

Development of a Smart Grid Simulation Environment, Part II: Implementation of the Advanced Distribution Management System

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Received: 26 September 2014 / Accepted: 30 September 2014 / Published online: 17 October 2014
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Abstract A smart grid is an electric power system with high levels of automation, dispersed generation, intelligent monitoring, and control; however, because the distribution networks in operation today do not have these characteristics, studies concerning the control, planning, and operation of the smart grid are difficult to perform. To overcome these practical difficulties, studies investigating the smart grid can be conducted in computational environments that are able to reproduce meticulously the electrical and communicational behaviors expected by the smart grid. Therefore, in this paper, the development of a platform to simulate the advanced distribution management system (DMS) from a reference model for smart grid, which has seven layers, is proposed. Part II of this paper refers to the four upper layers. First, it describes the system layer architecture where all computational hardware is virtualized to create the smart grid simulation environment. Subsequently, the three logical layers, Model, Analysis, and Intelligence, are considered in the construction of the advanced DMS supervisor. The uses of some applications of the supervisor are shown to reveal their potential.

Keywords Smart grid · Advanced distribution management system (DMS) · Virtualization · Supervisor

1 Introduction

Historically, electrical distribution networks have not been sufficiently attentive to operational efficiency. Today, the ris-

ing demand for electricity, coupled with new technologies, calls for modernization of the distribution system. Future requirements of monitoring and control of the distribution system must become more stringent due to the integrated architecture of the smart grid, which must facilitate data exchange between the DMS and market. For example, recent customer programs of distributed generation and demand response are affecting the operations of the DMS; consequently, the massive employment of sensors in the distribution network has become essential to the success of smart grid technologies. Clients of electric utilities consume and generate electricity using schedules and specific rules that require a network with bidirectional energy flow and effective capability of monitoring and control (Glover et al. 2010).

The impact of demand response management (DRM) and customer behaviors in particular time periods must be modeled or foreseen by the price rules and procedures of reward. These dimensions of modeling can be incorporated into load modeling and forecast algorithms (load flow algorithms, modeling of components of the distribution network, and load and topological forecasts) through direct links between applications of the DMS and DRM. For example, when an application of the DRM tries to release a load in response to an order from the system operator, it needs first to check with the DMS whether the load release causes any violation of connectivity, operation, or protection of the distribution network (Niyato et al. 2012). Therefore, the technological advances of the smart grid have a strong influence on the functions of the DMS that must adapt and support all requirements of monitoring and control. The main adaptations are (Fan and Borlase 2009)

- Inclusion of optimization for radial and loop-closed networks, multi-level feeder reconfiguration, multi-objective restoration, and evaluation of future loading;

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- Provision of the statistical data of operation and cost to optimize the operation of capacitor banks and voltage regulators in the distribution network;
- Consideration of bidirectional power flow in the protection schemes;
- Use of load estimation and management of load data in the planning and optimization of network operation; and
- Management and forecast of customer behavior in an intelligent way.

In addition, an advanced DMS must also provide applications and tools of analysis and visualization to incorporate the huge increase of data from field devices. Tools of visualization can provide a detailed and clear vision of the large amount of data; for example, they can show the voltage magnitude profile with colored contours in the distribution network diagrams, monitor, and alarm voltage deviations or show the energy flow in the distribution lines through a contour diagram whose color tones match the line currents. In this way, the system operators and service providers might benefit enormously from these tools in their daily activities.

In Part I of this paper, the advanced DMS was designed for the smart grid through a reference model with seven layers: Physical (elements of the power system), Interface (connection with physical elements), Communication (allow the data exchange), System (collects data from the communication), Model (abstract representation of the system), Analysis (supports the operator's system decisions), and Intelligence (advanced data processing applications). Moreover, the Physical, Interface, and Communication layers were described in depth and mathematically formulated to develop the electrical devices simulator. Here, in Part II of this paper, the computational resources of the System layer are virtualized and arranged using the Web-based SCADA architecture; the three logical layers (Model, Analysis, and Intelligence) are then studied and implemented to supervise a real distribution system.

2 Virtualization of the System Layer

In the smart grid communication model, the domains of service provider, grid, and customer are connected through a complex communication network to exchange information among them; thus, the Web-based SCADA architecture provides the necessary resources to implement the smart grid structure. The accessibility of the smart grid services through a typical Web browser allows full interoperability with the traditional Internet Web services, which is the key to success of a global open energy market (Bui et al. 2012).

2.1 Web-Based SCADA Architecture

The SCADA system has supported operations of the electrical power grid for more than four decades (IEEE PES 2003). Although primitive SCADA systems have been slightly modified and many elements of their architecture are still effective, the traditional SCADA system is not completely efficient in operating the smart grid. Fortunately, Internet/Web technologies have been improved for the solution of difficulties such as vulnerability to cyber attacks and loss of real-time performance. These technologies, which include a distributed database management system, internet protocol-based multicast communication, and the wide area server structure, increase the reliability of the Web-based SCADA architecture (Ebata et al. 2000).

In the Web-based SCADA architecture, users are clients who employ browsers to access the Web applications hosted in the servers. Each client is also free to perform any function in the electrical power grid because he does not need any one specific application dedicated to only one task; this increases the flexibility of the SCADA system. Compared to the traditional SCADA architecture, there are other advantages, such as

- (1) *System cost* the equipment required to implement a Web-based SCADA architecture is small compared to that required by the traditional architecture. For example, there is no necessity for many local area networks (LANs) or many servers.
- (2) *Data sharing* in the advanced DMS, the SCADA system is often solicited to share data with other computing systems. The Web-based SCADA architecture has the resources that facilitate data sharing via uniform resource locators (URLs), while the traditional architecture requires specialized tools to share data, making this operation difficult.
- (3) *Update system* when the traditional SCADA system is replaced by the Web-based system, the remote controlled units are reused; each remote unit is connected to the communication network via a gateway that sends and receives controlling signals from the servers.

The advantages provided by the Web-based SCADA architecture support the smart grid requirements and clarify its usage in the advanced DMS structure. In this way, the main components that constitute the Web-based SCADA architecture, such as Web, databases, and geographical information servers, are studied and implemented into a virtual environment.

2.2 Development of the SCADA System

The physical layer has the equipment of the electrical power grid, while the interface and communication layers are related to the devices of the communication technologies. Thus, the system layer supports the computational machinery that runs the various advanced DMS tools employed to process all smart grid information.

Figure 1 shows a block diagram of the simulation environment used to implement the SCADA system and develop advanced DMS tools. The logical blocks represent computers with specific functions. The first represents the electrical devices simulator (EDSIM), which emulates the physical, interface, and communication layers. The second block represents the Web server (WEB SRV), and the third represents the database server (DB SRV). All three computers are virtual machines created over a software layer called VMware ESXi. Each virtual machine has an internet protocol (IP) address and one virtual network adapter connected to a virtual switch that allows communication among the virtual machines. The virtual machines also exchange information with external computers when the host adapter is connected to the internet. For example, the virtual machines receive several types of maps from a geographical information system server (GIS SRV) on the internet.

The virtualizer, VMware ESXi, was adopted to emulate the SCADA system because it provides many benefits such as free cost of acquisition, capability to create powerful virtual networks, and reduction of the project total cost for the owner (Vmware. Inc 2011). Therefore, the resources of information technology required to operate the advanced DMS can be developed in this low-cost simulation environment.

2.3 Web Server

The EDSIM provides real-time metering data from the electric power grid to the system layer; it was formulated and described in Part I of this paper. The Web server is the entrance port to the advanced DMS because the Web-based SCADA architecture is used to manage the distribution system. The Web server has domain name system server (DNS) functionality that converts the computer names to IP addresses. It also has the main function of application server, providing essential technologies such as internet information services (IIS) that allow distributing and operating Web applications.

The Web application used to manage the distribution system has the characteristics of a webpage whose navigation map is shown in Fig. 2. The homepage is connected to two pages: a download page, which has documents and routines to set up the client browser, and the advanced DMS page, which is the supervisory application and has the EMS functions. The start page displays welcome messages and an initial report

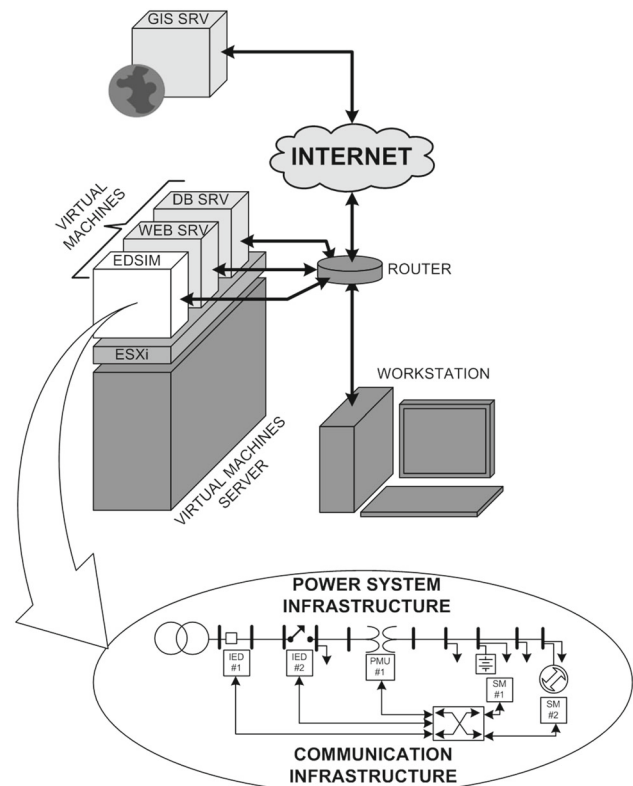


Fig. 1 Simulation environment used to develop the advanced DMS

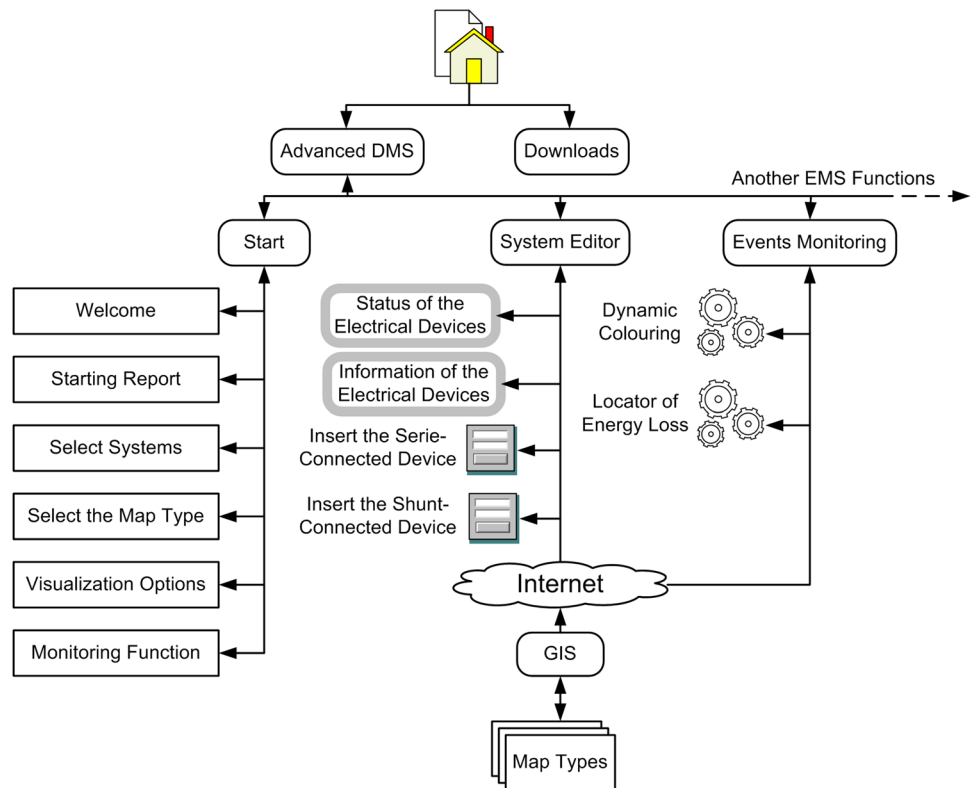
of the status of the SCADA system. There are also options to change the initial configurations of the EMS functions, such as select systems, select the map type, visualization options, and the monitoring function.

The system editor is an EMS function that allows modifying the topology of a selected distribution network or any other selected electrical equipment. The topological modifications are performed using forms that enable the insertion of series- and shunt-connected devices. The dialog window for electrical device status allows verifying the power flow, profiles of voltage and current, and also changing the device status; for example, opening or closing an automatic switch.

Events monitoring is another EMS function that permits monitoring the operational conditions of a selected distribution network through tools such as dynamic coloring and an energy-loss locator. The first one displays segments of the distribution network in different color tones according to their voltage profiles, while the second one can indicate electrical devices with energy leakage.

Both the system editor and events monitor have multiple layers in their work areas. The front layer shows the schema of the distribution network topology with the symbol of each electrical device; each device location is geo-referenced and shown over a map in the background layer, either a street map or satellite image provided by the GIS server.

Fig. 2 Navigation map of the main webpage hosted at the Web server



2.4 GIS Server

Geographical information system technology has been used to improve decisions, manage resources efficiently, and increase the efficiency of work flow, allowing reducing costs for small, medium, and large organizations. When the resources of geographical information are available on the Web, the geospatial data are stored by servers and can be accessed by several users with different permission levels. Moreover, many servers permit the access to the database to perform a consultation or generate thematic maps, as well as any other required function (Booth and Mitchell 2011).

There are several servers of geographical information on the Web; the most popular is the Google server. For this project, the ArcGIS server is the adopted provider of geospatial data due to its compatibility with the other components of the SCADA system and the availability of a cost-free database, which is accessed by the clients as a local database. The ArcGIS server provides many services, such as feature (for web editing), image (for providing control over imagery delivery), and map (for cached and optimized map services), that are employed by the Web application of the advanced DMS in its different layers. For example, the front layer uses the feature service, while the background layer uses the services of image and map that are automatically updated to facilitate navigation within the distribution network area.

2.5 Database Server

The database system is an essential component of the information and communication technologies infrastructure because it stores the data in a systematic manner and enables them to be retrieved, processed, and analyzed either immediately or later; hence, the database server is indispensable for the architecture of the advanced DMS (Shawkat Ali 2013). In the database server, the information is methodically arranged in tables; for example, each electrical device of the distribution system can own a specific table whose columns have values related to its electrical characteristics, control, and status.

Figure 3 shows a block diagram of the database server; the node named Main Server represents the virtual machine containing the database of the advanced DMS structure. The database, EMS, is split into two schemas of table groups. The first has the tables of all electrical devices that can operate in the distribution network, such as loads, transformers, and lines. The second schema contains the tables that store the metering data from smart meters, PMUs, and IEDs.

The database, GIS, and Web servers make up the core of the system layer that represents the last layer of the advanced DMS structure physically equipped with computers; thus, the next three layers are only logical.

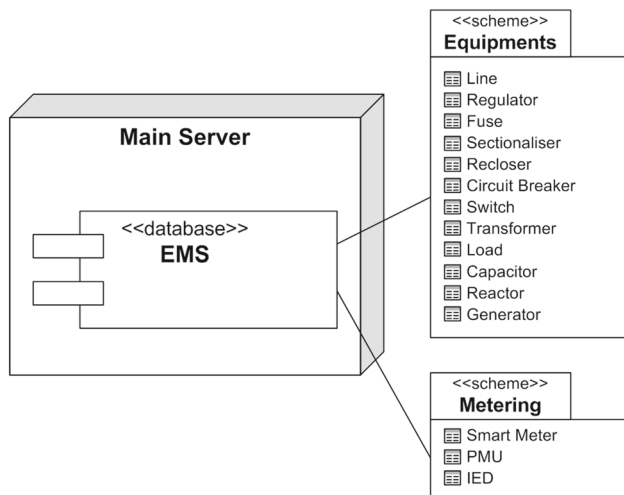


Fig. 3 Representation of the database server

3 Model Layer

The model layer is the first logic layer and is an abstract representation of the system, communication, interface, and physical layers through standards, such as IEC 61970 and 62325, that establish the rules to represent the topology and metering data of the electrical power grid.

3.1 Common Information Model (CIM)

The CIM is standardized by three different IEC standard series: IEC 61970, IEC 61968, and IEC 62325. Each has a particular background and respective focus on energy management system application program interfaces, application integration into electric utilities, and framework for energy market communication (Uslar et al. 2012). Indeed, CIM is an abstract model that represents all of the components in an electric utility, and it defines classes and attributes for these components as well as their relationships using the unified modeling language (UML) notation that can easily be converted into extensible markup language (XML) (Shahidehpour and Wang 2003).

Figure 4 shows a comprehensive CIM partitioned into many packages; dependency relationships are indicated by dashed lines with the arrow pointing to the supplier package. IEC 61970-301 defines and describes all packages; for example,

- *Core* contains the basic entities that are shared by all applications;
- *Topology* models the connectivity that is the physical definition of how equipment is connected together;
- *Wires* models the information on electrical characteristics of transmission and distribution networks;
- *Outage* models the information on the current and planned network configuration;

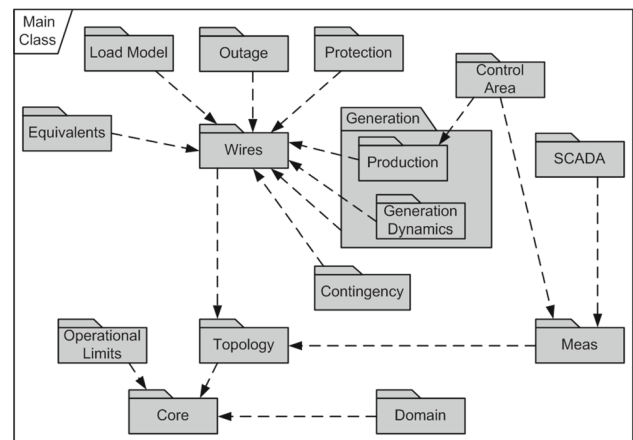


Fig. 4 CIM top-level packages of the standard IEC 61970-301

- *Protection* models the information for protection equipment such as relays;
- *Measurements* contains the entities that describe exchange of dynamic measurement data between applications;
- *Load Model* provides the models for energy consumers and the system load;
- *Production* provides the models for various types of generators and models the production cost information;
- *Generation Dynamics* provides the models for prime movers needed for simulation and educational purposes;
- *Domain* is a data dictionary of quantities and units that defines data types for attributes that may be used by any class in any other package;
- *SCADA* contains the classes that model the data points located in remote units.

Each CIM package contains a number of defined classes that describe the characteristics of a component found in the real electric power system using attributes; for example, Fig. 5 shows the class diagram of a distribution line with some relevant attributes. The Line is found in the wires package that has the class AC Line Segment, with consistent electrical characteristics given by attributes such as susceptance, resistance, reactance, and length. The Equipment Container has many types of equipment and is associated with connectivity nodes that are logical topological objects needed to link physical objects together.

The attributes of CIM classes provide information from all components of an electric power system to the analysis methodologies such as a state estimator.

4 Analysis Layer

The analysis layer has all of the functions and applications to support the operator and automatic decisions using either real-time or historical data from the system layer via the

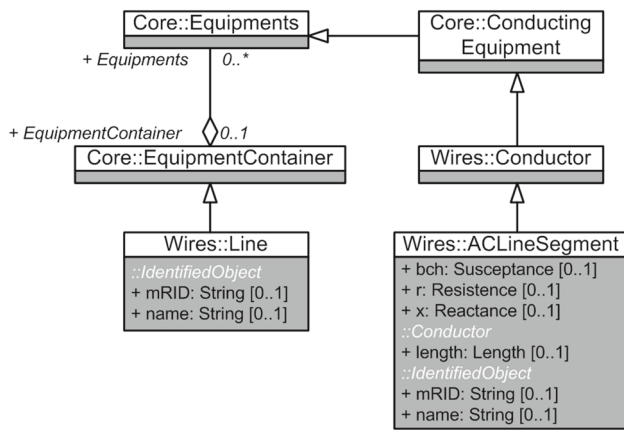


Fig. 5 Class diagram of the line relevant characteristics

model layer. One of main applications of the analysis layer is the state estimation that can obtain good estimates of the state variables by processing the available measurements together with knowledge of the network topology and line model parameters (Baran and Kelley 1994). The set of network states, Ω , is composed of the union of the bus voltages, V_i , branch currents, J_i , and current injections, I_i , for m pairs of branch buses along the distribution network, as given by (1). In (2), ψ_i^t is the set of measured states transmitted to the system layer; their union forms the set of measurements, Ψ . Lastly, the set of unknown states, X , contains all of the network states that are not metered, i.e., is the complement of Ψ in Ω as expressed by (3).

$$\Omega = \left\{ \omega \mid \omega \in \bigcup_{i=1}^m ([\dot{V}_i]_{3 \times 1}, [J_i]_{3 \times 1}, [I_i]_{3 \times 1}) \right\} \quad (1)$$

$$\Psi = \left\{ \psi \mid \psi \in \Omega \wedge \omega \in \bigcup_{i=1}^m \psi_i^t \right\} \quad (2)$$

$$X = \{ \chi \mid \chi \in \Omega \wedge \omega \notin \Psi \} = \Omega \setminus \Psi. \quad (3)$$

If a smart metering system monitors the loads of the distribution network, the available measurements must have a large amount data with high accuracy and resolution (Hu et al. 2011). In this way, Leite and Mantovani 2013 propose a rapid and non-iterative state estimation for distribution networks. It is based on the smart metering system that creates a sequence of calculations for each unknown state using the solution of the Hamiltonian cycle problem found by a search algorithm that minimizes an objective function, $F(X)$.

$$\min F(X) = \sum_{i=1}^{n_X} C(\chi_i). \quad (4)$$

In (4), $C(\chi_i)$ is the cost of an unknown state; during the search procedure, it becomes zero when the solution equation of χ_i is found.

$$[j_U^{SE}]_{3 \times 1} = [I_U]_{3 \times 1} + \sum_{i=1}^n [J_i]_{3 \times 1} \quad (5)$$

$$[\dot{V}_U^{SE}]_{3 \times 1} = [\dot{V}_D]_{3 \times 1} + [\bar{Z}_D]_{3 \times 3} [J_D]_{3 \times 1} \quad (6)$$

$$[j_D^{SE}]_{3 \times 1} = [J_U]_{3 \times 1} - [I_U]_{3 \times 1} - \sum_{i=1}^{n-1} [J_i]_{3 \times 1} \quad (7)$$

$$[\dot{V}_D^{SE}]_{3 \times 1} = [\dot{V}_U]_{3 \times 1} - [\bar{Z}_D]_{3 \times 3} [J_D]_{3 \times 1} \quad (8)$$

$$[j_D^{SE}]_{3 \times 1} = \left[\sum_{i=1}^n [\bar{Z}_i]_{3 \times 3} \right]^{-1} ([\dot{V}_U]_{3 \times 1} - [\dot{V}_n]_{3 \times 1}). \quad (9)$$

Equations (5) and (6) are solution equations of χ_i when it is upstream of known states. Similarly, Eqs. (7), (8), and (9) solve χ_i when it is downstream of known states. These equations are derived from Kirchoff’s current and voltage laws (KCL and KVL), where U is the index of upstream variables, D is the index of downstream variables, and $[\bar{Z}]_{3 \times 3}$ is the matrix of distribution line impedance. Sometimes a distribution transformer replaces a distribution line to connect the medium- to low-voltage networks.

$$[j_U^{SE}(t_s)]_{3 \times 1} = K_n^{-1} [\Phi]_{3 \times 3} [J_D]_{3 \times 1} + [\bar{Y}_m]_{3 \times 3} [\dot{V}_U]_{3 \times 1} \quad (10)$$

$$[\dot{V}_U^{SE}]_{3 \times 1} = K_n [\Phi]_{3 \times 3} ([\dot{V}_D]_{3 \times 1} + [\bar{Z}_d]_{3 \times 3} [J_D]_{3 \times 1}) \quad (11)$$

$$[j_D^{SE}]_{3 \times 1} = K_n [\Phi]_{3 \times 3}^T ([\bar{Y}_m]_{3 \times 3} [\dot{V}_U]_{3 \times 1} + [J_U]_{3 \times 1}) \quad (12)$$

$$[\dot{V}_D^{SE}]_{3 \times 1} = K_n^{-1} [\Phi]_{3 \times 3}^T [\dot{V}_U]_{3 \times 1} - [\bar{Z}_d]_{3 \times 3} [J_D]_{3 \times 1}. \quad (13)$$

Equations (10) to (13) are adaptations of solution equations for a distribution transformer using the quadrupole model formulation in which K_n is the transformation ratio, $[\Phi]_{3 \times 3}$ is the matrix of phase angle deviations, $[\bar{Y}_m]_{3 \times 3}$ is a diagonal matrix of magnetization admittance, and $[\bar{Z}_d]_{3 \times 3}$ is a diagonal matrix of dispersion impedance. In addition, the upstream states are the primary values while the downstream values are secondary values of the distribution transformer.

Minimizing $F(X)$ provides a sequence of calculation from the Hamiltonian path that allows the unknown states to be rapidly estimated through a non-iterative method. In this way, the state estimation procedure must solve only the optimization problem to find a new Hamiltonian cycle when the distribution system is alarmed because of a topological change or a fault on AML, as shown in Fig. 6. In normal operation, state estimation is performed rapidly by the Hamiltonian path that uses an updated set of measurements for each time period.

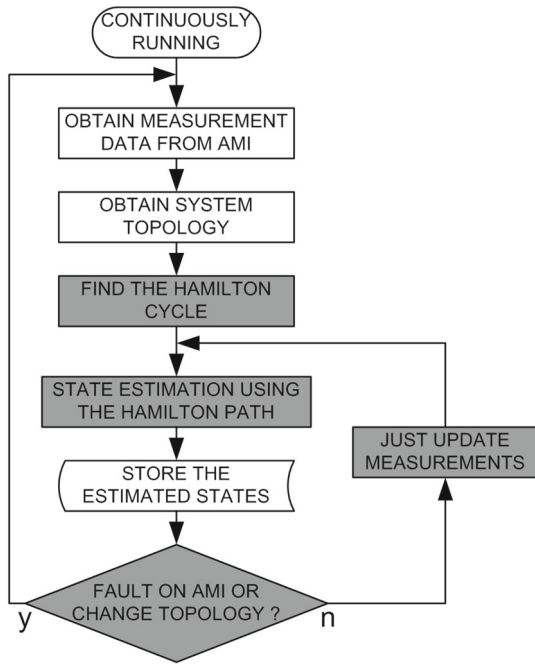


Fig. 6 Flowchart of the state estimation procedure

5 Intelligence Layer

This is the highest layer of the Smart Grid reference model and includes the advanced data processing applications that reduce the need for human intervention as well as provide intelligence to support decision-making. For example, the automated restoration procedure, also known as self-healing, might be deployed on the intelligence layer using remote control and visibility (Cespedes 2012). For self-healing, all protection devices need to have some knowledge of the current network configuration; thus, the localization of the affected points can be readily known during fault events.

Self-healing should be integrated with the dynamic coloring tool that permits to the system operator monitor the energy quality delivered to the end consumers using, for example, the monitoring of the voltage profile. The dynamic coloring tool uses many resources of the advanced DMS such as geo-referenced topological diagrams in multiple layers and the results of state estimation. If the voltage ranges are standardized and associated with a specific color, each branch drawn should have a color in the topological diagram in accord with its voltage value provided by the state estimation. Thus, the line model must have a color attribute given by the vector $[RGB_i]_{1 \times 3}$ that indicates the quantities of red, green, and blue for the line diagram.

$$[RGB_i] = \begin{cases} \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}, & 0.93V_B \leq |\dot{V}_i^{SE}| \leq 1.05V_B \\ \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}, & 0.90V_B \leq |\dot{V}_i^{SE}| < 0.93V_B \\ \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, & |\dot{V}_i^{SE}| < 0.90V_B \vee |\dot{V}_i^{SE}| > 1.05V_B \end{cases} \quad (14)$$

In (14), V_B is the reference voltage of the network and $|\dot{V}_i^{SE}|$ is the bus voltage magnitude at the end of the i^{th} branch. Then the color of drawn branch is either green for an appropriate voltage range, between 93 and 105 % of V_B , blue for a poor voltage range, between 90 and 93 % of V_B , or red for a critical voltage range, lower than 90 % or higher than 105 % of V_B . The dynamic coloring tool updates the coloring of the topological diagram in each time interval, which improves the decision-making process during stress situations.

6 Partial Results and Discussion

The computational resources of the System layer were emulated using the virtualizer VMware ESXi, where three virtual machines (EDSIM, DBSRV, and WEBSRV) were created and connected via a virtual network (VNLV) as shown in Fig. 7. The networking diagram also demonstrates the connection from WEBSRV to the physical adapter of the virtual machines server. The physical adapter is connected to an external network with access to the Internet; hence, the WEBSRV was set up as a router to enable communication between external computers and virtual machines in the virtual network and vice versa.

The WEBSRV virtual machine also has the functions of Web and DNS server; thus, an operator using a workstation connected to an external network can access the supervisory functions of the advanced DMS through its URL address. Figure 8 shows the start page of the supervisor that was accessed using the Internet Explorer browser. The address bar has the URL, and the browser window displays the start page whose welcome message is shown, as well as selected

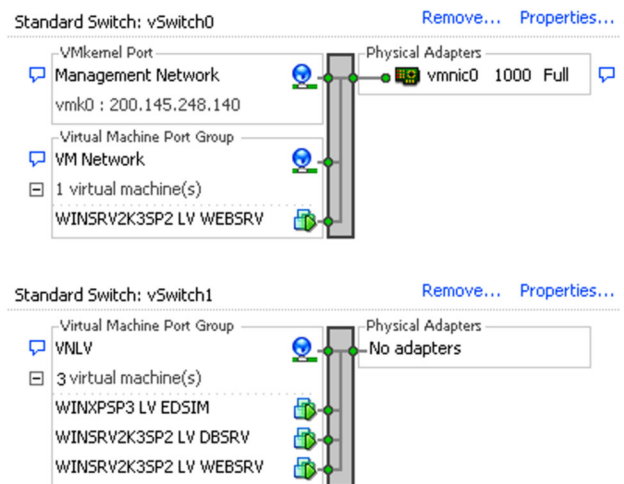


Fig. 7 The Networking diagram of the Smart Grid simulation environment

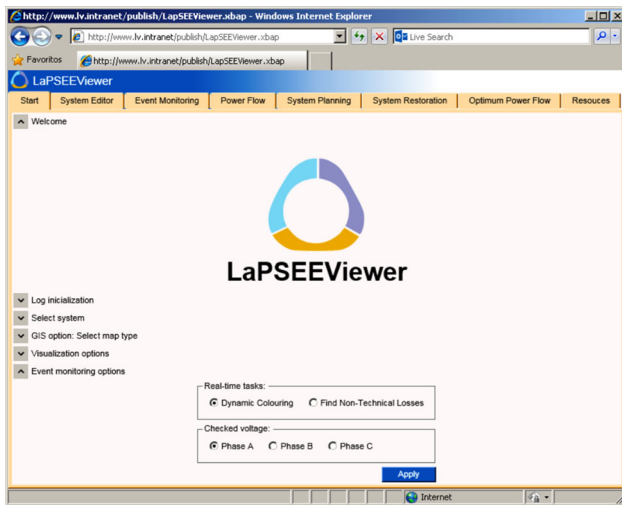
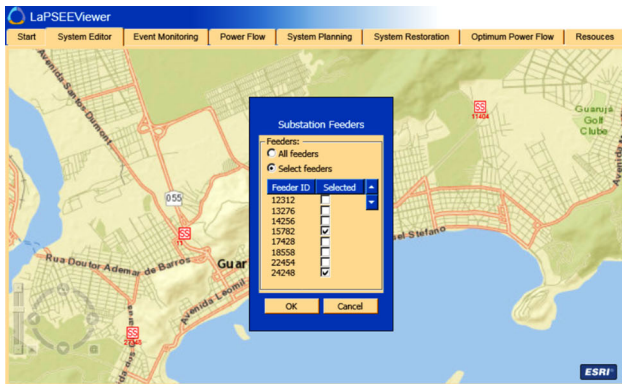
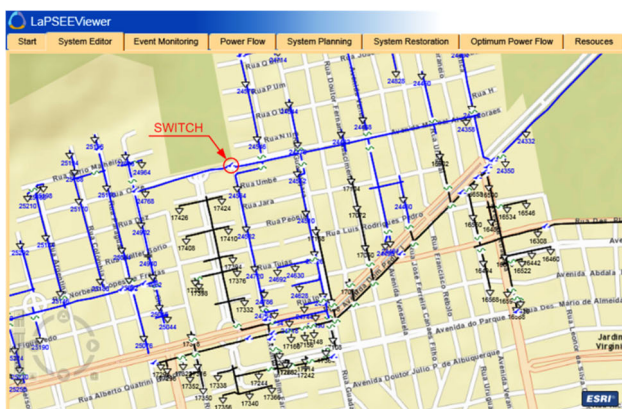


Fig. 8 Start page of the supervisory of advanced DMS



(a)



(b)

Fig. 9 System Editor application: a feeder selection; b visualization of the selected feeders

options of event monitoring, such as dynamic coloring for the phase A.

An important application of the supervisor is the System Editor that allows the visualization and modification of

the distribution network and their electrical devices. On the supervisor main page, one single click of the System Editor tab leads the operator to the application whose work area has a map type from the GIS server and the power substations of the covered region. If any substation is selected, the application launches a dialog box that shows all feeders of this substation, as shown in Fig. 9a, where feeders #15782 and #24248 are checked. Figure 9b shows the topological diagram of the two checked feeders, one black and one blue. The topological diagram is geo-referenced and overlaps the street map provided by the GIS server. It also shows the symbols of the electrical devices such as loads, capacitors, and switches.

The operator can access electrical device features by double clicking the symbol of the device of interest. For example, Fig. 9b indicates a switch whose features are shown by the dialog box in Fig. 10. The supervisor and control tab reveals the switch behavior through the monitoring of the electrical parameters such as apparent power, power factor, voltage, and current magnitudes provided by the EDSIM that simulates the distribution, interface, and communication layers. This tab also allows the operator to control the switch through the modification of its status to either closed or opened. In Fig. 10, the curve of apparent power indicates the moment when the switch is opened and closed again. The switch stays open for four hours; during this period, the power flow passing through the switch is null.

Opening the switch alters not only its power flow but also the electrical parameters along the distribution network. Dynamic coloring is the ideal tool to check this event. Because dynamic coloring was the selected option initially, the procedure to access it consists of a single click on the Event Monitoring tab followed by the selection of the substation and feeder. Figure 11 shows the results of the dynamic coloring tool during the time period that the indicated switch was open. The section of distribution network upstream of switch remained energized; consequently, its topological diagram was green because the estimated voltage of their buses and branches was in the appropriate voltage range. On the other hand, the downstream section was disconnected from energy source; thus, its topological diagram was red because the estimated voltage was zero along this section, and hence it was in the critical voltage range.

These results show only some applications of the advanced DMS supervisor; they realize the proposed methodology for the development of a smart grid simulation environment and demonstrate the feasibility to build it.

7 Conclusions

The proposed simulation environment provides an alternative way to elaborate new tools of operation, planning, and

