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Interfacing applications for uncertainty reduction in smart energy systems utilizing distributed intelligence

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ABSTRACT

Under the transition towards sustainable smart energy systems (SES), utilization of distributed intelligence has been gradually proposed along with the expansion of Information and Communication Technology (ICT) infrastructure and advanced control services. Distributed intelligence (DI)-based control and management solutions proved a perfect complement to the existing control structures to handle the SES' uncertainty which is getting quite complex with different system layers and involved stakeholders. Advanced modelling and simulation techniques are crucial here to realize and enable the applications of DI to enhance grid reliability while optimize market operation. However, several challenges arise while modelling DI applications and integrating them in the simulation platform due to the complexity of the multi-disciplinary smart grids. As an activity of IEEE Task Force on Interfacing Techniques for Simulation Tools, this paper mainly reviews the interface issues between modelling and simulation of physical, ICT, and application layers, as well as business processes of the whole smart energy systems. By means of a conceptual framework for SES development, this paper aims to position most of DI-based control applications in specific research domain and elaborate on their interface with the whole SES context.

1. Introduction

DEVELOPMENT of smart grids, or Smart Energy System (SES) in a broader sense, is facing challenges related to uncertainty in both securing the electricity networks and balancing energy supply and demand [1,2]. The anticipated massive integration of stochastic renewable energy sources (RES) and the introduction of new energy-intensive appliances, e.g. electrical vehicles or heat pumps, aggravates these challenges because of larger uncertainties on all time scales [3]. Distributed intelligence (DI) has been considered, among other computation intelligence methods, as an enabler for bottom-up modelling and control solutions to handle the SES' uncertainty which is getting quite complex with different system layers and involved stakeholders. Considering the increasing interest in DI-based applications from the research community, the IEEE Task Force on Interfacing Techniques for Simulation Tools carried out the task to assemble a comprehensive overview of DI-based applications in SES, as well as to address interface issues between modelling and simulation of DI within a conceptual framework for SES development.

1.1. Uncertainty in smart energy systems

The most obvious source of uncertainty in future SES comes from the intermittency of RES, which is way harder to predict and schedule than on-demand sources [4]. Meanwhile, stochastic behaviour of DERs changes energy demand levels and their patterns over time, as a result of heavy appliances such as EV, HP's and CHP installations. Therefore, the uncertainties make it increasingly difficult to both perform supply and demand matching (SDM), as well as to operate the electricity network within secure operation limits [3,5]. Besides these obvious uncertainties and notwithstanding the promising capabilities of proposed control applications and functionalities in future SES [6], the information and communication systems (ICT) in next generation power systems will face a greater variety of cyber vulnerability as those of today [7,8]. Security and privacy aspects will be stressed more, since the customers will participate actively in the whole energy supply...
chain. The increasing involvement of ICT systems and advanced control mechanisms also reveals uncertainty in the interoperability of SES [5]. Therefore, solving these uncertainty problems requires a comprehensive insight on the relevant system layers. These layers include the physical power grid, ICT, as well as the control functions and services deployed on top of this, to ensure safe, reliable and efficient operation of the electricity supply chain.

1.2. A variety of DI based applications

Besides the conventional centralized control applications and services, utilization of distributed intelligence (DI) has been gradually proposed [9,10]. These DI-based solutions proved a perfect complement to the existing control structures to handle complexity and uncertainty of the system which is getting quite complex with different layers and many involved stakeholders. In general, DI can be realized as embedded hardware and software with sensing, communication and decision-making capabilities [11]. This way, it can provide advanced control functionalities in transmission and distribution networks, facilitate network ancillary services, as well as dispatch of flexibility and demand side management (DSM) and demand response (DR) programs. To realize these functionalities in a scalable and efficient way for large size future SES, enabling technologies are required including distributed control, computation intelligence, distributed optimization and multi-agent technology, also called a multi-agent system (MAS) [12,13].

After the publication by IEEE MAS Working group [12] in 2007, there is still an increasing interest from the research community to address DI-based applications as illustrated in Fig. 1. This research portfolio is based only on the IEEExExplore database, while searching for the keywords smart energy system or smart grid together with multi-agent system. This gives a wide variety of DI-based applications in this record, addressing different aspects of SES development including both grid and market operation. Some highlighted works will be discussed in more detail in Section 2.

1.3. Modelling and simulation of DI based applications

Despite its proven advantage in handling system complexity and uncertainty [12], some applications of DI require intensive support from ICT and advanced control mechanisms [9,10]. Therefore, advanced modelling and simulation techniques are necessary for simultaneous simulation of the physical power system, ICT and the distributed intelligence applications. Simulations form a cost effective approach for repeatedly investigation of the system behaviour under various conditions. Due to the complexity of the multi-disciplinary nature of SES, several challenges arise in the interfaces between simulation of the physical, information and communication, as well as application layers of the whole system. These issues are extensively addressed by the IEEE Task Force on Interfacing Techniques for Simulation Tools [14,15].

Because of the diversity in deployment of DI-based applications, the challenge of modelling and integrating them in the simulation platform remains due to a lack of a common and comprehensive development framework [16]. This hinders also the evolution of DI-based applications towards commercial hardware/software design practices [17]. As a consequence, an advanced simulation environment is required to address comprehensively the complex interactions between the various business processes [18,19], and the different smart grid layers from the household level [20], microgrid management system [21,22], coordination of multiple microgrids [23,24], to the whole distribution grid as a cyber-physical system [25]. Developed simulation platforms are expected to be highly extensible and able to perform different grid control strategies [26,27], take into account the integration of distributed energy resources [28] as well as to deploy various market mechanisms [29,30].

1.4. Proposed approach and contributions of the paper

To follow up the research thus far, this article aims to specify on issues related to modelling and simulation of DI based business processes for uncertainty reduction in SES related to the mentioned challenges for grid operation and balancing. For this purpose, the paper will use a conceptual framework to classify applications and their modelling and simulation approach for the two aspects of grid operation and system balancing, including details regarding the relevant system layer, simulation domain and interfacing method. This way, it gives an overview on interfacing different simulation solutions for power systems, ICT systems, as well as the business processes themselves. It includes both non real-time and real-time simulations platforms, as well as simulation platforms supporting hardware-in-the-loop (HIL) configurations.

In this paper, a four-step approach as visualized in Fig. 2 has been applied including (i) a selection of DI-based applications, (ii) categorization of the application based on the proposed smart grid application framework; (iii) specification of DI-based application with associated modelling and simulation platforms; (i) identification of interfacing challenges.

The remaining part of the paper is organized as follows: in Section II, different advanced applications of distributed intelligence have been categorized within a conceptual framework of SES; Section III addresses challenges in modelling and simulation of such DI-based applications to reveal and cope with the uncertainty of SES; in Section IV, interfacing issues regarding individual simulations and their interaction with the whole system context are elaborated with different types of simulation platforms; finally, conclusions are drawn and an outlook is presented in Section V.

2. Conceptual framework for smart grid applications for uncertainty reduction

In this work, the various applications of distributed intelligence for uncertainty reduction in smart grids are categorized in two parts: 1) applications related to network operation and optimization; and 2) applications related to (local) market operation and optimization. Their relations and mutual interfaces are displayed in Fig. 3.

![Fig. 1. Number of publications related to DI-based applications in SES accumulated by years.](image)

![Fig. 2. The four-step approach to address interfacing challenges for various DI-based applications.](image)
The first category deals with all applications deployed by or related to grid operation. Within the physical network premise, several components are installed that allow to gain insight in the power grid and to deploy security and control mechanisms. These include sensors and measurement devices for the collection of monitoring data (e.g., smart meters, PMU’s), as well as protection and control devices for the deployment of local control actions (e.g., tap changers, inverters). Distributed intelligence can be enabled and embedded to local network components which will be represented by an intelligent network agent. These agents will interact with each other to collaboratively run distributed applications for monitoring, controlling and optimizing grid operation. Based on the network monitoring, network constraints can be determined that will serve as an input for both network control as well as possible interaction toward market operation.

The second category relates to all applications deployed to facilitate market operation. In the overview in Fig. 3, import/export and the energy of large consumers/producers directly connecting to the transmission network is traded on the conventional energy markets. Traditional passive consumers and producers connected to the distribution network also interact with the energy markets via their energy supplier. Active prosumers (consumers and producers) are prosumers that are able to offer flexibly in terms of their power consumption and production over time [31]. Each of them is represented by one or more prosumer agents, who perform short-term forecasting and determine the amount of flexibility that the prosumer is willing to offer (depending on the preferences of the prosumer) in the near future.

Both categories of applications (e.g., grid operation and market operation) will be treated in more detail in the next sections. In this, the role of a reliable ICT infrastructure will be highlighted, together with adequate requirements on modelling and simulation approaches, their interfaces and ICT requirements [6]. In future SES, both categories will have a strong intertwined operation. This will allow seamless integration of market and control mechanisms over time.

### 2.1. Distributed intelligence based grid optimization

Today’s distribution networks, once considered passive, have increasingly evolved to be active in all phases, from planning, operation, to control actions. The introduction of large amounts of RESs and DERs can lead to network problems such as current congestions or voltage variations. However, monitoring capabilities of Distribution System Operators (DSOs) are limited to few critical substations and measurements at the beginning of the main low voltage (LV) feeders [32]. Therefore, DSOs often cannot capture problems occurring in the distribution network. Besides, existing control functionality in the distribution networks is not flexible enough to handle the emerging situation of high penetration of RES. In order to cope with future operation limit violations in distribution network, advanced monitoring and control applications will emerge in the distribution network. Important applications of distributed intelligence related to network operation and optimization are categorized into: 1) distributed network monitoring; 2) network protection and restoration; and 3) distributed control functionality, as follows:
2.1.1. Distributed network monitoring

The diversity and complexity of distribution networks, with massive number of small-scale RESs and DERs, requires improvement of the conventional network monitoring tools. State estimation in transmission networks forms one of the key aspects in safe and secure operation of the power system, providing the necessary information for monitoring and control, like tap changer optimization, voltage control, optimal power flow, and contingency analysis [33]. In order to guarantee reliable grid operation, monitoring capabilities have to be extended to the distribution networks. However, as outlined in [34], the methodologies for monitoring and state estimation in the transmission systems cannot be directly applied to distribution systems. This is the result of mainly two fundamental aspects at which the distribution system differs from the transmission system, being: (1) the low amount of measurement units installed for the large amount of nodes in the distribution network, and (2) the distribution grid requires more complex models for representing multi-phase unbalance networks, challenging the development of robust state estimation algorithms. Various works have proposed methods for state estimation in distribution networks [35,36].

2.1.2. Network constraints

Due to the integration of DER in future power systems, network operation schemes will have to be reengineered to account for bidirectional power flows and different types of operation limit violations than faced in the past. From the distribution network monitoring, the network operator can analyse the network for possible (risks for) operation limit violations. These operation limit violations can include all kinds of grid related problems, like under/over voltages, congestions, overloading of lines and transformers, as well as voltage imbalances in unbalanced three-phase distribution networks. These operation limits imply network constraints for control functionalities as detailed in more detail in the next subsection.

2.1.3. Distributed control functionality

Network control and optimization applications may include distributed loss minimization, distributed Volt-VAr management, distributed power flow (DFP) optimization and distributed energy resource scheduling. The main variables for distribution network control are voltage, active and reactive power, which can be controlled at different grid levels. Adjustment of the set points for transformer tap changers or droop characteristics of inverters can cope with specific problems of overloaded or violation of voltage constraints [40,41]. Local information from network monitoring can be used to trigger distributed control schemes to regulate the output power of PV clusters in case of any disturbances [42]. However, although possibly increased, the hosting capacity of the distribution network for RES and energy intensive appliances will still be limited with such adaptive control functionalities.

A novel distributed Volt-VAr control scheme was proposed in [43] with a predictive capability. Basically when an intelligent agent detects an under or over voltage, it will broadcast an abnormal voltage message to its teammates, activating a voltage support scheme. By utilizing a DPF solver, the MAS works collaboratively to test all possible candidate control actions (shunt capacitor control and voltage regulator control). Only the best candidate control action will finally be selected for regulating the voltage profile back to the desired range.

Distribution automation in the future distribution network can be enhanced by advanced “self-healing” functionality that deploys decision making authority locally in the area of responsibility with a fast response time [37,39]. For example, the distributed restoration algorithm presented in [38] aims to separate outaged and healthy parts of the system by isolating the smallest faulted area possible. The restoration as a combinatorial problem for minimizing the number of disconnected customers while preventing operation limit violations such as under/over voltage, overloading/congestion and constraints on radial network operation. The multi-agent system in this context is based on agents working together in teams. In this, every team represents a section of the power system, where each segment is bounded by switching equipment. Agents in a team have the capability to communicate with each other and with neighbouring teams via common “teammates”. In case of fault conditions or other operation limit violations, the agents will negotiate with each other to reconfigure the network in the most optimal and expeditious way.

Emerging network concepts such as micro grids and the aforementioned network restoration reveal a necessity in switching given network areas from islanding to interconnection mode and vice-versa. Frequency control is thus crucial to retain autonomous operation of micro grids besides local balancing, voltage and power control functions [44].

2.2. Distributed intelligence based market optimization

By coordinating a liberalized electricity market on a national level, different trading mechanisms, e.g. day-ahead, intra-day, or balancing markets, have been developed to ensure a system balance in various time horizons. With a massive amount of intermittent power sources, it becomes increasingly difficult for the involved market parties to stick to their scheduled energy transactions, i.e. due to increasing forecasting errors. Therefore, besides this so-called global market, there is a necessity of having new market designs mapping electricity market participation to lower levels of small-scale producers and consumers [45]. New distributed and scalable market mechanisms and facilities have been researched to facilitate this, which is elaborated in more detail in the following sub sections:

2.2.1. Short-term forecasting

Local knowledge about expected energy production and consumption allows to schedule the flexibilities of producers and consumers in different time intervals. For this (very) short-term forecasting, there is an increasing trend towards using computational intelligence and machine learning and hybrid solutions [46,47]. Especially in [47], advanced machine learning, i.e. deep learning, was introduced the first time to examine energy prediction in various time resolutions and time intervals. By taking advantages from such computational techniques, energy predictions become more accurate and important to schedule and dispatch customers’ energy flexibility.

2.2.2. Customer flexibility

Several research works have been done to address possible ways to invoke flexibility from end users thru aggregators. They are different depending on the goals of using customers’ flexibility, considered time horizons, as well as other physical network constraints. Mostly one can distinguish two types of DSM/DR programs, being 1) price based mechanisms; and 2) contractual arrangements for direct load control. The principle of the first category is that software agents representing prosumers or their appliances participate in a local electricity or flexibility market. In this market, an auctioneer seeks to maximize social welfare by determining the market equilibrium between demand and supply as in [48–50].

In the second category, the entity responsible for controlling the devices has direct influence on how to schedule the devices, within the constraints of the end user and possibly taking into account preferences from network operators [51]. In [52], a demand response tool has been developed to prevent grid operation limit violations. This DI-based tool applies a decentralized algorithm based on DPF as mentioned in Section 2.1, which ensures fair scheduling of the customer loads independently of their geographical location in the network. The
approach is based on a priority scheme that would fit well in smart charging scheme for a cluster of electric vehicles.

2.2.3. Aggregating and matching

In [56], the Universal Smart Energy Framework (USEF) has been introduced which aims to invoke flexibility from the end users via aggregating agencies. The flexibility can be aggregated and made available not only for market operation but also support grid operation as displayed in Fig. 4. These aggregating agencies can pursue various objectives, like performing local power matching for frequency control in a micro grid, or dispatching and matching the flexibility for ancillary services for energy markets and imbalance markets by making use of various DSM and DR programs. While existing control functions can cope with network issues caused by the high penetration of RES by curtailing the electricity production [57], scheduling of active local consumption and generation profiles under USEF can be an alternative that can accommodate more RES’s power production. Either price-based or incentive-based signals from DMS and DR programs can be used to invoke and exploit flexibility from end users [56], where the interaction between market and network operation will be discussed in more detail in the next section.

The leitmotiv here is to highlight importance of flexibility which can be invoked by various DSM and DR programs like FAN, OpenADR, PowerMatcher and Intelligator for securing network or balancing system via a framework like USEF, as illustrated in Fig. 4. Nevertheless, it was pointed out in [59] evolution of demand response in the EU which is still in an early development phase, mainly due to regulatory barriers. Therefore, standardized regulation at a European level including clear roles and responsibilities is crucial.

2.3. Intertwined network and market operation

In order to use customer flexibility effectively for grid supportive DSM or DR, there is a need to develop new market models with a larger involvement of regional distribution network operators and proactive end users [53]. The introduction of a grid supportive local market concept is emerging to enable an active system management and resolve the network problems in the near future [54,55,80].

These local markets aim to not only optimize further the matching process with advanced scheduling solutions but also interact with grid-related optimization objectives. This mutual interaction reveals possible conflicts of interests between the involved stake holders, such as network operators, energy suppliers and balance responsible parties. Therefore, a suitable multi-objective optimization problem needs to be formulated, that respects the interest of each of the involved stake holders. Because of the conflicting interests, solutions for this multi-objective optimization problem likely cannot rely on a centralized approach, due to its inability to balance and weight the interests of the stakeholders. Instead, a MAS applying game theory can form a suitable approach to solve the multi-objective optimization in a fair way. For this, the multi-objective optimization should be formulated in such a way that it prevents gaming opportunities and that the Nash equilibrium can be satisfied. An example of game theory in combination with a MAS to resolve coalition formation in multilateral trade is published in [58].

3. Modelling and simulation challenges

As stated in the introduction section, the complex interactions between the different layers of the SES require an advanced simulation environment to comprehensively verify the correct functioning of the various business processes deployed within the SES.

In order to address the uncertainties in all the layers of the smart grid, the simulation environment must take into account some detailed aspects of network models, measurement infrastructure, the communication system, and the distributed intelligence applications running on top of them.

3.1. Individual simulation domains

3.1.1. Power system simulation

In order to reveal the thru system state of the distribution system, an accurate model of the power grid is crucial. Assumptions relating three-phase balanced operation, low R/X ratios in lines, and constant-power loads are typically valid when considering power systems at the transmission level. However, they do not necessarily hold when considering power systems at the distribution level, especially when considering low voltage networks. Consequently, the models need to be adapted to deal with the higher level of detail required to model these situations [44]. Since the LV network often involves unbalanced operation, a full model of the 3-phase power system is required, including neutral, grounding and mutual impedances [61].

According to [60], one can distinguish basically two types of simulations for power systems: 1) steady state simulations; and 2) transient dynamics simulations. The latter can be split in 1) continuous time; 2) time stepped; and 3) event driven transient simulations. Independent of studying steady state or dynamics in power grids, simulations of power systems usually focus on a specific domain of the power system (e.g. power generation, transmission, distribution and commercial or industrial consumption). Depending on the domain and the power phenomena of interest, different time steps of the simulation may be chosen. Transient phenomena would require smaller time steps, who deliver more accuracy, but also increasing computation time. Therefore, simulations may also include a variable step size, being small at the occurring of transients and relatively coarse in (quasi-)steady state situations.

3.1.2. Measurement and control equipment

Using the model of the measurement system, measurements of different quantities at different locations of the power system can be taken from the simulated power system. These measurements are transferred using the communication system model to the simulated monitoring application. For the measurement equipment simulation, the model needs to contain detailed information about the location of the measurement, noise, analog-digital conversion, anti-aliasing, etc. Also, for example in case of phasor measurement units (PMU), a model of the time synchronization and phasor data concentrators (PDC) is required. In order to enhance the usefulness of metered data, proper care has to be taken with respect to meter placement in the distribution network [62–64].

3.1.3. ICT infrastructure

One of the most important differences when comparing ordinary power system simulations with simulations of SES, is that a SES has to deal with communication delays, exchange of information, and market aspects, which all need to be included in the simulation. As outlined in [65], current power grid simulators do not model network communication protocols and the resulting traffic bandwidth and delay. Therefore, integrating power and ICT components will also require similarly integrated simulation frameworks.
Although it seems tempting to model the communication channel as a black box with a fixed bandwidth (throughput) and delay (latency), it has been shown in [66] how the complex interactions among different clients and access points make this less tractable. It gives an example of high non-linear relationship between the access rates, bandwidth and latency, making it clear that a detailed model of latency, bandwidth and reliability of the communication network is necessary for correct simulation of the data exchange between the various components of the SES. Because of the event-based nature of communication networks, for communication network simulations it is generally not common to use continuous time simulation with fixed or variable step sizes. Instead, communication network simulators typically are discrete event simulators [67], triggered for example when a message is send or received.

3.2. Interfacing the Individual Simulations

In order to perform simulations of SES, combined simulations of physical network and service layers taking distributed intelligence into account are required. Although there are many tools for simulating the individual aspects on their own, the availability of platforms capable of simulating SES as a whole is still emerging. A combined simulation of the power system, energy markets, ICT and distributed intelligence is needed. Difficulties arise in the fact that those simulations are usually of different nature, e.g. time stepped or event driven. This section will elaborate on the various aspects involved with interfacing the simulations of the different layers.

3.2.1. Co-simulation

Co-simulation solutions, as extensively described in [67], combine existing simulation environments of different aspects into a single simulation environment as for example described in [68,69]. This may be time saving and inexpensive compared to developing a new specialized simulator. Each simulator will have its own dedicated interface for data input, output, synchronization and control. A main drawback is that the interactions between simulators needs to be synchronized. Although certain tasks might run in parallel, simulators will often need to wait for each other’s output in order to continue. One of the methods to achieve this is to use explicit time-stepped synchronization at predefined points. By doing so, the processes for power system simulation, communication network simulation and DI simulation will run independently. Each process will pause as soon as they have reached a synchronization point. When all processes have reached the synchronization point, necessary information is exchanged and the processes continue until the next synchronization point. However, this synchronization method may easily cause simulation errors that will not reflect reality due to the fact that events and interaction requests appearing between the synchronization points need to wait for the next synchronization point.

One of the solutions to solve this problem as presented in [67,70] is to use a separate global event scheduler, scheduling both the fixed time interval for the power system simulation mixed with the events of the communication network and DI in chronological order. However, note that this will likely imply performance penalties since processes have to run one after each other and need to be suspended meanwhile. When using existing simulation environments, this may imply that simulation environments must be reloaded and reconfigured and that the new input data must be provided, which may cause a lot over overhead.

3.2.2. Comprehensive integrated simulation

As an alternative to co-simulation, [65] describes a comprehensive integrated approach, in which both the power system, the communication network and the (DI) applications running on top of this are simulated in a single environment. In this approach, a single interface is provided for input parameters, control and data output, with the advantage that system management involved with time and data exchange can be shared by both simulators, reducing overhead and the performance penalty caused by synchronization. However, note that the main challenge is to develop a simulation environment from scratch, not relying on existing simulation environments. Issues existing in synchronization between simulation of the power system, communication network and DI may easily be introduced in an integrated simulator as well. Therefore, when designing an integrated simulation platform, care must be taken to provide a sufficient level of detail for the different aspects of the SES simulation model regarding timing aspects.

In [71], an approach for modular simulation of smart grids based on Mosaic has been presented. These modular simulation approaches integrate control strategies, scenario speciation and simulation models by using semantic information. MASGiP is another example of an integrated simulation platform that allows new smart grid components like virtual power plant or microgrid agents interacting with each other, thus enabling DR or scheduling tasks effectively within the simulation platform [72].

3.2.3. Real-time hardware-in-the-loop simulation

In [65] and [73], an overview is given of the differences between non real-time simulation (also called offline simulation) and real-time simulation. Non real-time simulation refers to simulations in which the clock of the simulation has not the same speed as the clock of a real experiment of what is being simulated. This can come in two types, being (a) the simulator clock on average is slower than the clock in real time, or (b) the simulator clock is slower compared to the real time clock. The latter can be due to the amount of detail taken into account in a simulation. One can argue that it is not useful to have a simulation of something that takes longer than it would do with a real experiment, but then one ignores the fact that simulations may offer a cheaper and more important testing environment compared to performing a field test. Also, it can reveal information that cannot be captured with a real experiment. Note that a mixture of faster and slower clock intervals compared to the real time clock is also possible when dealing with variable time step simulators.

In a real-time simulation approach the simulation clock is synchronized with the real-time clock. The main benefit of this approach is that it can interact with real external hardware components such as local controllers, and therefore is called hardware-the-loop (HIL) simulations. This means that at each iteration, the simulation should be at least as fast as it would be in real time. Since the real-time simulator has to produce the outputs of the simulation model within the same length of time as its real-time counterpart, correctness of a real-time model does not only depend on the accuracy of the numerical computation, but also on the time accuracy within which the numerical results are reported to external components, either being software or HIL-components.

With HIL simulations, some components are real hardware and some others are simulated (using real-time simulation technologies). The reason for using hardware within a simulated environment can be that behaviours of specific components are difficult to be simulated, or to perform extensive testing to specific components in a laboratory environment. Therefore, HIL simulations have proven to be especially beneficial for assessing the performance of DI based protection and control schemes. Two important HIL approaches for power system simulations are described in [74] and [75], being 1) signal level HIL; and 2) power level HIL.

3.2.3.1. Signal level HIL. Signal level HIL is the most easily
implemented HIL setup. It is primary used to test a control segment of a system. In this setup, only the controller board of the hardware under test (HUT) is tested while no power is involved in the HUT. The rest of the system, like power electronics, transformers switchgear and the DI is simulated in the real-time simulator. For this reason, a bidirectional interface between the real-time simulator and the HUT is necessary.

3.2.3.2. Power level HIL. Power level HIL setup (also referred to as PHIL) refers to cases in which a complete power device is included as a hardware component. In this case, the HUT will absorb, produce or transfer real power, where power electronics are needed to create an interface with the software simulated environment. Note that also hardware simulations can be introduced in the system, like for instance a programmable load, which may behave like various types of appliances, but in fact is just a programmable impedance or Thevenin voltage source.

As mentioned earlier, it is important to capture the system status in (near) real-time to trigger control signal properly. Besides time delay related to communication traffic and computation burden, capturing rate is another factor influencing the accuracy of measured or estimated system state. An example of a HIL simulation to compare estimated values of a bus voltage magnitude and phase angle is presented in [76,81].

4. Classification overview and conclusions

Summarizing the content of this paper so far, we have seen that the application of DI has been expanded significantly in different application aspects to mitigate the uncertainty in SES. Realizing and enabling such DI-based applications requires advanced modelling and simulation techniques beyond the classical power engineering techniques. Depending on the specific application domain, modelling and interfacing issues in different levels of the SES might arise, from the physical or ICT to application level.

In order to address these issues in future development of DI for SES, a classification overview of DI-based applications is presentable in Table 1, based on the simulation domains and interfacing methods reviewed in this paper for both grid operation and market operation. It shows a relationship between application, simulation domain and interfacing method, of which the importance given by the research community is indicated by having more dots in a cell of the table. This gives a guideline for further development of distributed intelligence along with the development of smart energy systems.

To conclude, in this paper, a conceptual framework has been used to give an overview of DI-based applications in different specific SES domains. The ultimate goal for modelling and simulation techniques for SES and DI is to create an affordable testing environment to validate and verify various DI-based applications. This accelerates the development of the SES and smoothens the transition toward a suitable energy systems by reducing a great part of the uncertainty.

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