INVITED PAPER

An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification

In this paper, the authors envision a service-oriented architecture as a means of enabling modeling, verification, and control of microgrids.

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ABSTRACT | The microgrid (MG) paradigm is a new concept which is considered as a solution for addressing technical, economical, and environmental issues of modern power systems. The application of MG is the subject of extensive studies and experimental tests. It is recognized that there are a number of technical challenges concerning the operation, monitoring, control, and protection of MGs systems. In this respect, the rapid development of the information and communication technologies (ICTs) has opened the door for feasible and cost-effective solutions allowing more extensive intra- and interutility information exchange, diffusion, and open access to a wide range of real-time information. Consequently, the ICTs could represent a strategic tool in supporting effective MG operation. According to this statement, the paper proposes an advanced framework based on the service-oriented architectures for integrated MG modeling, monitoring, and control. The proposed framework is platform, language, and vendor independent, and thus it is an ideal candidate for an effective integration in existing energy management systems and distribution management systems (EMSs/DMSs).

KEYWORDS | Distributed energy resources; information and communication technologies (ICT); microgrids management

I. INTRODUCTION

Electrical power systems were traditionally characterized by the presence of numerous utilities, heterogeneous standards, overlapping territories, and a general lack of integration.

Recently, under pressure from deregulated electricity markets and the new environmental policies, the main limitations intrinsic to this environment have become clear and the structures of modern power systems have evolved to accommodate large changes induced by these new energy policy trends.

In this emerging scenario, the large-scale deployment of the microgrids (MGs) paradigm could play a strategic role in supporting the evolution of conventional electrical grids toward active, flexible, and self-healing web energy networks composed of distributed and cooperative energy resources.

From a conceptual point of view, an MG is a low-voltage distribution system with distributed energy sources (e.g., microturbines, fuel cells, wind generators) and storage devices (e.g., flywheels, energy capacitors, batteries, electrolyser) [1].

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MGs, if properly coordinated and managed, could increase the efficiency of power systems by: 1) supporting large-scale penetration of small-scale distributed generation systems (DGSs); 2) facilitating the integration of renewable energy sources; 3) reducing system losses and green house gas emissions; and 4) increasing the reliability of the electricity supply to the customers. As a consequence, a significant growth in the number of MGs connected to the existing power distribution systems is expected in the near future.

From this perspective, a crucial issue is how to integrate the MGs into existing low- and medium-voltage grids by properly coordinating their generator/storage unit operation and by restricting their potentially negative side effects on network operations and control. It is well known that the integration of MGs into running distribution systems affects the power flows and voltage conditions of customer and utility equipment by inducing a number of side effects (e.g., bidirectional power flows, increased fault current levels, and a need for new concepts of network protection [2]). This increases the complexity of control, protection, and maintenance of distribution systems, which are typically designed to operate radially without any generation at the distribution line or customer side [3].

Designing an MG interface control strategy is another important issue to be addressed. In general, an MG can operate as a *grid-connected system* or as an *island*. However, utilities and existing standards [4], [5] do not allow the islanding operation of MGs. The main reasons are safety concerns related to the energized part of the utility system during islanding, but also the complex control, communication, and protection functionality necessary to make intentional islanding viable [6]. However, exceptions are allowed when the island does not include any part of the utility system.

In the case of future MG applications, with the potential for autonomous operation, a fast and reliable detection algorithm is required to effectively distinguish between an islanding condition and other types of disturbance [6].

In this context, one of the major technical challenges are electromagnetic transients, especially those consequent to the commutation from the grid connected to the islanding mode. The technical challenges become even more severe when an MG has passive local loads [3].

Comprehensive management of this dual MG operating mode asks for the design of advanced controllers. During the grid-connected mode, this controller should operate in a current-control mode, in which it should regulate the exchange of active and reactive powers between the MG and the external grid. On the other hand, during islanded operation, the controller should operate in a voltage-control mode that is much more effective than the current control one [7]. In fact, after islanding, a severe power mismatch can occur, which affects the voltage and frequency conditions in the MG, requiring a fast and flexible reaction of undervoltage and/or underfrequency relays [8], [9].

Design of the local MG controller is a critical task, as well. It should be based on a detailed dynamic model of the overall MG, including the resistive, reactive, and capacitive (RLC) local load and the distribution system. This model should be adapted to the actual operating conditions of the MG in order to guarantee that the controller respond properly to the system's inherent dynamics and transients.

Further difficulties in MG operation are induced by the large scale management of the distributed energy resources. This requires extensive analysis aimed at: 1) identifying the optimal generation schedule that minimizes production costs and balances the demand and supply which comes from both microsources and the distribution feeder; 2) online assessment of the MGs' security and reliability levels; and 3) identifying proper preventive and corrective measures that mitigate the effects of critical contingencies. The main limitations that should be addressed in order to overcome these issues originate mainly from the following intrinsic features characterizing the MGs' operation, in particular:

- the rising level of MGs, which makes the distribution systems more vulnerable with respect to dynamic perturbations;
- the increasing number of smaller geographically dispersed generators that could sensibly raise the number of MG power transactions;
- the difficulties arising in predicting and modeling market operators' behavior, governed mainly by unpredictable economic dynamics, which introduce considerable uncertainty in short-term MG operation;
- the need for more detailed security studies by assessing the impact of multiple contingencies on the distribution system (i.e., N-2 security criteria);
- the high penetration of generation units powered by renewable energy sources that induces considerable uncertainty in MG operation;
- the low level of upgrade and interoperability of existing DMSs that are typically based on low scalable and proprietary software platforms characterized by different information technologies and standards for the data exchange.

In this context, the rapid development of the information and communication technologies (ICTs) has opened the door to feasible and cost-effective monitoring and control solutions, allowing more extensive intra- and interutility information exchange, diffusion, and open access to a wide range of real time information [10]. Consequently, they could represent a strategic tool in supporting effective MG operation. According to the above discussion, this paper proposes an advanced framework based on the service-oriented architectures (SOAs) for integrated MG modeling, monitoring, and control.

The proposed framework is platform, language, and vendor independent, and thus it is an ideal candidate for an effective integration in existing energy management systems and distribution management systems (EMSs/DMSs) [10], [11].

II. RELATED WORKS

The control and operational issues of MGs are presented and discussed in [12]. The analysis in this paper shows that the required control and operational strategies of an MG can be sensibly and conceptually different from those of conventional power systems. These differences will depend on the type and depth of penetration of distributed energy resource units, load characteristics, power quality constraints, and market participation strategies.

Consequently novel control strategies and *ad hoc* EMSs should be deployed for this new application. These facilities would allow MG operators to regulate the active and reactive power flows and control the distributed energy resources in both MG operation modes (namely grid connected and islanded).

In grid-connected mode, some of the system dynamics are supplied by the main grid due to the small size of the microenergy sources. In this operating mode, there is a significant potential for MG to level electrical load peaks (i.e., peak shaving) and provide ancillary services to the electrical grid (i.e., reactive power supply, load following, spinning reserve, system blackstart) [13].

In islanded mode, system dynamics are determined by the MG microsources and its power regulation control. In this operation mode, the control and management system of the MG must satisfy the following issues: 1) voltage and frequency management, 2) supply and demand balancing, and 3) power quality.

In both operating modes, MGs could play an important role in deregulated energy markets as outlined in [14]. In this context, MGs could be operated in order to serve the total load demand, using its local production as much as possible, without exporting power to the upstream distribution grid. This strategy represents a benefit for the distribution system operator since the MG, during the peak demand, relieves possible network congestion by partly or fully supplying its energy needs. Otherwise, MGs could directly participate in the open electricity market, buying and selling active and reactive power to the grid. According to this policy, the MG acts as a single generator capable of relieving possible network congestions not only in the MG itself, but also by transferring energy to nearby feeders of the distribution network.

To address these needs, the MG management system must ensure a subset of basic functions (i.e., economic scheduling, load and weather forecasting, DGS power production control, security assessment, and demand side management) that could be deployed according to a supervisory control architecture with a three level structure [15], [16].

- Distribution level: distribution network operator and market operator. This level is used to achieve dispatch functions at the distribution level.
- MG level: MG central controller. The interface between the MG and the main grid. It interacts with both level 1 and 3.
- Unit level: local controllers. They are developed for distributed energy resources and controllable loads. They could also be used to regulate voltage and frequency.

As outlined in [16], operational control and EMSs for MG should be implemented through the cooperation of various controllers, located in all of these levels, on the basis of communication and collection of information about distributed energy systems and control commands. This could be deployed according to a centralized or decentralized control paradigm.

In a centralized control paradigm, the MG controller optimizes the power exchanged between the MG and the main grid, thus maximizing the local production depending on the market prices and security constraints. This is achieved by issuing control set points to distributed energy resources and controllable loads in order to optimize the local energy production and power exchanges with the main distribution grid [12], [14], [17].

The decentralized control paradigm intends to provide the maximum autonomy for the distributed energy resource units and loads. This implies that local controllers are intelligent and can communicate with each other to form a larger intelligent entity. In a decentralized control framework, the main task of each controller is not to maximize the revenue of the corresponding unit but to improve the overall performance of the MG. Thus, the architecture must be able to include economic functions, environmental factors, and technical requirements; e.g., black start. These features indicate that a multiagent system (MAS) can be a prime candidate for decentralized MG control [12], [18], [19].

Armed with such a vision, papers [18] and [19] present a general framework for the control of distributed energy resources organized in MGs. The proposed architecture is based on the agent technology and aims to integrate several functionalities, as well being adaptable to the complexity and size of the MG. To achieve this in [18], a layered learning paradigm is proposed. The main feature of this paradigm is that the various controls and actions of the agents are grouped depending on their effect on the environment.

An agent-based paradigm for MGs control and management is proposed in [20]. This paper demonstrates that a collection of intercommunicating intelligent agents deployed by open grid standards is a useful and viable approach for enforcing operational policy in MGs.

A fully decentralized architecture for voltage and frequency control in MGs is proposed in [21]. This paper proposes a communication overlay toolbox extending the primary control of each DGS with the secondary and tertiary control. The secondary control ensures that the frequency and average voltage deviation of the MG is regulated towards zero after every change in load or supply. The tertiary control allows MG operation at an economic optimum by ensuring that, as far as power limits allow, all DGS units exchange power at equal marginal cost. In contrast to primary control, operating without communication, both secondary and tertiary control are implemented using communication between the DGS.

Another important issue to address for effective MG operational control is dealing with the problem of security assessment in both steady-state and dynamic scenarios [14]. The main steady-state security concerns for the operation of MGs are satisfying voltage constraints and maintaining power flows within thermal limits. Dynamic security concerns the MG operation under a number of contingencies both within and above it (i.e., during a transition between the grid connected and islanded mode of operation). Effective MG security assessment asks for detailed analysis of phenomena that can compromise MG operation. To address this need, Moreira and Peças Lopes [22] propose an artificial-neural-network-based methodology to assess the security index for a credible range of operating scenarios. The usage of artificial neural networks is emphasized due to its computational speed for online performance and its flexibility for providing corrective actions for insecure operating conditions to achieve a seamless transition from interconnected to islanded MG operation.

All of these functions require the design of reliable, resilient, secure, and manageable standards-based open communication systems [16]. These infrastructures represent a key issue in MG deployment as they would provide the fundamental backbone for connecting the MG elements, the data providers, and the decision-making entities in an open and interoperable framework.

They should support ubiquitous connectivity between decision-making points and dispersed and heterogeneous data sources characterized by varying degrees of transport, security, and reliability requirements [16], [23].

They must ensure the capability of MG control systems to transmit data to and from distributed intelligent controllers; moreover, the prospect of the development of innovative energy market policies imposes the need for the realization of efficient and reliable widespread bidirectional communication links between MG operators and customer premises.

In the light of these needs, the IEC 61850 provides a standardized framework for substation automation integration that specifies the following: the communication requirements, the functional characteristics, the data structure within devices, how applications interact with and control other devices, and how conformity to the standard should be tested [24], [25]. In the IEC 61850 Standard, details part 7–420, the information exchange between distributed energy resources units and monitoring and control devices [26], [27] is considered. It also defines some measures for the success of an integrated MG communication network design [28], which are:

- flexibility to adjust and grow the system topology as requirements change;
- performance, especially quality of service, to enable effective prioritization among competing applications and to meet critical requirements of the most important protection and control functions;
- reliability, for critical protection systems, but also because so many different systems are relying on the same infrastructure.

The deployment of a low-cost and high-performance communication infrastructure allowing the cooperation of distributed controllers on the basis of communication and collection of information about distributed energy systems and control commands is a challenge which should be faced by the emerging technologies [16].

The literature analysis discussed above reveals that as MGs control and management systems are designed to address only a specific functionality (i.e., energy management, voltage control, MGs modeling, security assessment, data acquisition, market interface) they do not deal with the definition of an integrated platform capable of easily executing very complex applications, built by composing required functionalities in a standardized, easy-to-use and well-defined way. To address this problem, SOAs, in particular those based on the standard web service technologies, seem particularly suitable for MG control and monitoring due to their ease of application programming, portability, maintenance, and integration with legacy services.

A web service is an interface that describes a collection of modular, self-describing, and self-contained applications that are network-accessible through standardized XML messaging. The use of standard XML protocols makes web service technologies platform, language, and vendor independent; thus they are an ideal candidate for use in the integration of legacy power system applications in MGs [10], [11].

III. AN INTEGRATED FRAMEWORK FOR MG MANAGEMENT

The proposed framework for MG control, modeling, and monitoring is based on the SOA model, which is a component model that interrelates different functional units of an application, called *services*, through well-defined interfaces and contracts between services. The interface is defined in a neutral manner that should be independent of the hardware platform, the operating system, and the programming language that the service is implemented in. This allows services, built on a variety of such systems, to interact with each other in a uniform and universal manner. The main benefits of a SOA system are the improvement of interoperability and the integration of new and legacy applications, the ability to survive evolutionary changes in the structure, and implementation of the internals of each service. SOAs are not a new concept, but an alternative model to more traditional tightly coupled object-oriented models that have emerged in the past decades.

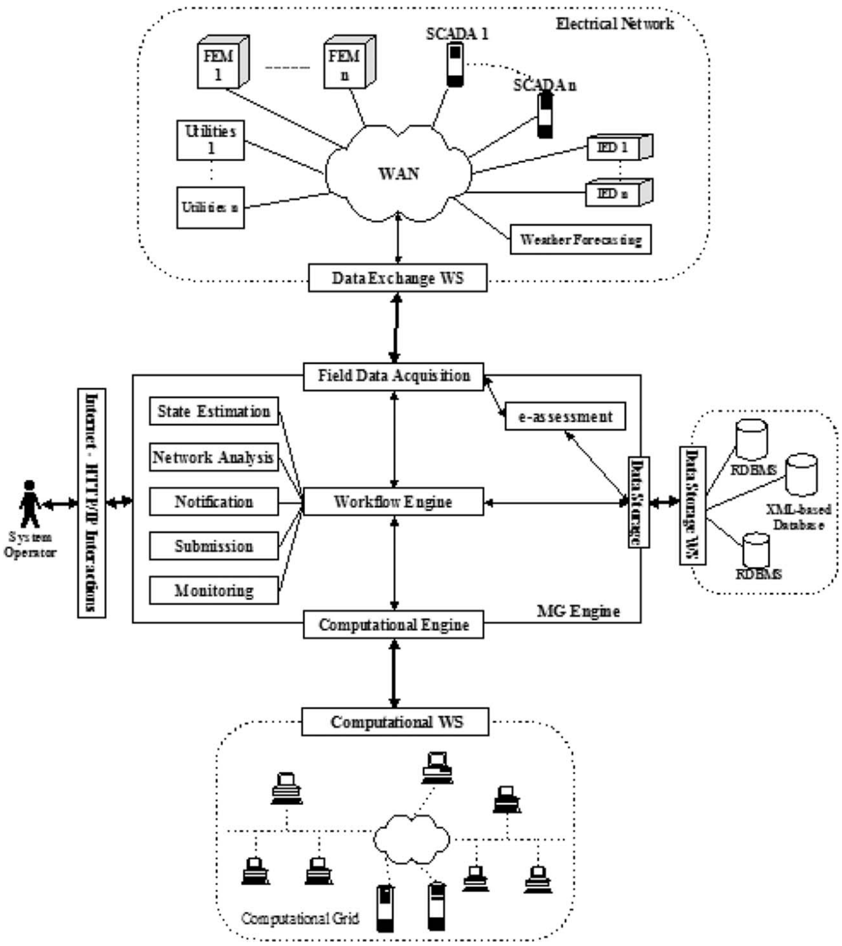

Fig. 1. ***The overall web-services based architecture.***

Many technologies can be adopted to implement a SOA. Examples are the common object request broker architecture (CORBA), and message-oriented middleware systems, and more recently the standard web services technologies, which are emerging technologies able to ensure a high degree of integration among existing or newly created services exposed on the web.

Web services extend the advantages of software components making it possible to employ an existing low-level middleware infrastructure based on web servers and HTTP protocol. A web service is a set of operations provided by some software applications. Such a service can easily be accessed through a well-defined interface independently from the service deployment details. In Fig. 1, the overall distributed meta-architecture for MG monitoring and control is shown.

The core component of the meta-architecture is the *MG engine* which is responsible for the execution of MG control, modeling, and monitoring functions in a geographically distributed scenario. It includes high level components which are mainly the submission service, the operation service, and the notification service.

The submission service is responsible for the handling of user submission requests and is designed to simplify the submission phase made by a nonexpert network operator. The MG operation service is responsible for the MG control and monitoring execution. Finally, the notification service is responsible for the asynchronous management of output data of an application able to notify specific events. A basic and fundamental component of the *MG engine* is the workflow enactor, which manages the execution of the *MG service* and adds some functionalities related to the specific monitoring application. Here the workflow enactor is traditionally described using its business logic description, and it is written in a certain workflow language.

The web service definition language (WSDL) interfaces of the three kinds of web services defined above are the following:

1) `GISinterfaceWS`: for georeferential information acquisition;
2) `DataAcquisitionWS` for real-time data acquisition;
3) `eAssessmentWS`: for MG generation/storage unit capability assessment;

4) `ComputationalWS`: to process the mathematical computations required by the MG control and monitoring functions;
5) `DataStorageWS`: related to the data storage functionalities.

In the following text, the above web services will be briefly addressed.

A. GISinterfaceWS

The `GISinterfaceWS` was defined for the acquisition of georeferentiated information on the MG. It delivers the following services:

- `GetNetworkdata` that acquires MG structural data concerning the geographical map, the network topology, and the sources of power supply;
- `GetControlDevicesAsset`: type, location, and characteristic parameters of the available control and monitoring devices;
- `GetElectricalNetworkDetails`: line parameters, power transformer rating and numbers, impedance values, bus bar scheme, and circuit breaker type and installation;
- `GetOperationalParameters`: substation equipment status, feeder breakdowns, failure of distribution transformers, tripping on feeders/lines, and consumer outages.

B. DataAcquisitionWS

The `DataAcquisitionWS` was defined for the real-time acquisition of the entire set of measurable MG field data.

This comprises, in particular, the MG topology, the available measurements of the electrical nodes parameters, and the actual state of the generator/storage units computed locally by intelligent electrical devices (IEDs). All possible kinds of measurable parameters are well defined; for each kind of parameter, a code and a basic measurement unit are defined according to IEC 61850-7-420 [26], [27]. This standard defines the communication and control interfaces for all MG devices, and develops distributed energy resources object models. The main benefits of using this standard are:

- consistent data models;
- easy maintenance of data models;
- share the interoperability of communication based on IEC 61850;
- seamless integration into the station automation and the power control system.

Each measurement value returned by the `DataAcquisitionWS` is correlated to a timestamp, which indicates the time at which the value was acquired.

The returned type by the described portType is a string that corresponds to the URL of the file containing the required information, which can be downloaded at a convenient time.

C. eAssessmentWS

A reliable assessment of the actual and future generator/storage unit capabilities appear to be crucial for reliable MG operation.

This demands a design of mathematical models able to predict—given the actual unit state and the forecasted environmental conditions—the evolution of the supply capabilities [29]. These predictive models should also exhibit adaptive features, to deal with the time-varying phenomena affecting the generation/storage unit performances (i.e., aging, parameter drifts), and low-computational requirements in order to ensure effective hardware implementation.

To address this problem, the proposed framework integrates a network of distributed IEDs to dynamically assess the supply capability of the main MG components. These IEDs are fully managed by a dedicated web service.

This web service delivers the `getCapabilitydata` portType that acquires the georeferentiated input data for the capability calculations by interfacing with dedicated web-based public services (forecasted environmental variables), and the `submitCapabilitydata` portType that submits the right input data to the distributed IEDs for the capability calculations.

D. ComputationalWS

To support the MG's monitoring and control functions, intensive online network computations are required. These comprise system state estimation, optimal power flow studies (i.e., voltage control), security assessment (i.e., contingency analysis), and economic analysis (i.e., the generators must be dispatched based on an economic assessment of fuel cost, electric power cost, weather conditions, and anticipated process operation).

All of these tasks require a comprehensive mathematical model describing the MG's dynamics for both islanded and grid-connected operation.

To this purpose, a modular MG model presented in Fig. 2 is adopted. In Fig. 2, the main components are obvious: a distributed generator (DG unit), connected over a connection cable/line to the external grid and load, and controlled over the suitable controller.

By neglecting the grid and writing the system equations for $v_{t,abc}$ and v_{abc}, the model describes the dynamic behavior of an islanded MG. It is common practice to transfer the model from abc to stationary $(\alpha\beta)$ and then to a rotating (dq) system. This model can be further used to extract the transfer function of the overall circuit. By making use of single-input–single-output (SISO) transfer function, a controller for the islanded MG can be built [3].

For the grid-connected operation, a *current-control method* has been considered. The load voltages v_{abc} are measured and transferred to a dq rotating frame. Using a phase-locked loop (PLL), the phase angle θ at the common coupling point is estimated and used to generate the dq quantities. Fig. 3 shows the designed PLL [30], [31].

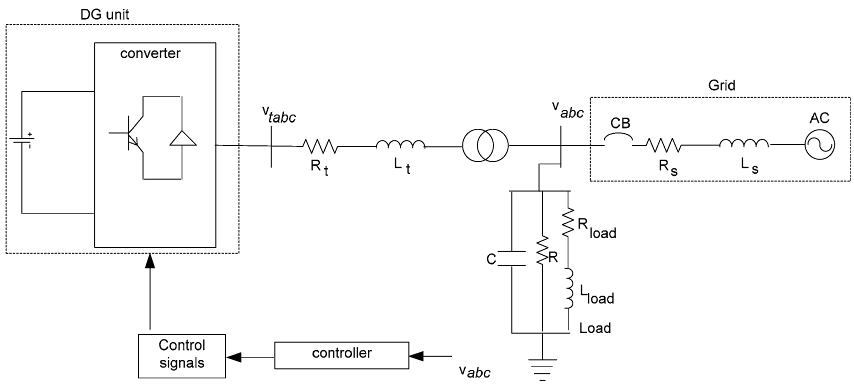

Fig. 2. ***Model of an MG with an RLC local load.***

In Fig. 4, the current-control method [32] is described. By making use of a *dq* transformation, *abc* variables for the current and voltage are transformed into *dq* variables, which are further used as input values for the controller. These controlled parameters result in $v_{t,dq}$ voltages and feed the pulse width modulation (PWM) block to generate the gating signals for the converter. In Fig. 5, a detailed block diagram of the controller from Fig. 4 is shown.

The online solution of these dynamic models is a computer-intensive task, especially for a large number of MGs, the extension of electrical networks, and the depth of analysis. So, in addressing these computationally demanding analyses in useful execution times, parallel algorithms to be executed in a distributed environment have to be adopted [33], [34]. In this context, to analyze the behavior of interconnected MGs effectively, characterized by an ever growing and variable structure, the computational engine has to assure high reliability, flexibility, and scalability. A practical solution is to exploit the enormous amount of computational power of the *grid-computing systems* through the Internet [35]. A grid-computing system allows any complex application to be solved by means of a large, dynamically extensible pool of computational resources acquired from the Internet. So, the paradigm overcomes the main limitations of small clusters of networked computers driven by environments, such as parallel virtual machine (PVM), or asynchronous remote method invocation (RMI), which do not assure enough flexibility and scalability to execute more and more intensive calculations. Today, many grid-computing middlewares and toolkits exist [36], which adopt different technologies, exchanged data formats and distributed programming approaches. All of these different platforms,

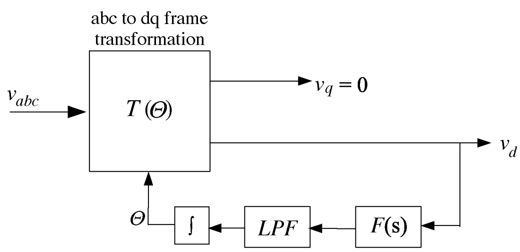

Fig. 3. ***Block diagram of the embedded PLL.***

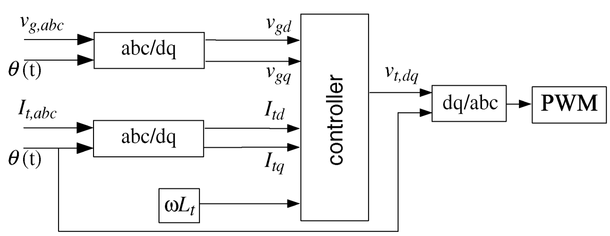

Fig. 4. ***Block diagram of the converter control system.***

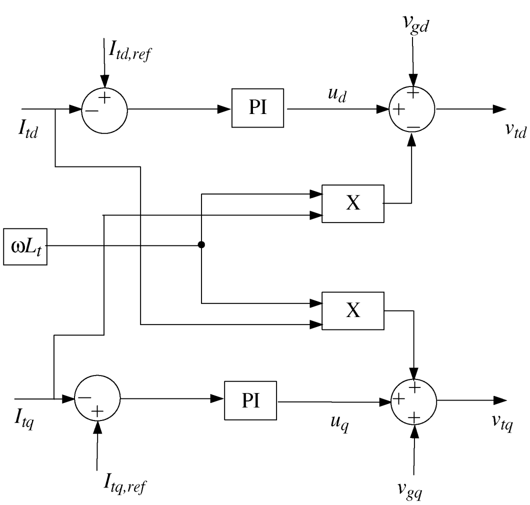

Fig. 5. ***Details of the controller block from Fig. 4.***

by means of a specific implementation of the JobSubmissionWS interface, can be adopted by the MG engine to execute the computations supporting the monitoring services and so be easily integrated into the overall architecture.

The JobSubmissionWS interface exports a set of brokering functionalities which are related to the interaction with a computational engine and are necessary to the submission of an application and to the management of execution results, both in an asynchronous and synchronous way. In this connection, the grid broker pattern proposed in [35] has been adopted.

E. DataStorageWS

Storage systems, used to permanently store alarm conditions which can be analyzed offline, for example by using a web browser or a dedicated application, are required. Since they can be adopted as a reference in networks planning or as a knowledge base for expert systems based on decision support systems, these historical data are extremely useful in power system analysis. These storage systems, in order to be composed with the rest of the framework, have to export a DataStorageWS WSDL interface. So, a standardized and convenient method of accessing and managing distributed and heterogeneous data storage resources, such as a remotely accessed real-time database management system (RDBMS) or XML repositories, must be defined. In this first design phase, it is intended to adopt an existing framework: open grid services architecture data access and integration (OGSA-DAI).

The OGSA-DAI implementation has been designed with the aim of allowing external data resources to be accessible via a standard grid services interface [34]. It includes support for the registration and discovery of databases and for interaction with those databases. The structure of the results, the method, and the location of their delivery can be set by the client. It is an implementation of the standard grid data service specification (GDSS) defined by the database access and integration working group (DAIS-WG) of the Global Grid Forum (GGF).

F. Workflow Enactor

The workflow enactor composes and integrates web services which deliver different functionalities, related mainly to: 1) the real-time electrical data acquisition from different sources; 2) supply of the high-computational power to develop MGs monitoring and control functions; and 3) storage functionalities to handle huge amounts of data.

The workflow enactor handles the execution request of the monitoring/control service described in a certain workflow language, which describes the temporal composition of the web services delivering the basic functionalities, submitted by means of the submission service. In Fig. 6, the action sequence performed by the workflow is shown, referred to a single execution of the monitoring/control application [34].

Typically, the monitoring/control application has to be executed continuously, requiring for each execution the acquisition of the current data of the MG's state, and in particular, the following.

Phase 1 getNetworkTopology and Phase 2 getControlAsset are performed to obtain the necessary MG description and the characteristic data of the available control and monitoring devices.

Phase 3 getCapabilitydata and Phase 4 submitCapabilitydata are performed to acquire the input data for the generator/storage supply capability calculations, to arrange these data for each IED in function of its geographical position and to submit to the distributed IEDs the corresponding information.

Phase 5 getNodesParameters is performed to obtain the real-time data of each node and is made

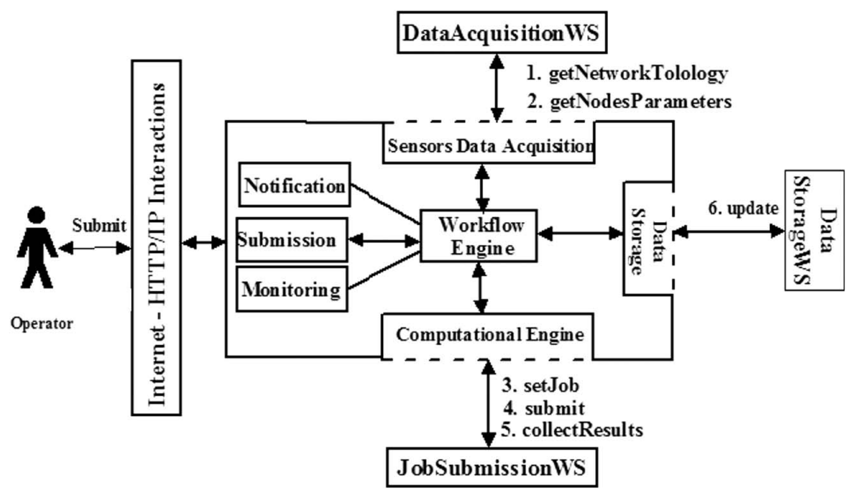

Fig. 6. ***Main actions of the workflow enactor.***

to interact with the service implementing the `DataAcquisitionWS` interface, typically delivered by the electrical network to analyze.

Phase 6 `setJob`, Phase 7 `submit`, and Phase 8 `collectResults` are performed to request the execution of the control and monitoring computations to a computational engine and in particular are made to interact with a service implementing the `JobSubmissionWS` interface exported by a grid-computing system. These computations comprise: 1) the MG's *state estimation* computed by processing the network data acquired and solving the system state equations; 2) the checking of the distribution network *operational constraints*; 3) the assessment of the system's *security* and *reliability* levels; and 4) the local MG's control and regulation functions (i.e., power factor, frequency and voltage control, and load management).

Finally, Phase update is executed to save the output data of the analysis in a data storage system interfaced through a service implementing the `DataStorageWS` interface.

IV. EXPERIMENTAL STUDIES

In the following section, the implementation details of the basic web services and the workflow enactor for MGs modeling and control are discussed.

A. Data Acquisition Web Service

Field data can be acquired by means of geographically dispersed resources [i.e., supervisory control and data acquisition (SCADA) systems, IEDs, field energy meters (FEM)]. A prototype web service implementing the `DataAcquisitionWS` interface considering the FEMs units located on each MG unit (load/generation/storage), and the direct interaction with them for real-time acquisition of the electrical parameters, was developed. In particular, a network of distributed FEMs based on ION 7330–7600 units were considered. They can measure demand on any instantaneous value and record peak (maximum) and minimum demand with a date and time stamp per second. The units are equipped with an on-board web server, which supports the XML format and the protocols ION, Modbus TCP, Telnet, for their full remote control. The FEMs were physically connected to a Fast Ethernet LAN, configured with an IP address. The authors prototyped the interaction through the HTTP protocol to access, in particular, an XML file, called `realtime.xml`, which contains the most recent measured field data.

To assess the supply capability curves of the MG components, a prototype version of an IED based on the ZWORLD-BL2100 unit (an advanced single-board computer that incorporates the Rabbit 2000 microprocessor) was adopted. These IEDs are installed directly on the MG components. They allow us to continuously monitor their state and to dynamically predict the corresponding supply capability curves in function of the forecasted climatic variables profiles. These functionalities are fully available by an IP-based connection [29].

The authors are currently developing another implementation of the `DataAcquisitionWS` interface, considering the interaction with proprietary SCADAs. This new functionality will allow the integration of all the information coming from existing distributed measurement systems, and so to decrease the response time of the service.

B. Job Submission Web Service

In order to realize the first implementation of the `JobSubmissionWS`, the authors adopted a specific grid-computing middleware. After the first analysis of existing middlewares, the Hierarchical Metacomputer Middleware (HiMM), version 1.1, developed at the Research Centre on Software Technology, University of Sannio, Benevento, Italy [37] was chosen. The main features of HiMM that are useful in this context are: 1) the virtual hierarchical topology which, allowing applications to exploit dedicated networks or clusters that are not directly accessible by the Internet, makes the system highly scalable; and 2) the support for the object-oriented programming paradigm and in particular for Java language, which simplify the application development and an easy integration with the web technologies.

In addition, HiMM supports a grid broker service, which allows an application to exploit grid resources in a simplified way, hiding the complexity of the underlying system. The grid broker delivers a specific service to submit a master/slave application easily by using its nearly sequential version and some information necessary for the deployment. It simplifies distributed programming since it supports the separation of concerns related to *functional* (algorithmic issues, such as the creation of high-level domain-dependent abstractions in the form of objects and classes) and *system* (lower level tasks such as object distribution, mapping, and load balancing) aspects of programming.

C. Computational Web Service

The computational grid used for performing the online computations was deployed on a testbed organized according to a logical hierarchical and heterogeneous topology of two levels, as shown in Fig. 7 [38]. The first level consists of a set of directly accessible heterogeneous resources composed of eight computers, and two front-end computers that were used as masters to coordinate computations of two pools of computers located in two different buildings and representing the second level of the network. The first pool consists of a cluster of workstations (COW) composed of eight homogeneous computers interconnected by a Fast Ethernet LAN through a hub 3Com TP16C. The second pool consists of a network of eight heterogeneous workstations (NOW), interconnected by a Fast Ethernet LAN through a Switch HP Procurve 2524. The first-level machines are interconnected by a Fast Ethernet LAN.

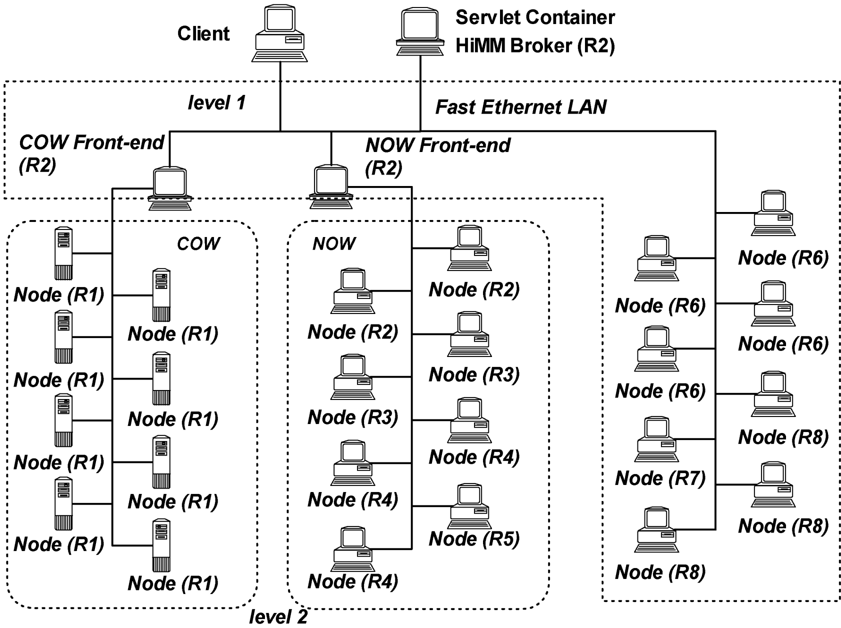

Fig. 7. ***The computational grid adopted for online MGs monitoring and control.***

The mathematical solution engine adopted to support the online computations is based on the MATLAB 6.5R13 environment equipped with specific power systems analysis features. It allows system operators to investigate steady-state and dynamic issues in electrical networks by performing load flow analysis, time-domain simulations, and economic analysis.

The interface with the MATLAB environment has been developed by using a dedicated class. An instance of this class allows the JAVA Servelts to locally open a dedicated MATLAB session, to import/export variables and to invoke a specific MATLAB routine. Thanks to the adoption of this distributed solution engine, advanced MG control and monitoring functions can be easily defined.

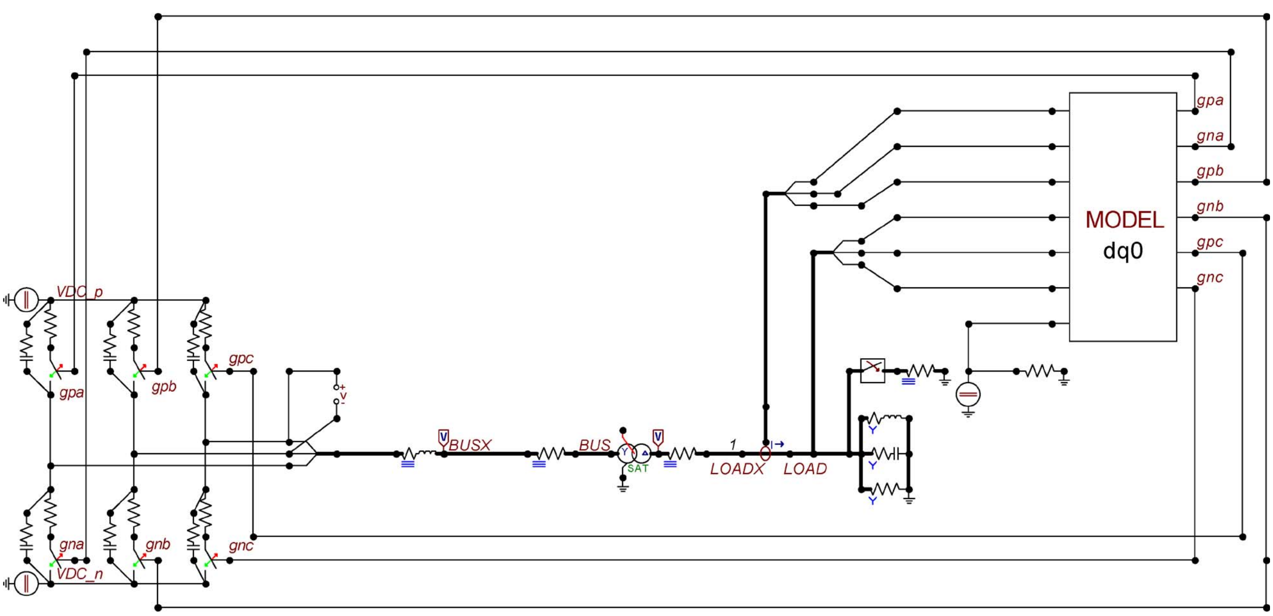

Fig. 8. ***ATP model of the MG of Fig. 2.***

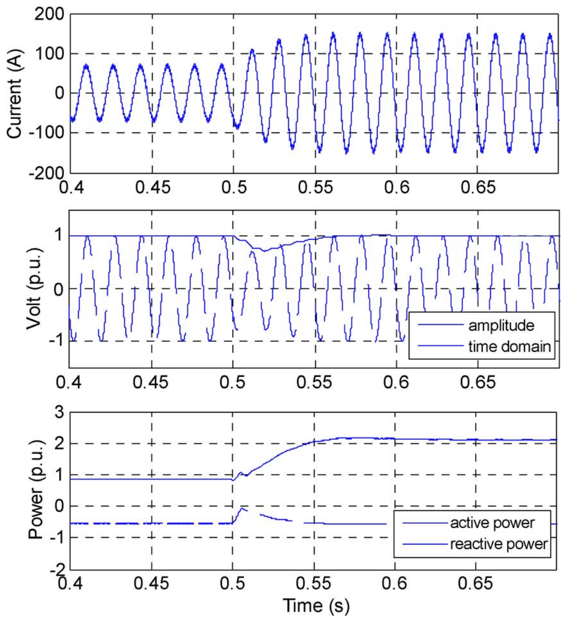

Fig. 9. ***Dynamic performance of the islanded MG for a load step increase: load current (upper graph), load voltage (middle graph), and load real and reactive powers (lower graph).***

It should be noted that the employment of MATLAB as solution engine was selected only to demonstrate the capability of the proposed architecture to easily integrate commercial-based software platforms. The adoption of a different software product does not cause complications since it only requires the design of a specific slave class of the computational engine of the system.

To confirm this statement, the results obtained by interfacing the `ComputationalWS` with a graphical preprocessor to the ATP-EMTP on the MS Windows platform (ATPDraw) are briefly discussed [39].

Fig. 8 shows the ATPDraw model of the MG of Fig. 2. The MG is modeled with the available power system components within ATPDraw environment. The converter is represented by six ideal type-13 switches in ATP-EMTP. The control outputs (Fig. 4) are given to a PWM block that generates gating signals for the insulated gate bipolar transistor (IGBT) switches of the converter.

The described ATPDraw model can implement multiple modes and control strategies required for simulating MGs for both the islanded and the grid-connected operation.

In order to test the system performances, a specific function for the optimal design of the local MG controller described in Figs. 4 and 5 has been developed. The obtained results for both islanded and grid-connected MG operation are summarized in Fig. 9–11. Fig. 9 shows the dynamic performance of the islanded MG operating with the designed control system for a step increase in the local load. The MG is initially operating in steady state, and at $t = 0.5$ s, the load resistance, inductance, and capacitance are changed. The MG reaches a new steady-state operating point after about three cycles, which indicates the effective response of the designed control system. Variations of the load current and voltage and the load active and reactive power components are shown in Fig. 9.

Fig. 10 shows the dynamic performance of the islanded MG operating with the designed control system for a change in the load voltage reference. The MG is initially operating in steady state, and at $t = 0.5$ s, the load voltage reference is changed. The MG reaches a new steady-state operating point after about four cycles, again indicating the effective response of the designed control system. Variations of the load voltage and current and the load real and reactive power components are also shown in Fig. 10.

Fig. 11 shows the dynamic performance of the grid-connected MG for changes in the MG real and reactive (dq) current references. The system initially operates in steady state with no real/reactive powers from the MG. The references of Id and Iq are changed at $t = 0.5$ s and $t = 0.7$ to 1000 and 500 A, respectively. Variations of the MG dq current components, the grid phase current, the grid real and reactive powers, and the converter output voltage are shown in Fig. 11. The results demonstrate that the designed control system effectively and smoothly transfers the overall system to the new operating conditions.

Further control and monitoring functions could be executed in parallel by the computational web service. It adopts a brokering service, based on an economy-driven model, to satisfy the quality-of-service constraints specified by the user (i.e., a time deadline to solve a specific

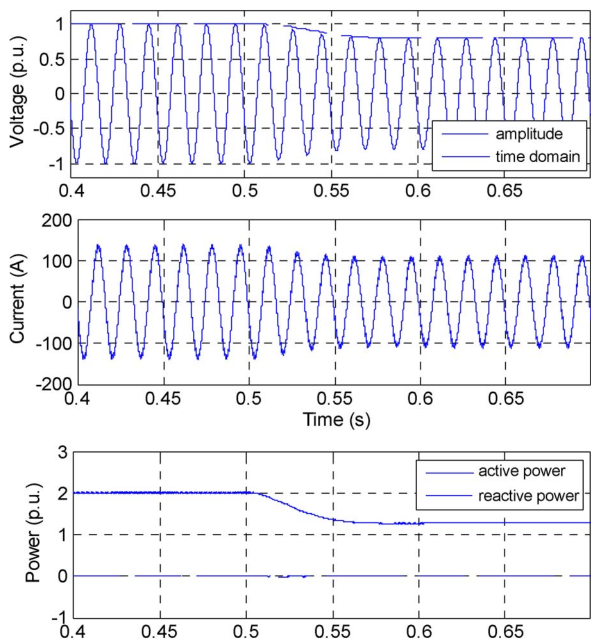

Fig. 10. ***Dynamic performance of the islanded MG for a change in the load voltage reference: load voltage (upper graph), load current (middle graph), and load real and reactive powers (lower graph).***

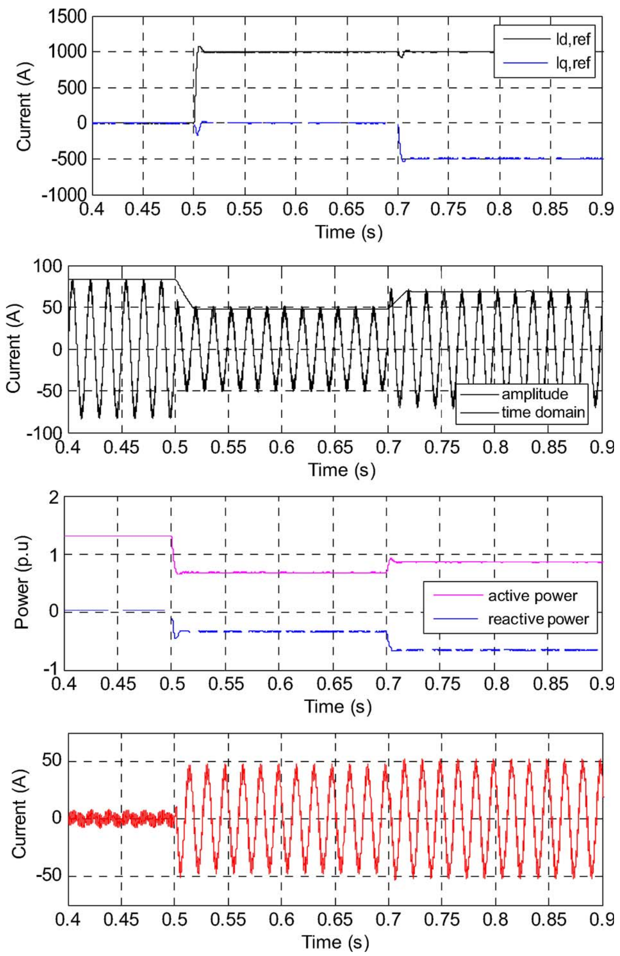

Fig. 11. ***Dynamic performance of the grid-connected MG for changes in the MG real and reactive*** (dq) ***current references: MG*** dq ***current components, grid phase current, grid real and reactive powers, and converter output current.***

computation). By using an economy-driven model, the broker is able to: 1) identify the optimal asset of the computational resources needed to satisfy the user requirements (i.e., resource discovery and resource selection process); 2) transparently split a sequential object-oriented task (i.e., a set of contingencies) into subtasks (i.e., a subset of contingencies), according to a hierarchical master/slave computing model; and 3) automatically distribute subtasks to the set of selected computational resources.

In order to evaluate the parallel processing performances of the computational web service, many experimental tests were executed by varying the number of machines used for the computational engine in order to evaluate its speedup factor. The computation time and the speedup obtained by increasing the slaves in powers of 2 (two, four, and eight slaves) were evaluated. Each computation was performed several times in order to use the average. The speedup obtained by using a two-level architecture is nearly linear with the number of slave machines and very close to the ideal case.

D. Data Storage Web Service

In this first phase, the authors used the OGSA-DAI grid services to access a relation database, installed on a Linux workstation and based on the Postgress RDBMS. This part of the framework is currently under development.

E. Workflow Enactor

The main implementation issue related to the workflow enactor is the choice of a workflow language and its related technologies which can be usefully adopted to describe the control/monitoring applications, in the context of a web-services-based approach. Many of the proposals have been made in the literature, especially by the major web services software providers, and many of them are continuously evolving. In these proposals, the application workflow is usually described with a textual scripting language (typically the XML format) that is used to provide the "glue" that links involved services together.

Among the possible solutions, the business process execution language (BPEL) was chosen (whose current version is 1.1). In particular, the workflow enactor is based on the workflow execution of BPEL4J integrated in Apache Tomcat, version 5.0.24 [34].

The web services implemented, in particular the data acquisition and the job submission web services, were written using the Java language and the Apache Axis toolkit. The Axis toolkit included essentially a simple object access protocol (SOAP) engine, which is a framework for constructing SOAP processors such as clients and servers, a simple standalone server, a server which plugs into servlet engines such as Apache Tomcat and extensive support for WSDL.

V. CONCLUSION

The paper proposed an advanced web-services-based framework for integrated MG control, modeling, and monitoring. The core component of the proposed framework is the *MG engine* which is responsible for the execution of the MG management functions in a geographically distributed scenario. It includes a network of remotely controlled units distributed in the most critical MG sections for field data acquisition and advanced protective functionalities, a GIS interface for the acquisition of georeferentiated information on the MG, a grid-computing-based solution engine for the online computations, and a web-based interface for graphical synoptic and reporting development.

The web-services-based framework has been deployed on a computational grid. The first experimental results have emphasized the important role of the web services technology in MGs control, modeling, and monitoring.

The application of this technology is very promising since it makes the proposed framework platform, language, and vendor independent, and thus an ideal candidate for an effective integration in existing EMSs/DMSs. ■

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