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The Evolution of Research in Microgrids Control

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***Abstract*—Microgrids (MGs), as novel paradigms of active Distribution Networks, have been gaining increasing interest by the research community in the last 20 years. Currently, they are considered as key components in power system decentralization, providing viable solutions for rural electrification, enhancing resilience and supporting local energy communities. Their main characteristic is the coordinated control of the interconnected distributed energy resources (DER), which can be realized by various methods, ranging from decentralized communication-free approaches to centralized ones, where decisions are taken at a central point. This paper provides an overview of this development focusing on the technical control solutions proposed by reseachers for the various levels of MG organization hierarchy. A critical assessment of selected, popular technologies is provided and open research questions regarding the trend to more decentralized power systems are discussed.**

***Index Terms*—Microgrids, decentralization, hierarchical systems, primary control, secondary control, tertiary control, distributed control, decentralized control.**

I. INTRODUCTION

MICROGRIDS, were first introduced in the 2001 IEEE PES WM Panel led by Bob Lasseter [1], followed by his conference paper [2] and the CERTS report [3] in 2002. The basic idea was further developed in two consecutive European projects, called *"Microgrids"* and *"More Microgrids"* [4]. The first project dealt with challenges, concepts and laboratory tests, while the second developed seven pilot installations, including the first application of distributed techniques in a MG in the island of *Kythnos* [4]. At the same time, several research projects and pilot MG installations have been developed in Japan, USA and Canada followed at an increasing rate in China, Korea, Latin America, and elsewhere [5]. Moreover, MGs have been considered as viable solutions for rural electrification in areas developing countries with weak transmission infrastructures.

These extensive activities have largely proven the many technical, economic, social and environmental advantages associated with MGs, and have been studied by all involved stakeholders. Advantages include increased energy efficiency, minimization of overall energy consumption, reduced environmental impacts and improvement of energy system reliability and power quality due to the ability to switch seamlessly to islanded operation. From a network point of view, benefits include reduced losses, support in congestion management, voltage problems and flexibility in planning by allowing cost efficient infrastructure replacement strategies, etc. [6]. Lately, MGs have gained increasing importance by their potential role in enhancing power system resilience against natural disasters [7, 8] and also as technical infrastructures to support Local Energy Communities.

In the context of Smartgrids, MGs are widely seen as one of the best ways to unlock the multiple DER benefits and have therefore been characterized as the building blocks of Smartgrids [9, 10]. Not surprisingly, MGs have attracted huge interest from the academic and research community, dealing with power systems, power electronics and control, although not always from the same point of view, same emphasis and using fully aligned terminology. International scientific organizations have published relevant papers [11, 12] and reports, like IEEE and CIGRE [13], dedicated standards have been developed by IEEE [14, 15] and MGs have been the subject of several international conferences, workshops, and symposia series, e.g. [16].

In the IEEE standard 2030.7 a MG is defined as *"a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes."* [14]. Similarly, CIGRE defines MGs as *"sections of electricity distribution systems containing loads and DER, (such as DGs, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded"* [13]. In both definitions, the two distinct features that distinguish MGs from any distribution lines with DER, are their capabilities to: i) operate islanded, thus achieving increased reliability and resilience, ii) appear to the upstream network as controlled, coordinated units.

These characteristics open opportunities for the integration of MGs in the power system, but also pose significant technical challenges to their operation and control, especially during the islanded mode of operation. Thus, the transfer from interconnected to islanded operation might face relatively large imbalances between generation and load that have to be managed seamlessly by efficient demand participation and use of new technologies. Power electronics (PEL) interfacing the interconnected DER allow the application of versatile solutions, e.g. they allow to relax the strict boundaries of voltage and frequency imposed mainly by the stability of directly coupled rotating electrical machines. This makes the operation of DC and hybrid AC/DC solutions viable alternatives for MGs. Nevertheless, the dominant presence of PEL significantly increases control complexities. The absence of inertia and the relatively short lines of MGs infrastructures increase considerably the difficulties of frequency and voltage control. The particular distribution network characteristics, e.g. relatively large resistance to reactance ratios, lead to strong coupling between active and reactive power with important control and market implications, especially for voltage. Fur-

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thermore, the limited contributions of PEL interfaced DER to faults causes protection and safety challenges that need to be overcome by innovative solutions. It should also be noted that MGs, as distributed structures covering limited geographical areas within distribution networks lack the computing and communication facilities available in typical power systems, e.g. they cannot afford dedicated control rooms, system operators, etc. Thus the applied solutions need to be cheap, besides efficient.

The first control methods applied to MGs have imitated the traditional techniques applied for primary and secondary control of large power systems. For example, the philosophy of the classic droop techniques used by the synchronous machines governors and AVRs have been emulated in the PEL interfacing DER [4, 6, 17–23]. The centralized philosophy of generation scheduling has been also adopted for the economic operation of the MG [22–24]. The specific characteristics of MGs however and the versatility provided by the embedded PEL have opened ways for the application of novel ideas and more sophisticated control methods and techniques. The aim of this paper is to sketch the evolution of research in MGs control, focusing on recent advanced and popular methods. Although several papers and books have provided excellent reviews of specific MGs aspects [25–29], the authors believe that this paper is different, because it embraces all levels of the MGs hierarchy. It starts from primary control and covers up to the MGs' interaction with the outside world, i.e. neighboring MGs and the upstream distribution network. Moreover, it provides a critical assessment of the various methods, categorizes the various applications according to the basic levels of hierarchy, identifies trends and draws conclusions regarding future research in MGs. It should be noted that it is impossible to cover the vast 20 years literature on MGs in a single paper. The authors have tried their best to include some of the most relevant references and apologize in advance, for not including several important works due to space limitations.

The paper is structured as follows: A definition of the classical hierarchical levels in the context of MGs is provided together with key applications followed by a more detailed description of selected distributed and decentralization technologies. The effects of decentralization on the hierarchical consideration of MGs is discussed leading to general conclusions and directions for further research.

II. FUNCTIONAL MULTI-LAYER STRUCTURE OF POWER SYSTEMS

The diversity of equipment and complex relations among multiple subsystems characterizing power systems implies multi-layer approaches for their control. While it is difficult to provide a precise definition of multi-layer hierarchical structures, every hierarchy is characterized by a set of common properties, namely: i) vertical arrangement of subsystems, ii) priority of action of the higher level subsystems and iii) dependence of the higher level subsystems upon actual performance of the lower levels [30]. Priority of actions is oriented in a top down, command fashion, although the effective usage of the multi-layer structure requires that decision units have a certain freedom of action, so that functioning on any level is, as independent as possible. Decoupling enables the more efficient and detailed study of systems behavior, while the level of abstraction provided by each level simplifies mathematical formalization. Description of the higher levels of hierarchy becomes broader and refers to larger subsystems and longer reaction times. Decision problems at the higher levels are normally considered as more complex, since they need to take into consideration the slower aspects of the overall systems behavior. The concept of layers is referred to the vertical decomposition of a decision problem into sub-problems. The different architectures proposed for tackling these sub-problems can be classified in groups, which mainly differ in i) the complexity of the model considered for describing the dynamics control of the system and ii) the necessary degree of communication among controllers of different operating units or different layers of the control system hierarchy (Fig. 1).

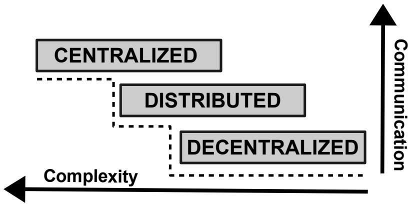

Fig. 1: Classification of control architectures.

In the context of large power systems, three control architectures have been developed, the *centralized*, the *decentralized* and the *distributed* topology. The main feature of the *decentralized* architecture is that the control system is composed of several individual controllers, which do not share any information, independently of whether or not the selection of the controlled variables takes into account the interactions within the system [11, 31]. Recent interest triggered by advances in technology and telecommunications has focused research attention into *distributed* control structures. In this architecture, it is assumed that some information is shared among controllers, so that each of them has some knowledge about the behavior of the others, thus raising the overall performance. However, there is always a trade-off between communication burden and performance. *Centralized* architecture consists of a single controller which manages and communicates with all the other components control decisions based on knowledge of all control inputs optimized in a single optimization problem. Comparison of the aforementioned control architectures in terms of various criteria is presented in Table I. An overall architecture of these approaches is illustrated in Fig. 2. In the following, the hierarchical control structures are described in the context of MGs control.

A. Hierarchical control of Microgrids

The MGs hierarchy follows the architecture of conventional power systems comprising three main layers that correspond to their main control functionalities, namely *primary* (field level), *secondary* (microgrid level), and *tertiary* (grid level). In the literature, many control methods have been proposed, while hierarchy is extensively discussed [2, 6, 11, 25, 32]. There is no general agreement however on the boundaries of

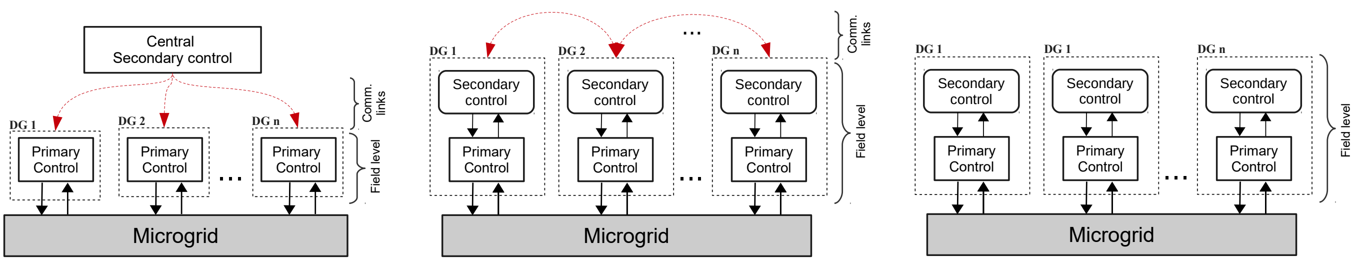

Fig. 2: Various architectures of secondary control: from the left the centralized, the distributed and the decentralized architecture.

the control functions, as further discussed in Section IV. In general, the different layers are separated according to their control functionalities and their time intervals, in a hierarchical dependence, as depicted in Fig. 3.

Before proceeding with the different levels of control hierarchy we would like to comment on the significant research that has taken place in the domain of DER control. This is referred to by some authors as level 0 [22]. DER units in MGs can be controlled either in grid forming or grid-feeding mode. In the grid-forming mode, the PWM reference signal is shaped according to the desired voltage magnitude and frequency. In grid-feeding mode, a current control loop is implemented in order to maintain the desired levels of active and reactive power injected or absorbed to/by the grid. In MGs, inverters controls (inner voltage, current, PLL, etc.) are a major concern for small-perturbation stability of the system, since their tuning is challenging issue in practice. Several stability issues arisen by due to PEL controls interfacing DER and their interactions with the grid or neighboring DER are reported in [33]. However, this paper does not address this basic PEL control level and the instabilities caused by incorrect control settings, since these are general concerns of modern PEL dominated networks, but are considered out of the scope of this paper.

B. Primary Control

Primary control operates at the fastest timescale. It maintains voltage and frequency stability of the MG and ensures proper power sharing among DER. Technical realization of the respective task is usually ensured by decentralized droop controllers providing several advantages in terms of plug and play capabilities [6]. Classical droop approaches however, suffer from poor transient performance, inability to provide accurate power sharing, unsuitability to serve non-linear loads and dependence on the *X/R* ratio of distribution lines [22].

The poor transient performance is due to the dominance of PEL interfaced generation in the system, which results in reduction of rotating machines inertia. Several techniques have been proposed for the emulation of inertia by PEL interfaced units to overcome this issue. In their simplest form, they use the rate of change of frequency, rather than the frequency deviation, to alter the power of the PEL interfaced units at the beginning of the transient. Thus, they achieve better frequency regulation compared to droop controls [34]. A lot of work has been done to overcome these limitations, several approaches have been proposed and extensive reviews have been published toward this direction [27, 35–40]. The pros and cons of the different active and reactive power sharing methods are presented in [27]. In [40], advanced droop controllers aiming to overcome conventional droop problems are presented. References [35, 36, 39] classify the power sharing methods based on their communication requirements as communication-based and communication-free techniques. In [37] several control techniques employed in MG are presented focussing on their different operational modes. In [38] the advantages and disadvantages of MG control solutions are summarized.

Typical communication-based primary control methods include master-slave control, concentrated control, current sharing control and distributed control. These schemes have a central processing unit and an information distribution block for computing and distributing shared information among the PEL converters. Although these schemes are proven to have fast dynamic response and good current sharing capabilities, they require a relatively high bandwidth communication link. It should be noted that communication delays can affect critically the overall stability of the MG in communication based primary control schemes, as discussed in [41–43]. A low-bandwidth communication based method immune to communication delays is presented in [44]. An adaptive voltage droop control is used to compensate for the effect of voltage drop across the line impedance.

Communication-free methods are based only on local measurements to control the DER. The most prominent approach includes the virtual output impedance method, where an outer cascaded loop is added to adjust the output impedance of the inverter to achieve accurate active and reactive power sharing [45]. Another approach is the adaptive droop control method, where the static droop characteristics are combined with an adaptive transient droop function to attain adjusted dynamic performance [46]. A robust droop controller able to achieve accurate load sharing, under components uncertainties and noise disturbances has been applied in [47]. A synchronized error compensation method for accurate active and reactive power sharing without central synchronization signal has been proposed in [48]. In [49] a voltage-based frequency controller has been proposed. The load-frequency dependence of isolated MGs is utilized so as to regulate the system frequency.

C. Secondary control

Secondary control is responsible for the mitigation of voltage and frequency deviations introduced by primary control. It can also facilitate the synchronization with the upstream network and perform optimal economic management. This

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control layer acts on a slower time scale and its computed control outputs are provided to the primary control level. Conventional MG voltage and frequency restoration is usually implemented by a centralized proportional-plus-integral (PI) controller. This centralized control design may perform well under certain operating conditions achieving optimal solutions [22], it suffers however from single point failures, poor scalability and flexibility.

Distributed and decentralized approaches have been proposed in [26, 50–55] for coordinating the units without the need of a central entity. In these approaches, the DER controllers utilize only local information or estimations about their neighboring units to restore voltage and frequency. In [50] a two-layer, multiobjective control framework that regulates both voltage and frequency, by controlling grid forming inverters and active/reactive powers fed to the grid is introduced for islanded MGs. In [51], a multi agent system (MAS) is proposed for the distributed control of MG operation and its participation in the energy market. Distributed secondary control based on the communication infrastructure of each local DER controller to compute the average values of the control signals is implemented in [52]. A linear-quadratic-regulator (LQR) controller with augmented integral structure to eliminate the steady-state error has been proposed for frequency regulation and accurate active power sharing in [26]. A droop-free distributed method has been proposed in [53] replacing the centralized secondary control and the primary level droop mechanism of each inverter. A washout filter-based power sharing method is presented in [54], that eliminates the impact of communication links and additional control loops in secondary controllers. An alternative, decentralized adaptive secondary control architecture, based on the estimation of the transient responses of the units, has been proposed in [55].

TABLE I

Method	Advantages	Disadvantages
Centralized	• Global optimal solutions	• Significant computational complexity • Communication infrastructure required • Stability affected by communication network • Reduced scalability
Distributed	• Better reliability • Reduced computational burden • Increased scalability	• Communication infrastructure required • Stability affected by communication network • Sub-optimal solutions
Decentralized	• Higher Reliability • No communication requirements • Reduced computational burden • Increased scalability	• No global optimal solutions

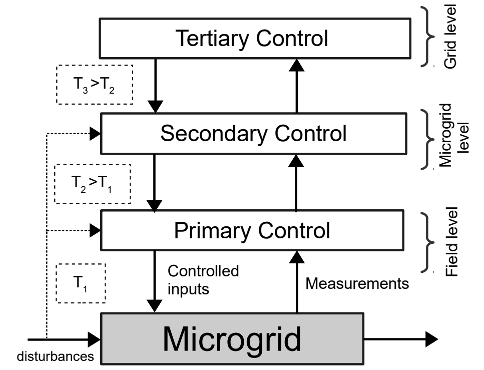

Fig. 3: Hierarchical control strategy of MGs.

Optimal economic operation is usually performed at a slightly higher time frame and its outputs are realized by the voltage/frequency regulation controllers. There is certain ambiguity on whether optimal economic operation belongs to the secondary or tertiary level. In this paper, we consider that economic dispatch of the interconnected MG resources is part of the secondary level, as long as it focuses on the optimization of a single MG operation. In the interconnected mode of operation the inflows or outputs of the MG are determined at the higher tertiary level.

Both distributed and centralized secondary control approaches utilize, to a certain extent, a communication network to perform their control objectives. The characteristics of communication networks, such as time delays and message drop out, can have a major impact on the stability of a closed loop system, as also noted in the primary control layer. Furthermore, the fast nature of MG secondary control makes them more prone to communication weaknesses compared to conventional secondary controls on larger power systems. Several recent works have assessed the robustness of MGs secondary control methods against time delays [56–60], using random modelling of the delays for centralized control [56] or Markov chains modelling of the delays for distributed secondary control [57]. Most of these studies focus on frequency and voltage regulation controllers, however optimal energy management controls on the secondary levels can be also affected by communication delays [58]. The robustness and limitations of such controls against communication issues need to be more thoroughly addressed in the future. A multi-objective optimization criterion is proposed for the optimization of communication network design, taking into consideration the secondary control convergence performance, network-relevant time delays, and communication network costs [60].

Finally, the robustness and fault tolerance of the system against uncertainties and unexpected faults should be studied to improve the stability and reliability of the system. Several techniques have been developed to deal with these issues, for instance, in [61] a fault-tolerant supervisory controller is proposed for a hybrid AC/DC MG taking into account uncertainties (output power, forecast errors etc). A robust, efficient and fault-resilient optimal power flow is accomplished maximizing the utilization of renewable DERs. Furthermore, a robust energy management control for MGs is developed in [62] minimizing electricity costs.

D. Tertiary control

The idea of several neighboring interconnecting MGs, called multi-microgrids (MMGs) has been early proposed [5, 17, 63] and further developed in [64–66]. More specifically, according to [6, 64, 67–69], MMGs represent high-level structures, mostly formed at the medium voltage level, composed by a number of low voltage MGs and DER resulting in a more stable and cost-efficient operation and a wider exploitation of the available renewable energy sources [70, 71].

The functionalities of tertiary control determine the MG's interactions with the the neighboring MGs and the upstream network being part of the overall distribution system operation. Taking into account economic, environmental and technological criteria from the external environment (electricity prices, weather forecast data, etc.) and the MGs' dynamical system (energy storage, distributed sources), this level the tertiary control is responsible for the coordination of the MG with the distribution system in order to solve an energy management problem. Tertiary level control provides inputs to the secondary level control by generating optimal profiles as references and setting the optimal operating points [72], which further improve the system's operation stability [23]. In the context of MG operation within a local energy or ancillary services market, the tertiary level controller will determine the energy flow that the secondary level controller should satisfy in order to obtain a cost-effective MG operation. In addition, the tertiary controller having the longest time intervals [73], further optimizes the power flow distribution [25] and the power dispatch of DER. For instance, in [74], the authors control the stored energy to achieve power balance and optimal power consumption. [75] proposes a solution at the tertiary level to further optimize the power flow in an islanded three phase distribution system providing the operating points for all the units. In [76] the optimal solution for economic dispatch is introduced through distributed hierarchical control. Moreover, several methods for tertiary control of MMGs have been developed and are discussed in Section III-C. A relevant method, recently proposed for MGs' optimal operation, is differential flatness, which predicts the system dynamics behavior in continuous-time following a set of constraints. In the domain of MGs, differential flatness has been employed either for cost or power loss minimization [77]. In [78], the authors use differential flatness to find the optimal power flow solution for cost minimization through the regulation of the energy storage system. In general, by taking into account the complete dynamics of the power system, differential flatness is a method used for day-ahead analysis providing off-line optimal profiles in continuous-time for nonlinear dynamical systems. An important property of this method is that it ensures controllability [79] and, combined with specific methods of approximation, can guarantee continuous-time constraint validation.

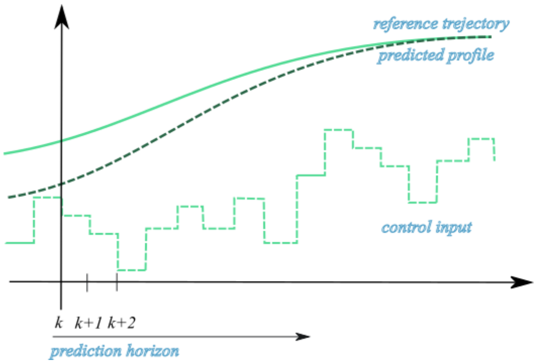

Fig. 4: Diagrammatic Representation of Model Predictive Control

III. ADVANCED POPULAR CONTROL TECHNIQUES

In this section, selected popular control techniques based on the recent literature review are discussed.

A. Model predictive control

Model predictive control (MPC) is a closed-loop control method which optimizes the behavior of the system under a set of constraints. As shown diagrammatically in Fig. 4, taking into account discrete-time system dynamical models and a finite horizon (prediction horizon), the MPC controller provides at each time step an open-loop optimal reference profile. Next, the current step (control input) is sent as input to the system which recomputes the states and regenerates the subsequent optimal profile (predicted profile) converging on the reference trajectory. The basic principles of MPC are outlined in Appendix A. Recently, there has been an increasing interest in the usage of MPC schemes to control power systems, including MGs. [80–83]. The key advantage of MPC methodology lies in the inherent ability of dynamic optimization. MPC can forecast the future behavior of a power system, comprising a feedback mechanism based on a prediction horizon which can handle uncertainties ameliorating its robustness [81]. A major advantage of MPC is the constraints' consideration, even in complicated or nonlinear form. Constraints are essential for MG, where limits are imposed in every component, from voltages and currents of distributed generators and storage units to power flows in the distribution lines [84].

MPC offers a wide range of model structures, prediction horizons and optimization objectives from long-term scheduling with long prediction horizons to fast computations with short prediction horizons and sampling times [84]. Thus, MPC-based controllers have been proposed for various problems, spanning from cost optimization to disturbances mitigation. MPC is not based on a specific control strategy but contains a wide range of control techniques. In general, the optimal and best solution is chosen among all feasible input sequences over a future horizon according to some criteria. The richness of this field allows control designers to customize MPC to their applications. In MGs, applications range from power quality issues requiring high-speed computational requirements to the integration of several MGs

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in complex networks structure with different criteria. For example, [85–87] apply economic MPC in MGs, in order to generate on-line optimal profiles and to solve optimization-based control problems including day-ahead load demand predictions, optimal operation of renewable sources, battery scheduling and cost minimization in MG. MPC is further used to reduce the deviations between nominal and actual values solving a tracking reference problem under a set of constraints. The tracking MPC is often linked to an economic MPC controller. Economic MPC provides optimal profiles (tertiary or secondary level), as control inputs, to the tracking MPC controller (secondary level) in order to mitigate the discrepancies among the actual and the reference variables for voltage or frequency regulation [88]. A stochastic MPC model is formulated to deal with uncertainties and disturbances causing significant performance degradation. In this case, a probabilistic description of the disturbance or the uncertainty allows the optimization of the average performance. In addition, constraint violation is enabled, by introducing the so-called chance constraints, leading to an increased region of attraction where the confidence level of the solution is high [89]. In [90], three different stochastic programming-based MPC techniques are used to deal with the uncertainty of power demand and power generation. These are:

(a) the multiple-scenario MPC, which considers different possible evolutions of the process disturbances;
(b) the tree-based MPC, according to which uncertainty spreads with time giving the possibility to predict more accurately the energy demand and production;
(c) the chance-constrained MPC, that uses explicit probabilistic modeling of the system disturbances to calculate explicit bounds for the satisfaction of the system constraints.

The use of MPC in decentralized and distributed control of MG has been applied to regulate the set points of multiple voltage controllers, operating in standalone mode [87]. In [91] decentralized MPC is used for cost-effective participation of renewable sources in rural communities, by producing day ahead forecasts of PV and load demand in order to optimize the operation of thermal generation considering system stability. In [92], a MPC controller for output voltage control of inverters in an islanded MG with proper power sharing is proposed. In [93] a distributed MPC for optimal power dispatch within a grid-connected MG is used , where each DER contains a local MPC. The overall optimization problem is decomposed into small scale optimization sub-problems, including algorithms which collaborate to provide energy management.

Centralized MPC controllers have high performance in reaching optimal solutions , since they consider globally the components of the system. Nevertheless, they face difficulties in large scale power system applications, with many control variables and complex dynamical models, which can require high computational times. Applying modern computing technologies however, calculation times have been hugely decreased allowing the use of MPC also in lower control levels [94, 95] and different architectures. Decentralized and distributed approaches have been proposed to tackle the scalability problem. However, in decentralized topologies, where each subsystem is managed by a single agent applying local optimization, the lack of knowledge about the overall system leads to sub-optimal solutions, since the prediction accuracy is decreased [96, 97]. Distributed MPC is also based on communication among neighboring agents, which, although limited, can suffer from related failures [84].

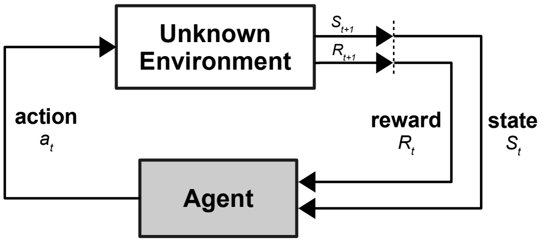

Fig. 5: Simplified diagrammatic representation of Reinforcement Learning

B. Reinforcement learning

Reinforcement learning (RL) methods allow controllers to learn based on interactions with the environment by observing their own actions. The basic idea behind an RL model is shown in Fig. 5. The basic equations describing the RL principles are provided in Appendix B. Most practical control problems are based on the *Actor-Critic* structure, where an actor component (learning agent) applies an action or control policy to the environment, and a critic component assesses the value of that action. A family of real time RL methods for finding optimal control policies have emerged under the broad name of approximate/adaptive dynamic programing (ADP). The main feature of ADP is that it approximates the optimal policy without knowledge of system dynamics [98]. Deep reinforcement learning (DRL) methods approximate the value and/or policy functions with deep neural networks. Thus, DRL combines the perception ability of deep learning with the decision-making ability of reinforcement learning [99].

An extensive work on RL and DRL applications in power systems have been presented in [99–101]. [101] focuses an overview of RL methods with emphasis on demand response applications. RL methods have been used for the control of standalone MGs [102–105]. A novel actor-critic based implementation for the regulation of autonomous MGs based on a heuristic dynamic programming algorithm with partial knowledge of the MG's dynamics was first presented in [102]. In [103], a RL fuzzy controller is proposed for the frequency regulation of an islanded MG is proposed. A cooperative scheme based on adaptive critics to regulate a network of islanded MGs has been used in [104]. The scheme uses local neighborhood information and partial knowledge of the MG dynamics, while an actor-critic neural network with particle filtering is proposed to implement the policy iteration. In [105] an adaptive secondary control method for MGs in the presence of parametric uncertainties is developed. A single critic neural network is used to approximate the local index function and an optimal distributed coordination controller is designed for the tracking problem, while optimizing local performance indices.

Novel control schemes based on RL have been proposed to address various MG problems, like participation in energy trading [106], power quality, energy and storage management [107–111], etc. A mixed iterative ADP algorithm to address the optimal battery energy management and control problem in residential MG is proposed in [108]. A dynamic energy management technique for economical operation of MGs is proposed in [110]. The real-time scheduling problem is formulated as a Markov decision process over a day and a recurrent neural network (RNN) architecture is designed to approximate the optimal value function. Similarly, an ADP-based approach for the optimal operation of islanded MGs by considering battery lifetime, is proposed in [111]. An electricity market model with dynamic pricing and energy consumption in a MG is studied in [106], where RL is applied to reduce system costs for the service provider.

Comparison between MPC and RL: In comparison to optimal control methods, typically employing mathematical programming, like MPC, the biggest advantage of RL is its rapid online computation. RL is model-free, adaptive, with low online complexity, but contrary to MPC, its stability and feasibility are not guaranteed and its robustness is not backed by a solid theory, while it faces difficulties in handling constraints [112]. In general, an MPC agent is expected to outperform the corresponding RL implementation, if the identified model used is accurate. Moreover, RL is difficult to adapt the behaviour of the controllers to unforeseen situations, i.e. the ones that do not belong to the training dataset. This might pose safety concerns for practical applications. High dimensionality of the action spaces, noisy environment, dynamic uncertainty (mismatch between the degree of the model and the degree of the actual system), limited number of actual samples for training are some of the technical challenges that RL face. In general, however RL has proven an effective approach for many power system control and decision problems, including MGs. From a numerical point of view, authors have noticed that MPC is less robust than the corresponding RL implementation [113]. A comparison of RL between MPC characteristics, reported in literature, is shown in Table II.

TABLE II

Characteristics	MPC	RL
Model	• Required	• Not required
Performance	• Optimal (dependent on the model accuracy)	• Sub-optimal
Online complexity	• High	• Low
Offline complexity	• Low (system identification)	• High (value and/or policy approximation)
Numerical stability	• Less robust	• More robust
Robustness	• Mature	• Not yet mature

Combination of RL approaches with MPC and other advanced control methods, like adaptive control, robust control etc. is expected to provide more rigorous techniques for real world applications. It appears that the synergy of MPC and RL opens a promising research avenue for handling stability guarantees.

C. Cooperative and non-cooperative methods

The problem of cooperative control aims to design appropriate distributed control laws, such that a group of agents meets certain coordinated requirements. In its simpler form this coordination focuses on reaching consensus or synchronization of all dynamic agents. In the consensus regulator problem each agent is reaching the same constant state while in synchronization tracking problems each agent reaches the state of the leader node [114].

Multiagent systems (MAS) have been applied for decentralized MG energy management, already in [51]. More recently, MAS based cooperative control, is proposed for distributed MG secondary control [50]. A droop-free distributed method replaces the centralized secondary control and the primary-level droop mechanism of each inverter by data exchange with few neighboring inverters to update its local voltage set points and synchronize its normalized power and frequency.

Furthermore, a distributed architecture for optimal dispatch of DER is proposed in [115]. The impacts of communication delays through sparse communication networks is tackled in [116]. A distributed optimal solution for energy storage systems to maintain the supply-demand balance, while maximizing their welfare and energy efficiency under a multiagent system framework, is proposed in [117].

Cooperative and non-cooperative coordination control approaches have been successfully applied at tertiary level for MGs and MMGs [118]. Consensus-based control considers that all MGs can be coordinated as a single unit, while non-cooperative coordination considers benefits of individual MGs and the entire MMG. A distributed cooperative control strategy for a MGs cluster is introduced in [119] to achieve frequency restoration and power sharing using a two-layer communication network. In [120] a non-cooperative distributed coordination control scheme based on game theory is applied for multi-operator energy trading of MMGs. The proposed method coordinates the individual benefits of each MG and achieves a global objective based on differential game theory.

Cooperative control has been applied for various control problems in MGs and MMGs. The performance of cooperative distributed approaches is strongly dependent on the operation of the communication topology and remains to be proven for applications on higher-order nonlinear systems and uncertain or unknown dynamics that comprise most practical applications. Game theory, due to its capability to model complex interactions among independent players, is expected to have a great contribution in the design and analysis of MMGs. This has led to a new sort of differential game named graphical games, where each agent has its own dynamics as well as its own local performance index.

IV. HIERARCHICAL BOUNDARIES ARE GETTING BLURRED

The specific characteristics of MGs challenge the classical hierarchical control structure applied in large power systems and characterized by different time response of the various levels. For example, the low inertia and short lines in MGs require that the highly variable nature of distributed renewable sources and loads must be compensated fast and accurately in one step, if possible. Thus, current research shows that applying distributed and decentralized techniques makes it possible that MG controllers can adapt very fast to variable and unknown conditions making the value of forecasting, which is extremely challenging at this level and the management of operating reserves mostly redundant. This means that the three levels of the control hierarchy can be integrated in two or one level, allowing as close to plug-and-play operation as possible, without imposing time- scales separation, as proposed in [72] and applied in [121, 122]. For example, in [123] a two-layer control scheme is developed to improve the optimal economic operation of hybrid AC/DC MGs by coordinating the frequency/voltage regulation in individual AC and DC sections with the power exchange of interlinking converters. The upper layer regulates the power exchange by the primary, secondary and tertiary coordination of interlinking converters, while the lower layer solves iteratively the decentralized economic dispatch for the individual AC and DC sections, properly merging all levels of control. This unified treatment of all control levels opens new possibilities for truly plug and play DER operation in MG environments.

V. CONCLUSIONS AND FURTHER RESEARCH

This paper sketches the research evolution in MGs from their first formulation until nowadays. It reviews the various hierarchical levels adopted for MG control, namely the primary, secondary and tertiary level and provides a systematic classification of the various methods applied, in centralized, distributed and decentralized methods. It also presents effective implementations of the various methods and compares their key characteristics. Published results show effective applications in all levels of MGs control that can be further adapted depending on the physical characteristics of each MG. It is shown that effective voltage and frequency stability of the MG and proper power sharing among DER is achieved at the primary level, restoration of voltage and frequency excursions to nominal values and optimal economic management is provided at the secondary level and interactions with neighboring MGs and the upstream network are effectively coordinated at tertiary level. Selected popular distributed and decentralized methods are further described and critically assessed. As a further direction for research, the authors believe that the combination of RL methods with MPC and other advanced control methods, is a promising area, able to provide more rigorous techniques for real world applications. Research on the performance of cooperative distributed approaches in MG and MMG applications is another important area for further studies. Finally, the possibility of considering a unified level of control merging the traditional hierarchical levels of MGs by applying decentralized and distributed techniques deserves further in-depth investigations. Such a unification of the hierarchical levels has the potential to improve the speed, efficiency and optimality of MG applications. The authors strongly believe that the decentralization of power system control aided by further evolution of MGs, in collaboration with large centralized systems at transmission level is essential to face the challenges posed by the increasing complexities of modern power systems with increased levels of DER integration [8].

APPENDIX A
MODEL PREDICTIVE CONTROL BASICS

According to [84], MPC makes explicit use of the system's model in order to solve an optimization problem by minimizing a cost function subject to a set of constraints.

Consider the following nonlinear discrete-time system:

$$\tilde{x}(k+1) = f_d(\tilde{x}(k), \tilde{u}(k)), \;\; x(t) = \tilde{x}, \;\; k \geq t,$$

with the state vector $x(k) \in \mathbb{R}^n$ and the control input $u(k) \in \mathbb{R}^m$. For the considered optimization problem, the cost function to minimize is defined as [124]:

$$\begin{aligned} \mathcal{J}_{MPC} = & \sum_{k=t}^{t+N_p-1} (\tilde{x}(k)^\top Q_{\tilde{x}} \tilde{x}(k) + \tilde{u}(k)^\top R_{\tilde{u}} \tilde{u}(k)) + \\ & + \tilde{V}_f(x(t+N)), \\ subject\ \ to: \;\; & \tilde{x}(k+1) = f_d(\tilde{x}(k), \tilde{u}(k)), \\ & \tilde{x}(k) \in \tilde{\mathcal{X}}, \\ & \tilde{u}(k) \in \tilde{\mathcal{U}}, \\ & \tilde{x}(t+N_p) \in \tilde{\mathcal{X}}_f \;\; (terminal\ \ constraint), \end{aligned}$$

where $Q_{\tilde{x}}$ and $R_{\tilde{u}}$ are matrices of appropriate dimensions, $\tilde{\mathcal{X}}$ is the set of state constraints and $\mathcal{U}$ the set of input constraints. The term $\tilde{V}_f(x(t+N))$ represents the terminal cost and forces the states to always exist in a particular set.

APPENDIX B
REINFORCEMENT LEARNING BASICS

Markov Decision Processes (MDPs) are mathematical frameworks to describe an environment in reinforcement learning and almost all RL problems can be formalized using MDPs. An MDP consists of a set of finite environment states $\mathcal{S}$, a set of possible actions $\mathcal{A}$ in each state, a real valued reward function R and a transition model $\mathbb{P}(S_{t+1}|S_t, \alpha_t)$. Our goal is to choose actions over time so as to *maximize* the expected value of the return, i.e. choose the optimal *policy*.

To maximize the long-term cumulative reward, the return G_t is equal to:

$$G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \ldots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

where the discount factor $\gamma \in [0,1]$, values the immediate reward above delayed reward. A *policy* π is a distribution over actions given states: $\pi(\alpha|s) = \mathbb{P}(A_t = \alpha | S_t = s)$.

The *state-value function* $V_\pi(s)$ gives the long-term value of state s, when following policy π:

$$V_\pi(s) = \mathbb{E}_\pi[G_t|S_t = s] = \mathbb{E}_\pi[\sum_{k=0}^{\infty}\gamma^k R_{t+k+1}|S_t = s]$$

The *action-value function* $Q_\pi(s,\alpha)$, is the expected return starting from states s, taking action α, and following policy π:

$$Q_\pi(s,\alpha) = \mathbb{E}_\pi[\sum_{k=0}^{\infty}\gamma^k R_{t+k+1}|S_t = s, A_t = \alpha]$$

An optimal policy π^* is a policy that achieves the largest cumulative reward in the long run.

The *optimal state-value function* $V_*(s)$ is the maximum value function over all policies:

$V_*(s) = \underset{\pi}{max} V_\pi(s)$.

Similarly, the *optimal action-value function* $Q_*(s,\alpha)$ is the maximum action-value function over all policies:

$Q_*(s,\alpha) = \underset{\pi}{max}\, Q_\pi(s,\alpha)$

We can find the optimal policy immediately by maximizing $Q_*(s,\alpha)$ over all actions:

$$\pi_*(\alpha|s) = \begin{cases} 1 \quad if & \underset{\alpha\in\mathcal{A}}{argmax}\, Q(s,\alpha), \\ 0 & else \end{cases}$$

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