Tools for Analysis and Design of Distributed Resources—Part IV: Future Trends

IEEE Task Force on Analysis Tools
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***Abstract*—Real-time testing of new and more sophisticated distributed resource interfaces during transients, representing the different physical parts (mechanical, thermal, hydraulic, chemical, electrical, electronics) of a nonconventional generator in a single platform, or analyzing the interactions of distribution systems with distributed generators, energy markets, and customer behaviors are scenarios that cannot be studied with current software packages. This paper analyzes the present status and discusses the future development of tools that could cope with these simulation challenges. This paper includes test cases that will illustrate the scope of some of these simulation tools.**

***Index Terms*—Distributed generation (DG), distributed resource (DR), distribution network, GridLAB-D, modeling, multiagent simulation, multidomain simulation, real-time simulation, storage.**

I. Introduction

THE increasing complexity of distribution systems with distributed resource (DR) penetration, the necessity of simulating components in which different physical parts (mechanical, thermal, hydraulic, chemical, electrical, electronics) may interact, and the coupling of energy markets and power systems for which detailed models of end-use applications and DRs may be required, are some of the main simulation challenges that cannot be covered by conventional software packages, and for which other tools are required. The importance of these tools is discussed in the following paragraphs.

1) Several power quality (PQ) and stability issues will arise in future distribution systems with multiple DRs interfaced through power electronic converters. Traditional PQ and stability software tools are not equipped with proper models to accurately perform critical simulations. Platforms capable of simultaneously simulating the fast transients caused by power electronic systems, faults and equipment switching, as well as slower electro-mechanical and voltage stability phenomenon are therefore required.
2) Advanced testing methods need to be developed to evaluate system functionality, security, and reliability within a reasonable time period and for operating conditions too dangerous to be tested on the actual system. The number of specific performance design requirements is finite, but the number of possible operating conditions and failure modes is almost infinite. Design of optimal testing methods related to very complex systems may be more complex than the design itself.
3) The first real-time simulators were applied in early 1990s [1]. They have proved to be very effective in a broad range of power system studies. The design of DRs and their controllers involve repeated cycles of simulation and testing from the conceptual stage to the prototype implementation stage. Due to the overwhelming complexity of DR configuration, modeling requirements and controller functionality, traditional non-real-time software tools can be very time consuming, thus creating unnecessary delays in the design process. A real-time simulator cannot only speed up the entire design process significantly, but it is also the only tool capable of interfacing with the device under test under real-time conditions.
4) The variety of generation and energy storage technologies that will interact in future distribution systems will require the application of simulation tools capable of connecting and interfacing applications from different types of physical systems (mechanical, thermal, hydraulic, chemical, electrical, electronics). Many programming packages offer a flexible and adequate environment for these purposes. Commercially and freely available simulation tools can be used to develop custom-made models not implemented in specialized distribution power packages.
5) The coupling of power systems and markets impacts broad areas of the electric power industry. Energy trading products cover shorter time periods and demand response programs are moving toward real-time pricing. Market-based trading affects the physical operation of the system, while the boundaries of these coupled systems extend beyond the boundaries of utility operations. Present simulation tools do not provide the analysis capabilities needed to study the forces driving change in the energy industry.

The objective of this paper is to summarize the present status of simulation tools that are required for performing the aforementioned tasks, and discuss their future development. The paper includes test cases that will show some of the applications that these tools can cover.

Manuscript received June 21, 2010; revised February 02, 2011; accepted February 06, 2011. Date of publication April 05, 2011; date of current version June 24, 2011. Paper no. TPWRD-00468-2010.

The authors are with the Task Force on Analysis Tools, which is with the Working Group on Distributed Resources, Power and Energy Society, Transmission and Distribution Committee.

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Digital Object Identifier 10.1109/TPWRD.2011.2116047

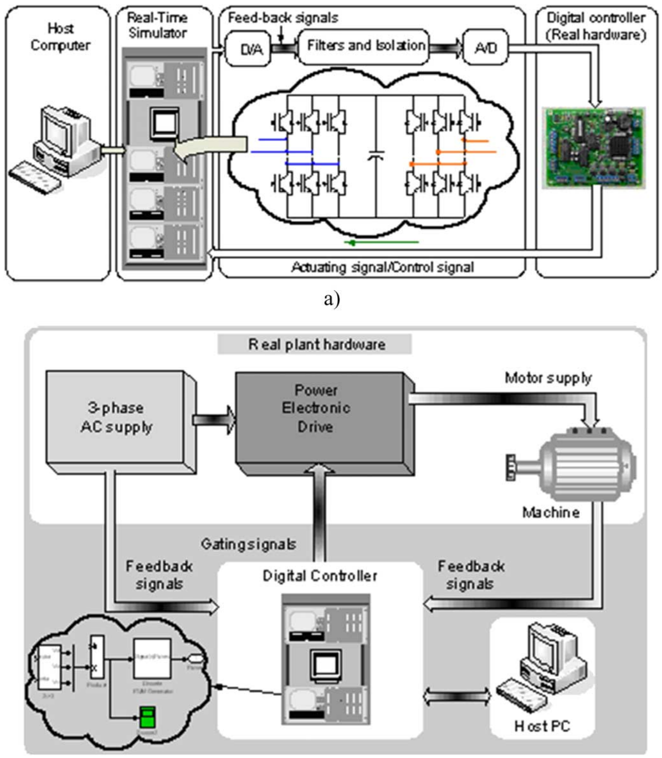

Fig. 1. Applications of real-time digital simulators. (a) Hardware-in-the-loop simulation. (b) Controller prototyping.

II. Real-Time Simulation Platforms

A. Present Situation

For more than 70 years, real-time analog simulators (also known as transient network analyzers) have been used for various applications in power systems, but over the last 15 years, significant advances have been made in real-time digital simulators. These simulators are useful for testing manufactured equipment in a hardware-in-the-loop (HIL) configuration or for rapid control prototyping (RCP) where a model-based controller interacts in real time with the actual hardware, see Fig. 1. Due to rapid advances in digital processors, parallel processing, and communication technology, these simulators are becoming increasingly popular for a variety of applications.

To emulate a physical system faithfully, a real-time digital simulator should be capable of solving the differential equations of the system within the allocated time step. For example, if a transient event occurs in 10 μs in the actual system, the real-time simulator should be able to perform the necessary computations for the transient and output the results within 10 μs. It is not sufficient for the end of the simulation run to coincide with the real-time clock; instead, the computation of every time step must be executed within the same corresponding interval of real time. The simulator must also be able to effectively interface and synchronize with actual external hardware. With the introduction of fast switching power electronic apparatus into the conventional power system model, the requirements for the real-time digital simulator have become even more stringent. Interfacing with real-time digital simulators is an ongoing research topic where several important issues are being addressed. One of these issues is the interfacing of discrete switching signals coming from a digital controller with a fixed timestep real-time model of a power electronic apparatus in the simulator. Several algorithms have been proposed for correcting switching errors and extra delays for power electronics in real-time digital simulators [2]–[4]. There are also commercially available packages, such as ARTEMIS [5], that address this issue.

Commercially available real-time digital simulators, such as RTDS and OPAL-RT, are at the forefront of this rapidly expanding market. Significant advances in the general-purpose processor technology and the development of accurate power system models in mathematical modeling packages, such as MATLAB/Simulink, are driving the current trend of using PC clusters for real-time and hardware-in-the-loop simulations. The PC-cluster-based real-time simulator is built entirely from high performance commodity-off-the-shelf components to sustain performance at a reasonable cost [6]. Real-time simulation and offline model preparation are divided between two groups of computers comprising the target cluster and hosts making the configuration flexible and scalable. The cluster nodes can be configured as centralized or distributed servers interconnected with low-latency high-bandwidth communication, such as Infiniband, which offers communication speeds of up to 10 Gb/s.

Alongside general-purpose processors, field-programmable gate arrays (FPGAs) are also making significant inroads into real-time simulators. FPGAs have been proven to offer high-speed high-precision simulations in stand-alone configurations [7], [8], and as accelerator components in PC-cluster simulators.

Currently, real-time digital simulators are used to address simulation needs for a large spectrum of power system studies, such as to test protective relays and digital controllers for power electronic-based flexible ac transmission systems, custom power and HVDC systems in closed-loop [1], [9]–[15], and for transient simulations of large-scale systems aimed specifically at analyzing a variety of operating scenarios and fault conditions, harmonics, and PQ evaluation [16], [17]. Not much experience is already available in the simulation of DR devices, although these simulators have been proveN to be very useful in the simulation of wind farms [18]–[21], and multimachine ship power generation [22]. The possibility of using a single simulation platform that could reproduce the performance of a complete distribution system with several inverter-based interfaced DR units in real time is a challenge for developers and manufacturers.

B. Future Development

HIL simulation is necessary to assess both the hardware and software during normal and abnormal operating conditions. For conventional power systems, several contingencies cannot easily be reproduced at commissioning or are simply not permitted due to cost or security reasons and must be therefore simulated. The increasing use of power electronic systems requires particular attention. Due to the large number of very fast acting devices, stability and security analyses of these systems are more complex than those of conventional power systems. Power electronic controllers can be optimized and tested in real time using prototype systems more or less similar to the production systems. This solution may be adequate at the subsystem level but it is impractical for very large systems containing dozens of subsystems, which are integrated with large electromechanical systems. Consequently, testing complex integrated power electronic systems may be one of the biggest future challenges. The advances in digital processor performance and communication technologies, as well as the development of efficient simulation solvers, enable the deployment of large-scale real-time digital simulators.

The new generation of real-time simulation tools should have the following characteristics [23]:

- capable of simulating very large systems, including interconnected power electronic systems, operating under both balanced and unbalanced operating conditions during long-term phenomena simultaneously with fast transients events requiring sub-microseconds time-steps;
- easily scalable to enable the simulation of very small and very large systems, and capable of starting projects with small, low-cost systems, and then increasing the simulator capabilities as needed;
- capable of performing multidomain and multirate simulation;
- based on simulation tools with an open architecture to facilitate the interface between simulation systems and prototype systems developed by several teams to form an integrated simulation;
- easily upgradeable and capable of integrating high-end general-purpose processors with reconfigurable processor technologies, such as FPGAs, to achieve the best performance at the best price.

III. Multidomain Simulation Tools

The variety of generation and energy storage technologies that will interact in future distribution systems will require the application of simulation tools capable of connecting and interfacing applications from different types of physical systems (mechanical, thermal, chemical, electrical, electronics). Several packages offer a flexible and adequate environment for these purposes, and they can be used to develop custom-made models not implemented in specialized distribution power packages.

The list of tools includes programming languages for modeling complex and heterogeneous physical systems, such as Modelica or Integrated Simulation Environment Language (INSEL), to simulation engines, such as VisSim or TRNSYS (TRaNsient SYstem Simulation Program). All of these tools have been applied to the development of models or specialized tools and libraries for the simulation of renewable energy-based generation [24]–[29].

MATLAB/Simulink is a well-known environment that can be included in this category. This tool has capabilities for solving large-scale systems and provides an open architecture which can be used for rapid testing of new solution methods and prototyping of new models. Several MATLAB-based toolboxes have been developed for DR applications (e.g., SimPowerSystems [30], Wind Turbine Blockset [31], PV Toolbox [32] or CETEEM [33]).

Capabilities for multidomain simulation of DR devices can be also found in other packages that offer different environment and solution methods. Open connectivity for coupling to other tools (e.g., to MATLAB/Simulink), a programming language for the development of custom-made models and a powerful graphical interface are capabilities available in some circuit-oriented tools that can be used for expanding their own applications and for developing sophisticated DR models. These capabilities are available in several EMTP-type tools and in other circuit-oriented packages, such as CASPOC [34].

Although all of the aforementioned tools are powerful simulation tools, one should not expect their application to the analysis and design of an entire distribution system. Dedicated distribution software packages are more adequate and efficient for those tasks. These tools could instead be applied for the development and testing of highly detailed and accurate models of DR devices or hybrid systems, which should be a good complement for computer-aided planning (CAP) and computer-aided design (CAD) tools.

IV. Multiagent Simulation Tools

Present simulation tools do not provide the analysis capabilities needed to study the interaction of power systems and markets in real time during long time periods.

A tool under development to address these simulation gaps is GridLAB-D [35]–[37]. This tool offers a simulation environment that can be integrated with a variety of third-party tools, and combines end-use and power distribution automation models. GridLAB-D can determine the simultaneous state of independent devices, each of which is described by multiple differential equations solved only locally for state and time. This tool can handle widely disparate time scales, is easy to integrate with new modules and third-party systems, does not need to integrate all of the device's behaviors into a single set of equations and can examine the interplay of every system part with every other.

The foreseen development will incorporate modules to perform power-flow calculations and models end-use appliance technologies, equipment, and controls, will use data collection on every property of every system object, and manage boundary conditions including weather and electrical boundaries, will include retail market models, energy operations (e.g., distribution automation, load-shedding programs, and emergency operations), will use models of supervisory control and data-acquisition (SCADA) controls and metering technologies, external links to other simulation and modeling systems or graphical user interface for creating input models, and for the execution and control of the simulation. These capabilities will allow users to study the potentials and benefits of deploying DR devices, the interactions between multiple technologies (e.g., how underfrequency load-shedding remedial action strategies might interact with appliance-based load-relief systems), or the interaction between physical phenomena, business systems, markets and regional economics, and consumer behaviors.

V. Illustrative Examples

This section includes three examples that illustrate the capabilities of some simulation tools analyzed in this paper. A similar organization has been used for each example: an introduction to the case study, a short summary of the main features of

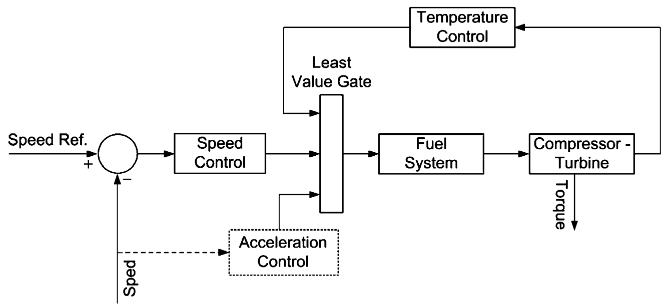

Fig. 2. Block diagram of a microturbine.

the simulation tool used for the study, and some results derived from the scenarios analyzed with each test system.

A. Simulation of a Microturbine System

Test System: This example presents the mathematical models of a single-shaft microturbine generation (μTG) system [38]. The basic components are the compressor, the turbine, the recuperator, the high speed generator, and the power electronics interface.

The system produces electrical power via a high speed generator directly driven by the turbo-compressor shaft. The shaft speed is normally above 30 000 r/min, and may exceed 100 000 r/min [39]–[44]. The high frequency output voltage of the generator must be converted to power frequency. This step involves rectifying the high frequency ac voltage to dc, and then inverting from dc to ac at the power frequency.

Fig. 2 shows the diagram of a microturbine model used in this example. This model is adequate for analyzing slow dynamics of a μTG system, and suitable for power management [38]. The modeling approach neglects fast dynamics of the μTG (e.g., startup, shutdown, internal faults, or loss of power). When the electromechanical behavior of the μTG system is the main interest, the recuperator is not included, since it basically serves to increase the turbine efficiency [44].

The system represented in this example is based on the model presented in [45], and has three important control functions: 1) speed control acting under part-load conditions; 2) temperature control acting as an upper output power limit; and 3) acceleration control to prevent over speeding. The output of these control functions are all inputs to a least value gate (LVG), whose output is the lowest of the three inputs and results in the least amount of fuel to the compressor turbine.

The speed control operates on the speed error formed between a reference speed and the rotor speed, and is the primary means of control under load conditions. A lead-lag controller is used to model the speed control block [41]. Since the operating speed of the system under study is closer to its rated speed, the acceleration control has been eliminated in the system model [46].

The fuel system consists of the fuel valve and actuator. The fuel flow dynamics are dominated by the inertia of the fuel system actuator and of the valve positioner [41], [46]. The output of the LVG represents the least amount of fuel needed for that particular operating point and is an input to the fuel system. Another input to the fuel system is the per unit (p.u.) turbine speed (limited by the acceleration control). The p.u. value of the LVG output corresponds to the p.u. value of the mechanical power from the turbine in steady state. The LVG output is scaled by a factor $K_3(K_3 = 1 - K_6)$, then delayed and offset by the minimum amount of fuel flow K_6 to ensure continuous combustion process in the combustion chamber. K_6 is the minimum amount of fuel flow at no load, rated speed.

The compressor is a dynamic device with a time lag associated with its discharge volume [46]. This is because its output cannot change instantaneously when there is a change in its input. There is also a small time delay associated with the combustion reaction and a transport delay associated with the transport of gas from the combustion system through the turbine. Both the torque and the exhaust temperature characteristics of the single-shaft gas turbine are essentially linear with respect to fuel flow and turbine speed [46].

The representation of the permanent-magnet synchronous generator (PMSG) is performed by using $dq0$ axis theory [38]. For a balanced system, the 0-axis quantities are equal to zero.

The power-electronics interface has the ability to control the real and reactive power by controlling the inverter output voltage and angle as well as maintaining the frequency at a prescribed level. A three-phase uncontrolled rectifier made up of six bridge-connected diodes is used to rectify the generator output from ac to dc. A three-phase voltage-source inverter (VSI) is employed to convert the dc output from the rectifier to ac power frequency.

Control of the voltage source inverter is achieved by means of two control loops, namely, the inner current control loop and the outer voltage regulator loop. The abc/dq transformation block takes the time-varying currents and voltages (in abc sequence) from the current and voltage measuring devices and converts them into dq (time-invariant) values. The voltage controller takes the error signals between the actual output in the dq frame and the reference voltage, and generates the current reference signals for the current controller loop. The current controller produces the dq control signals, which are converted back to control signals in abc coordinates through the dq/abc transformation block. These control signals are used to generate the gating pulses for the inverter to control its output voltage using sinusoidal pulse-width modulation (SPWM). More details on the operation of the power electronic interface can be found in [47].

The inner current control loop is designed to respond faster than the outer voltage control loop so that the two control loops can be designed independently. The current and voltage controllers are chosen as PI compensators.

Simulation Tool: The system model has been simulated with MATLAB/Simulink using SimPowerSystems [30].

Simulation Results: Fig. 3 shows the block diagram of the test case simulated in this example. The model for a 60 Hz μTG system with a rated power of 400 kW and rated speed of 70000 r/min was created by using the approaches summarized before. System parameters were obtained from references [46], [48], and [49]. See [38] for more details.

The response of the test system to a load change was analyzed. The speed reference was kept constant at 1 p.u. All power values are referred to a base power rating of 1 MVA. Initially, the system is supplying a load of $(0.2 + j0.1)$ p.u. power. At $t =$

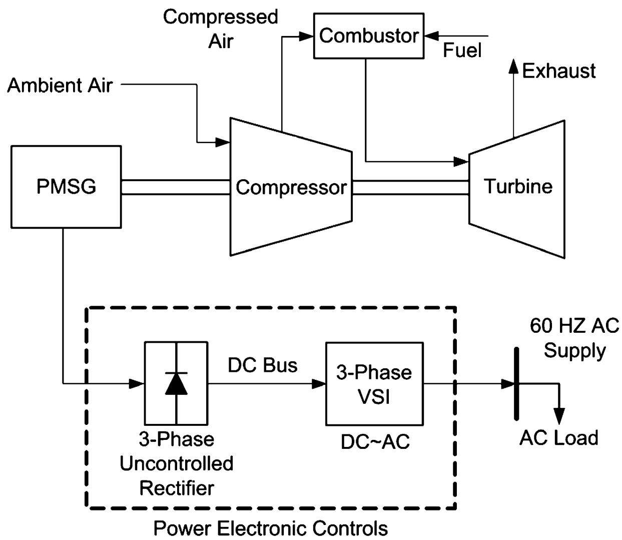

Fig. 3. Example A: Block diagram of the simulated μTG system.

12 s, there is a step increase in the load reaching a final value of $(0.4 + j0.2)$ p.u. power. At $t = 16$ s, there is a step decrease in the load, which comes back to its initial value $(0.2 + j0.1)$ p.u.

Fig. 4 shows some simulation results (in p.u. values). One can observe that the shape of fuel demand, real and reactive output power plots follow the load change, and that real and reactive powers produced by the μTG system match the load requirement. The rotor speed decreases from the initial value of 0.94 p.u. to 0.85 p.u. at full load.

The dc bus voltage (not shown in the figure) drops from about 0.94 p.u. to about 0.85, and returns to its original value when the additional load is removed. The VSI maintains 60-Hz voltage across the load (not shown in figure) at the desired level irrespective of the load applied on the system. Although the dc bus voltage changes with load variation, the ac voltage level across the load remains unchanged due to the ability of the VSI to control its output voltage.

B. Real-Time Simulation of a Multiagent System

Test System: The proliferation of DG will lead to complex situations where the power management becomes difficult, and a coordination of the various DG systems will be required. This case is aimed at solving a unit commitment problem for a multigeneration system using a multiagent system (MAS) approach and a real-time simulation platform [50].

The test system is composed of three μTGs connected to an ac bus, see Fig. 5 [50]. The μTGs must be coordinated to supply the required grid power $P_{\mathrm{ref-grid}}$.

The system views the problem as the interaction between independent agents [51]–[54]. The interaction protocol has to manage the communications and satisfy the operation constraints. Two kinds of agents have been created. The first one is called Grid-agent, and it is similar to the grid operator. The second one is called μTG-agent. There are three agents (μTG-agent1, μTG-agent2 and μTG-agent3), one per μTG.

The system has to ensure that the sum of local production fulfils the required grid power and the production of each μTG does not exceed its power limits.

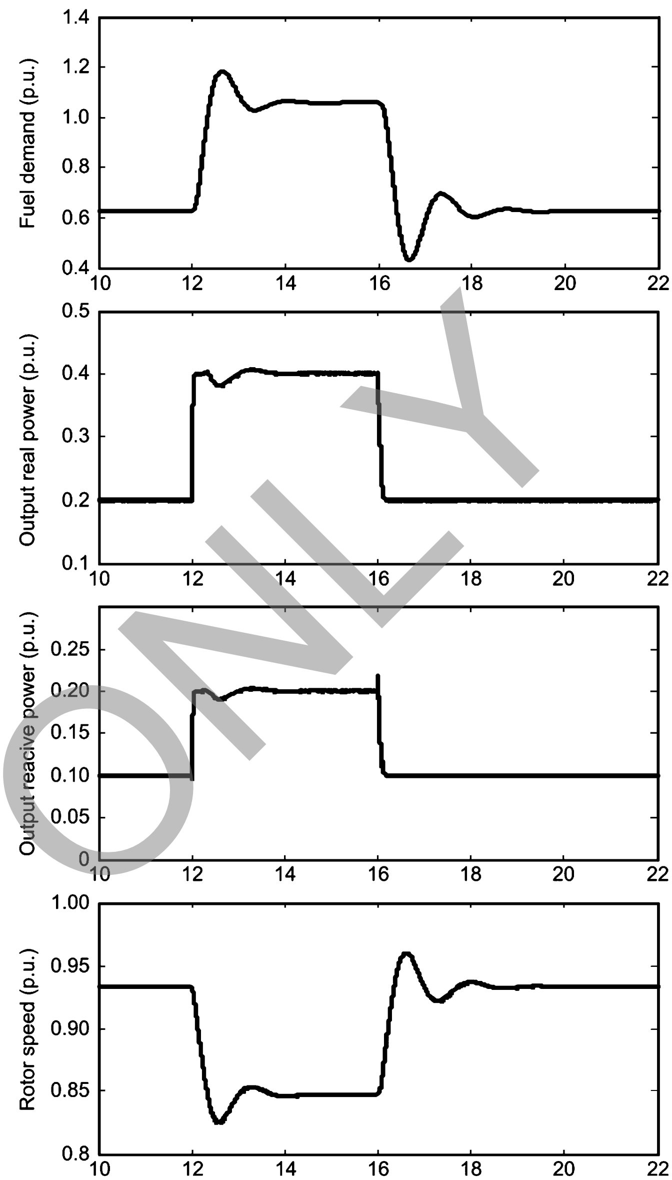

Fig. 4. Example A: Simulation results.

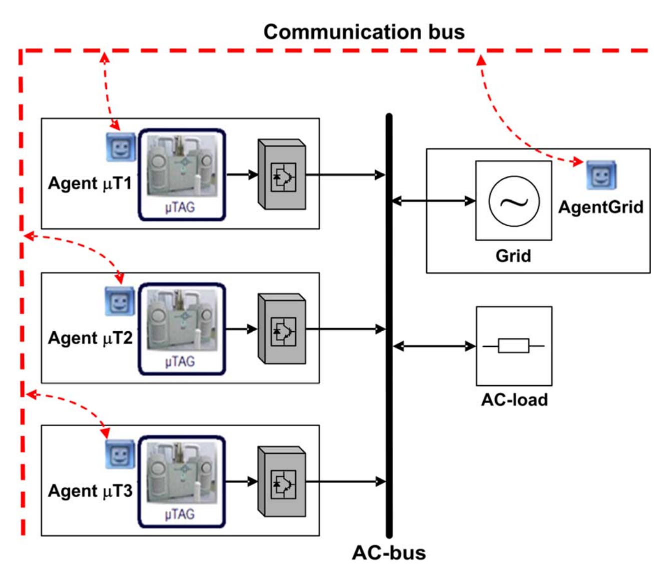

Fig. 5. Example B: Architecture of the multiagent system.

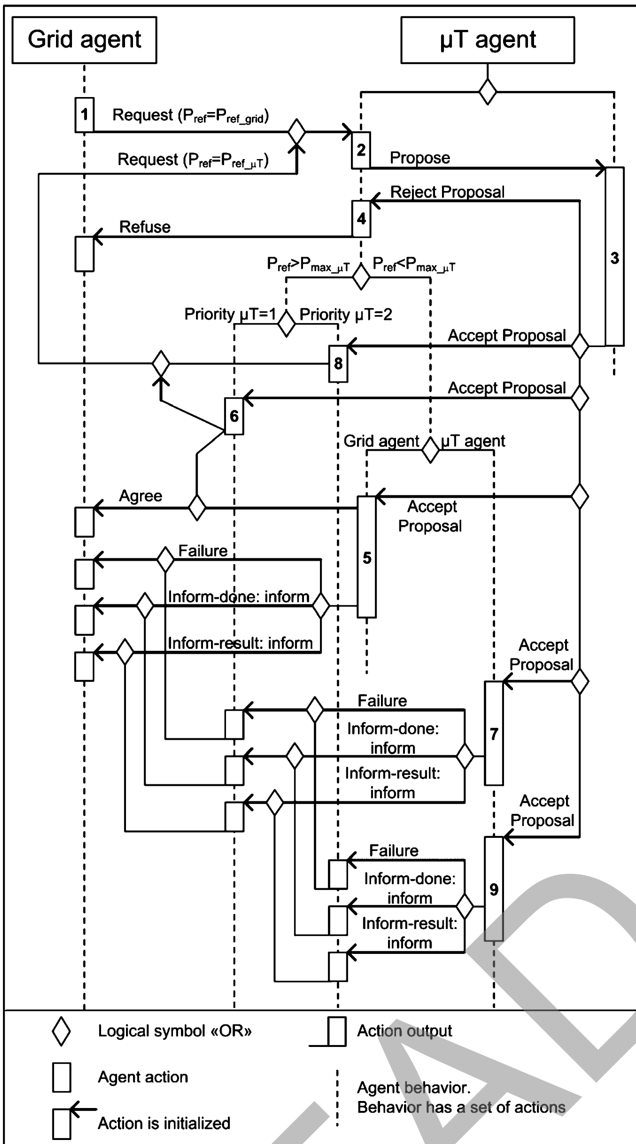

Fig. 6. Example B: Interactions between μTG agents and Grid agent.

For a proper μTG operation, each μTG-agent must know the best operation mode of its μTG.

The negotiation process is depicted in Fig. 6 [50]. Grid-agent asks μTG-agents to supply a desired grid power $P_{ref-grid}$. μTG-agents are coordinated to fulfill this request. To avoid conflicts, a priority on agents must be dynamically determined. This goal can be achieved by exchanging and comparing the information available (e.g., supplied power value) from all μTGs.

The main actions between agents are summarized as follows.

- **Action 1**: Grid-Agent sends a "Request" to all μTG-agents with the desired grid power $P_{ref-grid}$.
- **Action 2**: All μTG-agents process the request and interact together by sending a "Propose" message.
- **Action 3**: Each μTG-agent processes the proposal coming from other μTG-agents. Each agent compares the contents of the message with its own data and makes a decision whether to reject or accept the proposal.

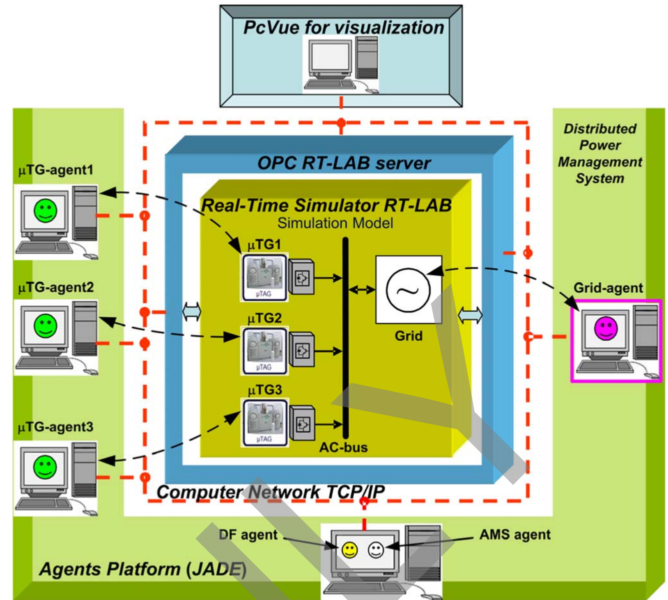

Fig. 7. Example B: Structure of the real-time simulation platform.

- **Action 4**: When a μTG-agent receives a "Reject Proposal", it sends a "Refuse" to the Grid-agent. Only one agent (e.g., agent 1) is chosen at a time. This agent must verify each time its capacity for providing the requested grid power.
- **Action 5** ($\boldsymbol{P_{ref-grid}} < \boldsymbol{P_{max-\mu TG1}}$): The μTG-agent1 communicates an "Agree" to Grid-agent. Afterwards, it must communicate either a failure, an inform-done, or an inform-result message.
- **Action 6** ($\boldsymbol{P_{ref-grid}} > \boldsymbol{P_{max-\mu TG1}}$): The μTG-agent1 can support only a part of the desired power $P_{\text{ref}-\text{grid}}$. So it communicates an "Agree" to Grid-agent and sends a "Request". Another agent (e.g., agent 2) is selected.

This decision process may be repeated until all of the power has been distributed and can be provided.

Simulation Tool: The test system model has been implemented in RT-LAB, a real-time PC-based platform that allows implementing Simulink-based dynamic models for hardware-in-the loop (HIL) testing [55].

The developed platform includes various subplatforms: 1) RT-LAB (Real-Time digital simulation and control LABoratory); 2) JADE (Java Agent DEvelopment frame-work) [56], a multiagent framework for developing distributed systems and peer-to-peer applications; and 3) PcVue [57] for the supervision of industrial processes.

A client/server architecture is used to establish the communications between these subplatforms, see Fig. 7 [50]. This architecture was chosen according to the available OPC RT-LAB driver. The OPC RT-LAB is connected to a simulation model which is running in the RT-LAB simulator where the system model is implemented. So it translates the data into a standard-based OPC format. The JADE MAS and PcVue can connect to this OPC RT-LAB and use it to read and write these data.

The MAS is implemented in the subplatform JADE. There are three μTG agents, one grid agent, an agent management system (AMS), and a directory facilitator (DF) agent. The AMS agent

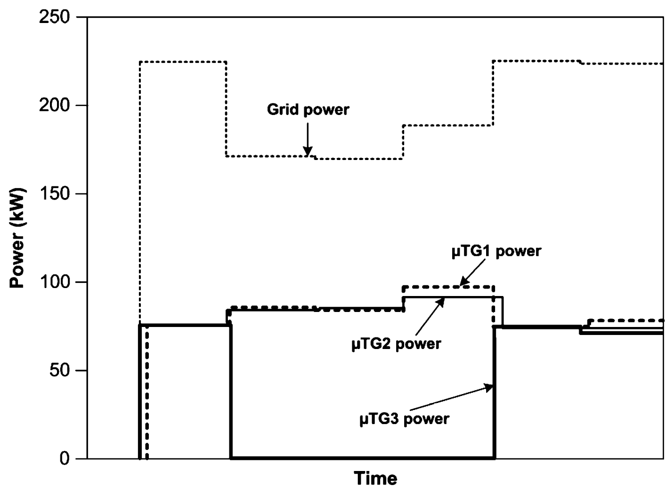

Fig. 8. Example B: simulation results.

is responsible for managing the operation of any agent (e.g., the creation of μTG-agents, the deletion of μTG-agents, overseeing the migration of μTG-agents). The DF agent provides yellow page services to other agents (e.g., it stores descriptions of the μTG-agents and the services they offer). An agent can use the DF agent to search for other agents that can help it to fulfill its own particular goals.

Simulation Results: Assume that the three μTGs are in waiting mode; none is generating power and the maximum capability of each of them is 100 kW. At a certain moment, the Grid-agent requests supplying 225 kW ($= P_{\text{ref}-\text{grid}}$), and sends a message to all agents. Fig. 8 shows the results derived from the model implemented in the real-time platform [50].

The Grid-agent uses the DF agent to find the available μTG-agents. Then, it sends a request to all of the agents which can perform the task. When the Grid-agent sends the request, it does not know the agents that can perform the task. For this purpose, it uses DF to find the available μTG-agents.

All μTG-agents process the request and interact together by sending a "Propose" message. First, μTG-agent1 has the highest priority (since it has a lower value accumulated work time) to perform the request of Grid-agent. However, the requested grid power ($P_{\text{ref}-\text{grid}} = 225$ kW) is higher than its μTG power limit ($P_{max\mu TG1} = 100$ kW). Therefore, it sends a request to other agents. The μTG-agent2 has the second highest priority to perform the request of μTG-agent1, but the requested power is also higher than its μTG power limit, so it sends a request to μTG-agent3. Finally, all μTG-agents have accepted to perform the request from the Grid-agent.

Fig. 8 also shows the subsequent changes in the power requested from the grid and the way in which it is distributed between the three μTGs.

C. Real-Time Simulation of a Wind Farm

Test System: In this case study, a detailed real-time simulation of a grid-connected wind farm is presented. Studies of a single grid-connected wind turbine have provided the fundamental building blocks and the necessary toolset for the model construction and analysis of a wind farm [58].

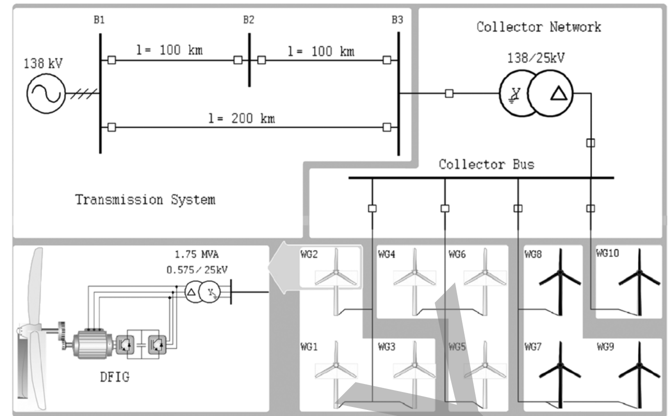

Fig. 9. Single-line diagram of the grid-connected wind farm [59].

As shown in Fig. 9, the doubly fed induction generator (DFIG)-based wind turbines of the wind farm under study have been electrically divided into four groups [59]. The detailed transient model of each wind power conversion system includes the complete aerodynamic, mechanical, and electrical components of the wind turbine, the back-to-back voltage-source-converter (VSC)-based power electronic interface, as well as the mechanical and electrical controllers of the wind turbine.

Each wind turbine had its own 0.575/25 kV distribution transformer connected to the subcollector bus. Through the collector transformer, the voltage is boosted to transmission level 138 kV. At the end of the parallel circuit, the infinite bus B1 is backed by an ideal three-phase voltage source.

The wind turbines are equally spaced on the same altitude with no surrounding obstacles. The variable wind source is made up of four components: 1) average speed, 2) gust, 3) ramp, and 4) turbulence. Average wind speed was assumed to be the same across the entire wind farm. The turbulence is a Gaussian distributed random signal. In order to reflect the geographical location and distance, the wind speed signals feeding to different wind turbines were individually coordinated.

Wirings internal to the wind farm are omitted in the model mainly due to the existence of transformers (behind the wind turbines), which have high impedance in comparison with the impedances of short-length wiring cables. Nevertheless, the cables connecting the subcollector buses to the main collector bus, and the transmission lines supporting the entire wind farm are represented with the conventional distributed-parameter line model.

The line sections between the collector and subcollector buses are modeled with a 50 km distributed-parameter line model. Although the line length and the impedances associated with the line may not reflect the real-world situation, the practice is considered valid for the study of real-time simulation realization and aggregation technique development.

All of the wind turbines were initialized under exactly the same conditions. The control objective for the wind turbines was to produce maximum active power at the unity power factor.

Simulation Tool: The detailed wind farm model was developed under MATLAB/SIMULINK. To complete a 100 s offline simulation in SIMULINK, 10022.0 s was needed on average on a 2.8 GHz CPU. The simulation timestep was fixed to 50 μs.

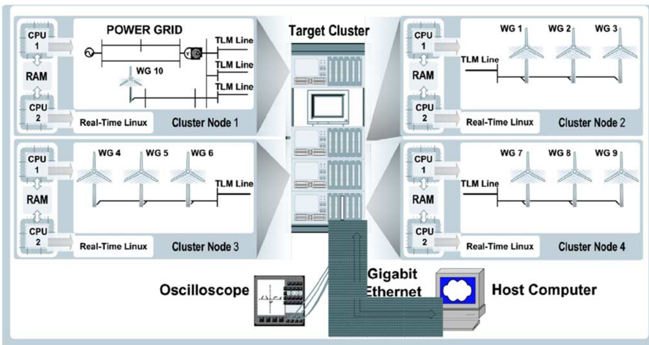

Fig. 10. Distribution of subsystems across the real-time simulator nodes [59].

One way to increase the simulation turnaround time would be to execute the model on an advanced PC-cluster-based real-time simulator [6].

Solving the wind farm model in real time required the computation power of eight 3 GHz Intel Xeon CPUs inside four shared-memory dual-processor cluster nodes.

By referring to the computation time recorded for the real-time simulation of a single grid-connected wind turbine in [58], it was concluded that a maximum of three detailed wind turbine models can be simulated on a single cluster node with the time step fixed to 50 μs. In order to evenly distribute the computation load across the PC cluster, the complete wind farm was divided into four subsystems, on the PC-cluster as shown in Fig. 10.

The various subsystems are processed in parallel on the cluster nodes. The master subsystem contained the transmission system and one wind turbine, while the three slave subsystems contained three wind turbines each.

Communication between the master and slave subsystems was established through the Bergeron transmission-line model. Due to the length and characteristic impedance, electrical signals sent from one end of a transmission line will be received at the other end with a time delay. Because of this delay, the transmission line can be modeled as two separate yet interdependent portions.

By knowing the history terms from one portion, the other portion can calculate its present state using nodal analysis. The transmission-line modeling (TLM) method is used to decompose the overall wind farm power system model. After splitting the transmission-line model in two, one portion was retained in the master subsystem connecting it to the collector bus, and the second portion was accommodated in the slave subsystems linking the wind turbines.

The timestep is small enough that the history terms from both portions were communicated to either side just with a one timestep delay.

Simulation Results: The real-time wind speed signals affecting the four groups of wind turbines in the wind farm over a 100-s interval are shown in Fig. 11. As the average wind speed was set to 11.3 m/s, a 19.16 s delay was created for the forefront of the wind variations to reach the consecutive sets of wind turbines. This explains why the variations in the wind speed signals sent to wind turbines 4 and 5, were started at $t = 19.16$ s. Based on the same principle, the wind signals delivered to

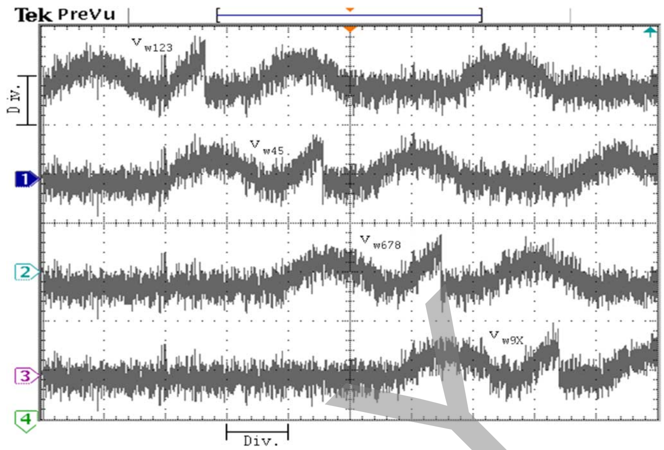

Fig. 11. Real-time synthesis of variable wind speed signals for the four groups of wind turbines. x axis: 10 s/div., y axis: 5.65 m/s/div.

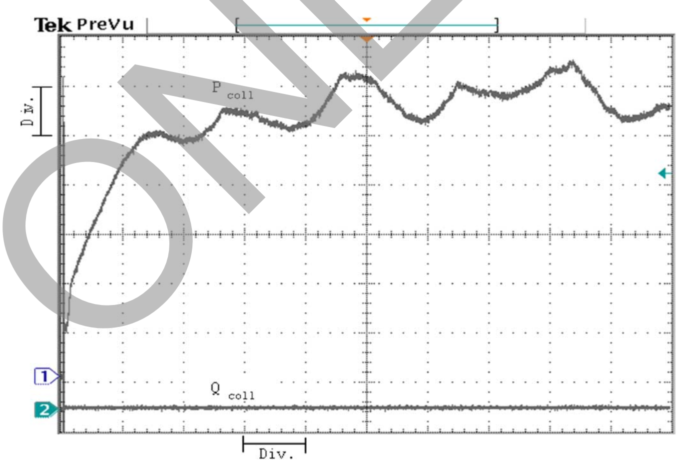

Fig. 12. Real-time trace of the wind farm response to variable wind speed measured at the collector bus: generated active $(P_{\rm coll})$ and reactive $(Q_{\rm coll})$ powers. x axis: 10 s/div., y axis: 1 MVA/div.

wind turbines 6, 7, and 8, and those generated for wind turbines 9 and 10, were, respectively, delayed by 38.32 and 57.48 s.

As the aggregated behavior of the wind farm is more important, the active $(P_{\rm coll})$ and reactive $(Q_{\rm coll})$ powers at the collector bus were measured and presented in Fig. 12. The variations seen in $P_{\rm coll}$ are the recordings of the collective wind farm response to the wind alternations. With the given controller design, the wind turbines would only monitor and regulate the reactive power at the low-voltage side of their own distribution transformer to zero.

As the internal wirings were ignored, the power factor at the subcollector buses should be very close to unity. However, the active currents flowing toward the collector bus have excited the shunt capacitances associated with the cables, and, in turn, increased the generation of reactive power by a small amount.

The detailed switching voltage and current waveforms for the stator-side converter of individual DFIGs in the wind farm are shown in Fig. 13. The grid interface for each wind turbine consists of two 6-pulse VSCs connected back to back at their dc terminals with a shared buffering capacitor. All of the aforementioned real-time results have been validated using offline simulation.

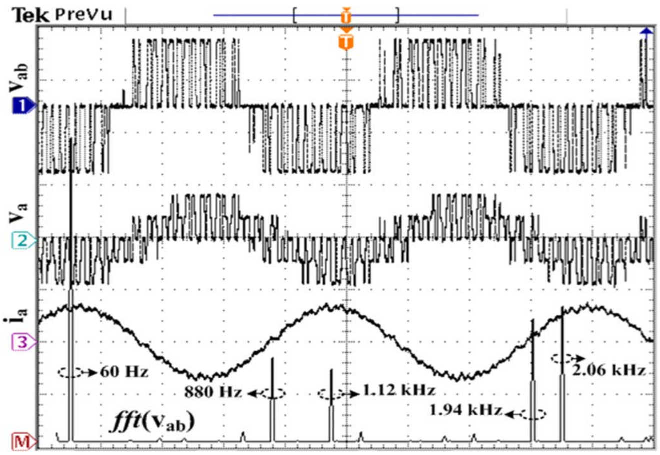

Fig. 13. Real-time trace of the interface converter line voltage, line-to-ground voltage, line current, and harmonic spectrum of line voltage. x axis: 0.4 ms/div, y axis: V_{ab} (1 kV/div.), V_a (1 kV/div.), and I_a (1 kA/div.).

VI. Conclusion

This paper has presented some of the simulation trends that could significantly affect the analysis and design of distributed energy resources.

An increasing use of power-electronic systems for interfacing DRs to the distribution grid will justify the application of real-time simulation platforms in design, analysis, and testing tasks.

Multidomain simulations are emerging as a powerful approach for the study and design of new microgeneration and storage technologies, in which mechanical, thermal, electrical, electronic, and control subsystems can play an important role.

The interaction between physical phenomena of a different nature, market systems, and consumer behaviors caused by the combination of distributed energy resources devices, new business strategies, and modern information technologies requires new simulation tools.

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