A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems

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***Abstract*—Renewable energy sources are one key enabler to decrease greenhouse gas emissions and to cope with the anthropogenic climate change. Their intermittent behavior and limited storage capabilities present a new challenge to power system operators to maintain power quality and reliability. Additional technical complexity arises from the large number of small distributed generation units and their allocation within the power system. Market liberalization and changing regulatory framework lead to additional organizational complexity. As a result, the design and operation of the future electric energy system have to be redefined. Sophisticated information and communication architectures, automation concepts, and control approaches are necessary in order to manage the higher complexity of so-called smart grids. This paper provides an overview of the state of the art and recent developments enabling higher intelligence in future smart grids. The integration of renewable sources and storage systems into the power grids is analyzed. Energy management and demand response methods and important automation paradigms and domain standards are also reviewed.**

***Index Terms*—Ancillary services, automation architectures, control concepts, demand response (DR), demand-side management (DSM), distributed generation, energy storage, inverters, microgrid, power balancing, power networks, power system automation, renewable energy sources, smart grid, standards.**

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I. Introduction and Motivation

THE electric energy systems worldwide have to satisfy a continuously growing demand for electricity and simultaneously provide a stable supply. Today, the worldwide power generation is dominated by fossil fuels resulting in an increase in CO_2 emissions and global warming as indicated by the "World Energy Outlook 2013" from the International Energy Agency [1]. In order to counteract, there is a clear trend toward a sustainable electric energy system. Minimizing greenhouse gas emissions caused by power generation will only be possible if renewable sources such as photovoltaic (PV) systems, wind generators, biomass, and combined heat and power systems are being installed on a large scale [2]–[4]. They are typically available in a decentralized way as distributed energy resources (DERs) [3]. Recent research results, technology developments, and regulatory alterations have been fundamentally changing the framework conditions; the planning, management, and operation of the power systems have to be redefined.

In addition, advanced metering, management, and optimization concepts on the consumer side are currently in the focus of research and demo projects [5]–[7]. The objective is to effectively manage load peaks, by load shedding, peak-load reduction, etc., to maintain or improve the security of supply.

The above-sketched developments are leading to complex architectures with a tremendous amount of interconnected and intelligent components and subsystems, which have to exchange both the information and the energy. Today, power utilities and system infrastructure operators are increasingly confronted with a highly dynamic and less predictable demand–supply balance. Moreover, consumers are evolving into so-called prosumers—local energy consumers and producers.

The availability of Information and Communication Technology (ICT) and advanced automation concepts provides various opportunities to operate highly interconnected power grids with corresponding components in a more effective way as today, known under the term smart grid [8]–[10]. According to Yu *et al.* [8], it covers the intelligent integration of all users/

stakeholders connected to electricity networks supporting a sustainable, economical, and secure electricity supply.

This paper therefore discusses important automation architectures, smart devices, control concepts, and energy management principles enabling intelligence, decentralization, and robustness in the field of future electric energy systems and involved components. It provides a brief overview of the state of the art, related work, important activities, and achievements dedicated to smart grid systems and components. Necessary functions and services to operate such an intelligent energy infrastructure are discussed and summarized.

In this review paper, Section II gives an overview of the future electric energy system, corresponding challenges, and necessary functions, which have to be provided by smart components, algorithms, and ICT/automation approaches exploring concepts from the field of artificial intelligence (AI). The integration of DERs playing a major role in a sustainable future system is discussed in Section III, followed by the topic of energy storages in Section IV. The importance of managing the demand side is pointed out in Section V, addressing demand response (DR) and energy management principles. Necessary automation and ICT concepts and paradigms, approaches, and corresponding domain standards are reviewed in Section VI. Finally, Section VII deals with the key findings and with an outlook about future research trends.

II. Future Electric Energy System

The large-scale implementation of DER from renewable sources during the last years fundamentally changed the design, planning, and operation of the power systems in various regions (U.S., Europe, Australia, etc.). It becomes already visible in power transmission and distribution grids. System operators and utilities have to manage the fluctuating power generation from DERs and uncoordinated responses to changing conditions of the power grids [10], [11].

In a number of countries (Denmark, Germany, Italy, Spain, Australia, etc.), levels of renewables (PV, wind, hydro) have already exceeded the local power grid's hosting capacity, resulting in power quality disturbances. Smart grids are one of the most promising solutions to use the existing power grid infrastructure extended with proper ICT methods in a more efficient way, allowing higher penetration levels of DER [12]–[19].

A. Toward Active Power Grids

In the past, the power system operation has been done mainly manually. The integration of DERs with smart power converters (PCs), the possibility to handle peak loads on the demand side, and technology developments in energy storage systems (ESS) together with advanced ICT solutions result in a higher automation degree, as outlined in Fig. 1.

All components in the future smart grid—flexible loads, energy storages, smart substations with on-load tap changers (OLTCs), DERs, metering systems, etc.—are interconnected in addition to the power system with a corresponding communication and automation infrastructure. Together with proper control approaches and strategies, a smart grid system can be implemented, which allows monitoring, managing, and optimizing the future electric energy grids and its components and

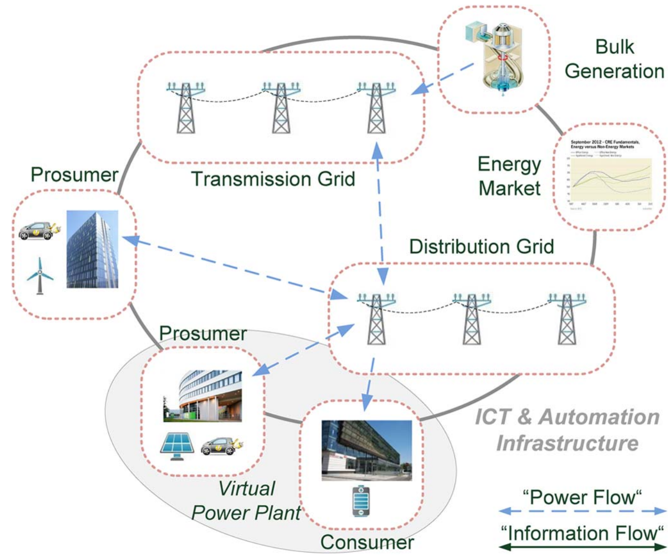

Fig. 1. Smart grid vision: intelligent integration of all users/stakeholders.

users in a more intelligent manner exploring the AI principles [10], [13], [14].

B. Necessary Smart Grid Functions and Services

The management and operation of the future power system and its components—particularly active power distribution grids and microgrids [20]—require new and advanced control functions. They have to be integrated in the corresponding automation solutions, intelligent electronic devices, and grid components. A brief overview of the most important functions and services is given by the following list [11], [21]–[23].

- *Advanced monitoring and diagnostics:* Monitoring and state estimation capability and real-time condition monitoring of components not only in the medium-voltage but also in the low-voltage distribution grids are important future features. Self-diagnostic capabilities are helpful new functions, which are valuable in a power grid with a large amount of DERs, flexible loads, and storage systems.
- *Optimization/self-optimization capabilities:* Fluctuating electricity generation from renewable sources requires the ability to (self-)optimize the operation in medium- and low-voltage distribution grids. In addition, the availability of flexible loads and storage systems add additional degrees of freedom for operating future smart grids.
- *Automatic grid (topology) reconfiguration:* Support of automatic or semiautomatic adjustment of the distribution grid topology due to optimization purposes (e.g., maximum amount of distributed generators and flexible loads) or due to fault management and power system restoration.
- *Adaptive protection:* Automatic or semiautomatic adaption of protection devices (e.g., protection relays and breakers) with respect to the actual power grid conditions (e.g., adaptation of the protection system settings due to the bidirectional power flow caused by DERs).
- *Distributed power system management:* Distributed control with automatic decision finding processes and proactive fault prevention have to be provided for the power system infrastructure operators in medium- and low-voltage grids.

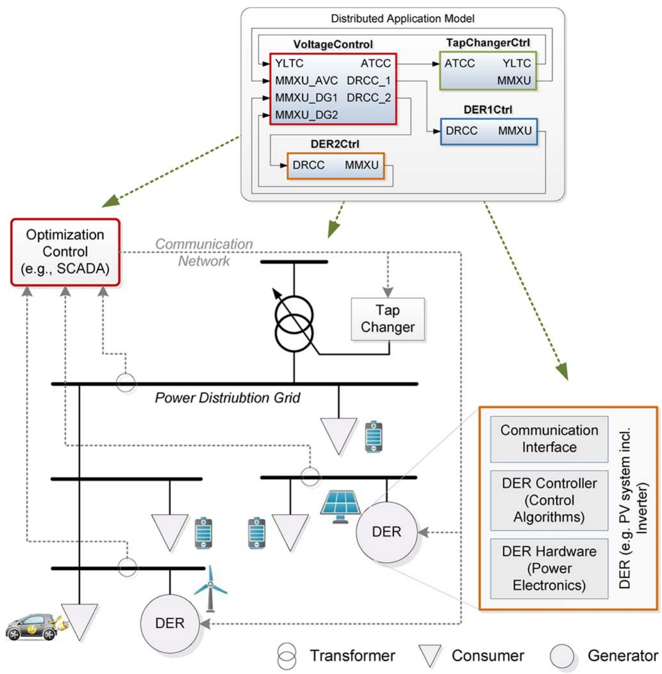

Fig. 2. Necessary intelligence in a smart grid system on different levels.

- *Islanding possibilities/microgrids:* Local operation of islands/microgrids can improve the availability of the electricity supply due to failures on higher voltage levels.
- *Distributed generation/distributed energy resources with ancillary services:* Usage of ancillary services provided by DER (e.g., local voltage or frequency control and virtual inertia) improves power grid optimization (e.g., enhancing the hosting capacity of DER in power distribution grids).
- *Demand response/energy management support:* Electric loads and ESS provide additional flexibility in power system operation. Energy management and DR principles and smart functions have to be provided by the used ICT infrastructure.
- *Advanced forecasting support:* Forecasting of (distributed) generation and load profiles for optimized grid operation.
- *Self-healing:* Automatic or semiautomatic restoration of grid operation in case of component/grid faults helps power system and infrastructure operators.
- *Asset management/condition-dependent power system maintenance:* Preventive maintenance according to component/device conditions and remaining lifetime.

C. Distributed Intelligence on Different Levels

In order to realize the vision of smart grids and the corresponding functions, distributed intelligence on different levels in the power system infrastructure is necessary. The following list and Fig. 2 provide a brief categorization of these levels and indicate what kind of intelligence is needed.

- *Subcomponent level:* Typically, power electronics are used in PCs of DERs. Improvement of local component properties such as harmonics and flicker due to advanced control algorithms and topologies is the main driver for local intelligence on this level. The DER controller and hardware part in the system configuration shown in Fig. 2 can be considered as subcomponents.
- *Component level:* For the integration of DER and distributed energy storages into the power system, advanced component functions such as the provision of ancillary services and adaptive protection possibilities are required. Such intelligence is either used for local optimization purposes (component behavior) or for supporting the optimization of subsystems and systems in a coordinated manner on the higher levels. DER components, as shown in Fig. 2, are typically part of this level.
- *Subsystem level:* Deals mainly with the optimization and/or control of subsystems such as microgrids or home/building energy automation systems. The objective is to optimize (sub)systems with few components (DER, storage system, etc.) in a coordinated manner. Typically, distributed automation and control approaches are used. A storage system together with a distributed generator installed at the customer side can be considered as a subsystem, as depicted in Fig. 2.
- *System level:* Power utility automation, demand-side management (DSM), or energy management is carried out from a systems perspective in a coordinated way using the provided functions and services of the underlying subsystems and components. Central and distributed control approaches and corresponding algorithms are usually applied, as represented in Fig. 2.

Flexibility, adaptability, scalability, local intelligence/autonomy, and open interfaces are key requirements for corresponding ICT/automation systems and component controllers (DER, storage systems, OLTC, etc.) to support and to enable the above-described functions on the different levels [23]. The AI principles and techniques can be used for this purpose with advantages on different levels.

In the following sections, a review of major achievements, technology developments, and research results in the domain of DER (i.e., controlling distributed power generation), ESS (i.e., managing storage capabilities), energy/demand-side management (i.e., managing electricity consumption), and ICT/automation concepts is provided.

III. Integration of Renewable Energy Resources

The integration of DER with the electrical power system requires the usage of PCs, necessary for adapting fluctuating produced energy with grid requirements; they are also necessary for efficient operation of ESS. The most appropriate topologies, devices, control, and modulation techniques are fundamental in order to fulfill grid codes/interconnection rules and for avoiding the occurrence of instability or synchronization problems, faults, and for obtaining high-efficiency operations. However, the nonlinear behavior of PC causes the injection of harmonic distortions at the point of common coupling (PCC). Moreover, stable outputs could not be ensured in every condition, such as during deep voltage sags. The subsequent generated electromagnetic interferences may lead to undesired situations, loss of synchronization of DERs, grid instability, and faults. These situations can be mitigated by insertion of special converters, namely, power factor controllers, static compensators, and ESS, as well. In addition, the implementation of ICT technologies and concepts allows prevention of abnormal situations [24]–[26].

To guarantee power quality at the input ac mains, harmonic standards and engineering recommendations must be also adopted to limit the level of distortion at the PCC [27], [28].

PC topology plays a significant role in full integration of renewable energies with the electrical power grid. Nowadays, there is a significant trend of considering multilevel converter (MLC) topologies for new smart-grid-related projects. They basically consist of arrays of power semiconductors in series and/or in parallel, producing output voltage with discrete stair-stepped waveforms. Typical topologies of MLC are diode clamped or neutral point clamped (NPC), active NPC, capacitor clamped or flying capacitor, and cascaded MLCs [29]–[31]. A significant part of their behavior (namely, the quality of output waveforms) depends on control and modulation methods. Popular methods are multilevel sinusoidal pulsewidth modulation (PWM), phase disposition, multilevel selective harmonic elimination, harmonic mitigation, and space vector modulation [32]–[38]. The higher the number of levels, the higher the quality of the output voltages and currents due to reduced electromagnetic emissions determined by chosen modulation technique is. Due to their intrinsic characteristics, MLCs operate at low frequency and at medium voltage; moreover, they eliminate common-mode currents. Additionally, they do not require expensive passive filters, while achieving significant improvements in terms of efficiency and cost. For such reasons, their usage simplifies DER design and allows direct connection of PC with power distribution lines.

Another emerging topology in DER is the so-called modular MLC (MMC) [39]. This can be considered a new and promising design approach consisting in connecting basic PC modules in series and/or in parallel. Typically, each module consists of a half-bridge or a full H-bridge with a dc capacitor for energy storage and all the necessary sensors and control circuits. With this approach design, realization and maintenance of high-power and/or medium-voltage converters are simpler because hardware can fully exploit modularity. Usually, the design of the single modules is often very complex due to the numerous constraints. Moreover, software and control become more complex, too, due to the additional intelligence and communication capability needed by interactions among the modules. One of the early applications of MMC was in high-voltage direct current systems, but due to their significant advantages in terms of flexibility, scalability, maintenance, and costs, their usage has been extended to DER, e.g., megawatt-range wind turbines and to other high-power applications as well. Of course, there are also some drawbacks, mainly caused by the intrinsic nature of modular systems, namely, the use of connectors with potential interconnection problems, the potential instabilities due to interaction among modules, the increased distances among critical components, and the additional design complexity, due to the modularity.

Comparison among MLC and MMC is not simple; moreover, MLC can be designed with a modular approach. However, in the authors' opinion, it should be expected a growth of both technologies and the diffusion of modular design approaches, both in hardware and in software as well.

In modern power systems, PCs are also providing ancillary services (e.g., local voltage or frequency control) using reactive and active power management functions and therefore providing additional possibilities for the power grid operation. Examples are local voltage control possibilities at the PCC, which can be also used in a coordinated way to maintain power quality due to a high share of distributed generation.

It is expected that, in the future, electromagnetic transformers will be replaced by electronic counterparts, the so-called "solid-state transformers (SSTs)," based on previous technologies [40] (an application example for SST is provided in Section VI-A). In fact, they can be easily integrated within the smart grid, interconnecting distinct electrical power grids operating with different characteristics (e.g., voltage and phase). They can simplify grid management during normal operating conditions and during faults. Moreover, they could simplify power factor control and harmonic reduction as well. In general, they are more compact in size and are expected to become cheaper than traditional transformers, penalized by the high cost of copper and of magnetic materials [41]–[43].

Since power levels become higher, optimum modulation of PC is fundamental for satisfying power quality demand and for improving design, performances, and efficiency. Elimination or mitigation of one or more harmonics from output without the use of passive filters is very important for achieving significant improvement in terms of cost, reliability, and space. Genetic algorithms and particle swarm optimization [44]–[46], AI methods based on bacterial foraging algorithms, ant colony methods, and homotopy and continuation theory [47]–[49] are typical methods capable of finding the converter switching angles necessary for modulation. However, all these methods require offline calculations, hence offer limited flexibility. Recently, some analytical methods capable of identifying all possible switching angles eliminating a desired harmonic, for a fixed modulation index, in a five-level cascaded inverter have been successfully developed, allowing real-time implementation without the use of lookup tables [38]. The transcendental equations characterizing the harmonic content can be converted in polynomial equations, which can be then solved using the method of resultants from elimination theory [50], [51]. It has been shown that a pair of harmonics chosen among third, fifth, and seventh can be eliminated in a five-level inverter output voltage using the method described in [52], based on graphical analysis by using Chebyshev polynomials and the Waring's formulas. In order to generate switching PWM patterns with low harmonic content, avoiding the elimination of some specific harmonics, the total harmonic distortion can be treated as a global problem by using a general-purpose random-search heuristic algorithm [53]–[55].

In summary, AI techniques and concepts play an important role for controlling and optimizing elements on the subcomponent and component levels. It is expected by the authors that, in the future, more intelligent algorithms and concepts are being used on this level.

IV. ESS Integration

The increasing share of intermittent and distributed generation units into the power system is the main driver for the integration of stationary storage systems into the power system. Future demand for storage will include both long-term large-scale storage such as hydrogen or natural gas and small-scale short-term storage systems such as batteries or flywheels within the distribution system [56], [57].

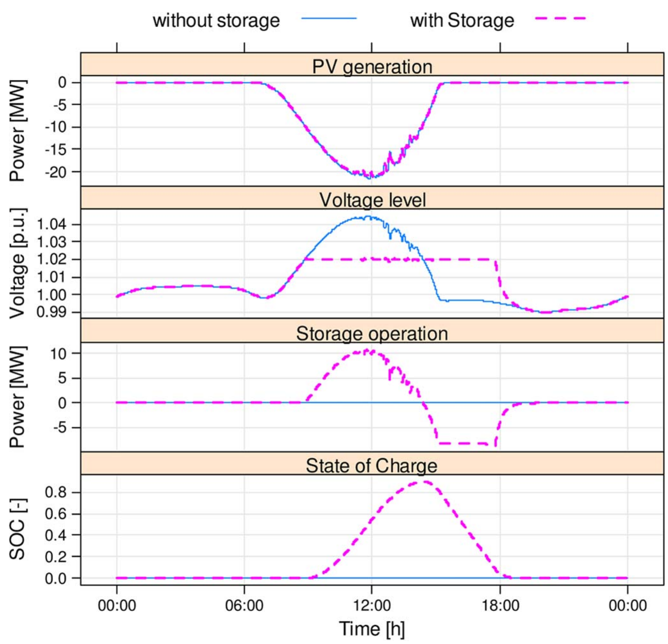

Fig. 3. Exemplary simulation of an ESS providing voltage control for a local PV generator [65].

The number of possible applications for grid-connected stationary storage is large. Depending on the methodology and the granularity of the segmentation between 9 and 16, distinguished services are reported in the literature [57]–[60].

Requirements to controls and ICT strongly depend on the necessary service or combination of services and the storage technology in use. A common picture showing the state of the art for all services and control architectures is hence not possible. This review focuses on the implementation and operation of ESS providing services for power quality. The most important service discussed is voltage control to maintain power quality and to allow for a higher hosting capacity of renewable sources [61]–[64].

Fig. 3 shows a simulation study of an ESS providing voltage control for a local PV generator [65]. It absorbs all active power above a defined threshold (e.g., 1.02 per unit) to avoid intolerable voltage levels. When they fall below the defined threshold, the ESS starts the discharging.

The storage system is not the only component participating in voltage control schemes. Often, such functions are provided by DER-based inverter systems and/or OLTC [62], [63]. In a number of cases, the analyzed storage systems also provide additional services such as local consumption of DER [66].

For the case of voltage control, different architectures, ranging from autonomous control with and without remote configuration ability to central control, are analyzed.

A. Autonomous Control With Central Configuration Ability

This approach describes autonomous control of single components based on predefined function characteristics with the opportunity to reconfigure functions from a central unit. The control algorithm can also be based on rules in combination with threshold levels. The configuration of the single components is often based on offline or online load flow calculations of the local power grid [62].

A control architecture based on predefined droop characteristics is discussed in [63]. It is shown that the simple adoption of the droop characteristics for single systems decreases the investment costs for the ESS by reducing the required capacity significantly. One approach to achieve this functionality is the implementation of a droop control function according to IEC 61850 [17] or SunSpec [67]. Both the standard frameworks not only provide a definition of standardized input and output registers of inverter-based distributed generators and storage systems but also define standardized functions and services. Each function defined in IEC 61850 or SunSpec can be configured based on a predefined set of parameters.

Marra *et al.* [68] discussed a threshold-based control algorithm for increasing local consumption and simultaneously providing voltage control. The defined threshold is based on the nominal power of each PV array. When the PV penetration in a feeder changes, the threshold for each storage system changes as well. Once the threshold is set for each storage system, they operate autonomously. While the strategy provides consistent voltage control, the impact on local consumption is not discussed. The authors of the work showed that, with an increasing PV penetration, the requirements for the storage system increase significantly. Only simple algorithms from the AI point of view are being applied in the current solutions, but there is space for more intelligent concepts and algorithms in future developments.

B. Central Control Concepts

In contrast to autonomous control, central approaches need a functioning control unit and a communication network. Attached components do not make decisions by their own. An algorithm where storages provide voltage control with OLTC simultaneously on the low- and medium-voltage levels is shown in [62]. Single actions are rated based on their costs and impact with offline load flow simulations. A central controller optimizes component behavior based on measurements.

The authors in [69] discussed a central control algorithm for voltage and frequency control for microgrids based on droop control. The battery storage system is the primary control unit for maintaining both voltage and frequency. It is only active when the microgrid changes to islanding mode. When in islanding mode, the battery ESS (BESS) is coordinated with local DERs over a central control unit.

Sugihara *et al.* [70] proposed a central control approach where the distribution system operator (DSO) has direct control access to distributed storage systems at customer sides. Access is granted in exchange of a subsidy for the storage system. The described approach takes advantage of the reactive power compensation abilities of the storage converter. Voltage control facilitated by active power control is not included in the proposed approach. Like other control approaches, the decision foundation is based on characterization of the network via load flow calculations. The authors showed that the described approach allows the DSO to maintain acceptable voltage level on a cheaper base than with other measures.

The paradigm of the distributed versus centralized control approaches is in the focus of attention, but the trend toward distribution is clearly identifiable. This is the only way out in such complex systems.

V. DR and Energy Management

Future electric energy systems endowed with smart metering, intelligent electronic devices, and advanced ICT will be characterized by greater responsiveness and efficiency decisions by the customers and the utility provider [5], [8], [9].

Recent research studies have confirmed, indeed, that DR is essential for the operation of future smart grids [7], [71], [72]. DR denotes variations of the electric consumption by customers when the price of electrical energy changes over time or in presence of financial incentives or reliability signals [71]. Regulatory and policy frameworks, such as the Energy Policy Act of 2005 in the U.S., have been recently enacted, which promote DR and allow customers and load aggregators taking part by means of DR resources in energy, capacity, and ancillary services markets [73]–[75]. In addition, the FERC Order 719 contributed to remove obstacles to the participation of DR in wholesale markets by allowing load aggregators bidding DR on behalf of retail customers into markets. In 2011, FERC Order 745 determined that DR resources should be compensated at the locational marginal price for their participation in wholesale markets, thus establishing an equal treatment between demand-side resources and generation [76], [77].

In Europe, even if it is recognized that DR could play a relevant role in favoring penetration of DER [78], policies are more devoted to energy efficiency and DSM, rather than DR, which is mainly considered in order to decrease the costs of load peaks.

A. DR Programs

Nowadays, mainly due to both new regulatory and policy frameworks and new technologies, a great share of the end-use electrical loads can be engaged in DR programs in a more controlled manner. Automated control systems operating on a continual basis are replacing traditional load control systems, and these new systems are now available for commercial, industrial, and individual residential customers. Often, residential DR should be aggregated in order to compete in the wholesale energy markets.

While the direct control of the end-use electrical loads existed for decades, price-driven response programs, using a price signal as a means for demand control, are beginning to emerge and to be the subject of study at the distribution level. Combining the automation of the demand bids and the strategies to respond to the growing user empowerment with respect to its domestic consumption, DR programs are the ideal solution to reduce demand power and prevent grid congestions.

Diverse time-differentiated pricing models have been proposed, such as real-time, day-ahead, time-of-use, or critical-peak pricing [71]. The basic ideas are the same for all these models; first, it is required that retail prices reflect fluctuations in wholesale prices so that users pay for what they consume at the market price and that users themselves are free to decide whether or when to buy the energy they need. In addition, these models encourage users to shift high loads during off-peak hours in order to reduce the cost of electricity and to help reduce the peak-to-average ratio of demand [79].

The authors in [80] aimed at evaluating the potential impact that the implementation of DR methodologies and the dynamic pricing could have on the operation of the electricity infrastructure. They state that models at multiple levels of analysis are essential in order to simulate a DR program using both a distributed and centralized control. Considering that DR techniques are moving toward approaches based on a more and more interactive model of communication, active, interactive, and transactive electricity markets are proposed.

In an active market, a price signal is sent from the central controller to the end-use customer so that he can respond to price variations. In an interactive market, the end-use customer can also send information back to a central controller so that the price signal can be changed. In a transactive market, interactive controllers are used, which are also able to automatically operate on behalf of the end-use electrical load.

B. DSEMS

In [81] and [82], the authors proposed a decision support and energy management system (DSEMS) that can be used for residential, commercial, and industrial customers. This concept is modeled as a finite state machine and consists of some scenarios that can be selected according to the customer's preferences. The inputs of the systems are the measured energy from available resources (i.e., from the distribution network and local or other electrical or thermal energy sources) and information related to hourly electrical and thermal energy tariffs, status of the network in terms of components availability, users requirements, contract constraints, messages from the DSO, and environmental parameters. The system generates the command signals for the management of thermal and electrical loads and the messages for the end user (i.e., information about controlled devices, load state information, energy consumption and energy saving suggestions for achieving energy saving, and messages from the DSO).

The DSEMS is also endowed with a climate control, both used during summer and winter seasons. The temperature set point of the split is progressively modified in order to decrease the power absorption when the maximum power limit is exceeded or during periods when the cost of energy is high [81].

In [82], the effectiveness of the DSEMS for residential applications is evaluated by varying the energy class of the house from A to G and considering different scenarios (e.g., comfort, economy, and energy) for two locations characterized by different external climatic conditions. The simulated and experimental tests evidence that the use of DSEMS allows decreasing both energy consumptions and costs by not deteriorating the user comfort. Higher benefits can be obtained for houses with high energy consumption and characterized by a lower initial energy class with a maximum reduction of about 30% of the initial energy consumption achieved for class G houses [83]. This system is also useful for DSOs as it can help mitigating peak loads due to air conditioners usage.

C. DRP Implementation

Customers can take part to DR programs through an intermediary or directly with the utility. In the case when end-use customers are gathered by intermediaries, generally called DR providers (DRPs), the end-use customers' aggregated capability is presented to an organized market by DRPs [71]. Automated response technologies, generally classified as control devices, monitoring systems, and communication systems, are required

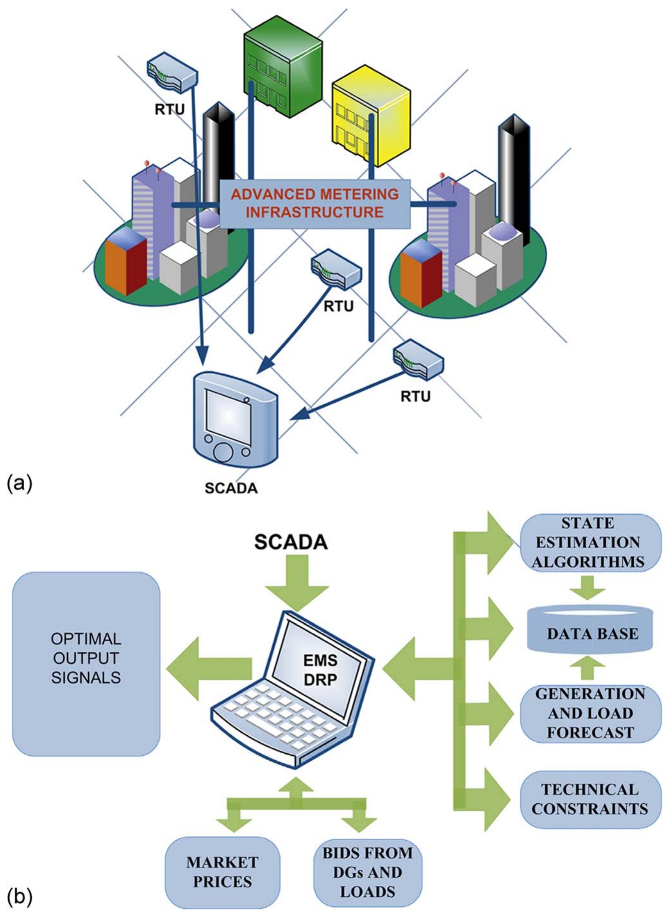

Fig. 4. Energy management system in the smart grid infrastructure: (a) Hardware system setup. (b) Logical/automation architecture [71].

in order to actuate the functionalities of a DRP and allow remote managing of peak load demand and energy consumption. An infrastructure to implement a DRP in a smart grid is presented in [71]. As shown in Fig. 4, it consists of energy management systems (EMSs) and DRP, supervisory control and data acquisition (SCADA), remote terminal units (RTUs), advanced metering infrastructure (AMI), state estimation algorithms (SEAs), and generation and load forecast system (GLFS). Measurement data provided by AMI and RTUs are transferred to the EMS by the SCADA system. The EMS performs monitoring, control, and optimization tasks by using SEAs and GLFS.

An AMI network, consisting of a smart meter, wide-area networks, home area networks, meter data management systems, and neighborhood area networks, is used to measure, save, and evaluate energy usage and to communicate information among the utility, the loads, and the consumers.

In summary, the tasks of monitoring, diagnostics, and predictive maintenance should play an important role in energy management systems. The model-based solutions were recognized as very successful for this purpose, but it is extremely difficult and expensive to obtain relevant models built from the first principles. Relevant approaches, including the model-based and fault-tolerant system approaches are reviewed in recent papers [84], [85]. In the DR energy management of today, the AI principles and techniques (negotiations based on price models, bidding and contracting) are strongly explored, despite that the authors from the energy management field do not mention this explicitly. The trend of the deeper exploration of AI will continue.

VI. Smart Grid Automation and Control

This section provides a survey of the applications of modern AI and software technologies to perform control functions in the field of smart grids. The requirements for such systems impose the adoption of technologies based on principles of decentralization of functions (e.g., monitoring and control) over distributed, interoperable, loosely coupled, and reusable entities used, for example, in DER, ESS, and DR, as covered above. The AI principles and techniques do start to play the key roles in the architectures, including the service-oriented architecture (SoA), multiagent and holonic systems, and in standardization.

A. Architectures

Automation architectures of future smart grids are being developed in a number of large-scale research programs worldwide. One significant research initiative is conducted by the center of Future Renewable Electric Energy Delivery and Management (FREEDM) funded by the National Science Foundation, USA. The FREEDM center envisions the backbone of the future grid to be a new power distribution infrastructure, allowing for integration of smart grid components in a "plug-and-play" manner and enabling bidirectional flow of electricity [86]. This new energy delivery infrastructure is also denoted by "Energy Internet" or "Internet of Energy" [86]. This vision is akin to the (information) Internet.

Fig. 5 illustrates the FREEDM vision. The core enabling technology is the SST [87], which is a new generation power transformer using power electronics enabling bidirectional electricity flow and supports ac and dc buses for direct connection of components (e.g., DER and ESS). It is controlled by distributed grid intelligence (DGI), which consists of two types of nodes: intelligent energy management (IEM) and intelligent fault management (IFM).

The first key feature of FREEDM is a plug-and-play interface, which enables components to seamlessly integrate with the rest of the grid. This interface includes an open and standard-based protocol, enabling interoperability and self-awareness of the devices. The second feature is an energy router or an IEM device. The IEM device is based on the SST concept. It manages the energy flow, provides power management, and has power-balancing capabilities. Furthermore, it manages connected DER, ESS, and flexible loads. The third feature is the DGI itself, formulated and implemented using open standards.

To address the fundamental challenges in controlling large numbers of distributed devices and dynamic loads, new control theories and distributed agent-based algorithms are required and currently under development. The FREEDM center envisions that the major challenge will be implementing DGI applications in a distributed manner across multiple execution platforms (i.e., IEM and IFM). Experience so far has emphasized the need of open source open standard-based software and communication platforms. Toward this goal, the center has proposed standard-based execution framework for IFM and IEM applications [88]–[93]. This framework is based on the IEC 61850 and IEC 61499 standards. The results have demonstrated successful deployment of agent-based

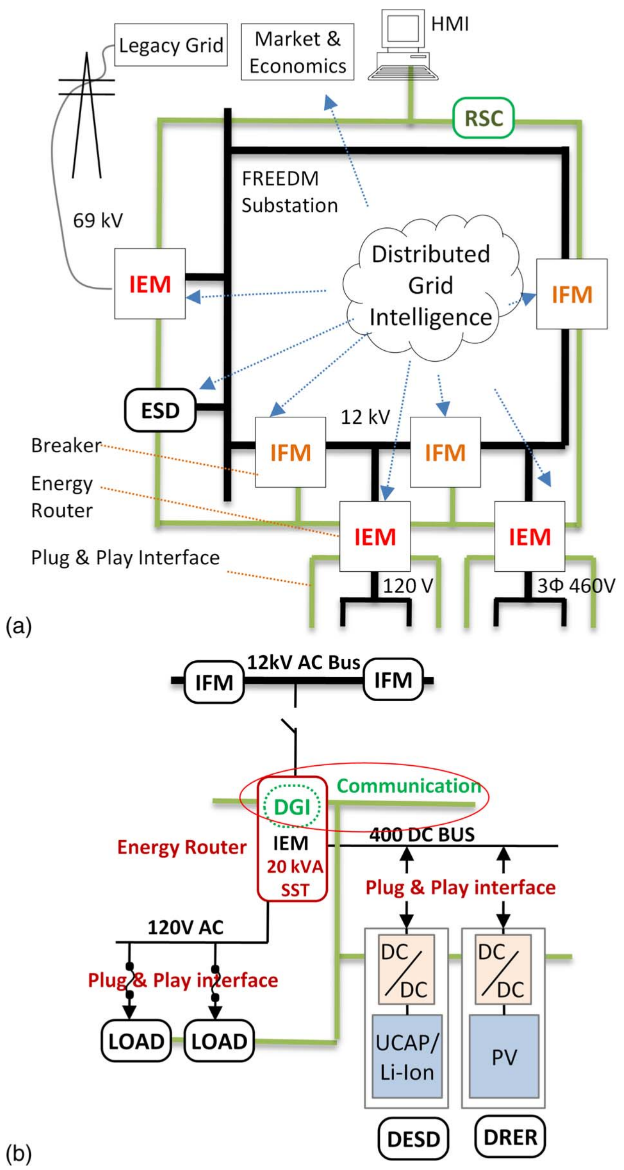

Fig. 5. FREEDM architecture: (a) Energy Internet. (b) Key elements [86].

power-balancing DGI application on a network of ARM controllers [94].

B. Agent-Based Solutions

To master the high complexity of future electric energy systems, where the intelligence is distributed over autonomously acting and interacting components, it is necessary to explore architectures and programming techniques based on distributed AI. One of the most relevant technologies seems to be multiagent systems (MAS). They have already proved its capabilities for developing robust, flexible, and adaptive industrial automation systems, with application domains, including manufacturing control, dynamic product routing, production planning and scheduling, logistics, aerospace, air traffic control, and many others [95].

In the effort to employ active elements in power grids with the local intelligence and coordination capabilities, it is apparent that the MAS approach receives a significant popularity also for developing smart grids [23], as shown in Fig. 6.

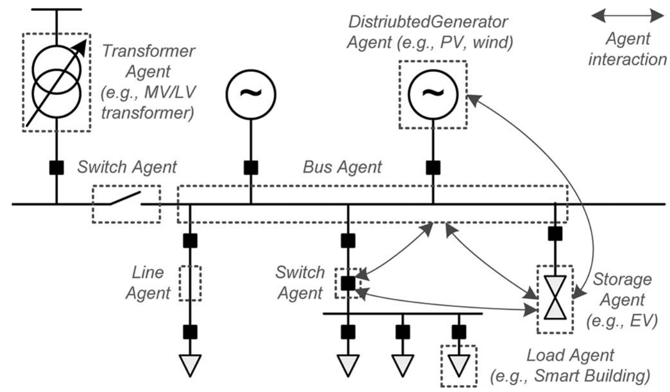

Fig. 6. MAS applied to active power distribution grids [96].

Using MAS principles, each component, device, or actor is monitored and controlled by an autonomous agent. Each agent has a set of specific capabilities (such as controlling household appliances) and local objectives (for example, minimization of energy cost while preserving the end-user comfort). The agents interact via messages to coordinate their behaviors in order to achieve an equilibrium between the local and system-wide goals (such as demand–supply balancing).

MAS technology has been employed for developing the distributed ICT infrastructure within various projects such as the FREEDM initiative and the CRISP project. A concept of grid cells was developed to divide the network into independently managed subnetworks. The agent assigned to each grid cell is responsible for managing the current and future production/consumption and handling the reconfiguration tasks in case of fault detection [97]. A very similar approach considering microgrids as small-scale electricity grids operating in low-voltage networks is presented in [98]. Each house in the microgrid is equipped with the intelligent load controller (ILC), which can communicate with house devices over the power line in order to intelligently control their load. The agent embedded in the ILC communicates with the microgrid central controller agent, whose task is to balance production and consumption within the microgrid.

The MAS approach has been also exploited in designing the concept of virtual power plants (VPPs). A VPP is comparable with a microgrid—it is an aggregation of generation units, such as PV systems, combined heat and power units, or wind turbines together with controllable loads. They are represented by agents grouped into an MAS, which is represented by a management agent as a single entity on the energy market [99].

To allow the smaller entities to trade the electricity locally in order to achieve the demand–supply balancing, a concept of electronic power markets was introduced. The PowerMatcher tool is an MAS in which electricity generation and/or consumers are represented as agents trying to sell and buy energy. The process of price negotiation is managed by an auctioneer agent that finds the equilibrium price considering the bids collected from device agents [100]. The PowerMatcher tool has been used also in other projects such as INTEGRAL, which is aimed at the distributed control and coordination of aggregated DERs [101], SmartHouse/Smart-Grid focused on integration of smart houses into the smart grid [102], and EcoGrid targets the large-scale demonstration of the smart grid solution with 2000 residential consumers on the Danish island Bornholm [103].

An agent-based architecture for smart grids is also presented in [104]. The architecture is based on industrial standards IEC 61850 [105] and IEC 61499 [106] to facilitate the migration of agent technology into the industrial practice. The agents are so-called intelligent logical nodes (iLNs), capturing data from IEC 61850 LN. The idea is that the power system automation can be decomposed into LNs, capturing functional requirements of the desired system. Then, LNs can be enhanced with the desired algorithm. Each iLN is implemented with an IEC 61499 function block. The iLN architecture enables automatic generation of automation software and plant models given customer requirements captured with IEC 61850 means. SysGrid is a tool supporting such automatic transformation, which is proposed in [107]. A number of projects were implemented using iLN architecture [88], [104], [108].

The fault prevention and self-healing techniques for smart grids based on MAS are also widely discussed. One technique presented in [109] is based on calculation of optimal network configuration achieved by opening or closing the switching elements to isolate the fault. Another similar technique considers partitioning the grid into multiple islands that disconnect from the main grid in case of a failure. The agents responsible for those islands cooperatively prepare plans of action to isolate the faulty parts from the power grid [109].

C. SoA Concepts

SoA is a principle based on discrete parts of software that provides functionality as a service to other applications. SoA is therefore designed to be independent of any vendor specifications, products, or underlying technology. Loose coupling of software parts provided by SoA provides flexibility and interoperability to a system and enables dynamic reconfiguration possibilities.

As mentioned before, smart grids can be thought as the Energy Internet. From this point of view, SoA can become a core technology to enable easy interaction between heterogeneous devices and system integration. SoA can be also used for integration with the legacy systems. Moreover, it can enable flexible integration of various actors such as distributed generators at industrial and residential levels, market players (auctioneers, buyers, sellers, regulators, etc.), consumers, government bodies, and power grid operators [110]. The ability of service discovery and its advertisement as the key intelligent features would facilitate dynamic nature of smart grids.

At the level of heterogeneous system components (DER, EES, etc.), SoA can provide interoperability. Each node provides a set of services with a defined interface.

SoA requires protocols that describe how services are being sent, information are processed, services are described, and how to use them. To unify information exchange and representations, many researchers propose to use the IEC 61850 and Common Information Model (CIM) models [111]–[113]. Lehnhoff *et al.* [112] adopted OPC Unified Architecture (OPC UA) for smart grid applications, implementing SoA with OPC UA.

Systems built on SoA require enabling infrastructure. In this context, Takagiwa *et al.* [114] proposed a service-oriented network architecture for smart grids, including service-oriented routers. In addition, the SoA principle is also seen to play an important role in Smart Home/Building applications, enabling interaction between house and smart meters and implementing DR/DSM functionalities [115]–[117].

According to Pagani and Aiello [113], SoA can help to resolve such smart grid challenges as interoperability, scalability, discovery, mobility, robustness, service integration and composition, topology, advanced metering infrastructure, and real-time constraints. However, one of the important issues with SoA is how to test and verify services and systems built on it. This also raises issues of trusted service providers and security in SoA. These issues contribute into the bigger problem of smart grid transparency, security, and privacy.

D. Holonic Control Principles

Holonic principles [118] known from the AI field and general systems theory are being applied to the smart grids domain, trying to capitalize the intrinsic characteristics to model complex large distributed systems into potential benefits. An architectural model based on holonic MAS is proposed by [119] to structure the software entities within the ICT infrastructure of smart grids. The whole network is assumed as a holon that consists of some domain holons, namely, focusing on generation, transmission, distribution, control and operation, service provider, and market and customer domains.

Negeri *et al.* [120] applied the holonic approach to structure the smart grid organized on autonomous prosumers that are recursively clustered at various aggregation layers. These holons, named control holons, are organized in a bottom-up structure to form a complete control holarchy of the smart grid. Many functions are included in this holon structure, namely, the environment state acquaintance, state analysis, database management, forecasting, steering subholons, and scheduler. This holonic approach is extended by considering a SoA framework to support interoperability and reusability challenges [121], defining five major services: database service, state evaluation service, optimization service, transaction service, and stability service.

Frey *et al.* [122] proposed a holonic control architecture to address the current requirements of smart grids, namely, the need to control a wide variety of heterogeneous producers and consumers to attain global objectives at the macro level, while also taking into account local objectives and private interests at the micro level. For this purpose, they identified three main integration patterns for conflict resolution in self-managed systems, namely, hierarchic, collaborative, and stigmergic. These patterns are complementary and could be successively used according to the environmental conditions and the working mode of the power grid.

A holonic MAS architecture is also introduced by [123] to be capable of adaptively controlling power distribution systems, e.g., allowing the operation of a distribution system as an island mode in case of emergency, such as hurricanes/earthquakes or power grid failures.

E. Important ICT and Automation Standards

Due to the increasing number of available ICT/automation solutions for smart grids and constantly changing requirements, standardization is of crucial importance in order to handle interoperability and scalability requirements. These aspects have so far been covered by several standardization organizations and international projects. Specht *et al.* [15] and Gungor *et al.* [14]

provided a comprehensive overview of important smart grid standards and roadmaps.

As an international standardization organization, the International Electrotechnical Commission (IEC) plays a very important role by providing common rules for the planning and operation of smart grid systems. The "IEC Smart Grid Standardization Roadmap" suggests different core standards important for the implementation of smart grids, such as the following: 1) IEC TR 62357 (service-oriented integration architecture); 2) IEC 61970/IEC 61968 (CIM); and 3) IEC 61850 (power utility automation) [17]. Other organizations also provide similar roadmaps for the implementation of intelligent power grids. The "NIST Framework and Roadmap for Smart Grid Interoperability Standards" [16], the "DKE German standardization roadmap for Smart Grids" [19], and the "IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads" [18] are important examples of such roadmaps and guidelines.

The German DKE Smart Grids roadmap also goes one step further by suggesting standards for the implementation of control logic. For this, the usage of IEC 61131-3 for programmable logic controllers [124] or the IEC 61499 for distributed intelligent automation [106] is suggested. Both IEC 61131 and IEC 61499 provide promising concepts for the development of control and automation solutions in smart grids, which has already been demonstrated in previous works [19]. Recently, the OPC UA, which is defined in IEC 62541, has received an increased interest from the smart grid research community [125]. The previous OPC specification for data access (i.e., OPC DA) was particularly developed for Windows-based platforms using mainly COM/DCOM technology, whereas the new OPC UA specification was particularly developed to provide a platform-independent information and communication model, by using service-oriented principles for the data and information exchange. Due to its object-oriented and generic modeling approach, there have been several studies conducted, where existing data models and protocols have been successfully mapped to OPC UA, e.g., CIM and IEC 61850 [126], [127].

The IEC 61499 standard [128] was particularly developed as a reference architecture for the modeling and design of distributed control algorithms. The distributed nature of the smart grid approach makes IEC 61499 particularly also useful for this domain. This was demonstrated by Hegny *et al.* [129], where an IEC 61499 application was developed for energy systems focusing on the reduction in the downtime of reconfiguration tasks in energy management systems.

The integration of the IEC 61850 and IEC 61499 standards is explored in the literature as well. As an example, Higgins *et al.* [130] introduced an approach to power systems automation based on distributed intelligence combining the use of IEC-61850-compliant devices with the IEC-61499-compliant "glue logic." According to [131], the IEC 61499 reference model providing a distributed function-block-oriented architecture is a proper technology to implement the advanced functions of holons, particularly the bioinspired negotiation behaviors based on the stigmergic approach.

Strasser *et al.* [132] discussed the usage of the IEC 61850 standard for power utility automation together with IEC 61499 for distributed automation and the development of a related IEC 61499 Compliance Profile (CP) for smart grid applications. The developed IEC 61499 CP provides a mapping between the IEC 61850 structure with IEC 61499 artefacts, and it also describes common rules for the usage of IEC 61499 together with IEC 61850.

Under the scope of the 4DIAC initiative [133], [134], distributed reconfigurable control software for smart grids and components was implemented based on IEC 61850 and IEC 61499. In particular, low-level control algorithms and reconfigurable interfaces for the online update/adaptation of control functions in DERs are covered by [135].

Zhabelova and Vyatkin [104] introduced an automation architecture that supports distributed multiagent intelligence, combining IEC 61850 object-based modeling and interoperable communication with IEC 61499 function block executable specification. The proposed architecture was applied to achieve self-healing grid through collaborative fault location and power restoration.

Zhu *et al.* [136] proposed the function-block-based model for flexible intelligent electronic devices, combining the IEC 61850 and IEC 61499 models. A prototype system was developed in MATLAB/Simulink.

VII. Conclusion and Outlook

The future electric energy system consists of a huge amount of interconnected components and supports bidirectional electricity flow through the electrical network and an ICT infrastructure. Important actors in such a smart grid system are inverter-based DER, ESS, and flexible/controllable loads. Compared with today's power system, the future infrastructure is characterized due to a higher amount of distributed components (in hardware and software), whereas the hierarchical structure of the power grids will still exist.

In this paper, the importance of power electronics and advanced ICT/automation approaches has been highlighted as a basis to design and operate the future power system, which has to deal with fluctuating distributed generation and limited storage capacities provided by ESS. Power converters with ancillary services provide additional possibilities to optimize the future power grids. Moreover, with DSM/DR, the electricity consumption (i.e., load profile) can be managed, too.

The smart grid ideas have appeared to enhance the capabilities of the power distribution systems as reaction to growing requirements on better exploration of (distributed) energy resources. The smart grid visions are supported by the latest achievements in the field of AI and software engineering, namely, on holonic, MAS, and SOA principles. The trend is to use holonic control principles on the lowest, near to the physical equipment automation, level to ensure very fast reactions, particularly reconfigurations of the network. Both the MAS and SOA approaches are used to support services and decision making on a higher automation level and requires an additional communication infrastructure. From the philosophical point of view, the latter two approaches converge and are in some sense complementary [96]. As a rule, the MAS or the SOA architecture is being considered to ensure higher level optimization based on negotiation and cooperation principles in a highly distributed communication environment. The trials to explore the semantic web or big data technologies to support the distributed decision making in the MAS or the SOA architecture represent an up-to-date trend [96].

In contrast to the "classical," hierarchically, and 'rigidly' organized quite expensive power distribution infrastructure, the ideas of smart grids complement the power distribution elements by highly distributed autonomous decision making units with highly decentralized way of communication, negotiation, and cooperation on different levels in the system as pointed out in this paper. This strong contrast between hierarchically organized physical infrastructure of power distribution systems and decentralized communication and decision making control infrastructure does represent the key challenge for bringing smart grids into reality.

The first step is to achieve standardization everywhere to guarantee interoperability and scalability. The standards in the area of automation of power distribution systems are well developed and available (i.e., IEC 61850). The same is true for holonic systems (i.e., IEC 61499). On the other hand, the standardization in the field of MAS and SOA is in the early stage and needs substantial enhancements.

In summary, intelligent operation and optimization are required on different levels in the whole smart grid system. On the subcomponent and component levels, mainly research and development related to new PC topologies, advanced control algorithms, and the definition of ancillary services are the main drivers. The subsystem level has to integrate the provided component functions in a smart way. Central and distributed control concepts enable intelligent behavior on this level. On the system level, the optimization and control of the whole smart grid with all its components is in the focus of advanced research supporting the necessary functions and services, as stated in this paper.

Despite the growing awareness and the ongoing research and technology developments in smart grids, there are still many open issues, which have to be covered in future research work. The most important points in the context of this review paper are as follows: 1) *advanced control functions* provided by DER, ESS, and flexible loads; 2) *integration* of all ICT/automation concepts into one smart grid control solution taking all aspects into account (i.e., generation, distribution, storage, and consumption) and the technology developed in the AI and software engineering areas; and 3) the provision of *proper design, development, and validation methods* for component design and integrated ICT/automation solutions. There is still a lot of work necessary in order to implement a real smart grid system. Industrial electronics and informatics together with the AI techniques will play an important role of such an integrated approach in the near future.

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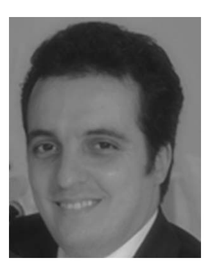

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