads restoration can be made according to the priority of the loads. Furthermore, in order to ensure the fast and stable convergence of the consensus algorithm, this paper also proposes a distributed adaptive weights setting method and compares this method with existing algorithms. This approach is demonstrated in the simulation that it can be applied to MGs with any kind of topologies while guaranties better convergence of the global information discovery. Similar approach is applied also in [98] for balancing the generation and consumption by coordinating the operation of doubly-fed induction generators.

Considering the localized generation, storage and consumption feature of future smart grid, wireless communication network is generally accepted as high flexibility and low cost way for facilitating the control and monitoring in MGs. Accordingly, a consensus theory based distributed coordination scheme for MG via wireless communication is proposed in [99] for coordinating the generation, storage and consumption. Two types of information states are included: status and performance. The status information indicates the binary state of apparatus, such as fault/normal, available/unavailable, etc. The performance information provides the measurement values, for instance power generation, energy storage, etc. By using consensus algorithm, all the agents discover the status and performance of the apparatus in the MGs, and take decisions locally. In addition, the practical issues regarding wireless communications are also considered, such as the communication rates and range.

Another critical role of tertiary control is to manage the power flow between MGs. In order to maximize the utilization of RES and relieve the local power stress, the power exchange in MG clusters has to be properly managed. A fully distributed hierarchical control scheme is thus developed in [101] as shown in Fig.11, a local tertiary agent and a global tertiary agent are designed to coordinate the MG internal power flow and MG cluster power flow, respectively. Both local and global agents are coordinated with their neighbors through consensus algorithm in order to reach agreement on power sharing and exchange. The results show satisfactory performance on maintaining voltage levels and regulating power flows in both microgrid level and cluster level. In [102], the reactive power flow is set as the control objective in order to minimize the voltage errors in critical nodes in an electric power system. In the proposed scheme, each DG performs local optimization with respect to its own objective function while considering the information from neighboring units. The overall control scheme enables the microgrid to have a unified voltage profile.

As described in Section IV, the objective of secondary control is to maintain the voltage and frequency level, nevertheless, it is also in contradiction with tertiary power flow control since the power flow and voltage/frequency are correlated. The authors of [103] have mathematically designed fully distributed secondary and tertiary controllers realizing voltage drifts cancellation and optimal power injection maintaining at the same time.

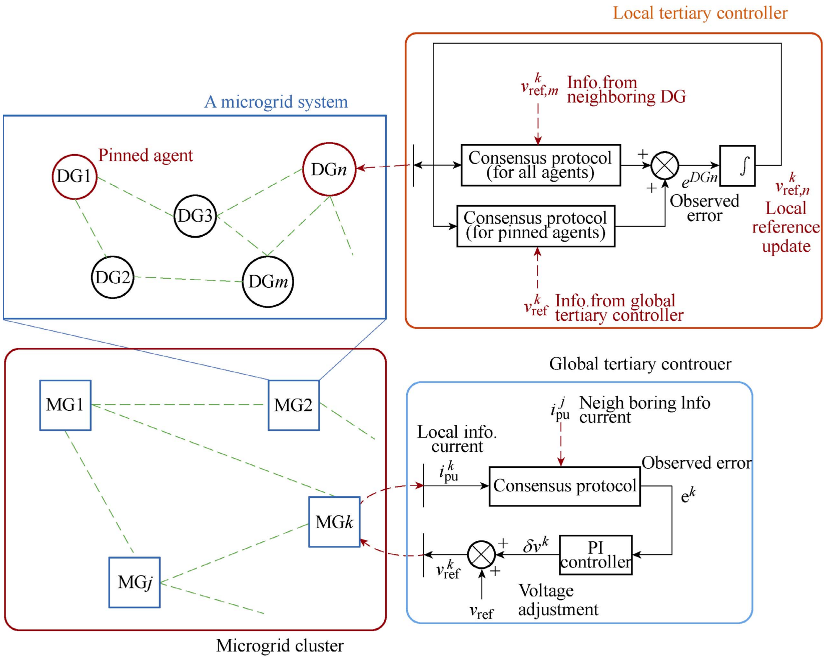


Fig.11 A fully distributed two level tertiary control scheme

5.2 Distributed optimal dispatch

Economic operation is the common and ultimate goal of energy systems. Efficiency, operational costs and market real-time pricing are the major factors in this regard asking for a proper dispatch of DGs.

The authors in [88-90] propose a consensus algorithm based distributed hierarchical control for both DC and AC MGs. In those cases, the primary power sharing control, secondary voltage/frequency restoration and power quality compensation, as well as tertiary optimization and decision-making are all implemented in locally distributed controllers, facilitating the flexible operation of DG units. Two study cases are established to verify the proposed method. In [90], the optimal load power sharing is achieved among several paralleled converters with enhanced overall system efficiency. Global information like total power consumption and number of operating DGs are discovered in each local controller by using dynamic consensus algorithm assisting the realization of local decision-making. Similarly, in [89] the essential information is obtained in each local controller for optimization and optimal sharing of compensating efforts among DGs in an islanded AC MG.

Apart from pure efficiency consideration, some studies also take DG operational costs into consideration. Quadratic cost functions are widely accepted as the standard form for evaluating DG incremental cost. A multi-agent based decentralized hierarchical control scheme is presented in [104]. Agents are defined in three levels: tertiary level area electric power system agent, secondary level microgrid operator agent and primary level DG operator agent. Consensus based algorithm is implemented to reach an agreement through information exchange between neighboring units facilitating the local DM according to DG incremental cost. Similar cost functions for DG units are also used in [105-108]. In [105] and [106], a nonlinear tertiary control algorithm is applied, which essentially is based on a derivative term of quadratic cost function. The authors of [107] propose a fully distributed information diffusion strategy to share critical data and achieve minimized operation cost of DGs. A distributed Lambda iteration scheme is introduced in [108] to coordinate the active power dispatch showing improved robustness and fault-tolerance in system level control. Another distributed algorithm, the alternating direction method of multipliers, has also been applied in microgrids for cost minimization, such as the cases presented in [109] and [110]. All the above mentioned studies are good examples of applying distributed computing algorithms in microgrid applications, specifically, for coordinating the DGs with regard to their operational costs.

6 Concluding remarks

MGs have matured from an emerging technology to a well-established and marketable solution for power supply of remote applications, and also as a valuable building block for future Smart Grids. Control structure of a MG can be systematically decoupled into several layers, with each one of them playing different role. Historically, most research efforts in this area have been focused on enhancing the performance of the lowest one, which covers automatic line-interactive operation of multiple paralleled sources. Typically employing a droop-control strategy, it is commonly referred to as the primary control layer and has fundamental importance since its proper operation is not only the prerequisite to safely operate the MG, but also for implementation of upper layers on top of it. While the root cause for realizing a hierarchical control structure was enhancement of the overall MG controllability and intelligence, conventional solutions implied centralized communication architecture, entailing several disadvantages such as high communication cost, single point of failure and inflexibility. In order to circumvent these obstacles, different kinds of decentralized approaches in both laboratory scale and real world MG applications have been recently proposed. Starting with a brief review of classical MG control structure, this article presents several methodologies on how these new control strategies may be incorporated within the conventional MG framework. The features of most prominent methods such as DBS, DSC, and MAS are explained and elaborated. Obtained benefits typically include decreased deployment cost, modularity, avoidance of single point of failure, and others, leading to overall better performance.

Conversely, it is important to recognize that application of most decentralized control algorithms lies on the border between electrical engineering and computer science domain. For that matter, one should bear in mind the root differences of common approaches used in the two fields. While the primary concern of a computer scientist is derivation of rigorous mathematical indicators of algorithm's performance in deterministic environment, an on-field electrical engineer deals with a system composed of a number of non-ideal devices. In that sense, he will regularly face application-specific problems, while at the same time the response of the system under his consideration will not exactly follow the patterns predicted by theory. Not diminishing a big value of theoretical analysis which can provide useful insights in advantages and limitations of given algorithms, successful lab-scale and real-site experimental demonstrations are those inevitable steps forward which give a key momentum for a certain technology to reach an industrial market. Indeed, we are presently at the stage where more than a decade of immense progress in computer science and automatic control is starting to show its face in practical applications with more than promising initial results.

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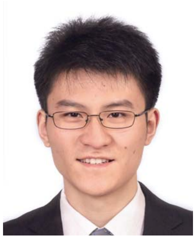

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