Seamless Energy Management Systems

Part I: Assessment of Energy Management Systems and Key Technological Requirements

Final Project Report

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

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Final Project Report

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PSERC Publication 14-4

September 2014

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Power Systems Engineering Research Center

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Acknowledgements

This is Part I of the final report for the Power Systems Engineering Research Center (PSERC) research project entitled "Seamless Energy Management Systems" (S-53G for 2012-2013). The project has been sponsored by EPRI. We express our appreciation to EPRI and in particular Paul Myrda for his support and guidance for the project. We also express our appreciation for the support provided by PSERC's industrial members, as well as EPRI members, and by the National Science Foundation's Industry/University Cooperative Research Center program.

The authors wish to recognize the following advisors for insightful comments and suggestions to this research project:

- Mel Gehrs (Gehrs Consulting)
- Jamie Weber (PowerWorld Corporation)
- Caroline Marzinzik (PowerWorld Corporation).

Executive Summary

This report is the first of a series of reports on seamless energy management systems. Seamless energy management describes a set of new elements, technologies, and applications for next generation energy management systems characterized by the elimination of unnecessary data management, tool integration, or analysis initiation issues that prevent the user to fully focus on specialized system operation or engineering decision-making. This first report provides an assessment of EMS system and planning decision-making tools, and it develops requirements and strategies for the development of solutions and the integration of seamless systems.

Control centers that manage the transmission-generation grid, known as energy management systems (EMS), have existed since the 1960s. Over the past few decades, EMS have evolved gradually from their early start as digital computers to a slightly more sophisticated form, but now major transformation is essential to support emerging power system operations and grid objectives. The expanding power grid requires operation and control of system behavior that is emerging at temporal and spatial scales, different from the scales traditionally considered by the EMS. New advances in measurement, communication, computation and control technologies make such transition to a new generation of EMS possible. These same technologies are increasingly being applied to the distribution system, and a new generation of distribution management systems (DMS), are now in the process of being deployed.

Beyond control and operation of power systems, power system planning has numerous challenges associated with the limitations of some of the existing methods, tools, and practices to manage a system that is dramatically changing with renewable generation, larger transfers, and distributed resources including demand response resources. Some of the challenges of power system management at the levels of architecture, data modeling, computation, visualization and integration are summarized below.

- The present communications infrastructure is inadequate for handling the increasing real -time data transfers imposed by PMUs at the transmission level and new measurements at the distribution level. The requirements are stretched by the data rates at the transmission level and by the data volumes at the distribution level.
- The present proprietary data structures at each control center are a major impediment to data transfers between the distribution and transmission levels, as well as between EMS in the same interconnection. This issue impacts the ability to seamlessly monitor, operate and control the interconnected power system.
- Models and computational frameworks utilized by EMS systems and planning tools are not unified and interoperable and are not easily compatible with HPC. This makes integration of system components and functions difficult and in many instances, not possible.

- Visualization of the power grid is the most important tool available to operators to monitor the grid, but today it is limited to the jurisdiction of the individual control center. This inability to seamlessly move data means that operators monitor their systems with blinders on, a condition that is flagged by every blackout report to be one of the root causes.

To help address some of these issues, several new approaches and techniques are described. A unified geo-spatial model is introduced, and its advantages for both operations and planning are illustrated. Layered models and architectures for data management and integration are introduced. A novel approach to visualizing power system information is presented. The seamless architecture and data management of control centers will allow the integration of applications across diverse systems.

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1 Introduction: Energy Management Systems

The first digital control centers were introduced in the 1960s to replace the hardwired analog control centers whose functions included supervisory control, data acquisition, and automatic generation control (SCADA-AGC). In the intervening decades, the advancement of information technologies has enhanced the functionality of these control centers manifold, but the general architecture of collecting and processing all of the measurement data in a central location has not changed. It is clear that this centralized architecture will not be able to handle the increasing volume of measurements and the faster wide-area controls that will be required for the operation and control of the future grid.

Measurements at substations are sampled every few seconds and collected at the remote terminal units (RTU), which are then polled by the SCADA system. The new phasor measurement units (PMU) are sampling voltages and currents at 30-60 times per second at the substations, but the present SCADA communication systems cannot transmit this rate of data to the EMS. The slow scan rates of the present communication system is adequate for sending automatic generation control (AGC) signals but not those needed to control fast power electronic controls, such as static VAr controllers or high voltage DC transmission lines.

In addition, more measurement devices are being installed in the lower-voltage distribution systems all the way to smart meters at the customer level. Cheap communications can bring back at least the feeder measurements to a Distribution Management System (DMS) for monitoring the distribution feeders and remote control of sectionalizers. The modern DMS is consolidating several separate functions such as trouble call analysis, crew dispatching, automatic sectionalizing, integrated volt-VAr control, conservation voltage control, etc. The main issue for DMS is less the development of technology and more the payback in energy savings and reliability.

The new measurement and control technologies have raised the expectation of more secure and optimal operation of the grid, which will be enabled by the evolving computation and communication capabilities. This report explores what this means in terms of the needed evolution in control architecture, data modeling, computation, visualization, and integration. Although we will explore these issues in separate sections below, the intent is to show their inter-relationships. For example, the communications architecture influences the data modeling and management, and limits or enables new and faster controls. Although much of the research and development are still done in silos – visualization, controls, optimization, etc. – we will try to show in this and subsequent reports that the next generation of control centers and power system management processes will have to be designed by considering all these issues as a whole.

2 EMS SCADA-Based System Control Architecture

The emerging power system control problems are complex and require new and more powerful functionality and capabilities. It is not sufficient to improve on the existing tools, but a revision of the *control architecture* for the grid is needed. The present control architecture consists of a hierarchy of control centers: (1) at the lowest level a SCADA system gathers all substation measurements from a defined region at a sampling rate of a few seconds; (2) the load-generation balancing function done by the balancing authority (BA) can be done at this lowest level or at the next level control center in the hierarchy (the tendency has been to combine SCADA regions into larger BAs); (3) to coordinate the grid reliability of the interconnected BAs a control center for the reliability coordinator (RC) at the next level of hierarchy is designated to oversee the reliability of a large geographic region; (4) in North America the RC is the highest level resulting, for example, with about 11 RCs overseeing the Eastern Interconnection whereas in other regions in the world (China, India) there is one control center over the RC level that oversees the whole interconnection. All large interconnections in the world have evolved control center architectures of this type (Figure 2.1).

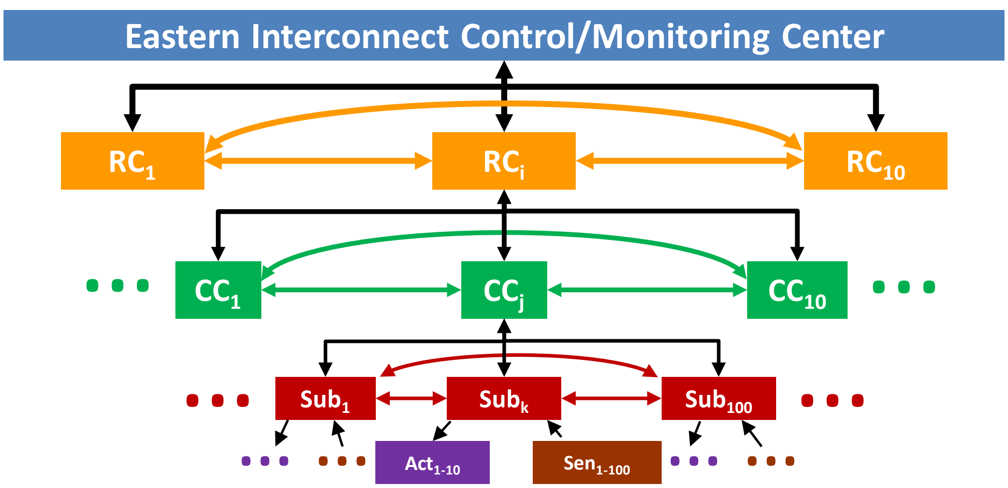

Figure 2.1: Communication architecture of EMS for an interconnected power grid

2.1 Handling of Spatial Scales

As the interconnection size has increased, this hierarchical structure of control centers has gotten bigger resulting in real-time data having to travel up the hierarchy and control decisions traveling down. Given that the present measurements are not time-tagged and the communication times are not tightly controlled, reliable automatic controls are difficult to implement in this structure. Thus the responsibility for control decisions, either manual or automatic, are kept lower in the hierarchy. To be able to do more automatic (thus faster) control to impact larger portions of the interconnection (wide-area) will require more communications of real time data and control signals with tighter specifications on communications performance.

2.2 Handling of Temporal Scales

Although phasor measurement units (PMU) are being installed rapidly at many substations, this real time data is being handled separately from the SCADA data. The future EMS will have to be designed to handle ubiquitous PMU data, that is, all SCADA points and more may become sources of PMU data. It is also obvious that not all of this data will be centralized even up to the SCADA control centers not to mention the control centers at the higher levels of the hierarchy. This means that the present data acquisition procedures will have to be replaced by data transmission procedures that will have to be developed to support all the new applications. The data management issues are addressed in the next section but the applications, the communications architecture and data management are intimately dependent on each other and have to be designed together.

2.3 Enterprise Architecture

The control center architecture has always been independently designed and developed with limited regard to the rest of the functions in the power company, leading to many difficulties of transferring data and decisions of one domain to another. The most glaring example of this is the incompatibility between the operations planning environment and the control center environment. The schedules and reliability considerations determined in the operations planning environment have to be transferred to the real-time operations environment but there is no automatic way to do this.

Another consideration is that all the control centers in a given hierarchy, although connected, are not compatible with each other. Information has to be translated from one data frame to another as data (real-time measurements, static system data, control signals) traverses the hierarchy. These inefficiencies get in the way of implementing the new seamless applications that are needed in the future grid.

The core network EMS applications are proprietary and were originally written in FORTRAN or C. Complex EMS system applications have been incrementally built around the core code using other languages and better structure. Integration and interoperability efforts have been driven by XML and SOA. However, indiscriminate use of CIM wrappers for legacy applications has the risk of fossilizing core applications. The transformation of the electricity industry will be unprecedented and massaging models and application so they can fit the legacy code may not be the optimal approach. Integration must be balanced with innovation objectives. We study innovative architectures for application integration, which provide such balance.

3 EMS Underlying Power Network Models

3.1 Unified Data Models

Unified models in which the divisions between temporal scales (e.g., operations and planning) and spatial scales (e.g., transmission and distribution network) are eliminated or abstracted to the application are desirable. As described in the previous section, a significant portion of the EMS applications are arising at the continuum of temporal scales from milliseconds (PMU) to day-ahead. Complex analytics, similar or superior to some of the existing planning tools, must be combined with enhanced functions to realize the required operational EMS tools. This will require a seamless underlying data model framework.

The lack of unification of data models is a pervasive problem in the power industry. Various representations of a utility's power system network model can be found in a utility's EMS systems: Input Relational Database, Real-Time Database, Internal Bus-Branch Model, Exported Snapshot Planning Case (with varying bus numbers), and CIM. None of these models are compatible with the Planning Case used in the off-line environment.

Several efforts such as the Common Information Model (CIM) provide standardized definitions of power system data. Presently, however, the vast majority of applications continue to require converting CIM or other models to their native underlying format. Recently proposed solutions rely heavily on model conversion from an operations model to planning cases, a method that essentially "changes the data model to support legacy applications". Such methods do not support interoperability and will represent barriers in the long term.

Seamless EMS data modeling means that a common model is used across applications and across all relevant temporal and spatial scales. For instance, DMS data should seamlessly be propagated (either at data point or aggregated level) into the EMS database. If the ISO would like to "zoom in" into the utility model and have their applications take into consideration specific conditions of the distribution system that should be possible. (Today it is almost impossible to have applications or visualization that moves across control center boundaries.)

By the same token, PMU data must be integrated with SCADA primary data, model-based data, or application-generated data. Unified handling of the underlying new temporal scales represents a challenge. For instance, different ISOs use different temporal granularity for ancillary services optimization. Combined datasets must not only deal with synchronization, but also with non-unified granularity.

3.2 Support for Massive Data

The data architecture must support high volumes of data from PMU, substation automation, and smart meters. Models of these data must be compatible regarding geo-referencing, ID-ing, time-tagging, and verification for the various application scopes. Model data must be validated. Estimated data and parameters must be qualified.

The emerging power system will push the capabilities of existing historians and temporal databases, as well as of spatial databases. Power system domain-specific, on-the-fly processing of data for efficient storage and compression methods must be developed.

Machine learning and data mining applications are very promising tools that would provide powerful analytics and discovery. Such applications will allow exploiting the already significant amount of data being collected.

3.3 Support for Distributed Control

The electricity industry transformation requires deploying massive amounts of distributed renewable energy. It is not sufficient to just connect the source devices to the grid. The local controls, the system controls and the market functions must also become more distributed and flexible. There is a rapid trend towards distributed control evidenced in various efforts towards enhanced energy management at the distribution, microgrid, building, and home levels, and the corresponding advancement towards integrated DMS, microgrid EMS, building EMS and home EMS systems. Ultimately, grid control will span all the spatial scales from interconnections to control of appliances. The data models used by the industry must therefore support such distributed controls.

At the same time distributed control can take place at the ISO, providing either intra-substation or inter-substation (PMU-based) control. The data model must hence address system modeling, local data collection, local data processing, local storage, data exchange and relying, synchronization protocols, etc. Beyond raw data, the information and the communication architectures associated with the EMS applications required for control will play a fundamental role in enabling distributed control use cases.

4 Algorithms and Application Capabilities

4.1 Introduction

Basic and new power system computer applications are fundamental to the successful real-time operation and planning of power systems. The current approach to power system analysis has developed over the last several decades in a piecemeal fashion where most applications are highly siloed running separately with their own databases, formats, system models, and user interfaces. Although some of the available tools have improved, many of the programs are built upon core technology and software architectures that were proposed decades ago, each developed individually, for its own unique purpose, often containing legacy code that implemented algorithms designed for sequential computing hardware. Most existing applications have their various components tightly coupled, non-separable, some written in Fortran, a language today's young engineers rarely know. The internal code is often not structured. In addition, external data interfaces are unwieldy, the user interface is weak, there is usually no centralized engine to house the numerical methods used in the applications, interoperability for applications is cumbersome, and deployment to high-performance computing platforms is difficult. Despite the need to address growing scenario uncertainty in most power system analysis problems, codes are usually entirely deterministic. The result is that applications are difficult to use, updating or extending such software is very tedious (it is often easier to create new software completely), computational speed is below its potential, and results can be limited in applicability.

These limitations need to be overcome by state-of-the-art analytical tools that can support modernization of the electricity industry. New models and tools are required to handle emerging needs driven by increasing model size, renewable penetration, phasor measurement-based wide-area monitoring and control, and the need to share models, simulation, and results across a wide spectrum of organizations. Current and future computing requirements necessitate an integrated approach that builds upon state-of-the-art algorithms, hardware and modern-day methods for data management across a shared environment.

We propose the development of seamless analytics for power systems, defined as follows:

> Seamless analytics is an organization of computing levels, each one comprised of individual components, such that each component at any level may interface with, use, or be used by any component at any other level, with minimal effort on the part of the human analyst. The levels are:
>
> 1. Applications: operational, operational planning, protection, long-term planning
> 2. Functions: numerical methods and basic linear algebra manipulations
> 3. Data: Equipment condition, DMS, customer, EMS, Market

The human user may simply use the applications and data, or s/he may also manipulate the applications using different functions and/or architectures.

A conceptualization of seamless analytics for power systems is provided in Figure 4.1 which includes the following: data (yellow, lower left corner), numerical methods (grey, bottom), applications (orange, middle), computing architecture (green, upper right corner), coordination system (blue, top), and human analyst (white, top left corner). The power systems seamless analytics engine is envisioned to operate efficiently on data to arrive at good decisions, as illustrated in Figure 4.2.

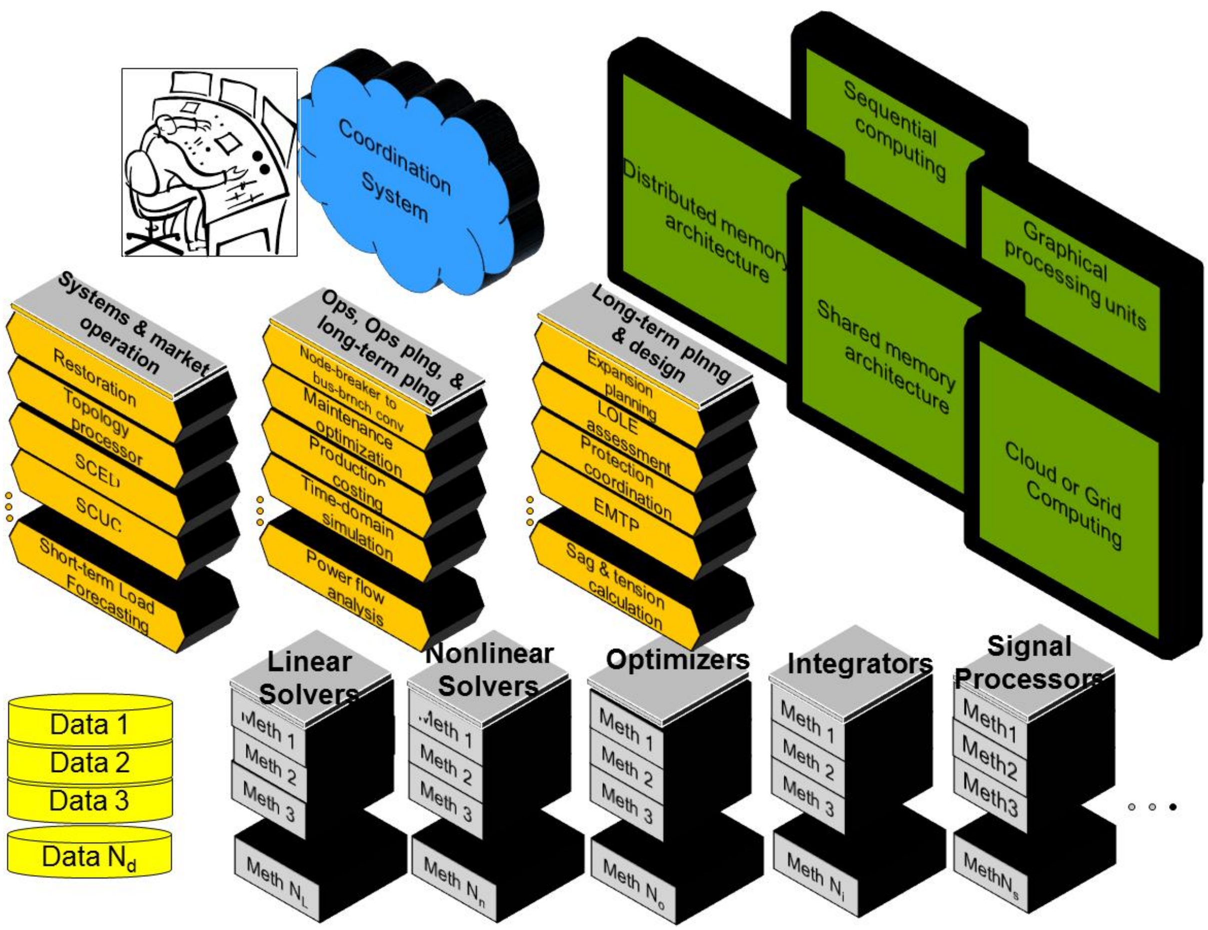

Figure 4.1: Conceptualization of seamless analytics for power systems

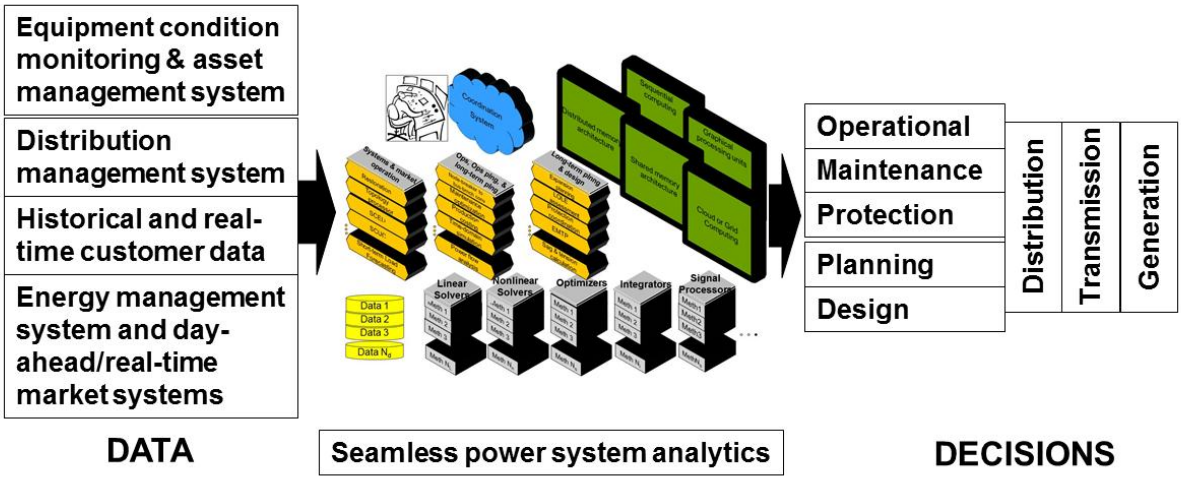

Figure 4.2: Seamless power system analytics functionality – data to decisions

Design requirements to transition to a new systems analysis platform that encapsulates a comprehensive power system model with seamless analytics are presented. Section 4.2 identifies existing applications and needed new analytic applications. Section 4.3 specifies requirements associated with the new architecture. Section 4.4 identifies existing gaps and challenges. Section 4.5 identifies barriers, Section 4.6 provides a list of prioritized next-steps, and Section 4.7 concludes.

4.2 Applications and Required Analytics

In this section, we summarize applications and corresponding analytical methods required. Organizational groups within the electric power industry needing access to power system analytics (datasets and applications) include generation owners, load serving entities, transmission owners, coordination organizations (ISO/RTOs), and oversight organizations (NERC, FERC, state-level regulators). We recognize that manufacturers, vendors, consultants, and researchers also need access to power system analytics, but most of these needs are similar to those of industry; where unique needs arising for special R&D objectives exist, we assume they are addressed on a case-by-case basis. An identification and classification of power system analytic applications is provided in Table 4.1. The applications are divided into three areas: those used primarily in systems and market operations, those used primarily in long-term planning and design, and those used in both and/or in operations planning, corresponding roughly to temporal delineation by short, long, and mid-term time scales, respectively.

Table 4.1: Classification of Analytic Applications by Organizations and Application Areas

Application area	Analytic applications	Generation owners	Load serving entities	Trans owners/ operators	Coordinators (BAs & ISO/ RTOs)	Oversight (NERC, FERC, State)
Systems and market operations	State estimation			■	■	
	Alarm processing			■	■	
	Load forecasting (short-term/mid-term)		■		■	
	Wind/solar forecasting	■			■	
	Network Topology Builder & Processor			■	■	
	Restoration	■	■	■	■	■
	Event recreation			■	■	■
	Switching sequence management		■	■		
	Interchange scheduling				■	
	Fault detection & location		■	■		
	Switching optimization			■	■	
	SCED	■	■		■	
	SCUC	■	■		■	
Operations , operations planning, and long-term planning	Steady-state frequency performance eval		■	■	■	■
	Reserve management & optimization		■	■	■	■
	Power flow analysis		■	■	■	■
	Static security assessment		■	■	■	
	Voltage stability analysis			■	■	
	Visualization &geo-info system GIS layer			■	■	
	Transient & oscillatory time-domain sim			■	■	
	Load modeling		■	■	■	
	Extended-term dynamic analysis			■	■	
	Available transmission capacity			■	■	■
	Production costing	■	■	■	■	
	Hydro-thermal coordination	■			■	
	Outage management/scheduling	■	■	■	■	
	Maintenance optimization	■	■	■		
	Node-breaker & bus-branch model convrsn		■	■	■	
	Unbalanced three-phase power flow		■			
	Volt / var optimization		■	■	■	

Table 4.1 (continued): Classification of Analytic Applications by Organizations and Areas

Long-term planning and design	Generation expansion planning					
	Generation siting					
	Load forecasting (long-term)					
	Eigen-analysis					
	Reliability assessment					
	Short circuit analysis					
	Protection coordination					
	EMTP					
	Arc flash analysis					
	Line impedance calculation					
	Line ampacity calculation					
	Line sag & tension calculation					
	Cable ampacity calculation					
	Cable sizing					
	Transformer MVA sizing					
	Transformer tap optimization					
	Capacitor placement					
	Motor starting analysis					
	Harmonic analysis					

A general application, which is useful across most of those identified in Table 4.1 is case processing, where many simulations are run and results are processed in order to use the application to answer some particular question, e.g., "What is the flow limit on a key interface to avoid violation of reliability criteria?"

In addition to the applications summarized above, there are a number of applications which are needed but not yet commercialized. Most of these applications are not deployed or are deployed only as research-grade software or early prototypes. These applications are listed below, grouped in appropriate categories.

1. Applications spanning operations and planning
    a. Bridging operations and planning models
    b. Protection system modeling
    c. Determining right-sized models
    d. Distribution system needs (distributed resource forecasting and dynamic analysis)
    e. System study tools to perform stochastic analysis in any time domain

2. Operations
    a. Market applications
    b. PMU-based monitoring and control
    c. Dynamic state estimator
    d. Risk-based security assessment
    e. Extended-term high consequence analysis
    f. Look-ahead analytics
3. Operations planning
    a. Frequency performance assessment
    b. Short-term stochastic scheduling
    c. Communication dependencies
4. Planning and design
    a. Long-term load forecasting
    b. Transmission and generation expansion planning
    c. Transportation and energy system planning
    d. Uncertainty modeling for long-term planning

4.3 Numerical Methods Comprising Each Analytic Application

Each computing application is an integration of various basic numerical methods, including, for example, linear equations solvers, nonlinear equation solvers, numerical integrators, and optimizers. Each of these may be implemented using any of several algorithms; for example, linear solvers, perhaps the most common function within power system analysis applications, can be either a direct solver or an iterative solver, and there are various implementations of each. Likewise, numerical integration methods may be classified into explicit and implicit integrators, with multiple implementations of each. And there exist a range of optimization algorithms, even for a single type of mathematical program, e.g., linear programs, integer programs, nonlinear programs, and mixed integer programs. We summarize four of the most ubiquitous numerical methods in the following four subsections.

4.3.1 Linear solvers

Linear solvers fall into 2 categories: the direct linear solvers and the iterative linear solvers. Direct linear solvers are more robust but memory intensive compared to iterative solvers. For very large problems involving in excess of a million equations, iterative solvers are the only solvers of choice due to memory limitations.

There are a number of algorithms available for both the direct and the iterative solvers. However not all algorithms are suitable for all applications. The choice of the method depends on the problem at hand and the numerical characteristics of the matrices involved. Some of the characteristics that impact the choice of the methods are diagonal dominance, numerical stability, symmetry, conditioning, and structure (e.g., banded or tridiagonal). Iterative solvers often require a good pre-conditioner for the method to converge especially for ill-conditioned matrices and non-symmetric problems like those found in transient stability analysis.

There are a number of state-of-the-art direct sparse linear solvers for unsymmetric matrices (typical of power systems) available with different algorithms and for hardware platforms, including those applicable for sequential computing (UMFPACK, SuperLU, KLU, HSL, and MA78), those useful for multithreaded computing (SuperLU, PARDISO, WSMP), and those useful for distributed computing (WSMP, MUMPS, SuperLU).

Choice of hardware also plays an important role in the selection of the linear solver algorithms. For example some algorithms are more amenable to parallelization than others. And even within the parallelization paradigm, some are more suitable to distributed computing and some for shared memory architecture. Most direct linear solvers need Basic Linear Algebra Subroutines (BLAS) libraries which are tuned for different architectures.

4.3.2 Nonlinear solvers

Newton methods and its variants are the methods of choice for solving nonlinear systems of equations. There are a number of different algorithms that fall under this broad category. Some examples are line search based Newton methods, trust region based Newton methods, gradient based Newton methods, and Broyden’s methods.

Newton methods and its variants are the methods of choice in general because of their excellent quadratic convergence characteristics. However they need good initial estimate (especially for power flow to avoid divergence). Newton algorithm with global Line search (LSN) method should be used in the power system analytic applications to increase the robustness of the algorithm. Once the solution is within the solution region it switches to full Newton for quadratic convergence.

On promising method is the new hybrid Newton and Steepest Gradient (HSGN) based minimization algorithm to solve nonlinear equations which do not easily converge with Newton method alone due to poor initial guess or stiffness. The strategy in this algorithm is to first solve the nonlinear equations as a least square minimization problem. This gives a very good starting point for the Newton method for fast convergence. Similarly the trust region based Levenberg-Marquardt algorithm and the Line Search Newton methods can be combined to develop a hybrid trust region line search gradient based Newton Algorithm.

For problems with good convergence characteristics, decoupled Newton (DN) methods can be used where the variables are decoupled and solved separately and iterated to get the final converged solution.

4.3.3 Integrators

Integration methods are categorized as implicit or explicit methods, multi-step or one-step methods, variable time step or fixed time step methods. The choice of the integration method depends on the stability, accuracy, convergence characteristics, order, and stiffness (ability to take large time steps). Explicit integrators are available in most standard transient stability packages. Where implicit methods have been implemented, trapezoidal methods and related variants have been most widely used. To achieve high computational efficiency one likes to use variable time step methods. However one has to use higher order (2,3,4…) A-Stable implicit methods to take large time steps. Higher order means more computational burden at both the solution of nonlinear system of equations and the solution of the linear system of equations.

However, when the system is in fast transient one has to take smaller time steps to capture the transients. In such situations explicit methods or lower order implicit methods are much faster. Therefore, variable-order-variable-time-step integration methods can achieve speedup especially for extended term simulations. The order and the time step of integration are chosen based on the previous integration steps and the truncation errors. Variable order variable coefficient BDF (Backward Differentiation Formula) and other methods are good methods for this approach.

4.3.4 Optimizers

A large number of optimization techniques are currently used in the industry today to serve the needs of various applications at various stages. A representative list of the applications with the corresponding methods is presented in Table 4.2.

Table 4.2: Power System Optimization Applications

Analytic applications	Optimization Method
SCED	Linear programming
SCUC	Branch & bound*, Lagrange relaxation
Hydro-thermal coordination	Linear programming, branch & bound
Outage management/scheduling	Branch & bound*
Maintenance optimization	Branch & bound*
Volt / var optimization	Reduced gradient, Newton, penalty function
Generation expansion planning	Dynamic programming, branch & bound*
Transmission Planning	Linear programming, branch & bound*
Switching optimization	Branch & bound*

* The power system engineering community often uses the term “mixed integer program” (MIP) to refer to the branch & bound algorithm or one of its variants (e.g., branch and cut). We view that MIP is a problem class rather than an algorithm.

In the 1970s and 1980s, it was typical to include optimization code directly within the power system applications. Today, it is almost universal to use optimization solvers, where input to the solvers is generally equation-oriented and generated by pre-processing code. IBM's CPLEX is a commonly used optimization solver for linear programs (LPs) and mixed integer programs (MIPs), which comprise the largest number of optimization problem types solved by the power industry.

Optimization in power system analytics is being driven by three issues: a) need to address optimization at various scales (e.g., reserve management), b) uncertainty due to resource variability, load variation and demand response, and c) the need to evolve from deterministic instantaneous optimization for real-time operations to stochastic dynamic scheduling. Seamless power system analytics will require the current optimization techniques to be enhanced and integrated carefully into the study tools.

Recently, Adaptive Dynamic Programming, which handles both dynamic and uncertain optimization problems, has emerged as a powerful method for solving a significant range of problems. Efficient methods for handling stochastic programming methods have recently emerged and are likely to be of great interest for SCUC and various planning problems.

Decomposition methods, including Benders and Dantzig-Wolfe, have been used in research-grade power system applications before, although they have not been used heavily in commercial grade software. For optimization problems which can be decomposed into sub-problems (equivalently, if the problem constraint matrix has appropriate structure), they facilitate solution modularity and can also offer significant gains in computational efficiency. SCED, SCUC, and planning-focused optimization are generally of this type.

5 EMS Visualization Systems

5.1 Introduction

Visualization of the real-time condition of the power grid is the best monitoring tool the operator has. Existing visualization tools have challenges in handling the growing data volumes and it is becoming critical to develop advanced tools that can digest data while providing easy to use, actionable visualization and alarming. Visualization of the grid outside a control center boundary is currently unavailable or very limited. This is a major drawback in the operation of large interconnected systems – considering that it takes about 100 balancing authorities and 10 reliability coordinators to monitor the Eastern Interconnection with none of them having a complete picture of the state of the whole system. The limited ability of knowing what is going on in the neighboring system has been a consistent element among the causes of large blackouts.

Innovative visualization methods developed by in the late nineties by PowerWorld and others have made their way into mainstream control center visualization. However, the static 2D visualization may not be sufficient for the emerging requirements. In particular mechanism for handling emerging multi-dimensional and multi-scale data are needed.

Planning, simulation, operation and control of electrical energy systems involves dealing with information that is naturally associated with spatial and temporal dimensions ranging from continental interconnections to homes and from years to microseconds, respectively. It also involves the analysis of a potentially large number of scenarios (security) dimensions. Each one of the dimensions has specific scales and granularity requirements associated with behavior that is contextually relevant. The temporal variability of wind and solar energy, the ability to store significant amounts of electricity (in PHEV, utility storage, and pump hydro), the customer's ability for active response, and massive sensing result in new, complex grid behavior and new needs for visualization. The existing visualization applications for real-time operations are single snapshot (real-time) in the temporal domain and large-scale in the spatial domain. They are limited hence in their ability to discover meaningful patterns and capture relevant phenomena in other relevant dimensions and scales. Some of these limitations have been made evident in recent partial blackouts directly tied to the inability of operations support systems to capture the time scales associated with large-scale renewable energy variability [1,2,4].

At the same time, it is estimated that investment in substation automation, intelligent electronic devices, and smart meters will produce amounts of multi-dimensional data at least four orders of magnitude greater than previous data acquisition [3,6]. The existing visualization tools cannot support or exploit massive multi-dimensional data streams. In order to address these challenges, new mechanisms to understand complex grid behavior need to be developed. Visualization tools are the core of real-time operations and system simulation and analytics, and advanced, dynamic

Multi-Dimensional, Multi-Scale (MDMS) visualization software will be essential to addressing the emerging needs.

Advanced algorithms need to efficiently handle MDMS data for power system visualization, taking into consideration the semantics and engineering context of the information, the emerging behavior and operational objectives, the advances in scientific visualization, and the capabilities of existing hardware and programming languages. Three major challenges in power system visualization must be overcome: a) Understanding the structure of new massive data, b) Handling temporal scales in an operator real-time environment, which requires dynamic temporal scale compression and expansion, and b) Handling of multi-dimensional data in the spatio-temporal, and security dimensions, which requires navigational visualization.

MDMS visualization applications may include: a) forward-looking operation with large-scale renewable energy, b) demand response, c) real-time visualization of PMU-detected dynamic oscillations, and d) Synchronization of variable renewables with flexible loads, etc.

5.2 Energy Infrastructure Growing Complexity

Major disruptive forces are reshaping the energy and electricity industries in the United States and abroad. Distributed renewable energy and storage, smart grid technologies, massively deployed sensors, evolving energy markets, and security threats are drastically increasing the complexity of electric grid planning and operating processes. Advanced metering alone is increasing the existing data acquisition by four orders of magnitude [3,6]. Renewable energy, which is distributed and highly variable, acts on temporal scales that are different from those addressed by existing decision-support systems [4]. Phasor measurement units (PMUs) sample at 30-60 times per second achieving wide-area synchronized monitoring. PMU concentrators integrate massive amounts of data to capture dynamic frequency oscillations and provide ultra-fast monitoring [5]. These are examples of a broader trend of unprecedented availability of massive MDMS information and growing control complexity. Existing evidence suggests that decision making requirements are rapidly exceeding the human ability to comprehend and respond to emerging system conditions and events [6,7,8]. The existing monitoring and control processes through which the electricity infrastructure is operated can therefore be compromised in a few years if the existing situational awareness tools are not replaced by drastically more powerful systems [10].

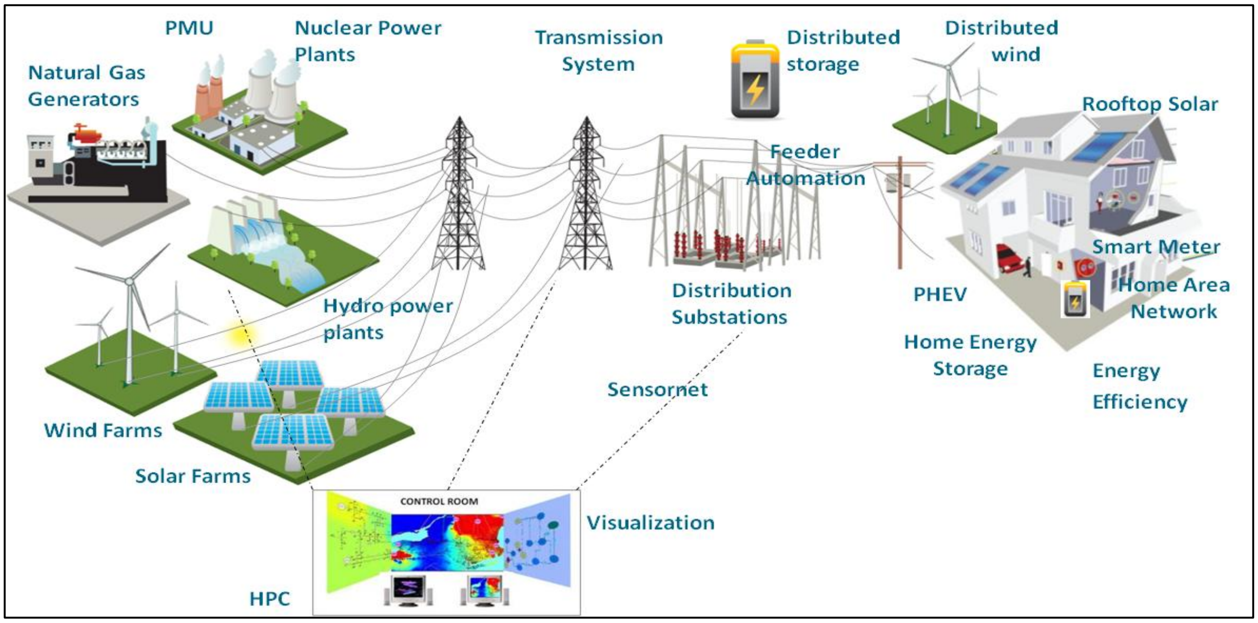

Figure 5.1: The emerging electricity grid

Figure 5.1 shows some of the elements that are becoming common in emerging electric grids. Massive deployment of sensors at all levels, renewable energy and storage, and active loads result in highly complex data processing and MDMS problems. Many of these components did not exist a decade ago, including: large-scale renewable wind and solar, advanced substation and feeder automation systems, utility scale storage and PHEVs, rooftop solar installations, smart meters, and AMI, and two-way communication systems. While pursuing simultaneous objectives of efficiency, reliability, and sustainability, the electricity industry faces numerous engineering challenges to ensure safe and integrated operation of all these components.

In addition, the criticality of electrical energy delivery to the functioning of society, implies that control actions require the evaluation of “what if” events in real-time. Thus, a very large number of scenarios must be tested to ensure that especified operating limits are not exceded. Failure to do so may result in insecure systems conditions and potential cascading and broader failures [7]. The resulting security dimension datasets contains the system conditions and opearting regions that should be avoided. Figure 5.2 illustrates the visual pattern of the security dimension obtained by evaluating the N–1 thermal overloads of transmission devices in a small system. Large-scale systems are hundreds of times larger, and N–2 security analysis is usually required.

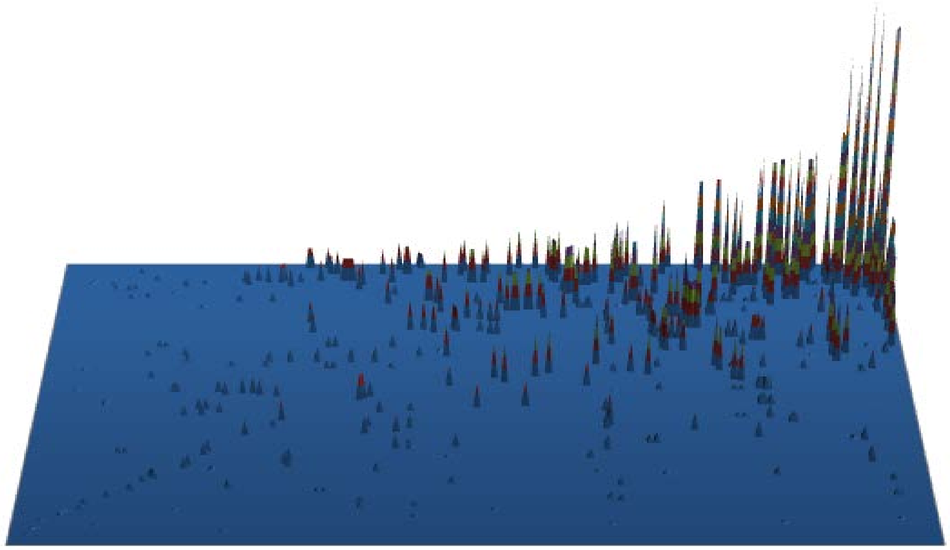

Figure 5.2: The security dimension

Figure 5.2 illustrates a clustered thermal overloads in a 100-node electric system. The vertical axis represents the megawatt overload of a transmission component upon the single outage of another transmission device. Realistic system size is in the order of 104 nodes, which results in 108 data points for an $N-1$ security analysis of the system at a single point in the temporal dimension.

5.3 Large-Scale Visualization: State-of-the-Art

Electricity grid visualization has become increasingly important and a topic of significant research in the last decade [10,11]. Visualization has been the mechanism to drastically increase situational awareness in bulk energy control centers. Systems with 2D-spatial visualization of the controlled region are the norm. Typically, the visualization requirements for these systems are at the level of 10^3 to 10^4 measurements every 5-10 seconds. Zooming and panning is usually too slow for real-time response in this environment. In general, interactive visualization in real-time has not been possible due to slow performance. Spatio-temporal and spatial-security 3D visualization has been proposed [11], but it has not been deployed for either operations or planning due to performance limitations even with Graphics Processing Units (GPUs).

Visualization at the distribution level is driven by geo-referencing requirements and hence it is coupled with Geographic Information Systems (GIS). The norm is a 2D-spatial GIS representation [12]. Neither spatio-temporal nor spatial-security techniques have been proposed for distribution.

GPUs have emerged from being fixed function pipelines to massively-parallel, Turing-complete machines capable of performing general purpose computation [16]. The latest generation of

GPUs, consisting of hundreds of stream processing units, is capable of supporting thousands of concurrently executing threads with zero-cost hardware-controlled context switching between threads. While CPUs have traditionally added hierarchies of caches to tolerate memory latency, GPUs address the problem by providing a high bandwidth processor. Memory links supporting high degrees of simultaneous multithreading (SMT) are available within the processing elements.

Cluster GPU applications have been proposed [13] but have not been implemented at control centers. 4D (spatial + temporal + security) has been proposed for small data sets. Multi-scale 2D spatial visualization is rudimentary available only for snapshot data sets and in off-line modes [14,15].

Because of the performance and design of the GPU, highly parallelized and efficient computation is possible. Several General Purpose GPU (GPGPU) libraries have been developed to provide a better match to the computing domain. In recent years, numerous algorithms and data structures have been ported to run on GPUs [20]. Scientific visualization generally has a spatial 2D or 3D mapping and can thus be expressed in terms of the graphics primitives of shader languages. In general, the current GPU programming model is well-suited to managing large amounts of spatial data. An example of a GPU generated image is shown in Figure 5.3. GPU visualization for large grids has been reported to be about 30 times faster than CPU-based visualization [13]. GPU clusters can theoretically yield visualization speeds in the order of 10^3 times the current levels, opening a large number of research and application possibilities.

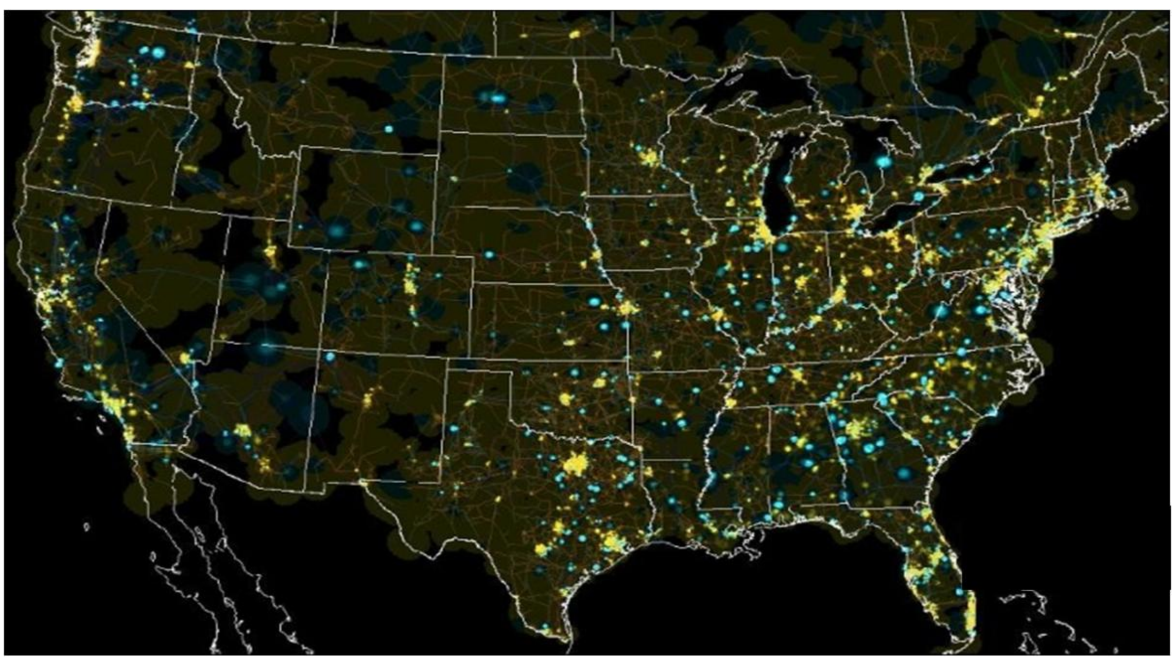

Figure 5.3: 2D visualization

Visualization is achieved by a stand-alone application on a single GPU processor using PowerWorld®. The contouring visualization represents load and injection of active power with overlying high voltage grid. About 100k points are contoured.

Massive deployment of advanced sensors (intelligent electronic devices) at substations and smart meters is producing large amounts of new data. This volume of data has tremendous scientific value that is currently under-exploited because of: the difficulties of integrating and interpreting across diverse data formats, numerous variables, a range of spatial locations and depths, and the wide range of spatial and temporal sampling regimes [17]. The structure of these datasets in the electricity industry has not been standardized and is an issue of concern. Human analysts face significant challenges in synthesizing and assimilating emerging complex multivariate and spatiotemporally heterogeneous data collections. Existing analysis tools in the electricity industry are currently well below the needs.

GIS systems support integration and investigation of data with spatial dimensions but lack adequate support for investigating temporal dynamics, which is critical for emerging electricity system analysis. Similarly, time series analysis tools are available for querying and visualizing multivariate time series [18,19], but these tools lack support for spatial dimensions. New tools for the exploration and visualization of complex datasets are crucial.

5.4 Existing Limitations

In order to study electrical energy system behavior assumptions have been made in the past about the dimensions and scales of the relevant engineering phenomena. The control architecture of the electricity infrastructure was also designed based on these assumptions. In many cases, these assumptions were needed in order to make the associated computational problems tractable. For instance, hourly granularity has been used in the operations stage for problems such as unit commitment or the economic dispatch of active power generation [23]. Current unit commitment problems though involve modeling a large number of geographically dispersed renewable energy sources and require temporal resolution at the level of minutes or seconds [24]. More powerful unit commitment applications equipped with visual analysis tools are hence needed.

The industry faces an increasing number of engineering challenges, which will benefit from advanced visualization. Among the most relevant are:

a) *Real-time Operation with Large-Scale Distributed Renewable Energy*: Challenges arise due to the variability of wind and solar energy and the limitations of conventional generation to balance generation production. Integrated forecasting of renewable production and load coupled with visualization of security dimensions and reachability of secure states is required to produce optimal scheduling and support system operator's decisions.

b) *Visualization of Smart Meter Dataset*: Utilities can developed advanced understanding learn from customer and load datasets to enhance a number of engineering and business processes including demand response, volt/var control, billing, outage management, etc. Applications related to consumer pattern discovery usually require processing a year's worth of 15-minute smart meter data for millions of customers.

c) *Real-Time Security and Resilience Analysis*: When faced with imminent weather events, Independent System Operators (ISOs) need to quickly analyze results of contingency studies consisting of an intricate data set of coupled weak elements and severe outages. Existing tools have limited contingency data visualization.

d) *Disaster Response*: Recent weather related events have made apparent the interdependence of critical infrastructures, such as electrical, communications, water, fuel, and transportation, in times of crisis [21,22]. Optimal emergency response actions require real-time, multi-layered, multi-scale visualization, currently unavailable.

e) *PMU-Enabled Applications*: ISOs need to process and visualize data from geo-referenced synchronized PMUs at high granularity over one hour to identify insecure system conditions including dynamic oscillations. Processing of massive data sets needs to capture relevant phenomena on-the-fly. In addition, system behavior that is too fast or too slow (such as growing oscillations) needs to be brought to natural human frequency for active response. The mechanisms for such interactions can be understood through temporal multi-scale visualization.

f) *Transmission Planning for Wind*: This is a MDMS problem with a horizon of multiple years, but relevant behavior in seasonal, daily, hourly, and minute scales. The problem involves multiple spatial scales due to farm aggregation as well as security dimensions associated with proposed transmission expansion options, demand scenarios, policy issues, etc. Advanced visualization can assist on complex decisions related to the prioritization of solution.

The availability of massive data, novel multi-scale methods, ever growing computational power (GPU) and strong needs lead to research on transformational methods for critical decision-making. Advanced visualization is essential to enhance the current understanding of emerging grid behavior and to provide analytical capabilities for numerous critical problems. Challenging MDMS monitoring, optimization, and control problems are arising in a variety of areas of electrical energy research. Visualization will provide a powerful to address these problems in a comprehensive manner.

We propose advanced visualization algorithms and techniques that will allow operators to act on massive datasets from utility sensing systems; discover new operational patterns and risks in energy production, transmission, distribution, storage, and utilization, and their interrelation; and understand emerging complex behavior in system and market operation. These new capabilities will help to ensure that:

a) The operational processes being introduced in the industry continue to meet the required system reliability and quality of electricity service at all times,

b) The control mechanisms proposed are efficient and economically optimal,

c) The technologies being deployed serve their objectives and perform as expected, and

c) The emerging infrastructure will deliver the promise of flexibility, support for sustainable sources, and efficient energy utilization.

6 Unified Geo-Spatial Model Requirements

6.1 Introduction

For historical, performance, and security reasons, the power system real-time operation and planning stages have grown separated, both from the business architecture point of view and from the software technologies therein utilized. Since the inception of digital bulk power control, data acquisition and real-time control requirements forced vendors to use real-time operating systems, closed platforms, and proprietary models when developing Energy Management Systems (EMS) [25]. On the other hand, the planning environment was quick to adopt a stand-alone application, personal computer approach, and simplified network models [35].

This separation persists today. Network applications continue to be developed around either operations models as part of EMS systems, or planning models for off-line use in a perpetual two-model industry paradigm. The network applications used to solve these models remain incompatible and the business processes are not integrated.

Emerging electricity industry operational and market challenges associated with integration of renewable energy and storage, research scheduling, and demand response require tight coordination and integration between operations and planning. Numerous emerging needs and desirable use cases require seamless information exchange and network solutions across the various engineering stages. The lack of unification regarding models and applications represents a major barrier to addressing these challenges [25].

Several efforts by utilities and vendors have taken place during the last two decades in the quest to obtain a common format and definitions that would allow different vendor applications to interoperate. Part of this effort is the Common Information Model (CIM) [29,30,31] originally proposed by EPRI in the late 90s, which provides standardized definitions of power system data. Presently, however, the vast majority of network applications continue to require converting CIM or other models to their native underlying format. More importantly, the two-model paradigm remains pervasive in the industry, with EMS applications unable to understand or solve planning cases and planning software unable to understand or solve operations models [25].

This section proposes the need for a new algorithm that realizes unified network applications, and offers a framework for seamless power system operations and planning. Unified network applications realize the following combined functionality:

a) Model unification: a single, operations-type model is used, but this model does not have to be CIM.

b) Seamless model solution: a single software engine can be used to transparently solve either operations or planning models without requiring model conversion or data mappings.

c) Application unification: the same application can be integrated in a real-time environment or used off-line.

d) No new format is proposed or needed. The application is though compatible with CIM formats.

This overall functionality can be enabled by a new algorithm, which is dynamically capable of solving arbitrary topologies and configurations of switching devices in a substation. The following sections discuss the implementation of unified applications.

6.2 Power System Models

At the core of the process separation between operations and planning lies the power system models adopted by the industry decades ago. The *Full-Topology, Operations*, or *Node-Breaker Model* is a physical model, which represents the power system at the individual node and switching device level. In real-time control this representation is needed by the data-acquisition functions and by the operator, who requires access to the detailed substation topology for maneuvering and control of the switchyard devices. On the other hand, the *Planning Case, Off-Line,* or *Bus-Branch Model* is a higher-level, simplified model of the power network. In this model, all the physical nodes, junctions, and bus-bars that are connected through closed switching devices (breakers and disconnects) correspond to the same electric point and have been grouped together into a single *Bus*. None of the switching devices are present in the planning model. This model is thus less detailed and smaller making it easier to deal with computationally, something that was extremely important to being able to solve a realistic power flow in the early years of the computer. With today's computer power this simplification is no longer needed. However, utilities continue to use these two types of models to represent the network for operations and planning purposes. This two-model paradigm is pervasive and poses major problems:

a) Numerous emerging industry problems such as operation with renewable energy and storage, reserve scheduling, and demand response require integrated analytics and seamless information exchange at the intersection of operations and planning [42].

b) Analysis of the various steps of substation maintenance remains cumbersome, requiring complex scripts to alter planning cases to represent various topologies [34,35].

c) Contingency analysis in the planning environment cannot model events that include bus mergers or splits. This is dangerous enough because events can happen in the physical system, which are not being routinely evaluated during the planning stage.

d) It is very cumbersome to compare real-time power system solutions to planned power flows developed off-line for the same footprint. This drastically limits the opportunities for direct post-operational feedback, enhanced operator training simulators, etc.

e) There is a proliferation of power system model repositories even within the same utility. Figure 6.1 illustrates a traditional EMS data framework, where up to five different instances of a utility's power system network model can be found: Input Relational Database, Real-Time Database, Internal Bus-Branch Model, Exported Snapshot Planning Case, and CIM. None of these models is compatible with a sixth model: the Planning Case used in the off-line environment.

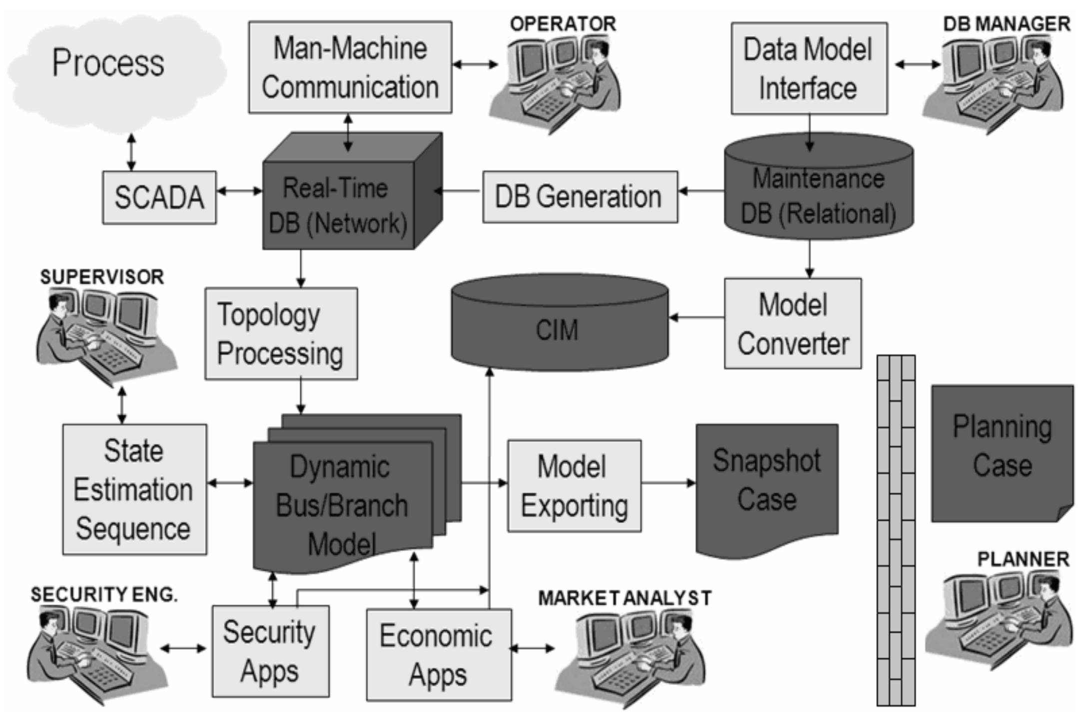

Figure 6.1: Power system models used in a typical EMS system

The model incompatibility problem is compounded by the fact that different EMS vendors use different formats and modeling conventions to represent power system devices. We call the current method "changing your data model to support your legacy applications". A drawback of this approach is that it would perpetuate the two-model paradigm and the need to use two different suites of network applications for largely similar numerical problems. For instance, a real-time power flow and a planning power flow for the same utility footprint are computationally identical problems. However, two suites of entirely different planning and operations applications are currently needed to obtain their numerical solutions. As more data from intelligent electronic devices and PMUs is acquired, seamless integration and use of these data will become critical.

6.3 Model Unification

We propose an approach radically different to having to maintain two different models for operations and planning for all applications that, at their core, require modeling a power system network. For these types of applications, we propose eliminating the application-specific models, such as the planning case, and instead using a single model. We demonstrate that the proposed method and framework allows not only unification of model and format, but also unification at the application level.

Because the *Full Topology* model contains all the required information for monitoring, user interaction, and numerical solutions, this is the model that should be used. As it will be described, the changes required in existing planning software to be able to support operations models do not involve changes to the core power flow or contingency analysis numerical routines used or adoption of a new power system format.

Eventually, under the assumption that all power system applications are converted to work off the full-topology model, the block diagram becomes much simpler. More importantly there is now only one model to maintain considerably reducing errors, personnel training, etc. In addition, the wall between operations and planning processes can be removed. This is shown in Figure 6.2.

A key step in the process of model unification is the realization that any full-topology power system model can be formatted in the existing planning model format without requiring format changes. To do so, the following simple assignments must be made in order to support objects that are commonly not present in planning cases:

- All bus-bars, junctions, nodes and any other connection points are described as bus records.
- All circuit breakers, disconnects and any other switching devices are described as (low-impedance) branch records.

Using the same planning format and data structures to model the full-topology system has significant advantages:

a) The user deals with the same interface to edit either model, removing the need of the Data Model Interface and the Database Generation process shown in Figure 6.1.
b) Using this approach, the EMS exported model does not necessarily need to be a planning case of reduced size, but it can now be the entire full-topology model. It is trivial from the application side to classify the branch records as transformers, lines, breakers, disconnects,

etc., and with current memory capabilities, preserving all the switching devices in a model is not a problem. The number of generators, loads, transformers, shunts, and lines remains the same.

Maintenance of the power system models, a very complex activity in the industry is drastically simplified and becomes a centralized task.

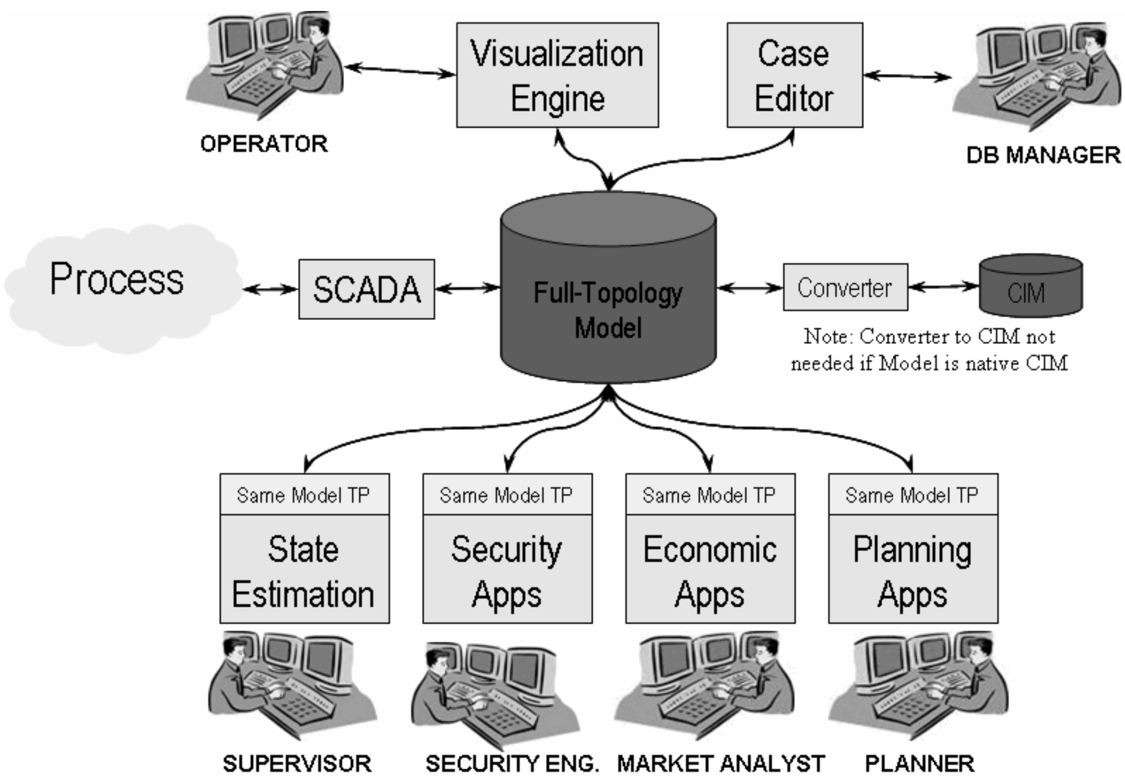

Figure 6.2: Proposed unified full-topology model

6.4 Handling of Switching Topologies

In this section we describe a novel and computationally efficient algorithm to handle arbitrary configurations of switching devices in a substation –the key difference between operations and planning models. This algorithm is the core that enables unified network applications.

Existing planning tools are able to model a few switching devices by treating them as (very) low impedance branches. However, as the number of switching devices increases to more than a few, the network matrices become ill-conditioned and numerical instability problems arise. Reference [17] describes the low impedance branch numerical instability problem in detail. Current planning software therefore does not support full-topology operations models. Several efforts by researchers have taken place in the direction of being able to model switching devices in network applications. In particular, topology error detection in state estimation proposes estimating breaker statuses as part of system estimation [36,37], an approach broadly known as Generalized State Estimation (GSE) [38,39]. GSE has not been deployed widely in the industry due to the complexity of handling mappings between the associated node-breaker and bus-branch models.

Topology Processing (TP) is the algorithm used by EMS systems to generate an internal planning model of the physical system that can be used for numerical solution [32,33]. Although topology processing has been used for a while, the *single model* topology processing proposed below is a radically new concept. To describe this process, we will use the term "*planning case*" to refer to the actual file containing a bus-branch model traditionally used in the off-line environment or to the EMS-generated bus-branch model resulting from topology processing.

Traditional topology processing uses separate data structures to store objects of the full-topology model and the planning case. In particular two different types of classes: *Node* and *Bus* are required in this algorithm. For instance, CIM considers a Connectivity Node class to represent nodes in the node-breaker model and a Topology Node class to represent buses. We proposed a method that uses a single class to describe both nodes and buses.

We will use the term *Consolidated Representation* to refer to a bus-branch "view" of a full-topology model. In order to illustrate how this is achieved, consider Figure 6.3, which shows the configuration of a very small full-topology system, comprised of 11 nodes. Transmission lines are connected to the bus bar sections through circuit breakers. The statuses of the breakers at a given point in time allow determining groups of nodes that correspond to the same electric point (a bus). Figure 6.4 shows the 4-bus (bus-branch) planning case, which would be obtained by taking into would account the statuses of the breakers shown in Figure 6.3. This planning case would be needed to obtain numerical solutions.

Instead of building this second model (a planning case), single-model topology processing changes the *representation* of the network to be either full-topology or consolidated. The user and the numerical applications are able to "view" the system in either representation at will. This is internally handled by the software application.

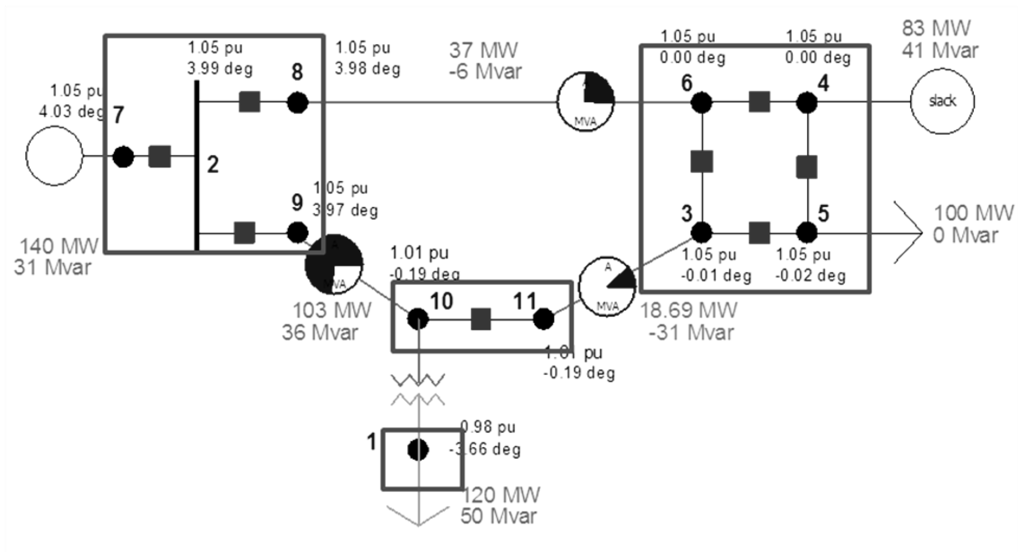

Figure 6.3: Full-topology model showing groups that become buses in the planning case

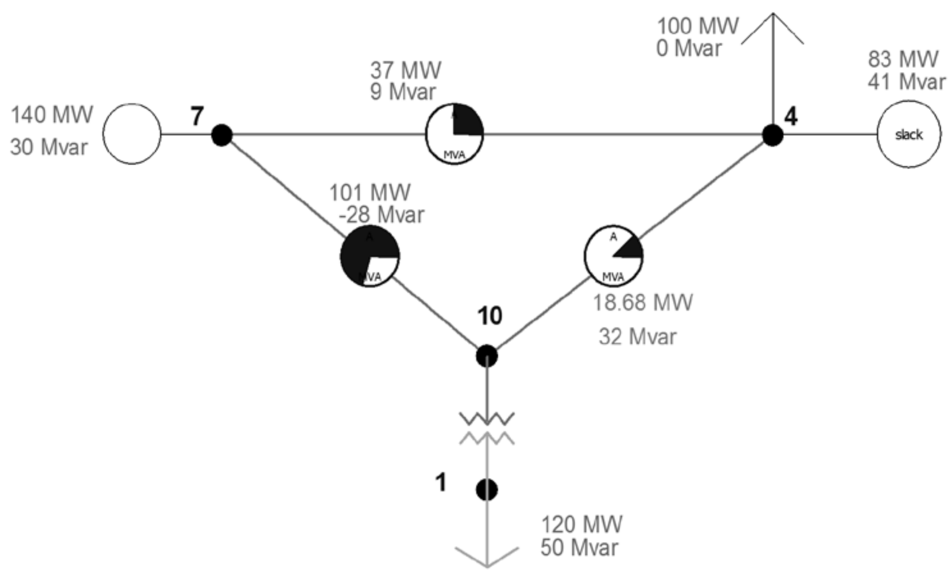

Figure 6.4: Planning case corresponding to the full-topology case with given breaker statuses

The single-model topology processing algorithm starts by identifying the groups of nodes connected by closed switching devices (breakers in this example). For instance, if the breaker statuses shown in Figure 6.3 are assumed, then each group of nodes {1}, {3,4,5,6}, {10,11} and {2,7,8,9} correspond to nodes that are the same electric point. Single-model topology processing then selects one node from each group to be preserved in the system. This selected node is called a *Primary Node* (*pnode*). Although any node in the group can be chosen as pnode, a priority rule is used that prefers device terminals, or voltage regulated buses over regular nodes. In the example, nodes 1, 4, 7, and 10 are selected as pnodes of each of the corresponding groups. Pnodes are then assigned to each one of the nodes in a group. Computationally this is achieved by using pointers: each node points to a pnode. In the example, the node and pnode pointer references look as in Figure 6.5. We note that the pnode property in the Node Table is a pointer to a record in the same Node Table. For instance the pnode of node 1 is node 1 (itself).

Power system devices such as generators, loads, and transmission lines (modeled in the corresponding tables) have connection terminals represented by nodes in the Node Table. During user access functions, model editing, and result presentation, the physical terminal node of the device must be used. For instance, Line 6-8 is physically connected between nodes 6 and 8. However, during system matrix creation and numerical solutions, not the node, but the pnode pointers are utilized instead, which enables bypassing the switching devices, while obtaining an electrically equivalent consolidated representation.

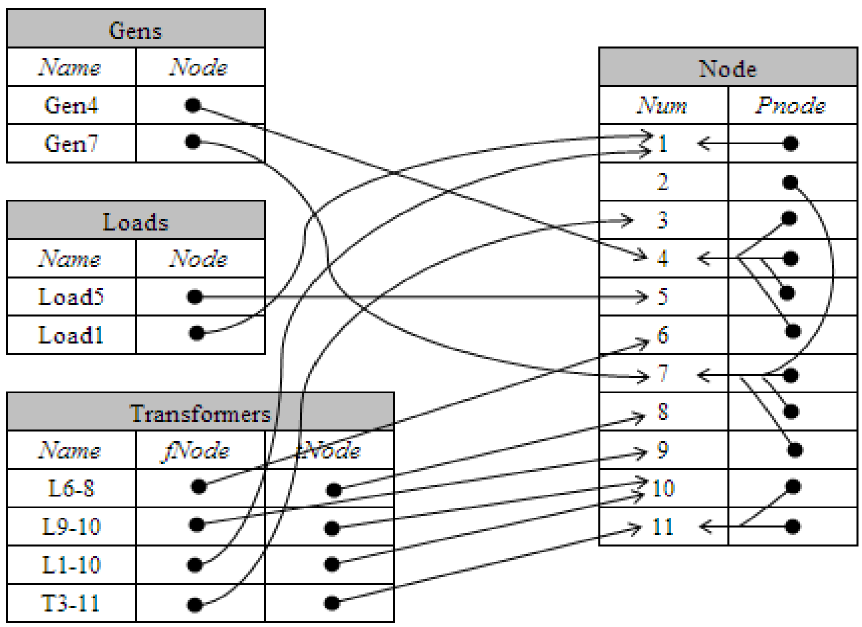

Figure 6.5: Pnode references in the 11-node case

In the example above, during all numerical solutions Load 5 will behave as being connected to Node 4 because Node 4 is the primary node pointed to by Load 5's terminal Node 5. Similarly, Line 6-8 will appear to be connected between nodes 4 and 7, which are the pnodes of nodes 6 and 8.

By using the pnode pointers instead of the terminal nodes, all the devices appear connected to pnode nodes only. We call the operation by which the node pointers are set to point to the pnodes *Consolidation*. During the physical operation of the system, a change in breaker status will result in the groups of nodes changing and possibly in new pnodes being defined or some removed. When this occurs, the pnode pointers are automatically recalculated.

Figure 6.6 illustrates all the device terminal pointers pointing to the pnodes. Note that the presence of the closed breakers becomes irrelevant. They can be ignored altogether during the numeric solution. By the same token, all the non-pnode nodes (3,5,6,2,9,8,11) can be removed.

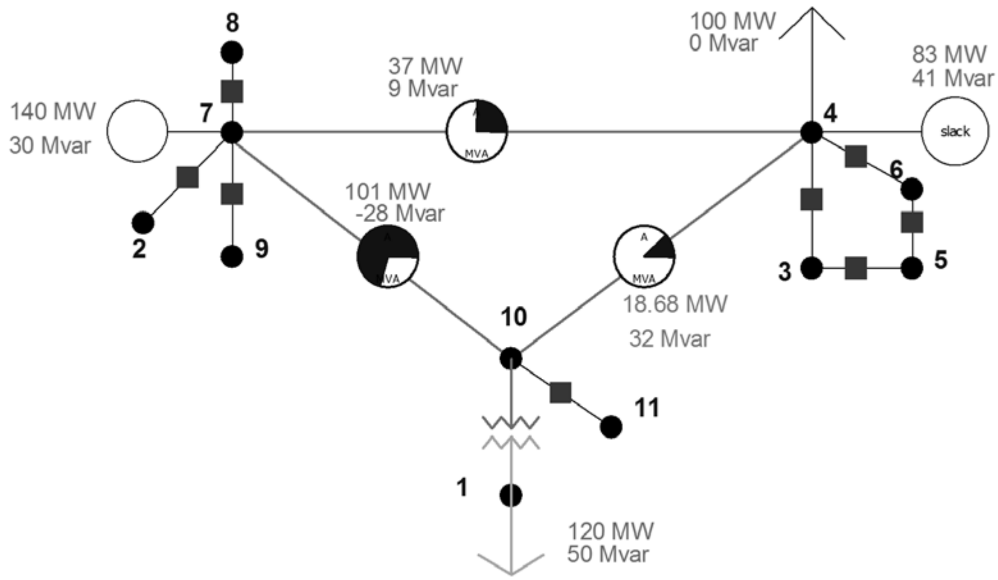

Figure 6.6: Representation of device relocation

If all breakers and all non-pnode nodes are removed from the system in Figure 6.6, one would obtain the consolidated representation, which is the exact electric system shown in Figure 6.4 (a planning case). Note that this is achieved by using a single, full-topology model. We emphasize that there is no need define a Bus class, use a Bus Table to store bus objects. Only one class is needed: Node. Because buses are not needed, there is no need to have a second, bus-branch model.

The utilization of pointers to the same type of object (a node) is at the center of the proposed single-model topology processing algorithm. It is this fundamental principle of using only the Node class that allows unifying the power flow applications. Once all devices appear connected to the pnodes, the power flow can be solved without any further changes.

6.4.1 Full-Topology Processing

In single-model full-topology processing, the consolidated representation is obtained from scratch from the full-topology model and the current breaker statuses. Single-model full topology processing consists of determining the groups of nodes, selecting the pnode, and assigning the pnode pointers. Each node in the full representation must belong to a group. The identification of these groups of the system is implemented using a depth-first search function whose implementation is summarized as follows:

```
Procedure SMFullTopologyProcessing
begin
  set all Node[i].visited = false
  i = 1;
  while i < NumNodes
    if Node[i].visited = false then begin
      NewNodeGroup = TNodeGroup.Create
      NewNodeGroup.NodeList.Add(Node[i])
      NodeGroupList.Add(NewNodeGroup)
      SetNodeGroup(Node[i],NewNodeGroup);
    end
    Inc(i)
  end
end

Procedure SetNodeGroup(Node,NodeGroup)
begin
  set Node.visited = true
  Connection = Node.ConnHead
  while Connection <> nil do
    if Connection.Branch is ClosedBreaker
    then begin
      OtherNode = Connection.OtherNode
      if OtherNode.Visited = false then begin
        NodeGroup.NodeList.Add(OtherNode)
        NodeGroup.BreakerList.Add(Connection)
        SetSuperbus(OtherNode,NodeGroup)
      end
    end
    Connection = Connection.Next
  End
end
```

This function is very fast and can identify the groups of nodes in very large models in a few milliseconds. Thus it is reasonable to run this dynamically even on systems with hundreds of thousands of nodes. The second step in the single-model full topology processing is to identify a pnode for each group of nodes, and set this pnode as pnode pointer as in Figure 6.5.

At the end of this process, all except one node from each node group is preserved in the list of nodes. The preserved pnode now shows connected to it the devices that were previously attached to other nodes in that group. All closed circuit breakers, as well as all closed disconnects and ZBRs, have been removed. All external transmission lines, series devices, phase shifters, etc. that had a terminal in a node of the group moved their terminals to the pnode. All other pointers of remotely regulated buses, etc. are updated to point to the pnode. We call changing the model representation from full-topology to consolidated representation *Consolidation*, and the reverse process we call *De-consolidation*.

```
Procedure Consolidation
for each NodeGroup do
  NodeGroup.pnode = apnode
  for each node
    Set node.pnode = NodeGroup.apnode
    NodeGroup.AssignGensLoadsAndShunts
    SystemBreakerList.HideConsolidatedBreakers
    SystemNodeList.HideNonpnodeNodes
  end
end

Procedure Deconsolidation
SystemNodeList.RestoreNonpnodeNodes
SystemBreakerList.RestoreConsolidatedBreakers
for each Node do
  Node.pnode = Node
end;
SystemDeviceList.AssignGensLoadsAndShunts
end
```

6.4.2 Single-Model Incremental Topology Processing

In Single-Model Incremental Topology Processing mode, the existing consolidated representation is incrementally updated as switching device statuses change. This update is done by processing small regions of the grid one at the time. We define a *Subnet* as a collection of nodes grouped together by switching devices regardless of the status of the switch. If there is a breaker or disconnects between two nodes A and B, those two nodes always belong to the same subnet. Transformers and transmission lines separate subnets from each other. Their terminal nodes always belong to two different subnets. It is noted that subnets are static –they always contain the same nodes and switching devices. Network subnets can be determined by running the same single-model full-topology processing algorithm once, assuming that all the breakers are closed (disregarding their statuses). This can be done when the full-topology model is read for the first time.

To update the consolidated representation due to changes in breaker statuses, single-model incremental topology processing re-processes only those subnets that contain breakers that changed their statuses. This is implemented by first resetting the subnet node pnodes to “self”, and then running single-model topology processing only for the affected subnets. The following algorithm implements single-model incremental TP, assuming that the subnets have been determined and that the initial pnode pointers have been set:

```
Procedure
SMIncrementalTopologyProcessing
Set all Subnets.Affected = False
for each Breaker do
  if Breaker.StatusChanged = true
then
    Breaker.Subnet.Affected = true
  end
end
for each Subnet do begin
  if Subnet.Affected = true then
begin
    Subnet.Expand
    Subnet.Reconsolidate
  end
end
```

A power system network can therefore be in three different consolidation states: a) Full: all node pointers point to self, b) Consolidated: all node pointes point to the pnode, and c) Expanded: all the nodes of at least one subnet in the system point to self. Figure 6.7 illustrates the relations between the consolidation states and the full or incremental single-model topology processing actions.

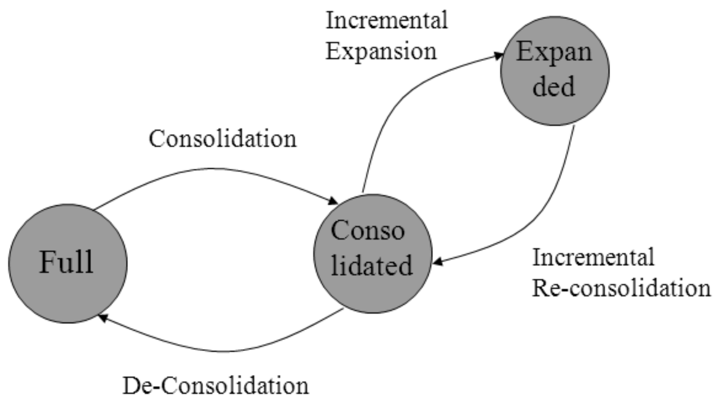

Figure 6.7: Illustration of power system representation consolidation status

6.5 UPF Application Integration

In the proposed unification framework, the power system representation is only consolidated during calculations or when saving the consolidated model to file for exchange with existing planning tools that do not support full-topology models. Consolidation is also required prior to performing any calculations that can change the power system state or require a solved power system state. Many applications either operate alone or are utilized as routines of other applications.

Consolidation and de-consolidation should only be done once during any application so as not to incur the overhead, although minimal, of repeated consolidation and de-consolidation processes and to maintain correct calculations based on the consolidated model. Therefore, a hierarchical application integration strategy is required. Applications are assigned to levels based on other applications that they use. The consolidation and de-consolidation processes are aware of the power system consolidation states shown in Figure 6.7 and take place only at the highest level of the hierarchy. A stand-alone application such as the Power Flow in Figure 6.8 will consolidate and de-consolidate itself, but if the power flow is used as part of another application such as Contingency Analysis, consolidation and de-consolidation occurs only once at the highest level of that application. Applications at higher levels call the lower level application while being aware of the consolidation state.

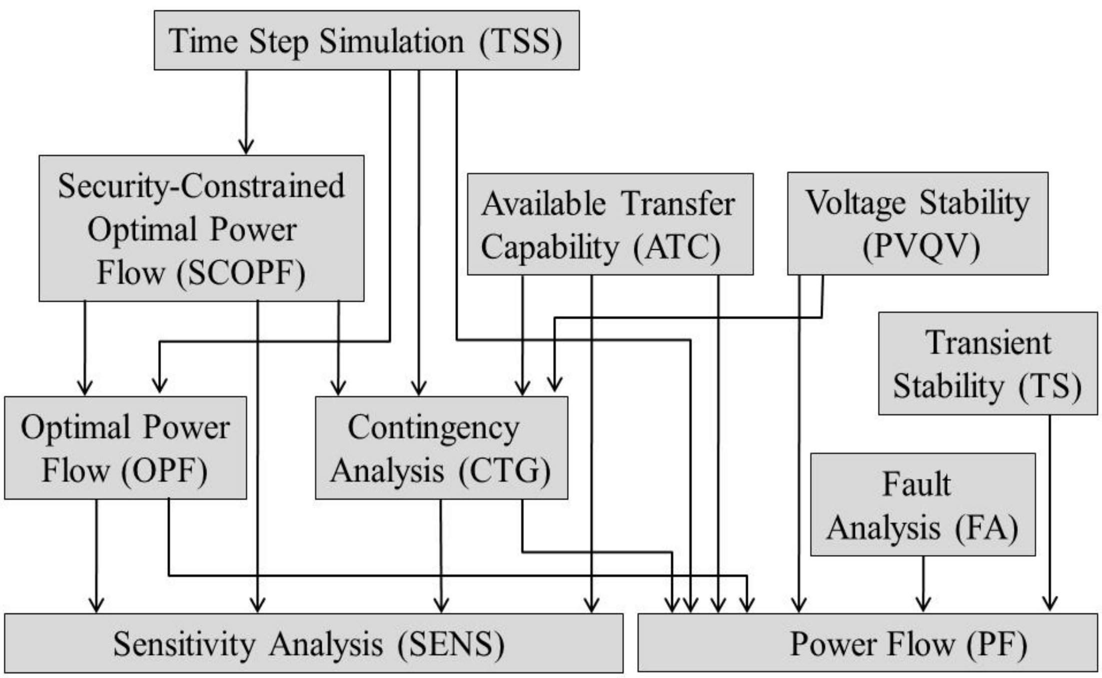

Figure 6.8: Example of application integration

Using this application integration strategy, the algorithms described here have been incorporated in commercial PowerWorld Corporation software suite. The tool is capable of solving very large ISO real-time models using the consolidation/de-consolidation approach. Comprehensive testing of the unified network applications was developed using full-topology models of two ISOs systems described in Table 6.1, for the case of power flow and contingency analysis.

Table 6.1: Properties of Sample ISO Models

Property	System A	System B
Number of nodes	10,437	60,257
Number of branches	11,668	67,295
Breakers	9,074	52,210
Node Groups (buses)	2,033	13,076

The full-topology models were obtained by developing queries to EMS databases. Both systems included modeling of breakers only, although the unified applications support modeling of arbitrary numbers of disconnects as well. The models tested corresponded to the exact network models used by the control center EMS. The base case power flow solutions obtained were corroborated with the EMS power flow solution to negligible error. Interoperability testing was achieved with respect to EMS security assessment runs involving a detail comparison of results from about 1,200 AC contingencies for each model. Again, the differences were negligible. About 12% of the contingencies tested included bus mergers or bus splits. This corresponds to the percentage of contingencies which cannot be studied using planning models. Further comparison of DC power flow and DC contingency analysis resulted in negligible errors as well.

The possibility of using a familiar planning application to perform advanced analysis in a real-time operation environment is very appealing and presents advantages that may prove to be of significant service. On the other hand, having a real-time snapshot model available off-line allows planners to thoroughly explore the real-time case. Eventually, seamless exchange of cases and information from real-time to planning becomes possible under the proposed unified framework. A variety of emerging analytics needs in the hour-ahead to day-ahead timeframe will greatly benefit from that capability.

6.5.1 Deployment Status

The unified network applications as described has been implemented within the control centers of several large utilities and ISOs. In North America these include ISO-New England (ISO-NE) and Bonneville Power Administration (BPA), while in Australia the transmission utility TransGrid has implemented them. Other companies, such as Tennessee Valley Authority (TVA), have used the full-topology models for use in visualization displays.

At ISO-NE, the unified model was implemented to perform Contingency Analysis, Available Transfer Capability, and PV Curve generator based on real-time system models. Prior to deployment of this software at ISO-NE, the process of calculating daily interface MW limits involved a full-time engineering staff position who modified the input data for a planning model to build a planning model of the power system each day. After creating this model, studies were then run to calculate limits. Building the planning model representation took several hours and this effort had to be repeated every day. It also involved a large amount of manual data entry which is always inherently error prone. Utilizing the full-topology methods has automated this process and the full calculation now takes a few minutes.

BPA has developed the ability to create full-topology models and performs Contingency Analysis, Available Transfer Capability, and PV Curve generation in real-time. Testing of this functionality is presently on-going at BPA. BPA has also incorporated PowerWorld's Transient Stability tool based on a full-topology model.

The Australian company TransGrid has been utilizing full-topology models for several years to build an operator training simulation environment. The operator training must include the full-topology model to be of use in training operators on switching actions. The training environment primarily utilizes the power flow solution, but contingency analysis has also been used.

TVA has implemented a visualization environment which uses the full topology model along with algorithms for determining transmission branch status. The status of circuit breakers is measured (or kept track of manually), but the status of transmission lines is not typically a measured quantity in an EMS system. In TVA's system, all of the statuses of circuit breakers are passed to the visualization environment, which is built using the full-topology model. From these breaker statuses the software can then automatically derive the status of transmission lines and breakers based on the topology at each end of the branch. The algorithm can also calculate flows through individual breakers in arbitrary meshed configurations.

6.6 Advantages for Operations and Planning

Having the full-topology model and the consolidated representation of the power system available in the same format, model, and GUI has numerous advantages:

1. The off-line tools can be directly used in the real-time production environment without requiring changes to the planning application core code or EMS modeling.
2. Seamless exchange of cases between real-time and planning environment would facilitate comparing the actual operating outcome with the planned operation to correct model discrepancies and enhance overall control center processes
3. The proposed architecture has the potential to greatly simplify maintenance and operation allowing data managers and engineers to deal with a single repository and a single format.

There is no need to understand multiple models with diverse data structures that should represent the same physical system.

4. A unified set of applications and graphical user interface (GUI) can be presented to operators, supervisors, and planning engineers.
5. Powerful visualization and analytics tools available in the off-line environment can be used for real-time operations, thus enhancing situational awareness.
6. Unification of power system models would help improve the current operating practices increasing the ability to predict insecure conditions of the system and making better tools available to identify economic opportunities in the electricity market.
7. Unification of control center technologies will result in savings in time and cost of personnel training.

Unification of power system network solutions can be understood at three levels: format, model and application. The Common Information Model, CIM RDF format requires translation from EMS proprietary formats or from planning standard formats to CIM. Hence CIM RDF does not contribute significantly to the unification at the format level. The proposed unified power flow does not require a new format and can read and write CIM if needed.

At the model level, CIM is an important step in the unifying model description because CIM proposes a model at the physical (full-topology) level. Existing products that attempt to integrate operations and planning models though continue to be based on the two-model paradigm. If based on CIM, they make use of the Topological Node Class to form the buses needed to generate the planning case that can be solved in traditional planning applications. Our proposed method uses a single model hence avoiding model conversion. This single model can be CIM-based.

The proposed unified power flow method is the first software capable of unifying solutions at the application level, with the advantages described here. Existing planning applications can only handle a few breakers as low impedance branches or cannot handle switching devices altogether. The proposed method achieves seamless unification at the format, model, and application levels.

Operations models are descriptive and they provide a more accurate representation of the physical world. As described through this report, bus-branch cases are simplified models maintained by the industry for historical reasons. If continued to being used, the two-model paradigm will perpetuate formidable challenges associated with maintaining, comparing and using formats, models and applications even within a single electric utility. Seamless data integration required to address the new challenges will be very difficult in a two-model paradigm. The proposed unified power flow application can be a catalyzer to demonstrate to the industry that storing the model of the network in a bus-branch based model was a good idea years ago, but that there is no longer a need for it. We predict that in the future the modeling of power systems will be based on full-topology models and bus-branch cases will be ultimately abandoned.

It is important to mention that two-model paradigm is also used throughout the distribution systems community. The proposed method could be extended to distribution systems and microgrids to address emerging network modeling and solution requirements.

6.7 Conclusions

Addressing emerging issues at the intersection of power system operations and planning and removing barriers for seamless data exchange requires a unified network application paradigm. This section describes unified network applications for operations and planning that achieve not only model unification, but also application unification. This enables numerous desirable use cases including: ability to transparently solve either planning or operations models with the same software tool, utilization of existing off-line tools in real-time, seamless exchange of models between real-time and planning, centralized network model development, correction of model discrepancies, and reduction of cost and effort in operator training and software maintenance.

Network application unification is enabled by a novel single-model topology processing algorithm, which handles device terminal pointers dynamically. The algorithm uses a single class node class, is able to efficiently solve switching device topologies of arbitrary complexity, and it can run in full or incremental mode.

The proposed unified applications were implemented without requiring a new format or changes to existing core power flow solvers, and achieved interoperability at the level of massive contingency analysis using actual ISO models.

7 Seamless Information Architecture

7.1 Introduction

Architecture specifies rules about how to build systems, usually with the purpose of assuring certain long-term functional and performance goals of the system. EMS architecture is used to deliver system designs such that the life cycle cost is minimized, the system can be modified quickly to accommodate changing business requirements, and competitive innovation is enabled. *Information Architecture* is concerned with achieving interoperability of software components developed by different sources, and with achieving a model-driven design for data that allows new data requirements to be incorporated into the system at minimal cost.

System components require some data produced by another component and produces data that is used by one or more other components. Standard interface agreements for data exchange are required. System components from various vendors must be able to be integrated. We say that the exchanged data must be *Public Data*. Specifically, this means that the data is legally open and well-supported, and that it has documented interfaces. The EMS information architecture specifies how public data is handled. The information architecture considers the following elements:

1. The methodology for defining the structure of shared public data sets.

2. The standard interface mechanisms by which business components produce either full or incremental updates of public data sets.

3. The standard interface mechanisms by which business components access public data sets and consume full or incremental updates.

We propose an information architecture driven by CIM and the use of a unified model as described in Section 6. The model includes a master specification of the power systems, which includes both the infrastructure model (a cyber-physical system), and the business model. Based on this model, the information architecture specifies how information produced by one application component is made available others. There are fundamentally two modes: on-demand, and sharable via persistent public data. EMS systems will demand both types. EMS systems will also have other requirements:

a) Data partitioning: The EMS has high performance requirements. For instance, the availability of data from a network application to the user interfaces should be within one second. The unified model developed can be utilized as a basis that will support a persistent data model. Data partitioning allows specifying that a solution was obtained using a new system physical configuration (new substation), and not topological changes handled in a persistent manner by the unified model.

b) Contexts: The EMS supports a variety of operational and business processes. These processes conduct analysis in a variety of different “contexts”. For example, the real-time network state, the minute-ahead wind profile scenario, the day-ahead market, etc. These processes will utilize the same services and thus produce the same types of public data sets, but it is critical to know the context that produced each instance of a data set, and this must be part of the public data architecture.

c) Events: It is often practical to update individual items within the data set (e.g., SCADA data updated by exception). Events are able to trigger processing activity (e.g., alarm system). The information architecture must support incremental change and event handling.

d) Historical and Audit Archiving: It is increasingly important that EMS and Market systems leave a complete, auditable trail of activity including versioning. This historical record should support accurate reconstruction of the state of the system and of all actions taken on the part of users.

7.1.1 Terminology

The following terms are required in order to describe the information architecture:

a) *Common Information Mode. (CIM)* is a metadata document specifying an information model from which public data sets are defined as sub-models. The model has specific physical, cyber, and business semantics.

b) *Public Data Set (PDS).* An instance data, subset of the CIM, that is produced by one component and consumed by one or more other components. The content of each pds is specified by a metadata document.

c) *Interface Profile.* A document that specifies how a public data set creates an interface among components.

d) *Public Data Service* is the (cyber) infrastructure that manages public data sets. This infrastructure eliminates direct communication between producer and consumer components.

e) *Producer.* A business component that adds, modifies, deletes the data in a public data set.

f) *Consumer.* A business component that reads the data in a public data set.

g) *Context.* An activity or process that produces one or more public data set instances. Within a context, all instances of a given PDS specification are considered different versions of the same thing – usually representing different points in time.

h) *Event.* All or any part of an incremental update that is made available as a notification to subscribers.

7.2 Common Information Model (CIM)

The CIM model was originally proposed by EPRI in the late 90's as a method for various EMS vendors to be able to use each other's information for applications. Currently all the major EMS vendors as well as some planning vendors support CIM. CIM is an information model that describes the state of the real world at one point in time. Time is covered in the information architecture by stipulating how CIM state views are versioned through time.

Because CIM utilizes a state-oriented approach suitable for real-time control. The state of the system at any point in time is presented in state-oriented PDS. The progress of the state through time is accessible through incremental updates to public data sets. Reconstruction of states is supported by versioning and archiving of public data sets. EMS PDS are produced and maintained by one service within a system. Its public content is a subset of what is defined in the model. PDS refers both to a specification of data content and to instances of actual data output that conform to the content specification.

7.3 Data Management

In this section we describe at the high level how PDS are used and how services implement the information architecture. First we begin by describing the *context* and how it is related to the PDS. The context is defined by the business process. Every service within the business process is conducted within a context which defines how its public data set. The business process orchestration sets the context. PDS associated with context require setting versions, which describe how the PDS instances change over time. Public data flows from a producer via a data service to consumers using the following sequence: a) The PDS is under control of the producer until the producer declares the version complete, b) It then passes into the control of the data service to distribute, and c) Consumers acquire the data and process it, but it does not affect the persisted data.

The following rules are observed:

a) A single writer per context is the producer for a PDS.

b) The producer encloses all changes within transactions, with each transaction producing a new version of the PDS.

c) Consumers do not see any results until the transaction is closed, and multiple consumers per version are allowed.

d) It is critical to maintain referential integrity in the database. This is achieved by enforcing that PDS have references to other public data sets and references used by diverse applications may be correlated within a component such as a naming service. Identifiers are utilized for maintaining referential integrity.

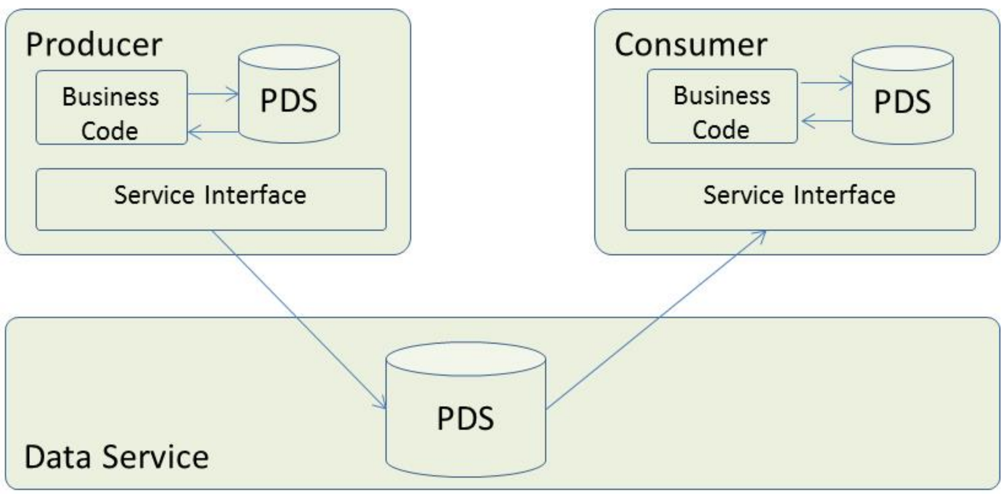

Figure 7.1: Data management in the context

PDSs divide the CIM into sub-models that are created by producers. A producer always packages a transaction, which is the set of changes from one version of a PDS to the next. The data is not released to consumers until the transaction is declared complete by the producer. The producer builds the transaction using add, modify, delete operations in the DBMS. A transaction can be seen as a set of deltas from the previous, where the special case is a complete version of the public data set. This leads to two views of a public data set from the point of view of the data service: a) The *Incremental View* is the set of changes, and b) The *State View* is the complete PDS instance for a given context.

If a producer is interrupted having provided some data but failed to close the transaction, none of the data is used. In failover schemes, a secondary application taking over for a primary would normally start from the latest completed input sets.

The PDS producer controls the transactional nature.

- A *Start Transaction* operation marks the beginning of a set of changes that make up a transaction.
- A *Full/Incremental* operation determines whether the transaction will completely specify the next version.
- A *Close Transaction* operation shall be supported that marks the end of a transaction and signals that the resulting state is a new version ready for consumption.
- A *Add/Delete/Modify operations changes the public data set contents.*

An *Event Consumer* operates directly from the incremental view of the transactions and is often not interested in context state as a whole. Events are used to trigger activity in an event driven architecture or state machine guided processes.

7.4 History and Time

A context is used to collect public data sets that represent the state of a business process for at a given time. As the business process takes place, new versions of PDS within the context are created. Context activity is based on the latest versions of all the public data sets included in the context, and a complete historical record is achieved if all versions of the public data sets are archived. Time is recorded when changes of state take place. There are important business processes that simulating a different time, and that must have their own context clock. Examples of this are look-ahead contingency analysis, wind forecasting, or day-ahead market applications.

Saving all PDS versions would preserve a complete record of activity, but at a cost of storage and data processing. Some use cases and critical information (energy metering) may require such level of storage. There are other use cases for historical data in which storing all the versions is impractical. The following are common guidelines for storage.

- A specific analog recording interface with the bandwidth to keep up with large amounts of real-time data, for instance for PMU data.
- A generic save/retrieve interface for PDS archives (save cases) supported by public data management.
- A generic save/retrieve interface for incremental update events to a historical relational data base supported by public data management.
- A state-based supported query.
- A query for future computed states.

7.5 Information Architecture Implementation

An information architecture would provide guidelines for organizations to implement conforming systems. The basis of the information architecture is a common information model, not necessarily the CIM, but some common model. We will call this aCIM.

The advantage of aCIM is the definition of interfaces. Components using aCIM will define interfaces that can be tested against the same model, and hence the components can be expected to interact with one another without modification. Ideally, all aCIM modeling will be done with enough information to guarantee interoperability, and all changes to aCIM would take the form of extensions only, as opposed to modifications. Modifications destroy the semantic integrity.

The ability for vendors to develop plug-and-play applications requires:

- *Data Interoperability* addressed by information architecture, and achieved when components produce and consume only standardized public data sets via standard interfaces.
- *Integration Interoperability* integrates a component within its system infrastructure, dealing with issues like message buses, error logging, high availability schemes, business process invocation, etc.
- Temporal Interoperability integrates application that work in diverse contexts in time, e.g., planning or operations.

We say that a producer is conforming with the information architecture if it uses standard services to update its public data sets or if it produces a standard XML document representing the next version of its PDS. It must be possible to create a new version of any PDS context by providing an XML document containing the full content or by providing an XML document containing the incremental changes from the previous version.

We say that a consumer is conforming with the information architecture if uses a starndard services to access PDS or if it reads standard XML document representing the next version of PDS. A service must accept an XML document containing the full contents of any instance of a PDS and must accept an XML document representing the differences between one version and the next version for any context of a PDS.

We say that a service is in conformance with the information architecture if it supports standards services for access and update of public data sets and supports input and output of standard (incremental or full) XML document representing the next version of PDS. A service must produce an XML document containing the full contents of any instance of a public data set or the differences between one version and the next version for any context of a PDS.

8 Seamless Application Architecture

8.1 Introduction

Market Management Systems (MMS) and Energy Management Systems (EMS) are composed of complex functions provided by multiple vendors and multiple phased development projects. The recognized need for efficiently integrating these functions, while supporting critical functions has placed a very high priority on integrability and interoperability. Architecture must facilitate integration. The system will have integration requirements that need to be addressed from the beginning.

The Architecture can be based on the concept of a Service Oriented Architecture (SOA), which can be summarized as an architectural style that guides all aspects of creating and using business processes, packaged as services, throughout their lifecycle. SOA represents a model in which functionality is decomposed into distinct units (services), which can be combined together and reused to create business applications. SOA supports both stateless and state services compatible with the information architecture. SOA allows for interoperable specification, testing, auditing, and replacement of the service. The architecture must support performance, security, scalability, or other service requirements and makes the best compromises in terms of complexity, reusability, and consistency.

8.2 Functional Description

The architecture considers the following design principles:

e) *Standardized interfaces*. Service interfaces are formally declared and known. A web-services definition language (WSDL) can be used to provide specific service contract definitions that enable clear and formal validation of the interface.

f) *Loose coupling*: Services are not dependent on internal interfaces or other dependencies beyond the standard interfaces. "Best of breed" components can be integrated into a system which does not conform to the internal architecture of the components.

g) *Abstraction*. Services are abstracted from such issues as technology choice and quality of service. The choice or modification of such abstracted qualities is possibly without change to the service components.

h) ***Reusability*****.** Services are reusable in different business contexts.

i) *Autonomy.* A service should have control of its environment (such as the hardware and its resource usage).

j) *Discoverability*. Services can be found at design time and run time such that existing functions are reusable. aCIM and the service contracts help make services understandable.

k) *Composability*. Services are well behaved and can be composed and orchestrated in new and creative ways to achieve business value

l) *Manageability*. Services are started and initialized by a well-defined interface. This is part of management of the system and provides for efficient and standard control of the system.

m) *Testability*. Services should be testable independent of the complete system. Such testing is required for quality control in deployment of new services or new versions. This also improves development efficiency and debugging of potential implementation or design defects.

The Architecture defines the working terms of *Function*, *Sub-function*, and *Abstract Components*. A function is a high level business descriptor that defines a top-level area of an business process. Sub-functions are discreet logical groupings of business functionality that occur within a function. Abstract components are the logical grouping of processes to support a sub-function. To have a forward market, the scheduling, real-time, contingency, and LMP abstract components are required. An application provider will provide applications that meet the functionality of one or more abstract components. Abstract components are logically organized into sub-functions and functions. The life-cycle of the service is to be managed through the Integration Layer. An example life-cycle is shown below in Figure 8.1.

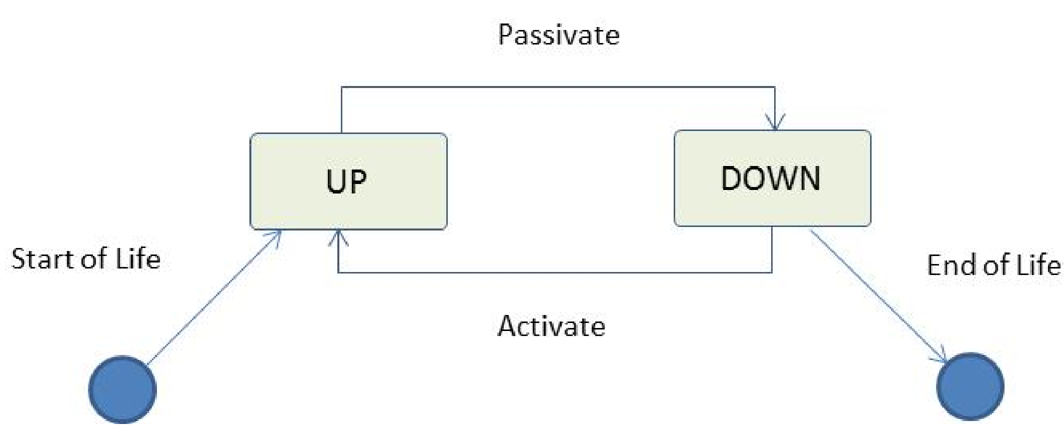

Figure 8.1: Example service life-cycle

8.3 The Interface Architecture

The architecture described in this section borrows from reference ITC-EAS and follows a SOA that is based upon the architectures of both the World Wide Web Consortium Web Services Architecture (W3WSA) and supporting standards including WSDL20 and the IEC 61968 part 1 (IEC61968-1) architecture framework. IEC61968-1 specified two logical adapters between a Component and the Middleware Services, the Component Adapter and the Middleware Adapter.

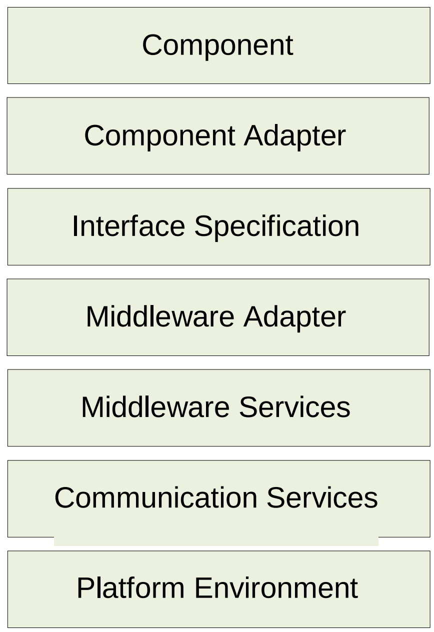

Figure 8.2: IEC 61968

All interactions between an application and an adapter shall be fully described/documented in human readable form (Adobe PDF, HTML, or Microsoft Word) using a formal definition language (e.g., WSDL, DDL). Included in the documentation will be definitions for all data elements. A compliant application is any piece of software that properly implements these standards as an integral part of the application. In order to achieve compliance with these standards a non-compliant application shall utilize an adapter.

Section 5.2 of IEC61968-1, states that for components that already are profile-compliant, the component adapter is not necessary. When a non-compliant component is used in the services-environment, at least one component adapter is present for that component to make it profile-compliant. It can also be the case that more than one component adapter is used to make a single component compliant with the services (for example one component adapter for each IEC 61968 series interface specification). For those components that are non-compliant, each component adapter is custom-made for that specific component because it depends heavily on the architecture and implementation of the component. A component also runs in a specific hardware/operating system (HW/OS) environment. Therefore the triple set component, (set of) component adapter(s) and HW/OS are fully dependent on each other. This is illustrated in Figure 8.3.

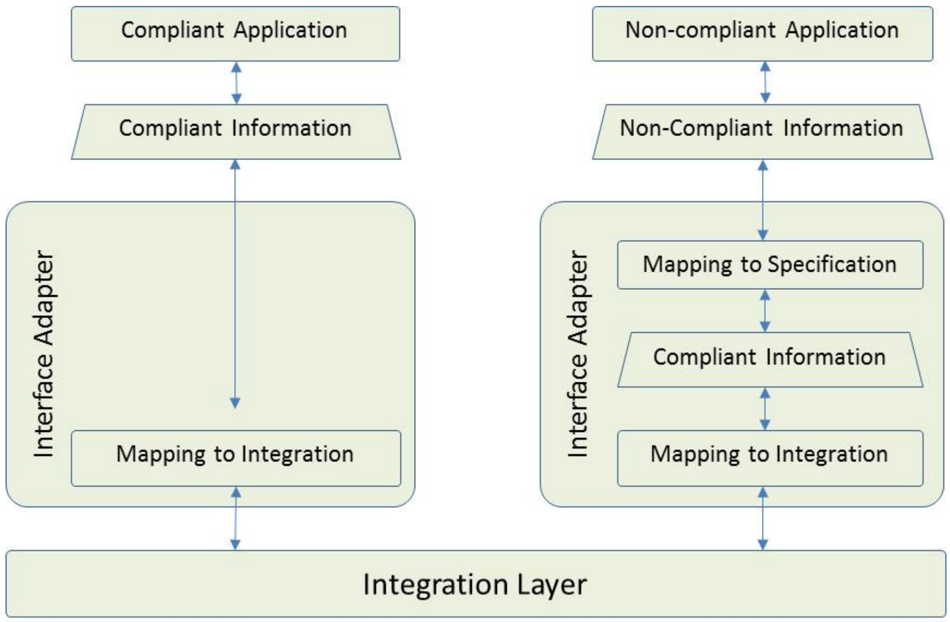

Figure 8.3: Compliant and non-compliant application integration

Applications may meet compliance one of two ways. One way is to natively support the standards within an application. Another way to achieve compliance is to "wrap" an application. Wrapping an application is the process where the application's interaction with services is provided by a third party piece of software typically called an adapter. The adapter typically uses one protocol on the application side such as file system, JDBC, ODBC, and JMS and has the ability to speak multiple protocols on the middleware side such as HTTP, JMS, MQ, and SOAP. Wrapping an application extends its flexibility but may decrease its reliability or performance since it is now dependent on an external piece of software for communicating with the enterprise. However, indiscriminate wrapping of applications can create application fossilization –the tendency to create black box application that are not updated and enhanced in time.

8.4 Integration Layer

The Architecture describes the abstract functional characteristics that enable services to perform inter-application interaction via an integration layer. The integration layer should be viewed as a set of technologies used to carry out inter-application communication. The integration interface should be viewed as a liaison that makes it possible for a service to send/receive messages through an integration layer, regardless of the specific technologies employed within the integration layer. Integration interfaces shall strive to support the commonly available integration layer technologies. Possible examples include:

- Message brokers
- Message Oriented Middleware (MOM)
- Hypertext Transfer Protocol (HTTP/HTTPS)
- Message-Queuing Middleware (MQM)
- Enterprise Service Bus (ESB)
- Business Process Management (BPM) Servers
- Relational Databases
- Object Request Brokers (ORBs).

8.5 Life-cycle Management

Application life-cycle management is a critical aspect of reducing total system cost. A service typically starts as from the business needs in terms of a requirements and goes through a development and testing and debugging stage before deployment. The integration must support the partitioning and isolation of sets of related services used to perform testing and debugging. The deployment processes must allow for deployment of specific versions of services into specific target environments and ideally audit and monitor such activities. Retirement of a service instance should be graceful and allow for clients to be notified appropriately.

The ability to abstract service components allows for and fully anticipates that service requirements will change. It should be possible to modify interface definitions, the semantic meaning of message payloads, and the quality of service provided as business requirements change during the life-cycle of a service. It is this same abstraction that allows for specific configuration of interfaces to provide high speed interfaces or transport mechanisms without the need for special service interface definitions, since as time progresses, the selection of functions requiring high-speed may shift in either direction depending upon technology advances, increased requirements, or increased cost pressures.

9 Seamless Computational Architecture

9.1 Main Features

9.1.1 Interoperability, data formats, and component models

Few power system analysis software applications today are interoperable, that is, they cannot easily be interfaced or ported. They cannot be easily used as part of other systems except as a component of the customized system on which it was built. Current software applications use inconsistent models and formats, contributing to the difficulty of migrating applications between platforms or to extend the analytical capabilities. There are a number of different formats for power system data used in studies. A significant portion of these formats are proprietary and based on non-unified models. For instance, in the planning power flow arena there is a de-facto standard provided by PSSE RAW format. However, description of this format, and code to read and write it, are not directly available to non-PSSE users. The IEEE Common format is used to a lesser extent. The Common Information Model (CIM) represents an effort in the direction of unifying the power system network models. However most vendors have created translators to CIM rather than develop new CIM-native tools. In addition, CIM is not comprehensive for power system analysis, with many domains and areas not covered by the standard. Finally, the current Resource Description Framework (RDF) implementation of CIM, a metadata model for information exchange over the internet, has drawbacks such as unnecessarily increased model size, which inhibits the model exchange objective. Nonetheless, CIM is the most promising approach to achieving this available today. Unless another approach is embraced, a significant challenge will be expanding and completing CIM so that vendor-neutral standard data formats can be made available.

9.1.2 Human interface

A significant portion of the applications used in the industry are still based on text-type result and command prompt interaction. They have not been updated with modern graphical user interface (GUI). They also do not provide a flexible mechanism to exchange outputs with other applications. Few applications provide easy and well-documented application programming interfaces (APIs) and automation interfaces. There are various graduations in terms of capabilities and usability which could be built into the human interface. Handling large input datasets and filtering bad data is essential. An ultimate objective would be to develop a master GUI that can manipulate and visualize results of all seamless applications across all time domains, providing the ability to both *see* the system and *see into* the system.

9.1.3 Analysis initiation

Current applications require a steep learning curve for analysts to overcome, and even after mastering an application, significant effort is required to prepare cases, to import and export data, and to perform various manual actions. Such human effort should not be needed in order to initiate analysis. One characteristic of a seamless analytics engine is the ability of the user to concentrate on the analytics and not on the mechanics of running the software or the development of workarounds in using the software for unique applications.

9.1.4 Post-processing

Analysis results are often data-intensive, stored in very large files. They must be post-processed in various ways using data mining methods, extracting knowledge contained in them to enable efficient human assimilation of that knowledge. A flexible suite of processing functions is needed, which can be easily accessed and used to process results of all applications.

9.1.5 Temporal scales

Emerging power system analysis requires addressing behavior at temporal scales that have not been studied in the past. Examples are PMU, wind variability, sub-hour scheduling, and shorter-term forecasting. A significant portion of emerging business processes are concentrated in operations planning from a few minutes to several hours. Current power system planning and operations are almost completely separate from the point of view of models, formats and applications used. Therefore, a major barrier to seamless power system analytics is to break the temporal scale divisions so that power system applications provide solutions to analytical needs at expanded temporal scales.

9.1.6 Validation

An important need for power system analysis is validation of simulation results. PMUs and high-bandwidth communication channels create opportunities today. The seamless power system analytics function may be able to use make use of these opportunities to develop validation capabilities for power system analysis applications.

9.1.7 Encoded intelligence for selecting software/hardware combination

Enhanced computational speed via new algorithms and high-performance computing is a high priority for the seamless analytics engine. The vast majority of existing software is not multi-threaded and is not suited for parallel or cloud computing. Powerful but inexpensive computational resources are available today, such as dual or quad core computers, but these are not well-used or if used are not fully exploited. For a given computing function, the most effective algorithm is often dependent on the type of computing platform. There is need to enable fast identification of the optimal algorithm/hardware configuration to implement a particular computing function. An essential feature of the proposed seamless analytics will be the ability to suggest, in response to user-requested assessments (e.g., power flow) and user-specified characterizations of those assessments (e.g., speed, accuracy), appropriate selections of software and hardware to perform the assessment. Designing, developing and encoding the intelligence to make this selection is a significant engineering challenge. The choice of software will be in terms of application and numerical algorithm for supporting the application. Summaries of representative applications and algorithms are provided in Section 9.4.

9.1.8 Capabilities of the system analyst – applications and numerical methods

We conceive of the *system analyst* as an individual who utilizes applications to generate information on which various power system decisions are based but who also performs high-level development by integrating various numerical algorithms with appropriate hardware to accomplish the purpose at hand. The typical power system engineer today has background sufficient to select and use applications; however, many of them do not have background sufficient to select appropriate numerical algorithms or integrate them with appropriate hardware. Therefore, seamless power system analytics may have functionality that is underused unless skills of the system analyst are sufficiently enhanced through education and training.

9.1.9 Testing and certifying code base

The code base will need periodic testing and certification. The difficulty of this task increases with the complexity of functionality offered by the code. It will be economically justifiable to develop and embed self-testing facilities within the software system.

9.1.10 Critical infrastructure protection standards

A desirable strength of the seamless power system analytics is an ability to provide analytic services across the organizational enterprise. However, the broader is its accessibility, the more likely it is exposed to violation of critical infrastructure protection standards (CIPS). There may be a need to balance accessibility and CIPS compliance.

9.2 Computational Architecture Requirements

The vision described in this document of a seamless power system analytics capability requires an overarching architecture. This architecture, once developed, should be considered the computational foundation for the entire industry. In this section, we provide an initial view to illustrate some possibilities; however, identifying options for this architecture will require significant additional research. There are various types of computing hardware available; a broad classification include sequential machines, multi-core shared memory machines, high-performance distributed memory machines, and GPUs (graphical processing units). The choice of software architecture will be influenced by the hardware architectures available.

Several developments in computing concepts and software frameworks present opportunities to develop a seamless, interoperable architecture for power system analytics, including layered models, service-oriented architectures (SOA), cloud computing, and Web 2.0. These software paradigms allow some merging of the traditional roles of the application user and the software developer. We describe the first two of these in what follows.

9.2.1 Layered model

Figure 9.1: Layered model illustrates a layered model paradigm software system. The layered model allows us to abstract the functionality of the lower layers from the higher modeling and application layers. There exists a computation layer, a solver or algorithm layer, a data layer and an application layer. The software frameworks existing in the industry can be applied at various layers providing an abstraction, which enables interoperability. We describe each layer in what follows.

- The *computation layer* consists of a computing framework, which can be single-processor, parallel, distributed, or cloud computing-based, and which drives computation hardware including possibly a network and multiple asynchronous nodes.
- The *solver layer* includes an analytics engine which selects and integrates one or more algorithm classes (e.g., linear solutions, nonlinear solutions, integrators, optimizers) to address a computing need, and within each algorithm class a specific numerical solver based on the attributes of the particular application.
- The *data layer* includes both the data structures internal to the application as well as external data connections and repositories. The external part may be part of interfaces to distributed algorithms.
- The *application layer* includes the user interface modules as well as automation engine which provide APIs, data interface, analytics interface, and process orchestration.

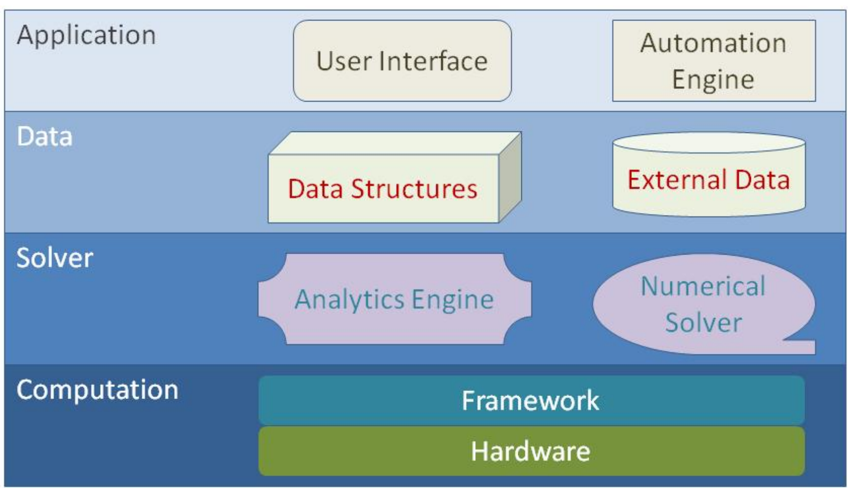

Figure 9.1: Layered model

Achieving seamless power system analytics requires both existing and new applications to operate under a similar paradigm and to be equipped with the modules and functionality described in Figure 9.1. We describe a few attributes of the various layers:

a) If an existing application cannot use multi-processor power, the computational framework and possibly the numerical solver needs to be modified.

b) If a current tool does not provide advanced analytics, an analytics engine needs to be developed and integrated with the data structures, the numerical solver, and the computation framework.

c) If an arbitrary application, e.g., fault location requires, but cannot obtain data from external databases, a database connector and the corresponding data handling routines must be developed or enhanced.

d) Finally, if the functions of an application cannot be invoked by others in an easy manner, automation engines need to be coded to allow such interactions, and the corresponding process orchestrator needs to be developed.

9.2.2 SOA model

An SOA-based collaborative decision model is illustrated in Figure 9.2: SOA-based collaborative decision model that would facilitate these kinds of needs. This model is built around three separate layers: decision processes, informational services, and external services. We describe each of these in what follows.

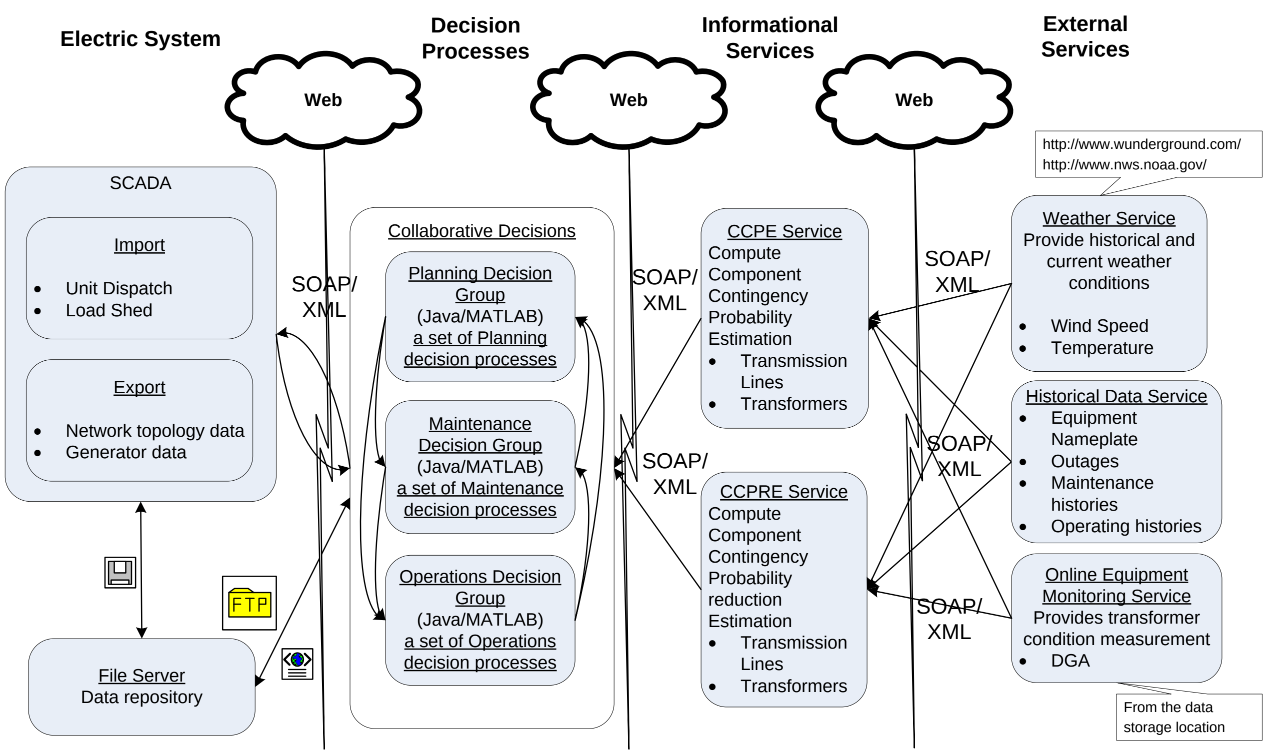

Figure 9.2: SOA-based collaborative decision model

1. External services: These assimilate and aggregate raw data from technologically diverse information sources distributed across the grid. These raw data do not directly interface with the decision algorithms and require additional data transformation. These services include

the *Weather Service* that provides wind speed and temperature, the *Historical Data Service* that warehouses historical data, and the *Online Monitoring Service* that provides online equipment condition measurements (e.g., transformer dissolved gas in oil analysis)

2. Informational services: These transform data from external services into metrics that can directly interface with decision algorithms. Representative examples include the CCPE and CCPRE services which compute component contingency probability and component contingency probability reduction from maintenance, respectively, for use by the decision processes.
3. Decision processes: These provide the central component of the decision making cycle, interacting with the OTS, informational services, and other decision processes to retrieve data for the decision algorithm, compute, and deliver decisions to the requesting entity. In this particular collaborative decision design, there are three major decision groups: planning, maintenance, and operations. Each decision group may have multiple sub decision processes. At the heart of each decision process is a master optimization routine which calls slave decision routines in a multi-level nested architecture. The strengths of SOA are utilized to support the communication needs of this architecture. Benders decomposition is used to support the algorithmic needs of this architecture.

All the components in Figure 9.2 are built as Web services implemented using Java 2 Enterprise Edition Web services and the JAVA programming language. They are then deployed on Apache Tomcat Web server with Apache Axis2 Web service container. The Web services interact with each other in the form of standard XML-based SOAP messages.

9.3 Barriers to Seamless Analytics

9.3.1 Financial commitment

It is likely that the time to build a complete system is in the range of a decade. After identifying a complete and realistic cost estimate, cost-benefit case, and high-level project schedule, obtaining buy-in from funding organizations to pursue the project will be challenging. It may be useful to pursue participation in stages: government, then utilities, and then vendors.

9.3.2 Institutional resistance

In developing seamless power system analytics, there are legacy codes for power system analysis which will have to be enhanced or possibly re-developed. This will be costly, and consideration of the necessary expenditures will result in resistance in favor of less costly alternatives, including the option of continuing to use the same legacy codes. Vendors will not make substantive changes in their software systems without significant commitment of funds from customers and/or government. Another source of resistance results from the fact that most legacy codes have been heavily used, and as a result, they are trusted. Re-developed codes will not initially elicit that same degree of trust, and as a result, users may migrate slowly, and knowledge of this effect will inhibit investment in the project.

9.3.3 Prioritizing tool development

With limited financial resources, re-development of existing functionality and initial development of new functionality cannot all be done simultaneously. The community will need to go through a process of prioritizing tool development. This process will need to be carefully developed and managed, as any given prioritization will benefit some organizations more than others. A particular issue here will be the existence of some tools that have a relatively small user-base due to the specialty of their function but are essential for some organizations, Hydro-thermal coordination programs are an example of such a tool.

9.3.4 Deployment of software engineering technologies

The development of seamless power system analytics will require advanced expertise in software engineering. Power system engineers are typically not exposed during their education to software engineering methods, although some pick up some related skills on the job. Designing, deploying, and maintaining systems based on state-of-the-art software engineering may necessitate a financial and educational commitment within the power system engineering community.

9.4 New Analytics Applications

9.4.1 Converting between bus-branch and node-breaker models

The models used within planning are normally developed independent of the models used within the energy management system (EMS) of operations. Whereas the planning model is bus-branch, the EMS models are node-breaker or are at least developed from a node-breaker model through the topology processor. The ability to freely transfer back and forth between bus-branch models and node-breaker models would provide benefits to both operational and planning analyses. The node-breaker model is especially important if protection systems are modeled.

9.4.2 Protection system modeling

Many power system analysis applications in planning and operations do not model, or do not model very well protection systems. This often results in significant misinterpretation of analysis results. To capture the effect of protection within power system operations and planning analysis software, models for each type of relay will need to be developed so that it can generically interface with power system simulation software.

9.4.3 Determining right-sized models

Many analyses today are performed using models of inappropriate size, either too large or too small, because of the difficulty in reducing or expanding an existing model to the right size. Key to almost all modeling needs is a first step assessment of the right model sized and a second step development of that model.

9.4.4 Distribution system needs

Emerging distribution system needs are driven by the consumer and its responsiveness to control signals, electric vehicle interactions, and distribution-connected storage and resources. To facilitate this, a great deal of new control and communication will be needed, and its design and implementation will be challenging. In this subsection, we focus on the analytic needs of addressing these issues [43].

Key analytical tools that should be made available include the traditional ones of power flow, fault current analysis and protective relay coordination, fault detection and location, reliability assessment, power quality evaluation, and load forecasting. Of these, the interconnection of new types of loads and resources will motivate significant refinement and extension of fault current analysis and protective relay coordination. New tools that will be necessary for distribution system analysis include distributed resource forecasting and dynamic analysis. All tools will need to be extended to allow for new types of loads and resources.

9.4.5 System study tools to perform stochastic analysis in any time domain

There exists uncertainty in analyses performed in operations, operations planning, and long-term planning for which analysis is significantly strengthened when those uncertainties are addressed. We have identified in subsequent subsections (operations, operations planning, and long-term planning and design) applications which are needed in the associated time from that require handling of uncertainty. These applications are (a) risk-based security assessment (operations); (b) short-term stochastic scheduling (operations planning); (c) uncertainty in planning (long-term planning). There is a need for a high level "uncertainty assessment module" which can be applied to perform stochastic analysis in any time frame.

9.4.6 Market applications

Today's electricity markets depend heavily on use of two computational tools: the security constrained economic dispatch (SCED) for the real-time market, and the security-constrained unit commitment (SCUC) for the day-ahead market. Although these two tools are relatively mature, there are a number of further developments necessary. Reference [44] summarizes many of these needs, among which some of the more significant ones are:

- Modeling of uncertainty
- Modeling of sub-hour optimization in SCUC
- Detailed modeling of emerging reserve requirements
- Modeling combined-cycle generators;
- Modeling dispatchable load;

- Modeling flexibility in “soft” resource limits (related to risk-based security assessment, below);
- Including AC power flow representation in SCUC
- Modeling reactive power pricing;
- Modeling flexible AC Transmission System (FACTS) devices

9.4.7 PMU-based monitoring and control

There is great interest today in using phasor measurements to monitor power system modal behavior. The extension to control will place greater emphasis on analysis speed. Signal processing methods are essential elements of the software necessary to support this functionality. This is a very wide and deep field which has matured in application areas which do not heavily overlap with power system engineering, and there are many signal processing methods which have not yet been explored for power system applications.

9.4.8 Dynamic state estimator

Availability of GPS synchronized measurements at substations makes it possible to extend monitoring to much shorter time scales. A dynamic state estimator would involve dynamic models of generators, loads, controllers, etc., not currently included in power system estimation. Polynomial model identification can be used to build the models and unspecified or suspect device or controller parameters. Auto-regressive time domain model-based algorithms with PMU data inputs can be used to derive the required dynamic state and parametric estimation.

9.4.9 Risk-based security assessment

The process of optimizing economics while managing risk associated with contingencies has been codified in the security constrained optimal power flow (SCOPF). This deterministic approach treats all selected contingencies in the same way: post-contingency violations activate binding constraints that prevent the violation, and contingencies resulting in no post-contingency violation activate no binding constraints and are therefore of no influence on the solution. The SCOPF approach suffers from a fundamental weakness in that *system* security is not quantified. Although its solutions are guaranteed to satisfy the imposed rules, those solutions may vary considerably in terms of actual system risk level. A method of managing real-time system security has been developed, and an industry prototype is being implemented.

9.4.10 Extended-term high consequence analysis

Analysis of cascading outages which have occurred in the past shows that a large percentage of them were initiated by very low probability events that caused the power system to subsequently deteriorate over periods of one to several hours. The 2003 Northeast US Blackout was of this sort. The operational paradigm in use today has no functionality to address such low probability high-consequence events. There is need, therefore, to develop new functionality for on-line applications which we refer to as high-speed extended-term time-domain simulator (HSET-

TDS). Such functionality would provide fast simulation of events for extended time periods up to several hours in order to capture the relatively slow degradation that is characteristic of some high-consequence scenarios. Development of HSET-TDS requires a re-evaluation of the basic components of time-domain simulation software, as illustrated in Figure 9.3. Modeling extensions, relative to traditional time-domain simulation, would necessarily include load and VG ramping, AGC, and good protection system models, in order to appropriately capture cascading events.

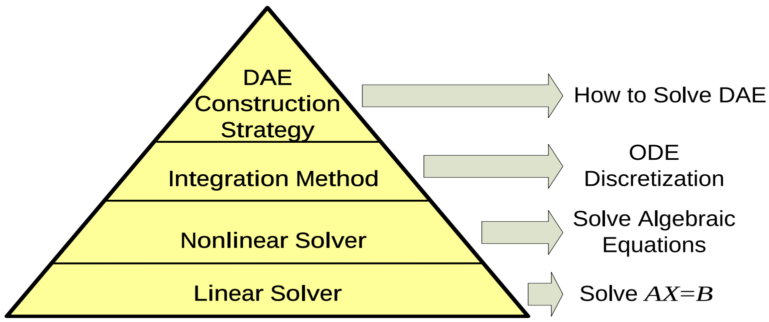

Figure 9.3: Basic components of time-domain simulation software

9.4.11 Look-ahead analytics

Today's security assessment is generally performed on the last state estimation result, which means that assessment is always done for a past condition rather than a future one. Significant benefit can be gained from performing look-ahead analysis for 15 minutes ahead, 1 hour ahead, and 4 hours ahead. To accomplish this, it is necessary to integrate the latest state estimation, day-ahead SCUC results, and forecasts of load, wind, and solar at the appropriate interval. We recognize that many ISOs have similar functionality in the form of the reliability assessment commitment (RAC). This functionality needs to be further developed to facilitate comprehensive security assessment for overloads, voltage, voltage stability, frequency performance, and oscillatory behavior.

9.4.12 Frequency performance assessment

The increase in penetration of variable generation (VG) technologies (solar and wind) across the nation has resulted in deterioration in control performance standards. This observation is based on CPS1 and CPS2 measurements reported by ISOs to NERC. This degradation can be mitigated through deployment of fast-ramping resources (generation, storage, demand), by controlling the VG, or by increasing control areas size. The ability to create a least-cost portfolio of mitigation measures requires a-priori assessment via software capable of simulating the effects of such portfolios. Standard time-domain simulation software typically does not model AGC and so is not appropriate for this task. Operator-training simulators typically model at the appropriate level, but are unwieldy for this purpose due to the fact that their intended function is training. New software is needed that will be efficiently available to the system analyst.

9.4.13 Short-term stochastic scheduling

Variable generation increases variability as well as uncertainty. Increased variability can be addressed by generation portfolios with higher ramping capabilities. For a given decision horizon (time between when the decision must be made and when it becomes effective), increased uncertainty requires unit commitment decisions which perform well under the increased range of possible conditions, i.e., the decisions must be more robust. This is particularly important for 4 to 48 hour-ahead unit commitment. Over the past 10 years, there has been significant maturation in methods to perform optimization under uncertainty, principally the methods referred to as stochastic optimization and robust optimization. Stochastic optimization identifies solutions which are optimal under a range of uncertainties, given the ability to take recourse for a given decision-future sequence. Robust optimization identifies solutions which are optimal and robust subject to a particular set of parameters which may vary within a certain range of conditions. More recent improvements have also added the ability to robust optimization methods to take recourse for a given decision-future space (continuous). These methods are applicable to power system problems in planning as well.

9.4.14 Communication dependencies

The power system is increasingly dependent on communication. It is therefore of interest to consider to what extent should traditional power system contingency assessment include communication failures. Most of the research on smart grid assumes a reliable and dependable communication network providing adequate bandwidth and latency support all the time. However, the need of a combined communications/power simulator has been already identified [45,46,47]. Reference [48] proposes a co-simulation method for power and communication systems using existing power system software (such as PSLF, Modelica’s SPOT) and communication network (such as NS2 or OPNET) simulators. Such co-simulators have the limitation that they do not translate all triggered events in the power system domain to the network domain and can work only with periodic events whose schedule is known beforehand. Researchers have also attempted to use IEEE HLA architecture to coordinate among different power, communications network, and control system simulators. But, this coordination is inefficient when simulating complicated scenarios due to overhead and amount of time and resources needed to make individual simulators compatible with HLA. The mutual interactions of power and communication networks are yet to be analyzed in detail.

In addition, NS2 and OPNET are network layer simulators, which assume a physical layer with consistent throughput and latency characteristics, omitting important aspects of physical layer design and operation. For example, a fiber optic or dedicated microwave link may be modeled as a communication system with consistent throughput and latency. Yet future grids would be built with a variety of communication technologies depending on the application. These networks cannot be used for most of the functionalities defined for smart grid due to their cost, deployment time, scalability and unsuitability for applications in transmission and distribution. A thorough understanding of what to expect for communication links with various characteristics is important in planning how a network can meet power system requirements. Simulations to test various communication links and their feasibility are essential.

9.4.15 Long-term load forecasting

Deployment of distributed energy resources (DER) will have a major effect on the ability to perform accurate long-term forecasting of the load the utility-scale generation has to meet. To address this issue, it will be critical to integrate the forecasting of load accounting for growth in demand response, energy efficiency, and distributed generation (DG).

9.4.16 Transmission and generation expansion planning

It is expected that investment in transmission and generation will significantly increase over the next 10-15 years, and so planning functions take on a higher level of importance than they have in the recent past. Traditional planning approaches seek to find the least-cost way to expand the system while satisfying reliability constraints during the most stressed conditions. Although this paradigm will remain of interest, a new market-based transmission planning model is needed which finds expansion plans that maximize the economic benefits provided by new line additions. This will require planning optimization tools which simultaneously (or at least iteratively) optimize generation expansion plans and transmission expansion plans. By iterating between generation planning and transmission planning results, a robust transmission investment plan can be designed which is best under most or all of the generation expansion futures. Doing so at the level of the ISO (regional) is a highly computational problem.

Another key need for transmission planning stems from the fact that the redistribution of generation occurring as a result of renewable growth causes significant change in power flow patterns. As a result, the existing transmission system configuration, designed for a mainly fossil-based generation distribution, is usually sub-optimal for a renewable-based generation distribution. Yet, it is not reasonable to completely redesign the transmission system. Therefore one would like to identify reconfigurations that could take place to strengthen the system for its new purpose, maximizing the system security level subject to a constraint on cost and possible right-of-way.

Key to the above two expansion planning problems is the ability to integrate equipment locational information with wind and solar resources. Geographical information systems (GIS) will play an important role to this end.

9.4.17 Transportation and energy system planning

Planning has always been done at the local or regional level and only for the electric system. Yet the advent of growth in low-GHG generation is causing a significant shift in generation location. This has implications in terms of the geographical level at which planning is done and the number of infrastructure sectors which should be included in the planning. Efforts are already ongoing to perform planning at the interconnection level and it may be that such efforts should be expanded to the national level. The shift to low-GHG resources will also have dramatic effects on the transportation systems used for fossil fuels, e.g., rail and petroleum, and enabling their inclusion in planning tools will be important. Finally, it is clear that transportation systems will become more and more dependent on electric energy, especially for highway passenger travel. These changes require that electric systems planning be done together with transportation systems planning.

9.4.18 Uncertainty modeling for long-term planning

Developing investment plans for long-term decision horizons requires extensive uncertainty modeling. Such modeling may be divided into two classes that can be called high- and low-frequency uncertainties. The former occur repeatedly and can be captured by fitting probability functions to historical data. Examples of these include uncertainties in fuel prices and component outages. The latter uncertainties do not occur repeatedly; therefore, their statistical behavior cannot be derived from historical data, but they may have great impact. Such uncertainties include, for example, dramatic shifts in weather and/or load forecasts, major policy changes, technological leaps, or extreme events (catastrophic contingencies). Low-frequency uncertainties become more important as planning horizons extend.

There is strong emphasis today by long-term planners on decision horizons that reach up to 20 years into the future, and it is infrequent that developers commit to constructing new facilities on the basis of needs that extend beyond this time frame. This is understandable because building significantly ahead of need can add expense due to the increased uncertainty of the longer time frame and the difficulty in convincing regulators to place economic burdens on current ratepayers for benefits enjoyed by future ratepayers. However, most of the investments have long lifetimes, some exceeding 50 and even 60 years, In addition, climate effects of GHG emissions are cumulative over multiple decades, so that response to GHG reductions are gradual and require long-term aggregation of measures to achieve them. Taking a view of needs beyond the typical 20-year decision horizon of current planning cycles need not require that today's investment decisions address what is built 50 years into the future but rather, that today's investment decisions fit into a 50- or even 100-year long-term plan, periodically adjusted to account for new information as it becomes available. Doing so will require addressing technical challenges associated with the necessary software tools.

10 Seamless Look-Ahead Visualization Requirements

10.1 Introduction

The electricity grid must evolve into a more flexible, efficient, and resilient infrastructure that can support a sustainable and empowered society. The emerging grid exhibits a significant amount of new behavior, and creates numerous challenges associated with informatics, uncertainty, and computational complexity. Visualization will be an essential tool to extend the knowledge on emerging electricity grids.

Lack of analysis and deep understanding of electricity markets, in particular the relationship between forward and balancing spot markets, resulted in the collapse of the California market in 2001, which caused $10 billion in losses for California [64] and slowed down deregulation efforts in the United States. Lack of awareness of system security caused the Northeast blackout in 2003, which resulted in loss of electric power to 50 million people [65]. The electricity industry's entropy today is many-fold that introduced by deregulation at the end of the 90s. In addition, electricity systems are operated under more stressed conditions compounded by an aging infrastructure.

Research and synergistic efforts on smart grid, unified power system modeling, computational methods, and complex systems are required to support visualization software for both planning and real-time operations [66] and simulation and of multi-dimensional security analysis methods [67]. Visualization must support operation under high penetration of distributed renewable energy [68] and multi-dimensional sensitivity analysis, wind generation transmission planning, power system control architectures, and optimization methods [69,70].

There is increasing awareness among the various industry stakeholders about the complexity and the computational challenges and opportunities derived from renewable energy integration and smart grid programs.

10.2 Visualization Environment

Figure 10.1 illustrates the major components and interactions of a hypothetical interactive look-ahead visualization environment. This environment should be multi-dimensional and multi-scale (MDMS). The visualization software should interact with three subsystems: the GPU hardware, the spatio-temporal database, and the interfaces to computational applications. Efficient interfacing to these subsystems is a requirement for achieving the functional and performance objectives of the visualization applications. A commercial database, such as the Oracle's 11g over OSISoft PI database, could be used for the spatio-temporal data repository. This database system should have the ability to host synthetic research data and primary utility datasets with support for multi-instantiation and concurrent access. Each database instance should support different granularity, which can be altered dynamically by the MDMS applications. The visualization system could provide interfaces to PMUs collectors, smart meter, and other sources of primary data.

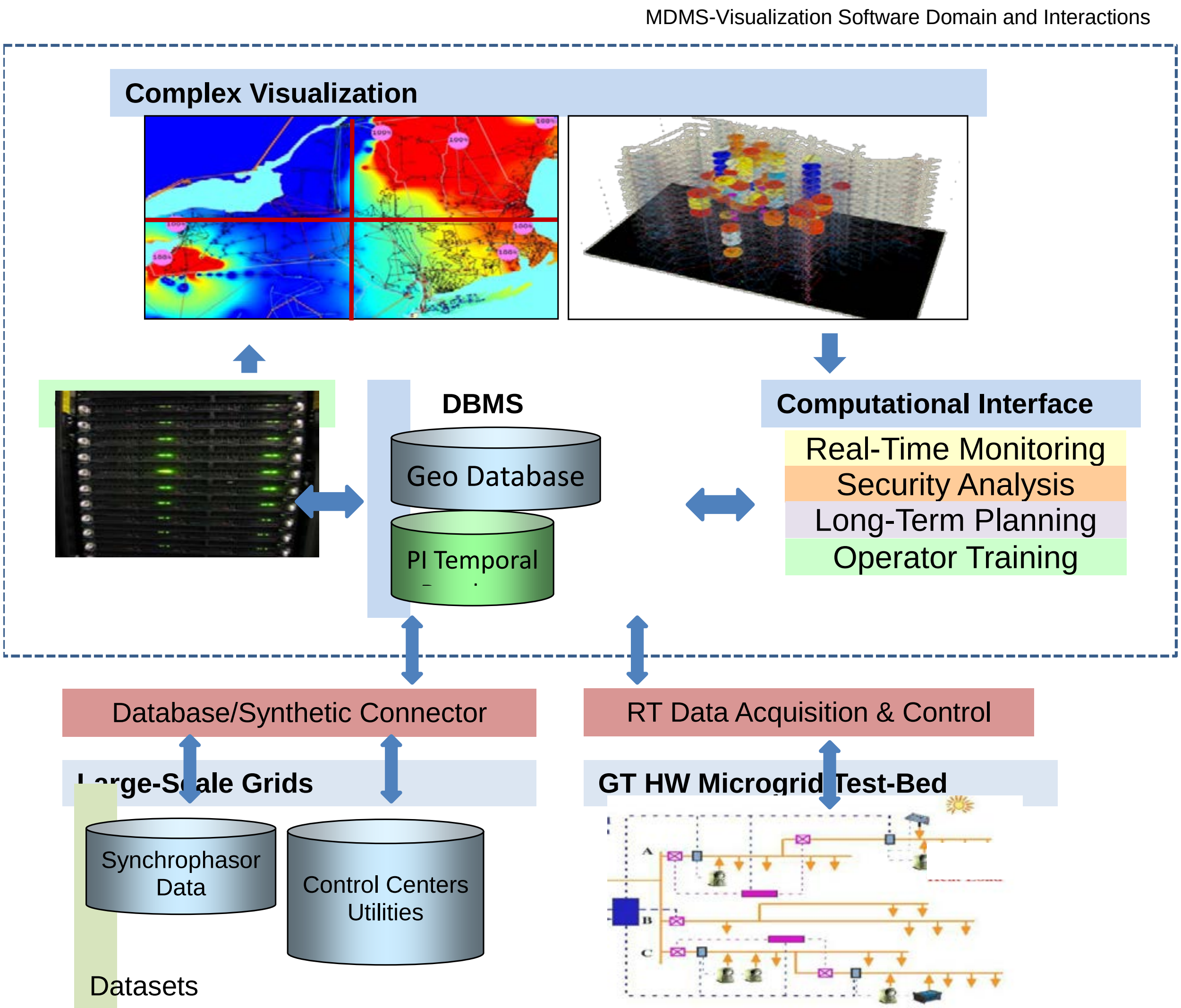

Figure 10.1: Proposed architecture for MDMS visualization system

The MDMS visualization should be based on a GPU computer system. The temporal database could store various datasets and data instances. Data connectors would allow live hardware microgrid measurements and external real and synthetic data to be fed to the databases. PMU data could also be stored in the database. Support for advanced simulation and visualization learning including complex cluster driven 3D MS analytics is desirable.

10.3 Visualization Engine Requirements

An advanced visualization engine will require a set of general routines that can be called by the visual applications. The visualization requires three components: a) generic data-handling routines to query information from the spatio-temporal database, b) generic routines to pre-process the data for visualization, and c) core visualization routines including: sparse cube management, generic dataset computations, multi-dimensional rendering, clustering, expansion and collapsing, dimensional rotation, dimensional mining, estimation, and visual navigation. In the following we describe the key concepts and techniques involved in a hypothetical visualization engine.

10.3.1 Dataset Navigation

The conceptual framework for navigational visualization and exploration is designed to assist human operators to act on spatial and temporal patterns, trends, and relationships among events that lead to advanced situational awareness.

Spatial and temporal dimensions in emerging electricity systems are multi-scale. The scales used are context dependent. The security dimension is single-scale, but can be largely sparse and unstructured. The most common element visualized is the graph of the electric grid. Various raster components such as weather, wind, and solar conditions interact with the electric grid graph and with related quantities such as security metrics or forecasted renewable production. Dynamic transparency techniques can be used for 3D and 4D representations. Simultaneous visualization of single-scale relevant phenomena can be achieved by 4D visuals. Dimension rotation and visual immersion can be used to navigate datasets associated with dynamic stability phenomena, which can cover the range from milliseconds to several hours. Simulated immersion and plane dragging along the temporal dimension are promising techniques far superior to multi-dimensional plot arrangements [57]. Multi-scale visualization requires interaction with the interface for immersion, zooming, 4D navigation, and magnifying effects. Aggregation and cube dataset clustering can be used for dynamic navigation [14,54]. The relevant phenomena are emphasized using various techniques, such as dynamic formatting and 3D zooming. User-centered design can be applied in developing the interfaces and visualization functions [18,19].

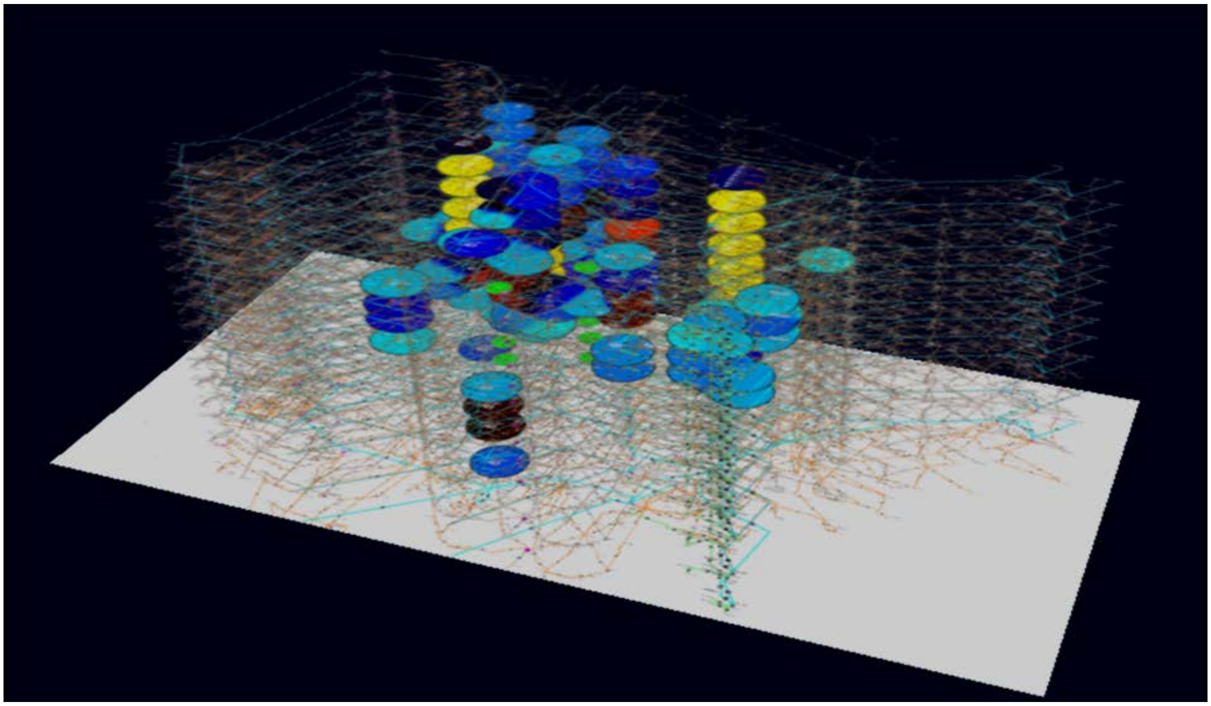

Figure 10.2: 3D visualization

Figure 10.2 above illustrates spatio-temporal visualization of the Tennessee Valley Authority (TVA) Electric System. Each element of the grid that presents problems in the security dimension exhibits a color-coded metric for alerting severity. The 3D tool allows navigating the temporal dimension (vertical axis) to further explore datasets interactively.

10.3.2 Multi-Dimensional Datasets

At the core of the proposed visualization engine is multi-dimensional scaling (MDS), a technique for dimensionality reduction, where data in a high-dimensional space is mapped into some lower-dimensional target space while minimizing dimensional distortion. MDS is used when the dimensionality of the dataset is conjectured to be smaller than the dimensionality of the measurements. When dimensionality reduction is used for information visualization applications, the target space will be 2D or 3D. The points in that space are drawn to help analysts understand dataset structure in terms of dynamic clusters or other relationships.

Several visualization techniques for multidimensional datasets have been designed, including parallel coordinates, scatter plot matrices, and dense pixel display. In particular, flow animation and contouring have been very useful in describing multi-dimensional behavior of the electricity production, transportation and consumption processes. Animation and contouring have been limited to steady-state analytics [19]. Dynamic system behavior has been traditionally described by 2D charts. Dynamic phenomena in electricity systems are spatio-temporal, i.e., the relevant quantities such as rotor angle and speed vary in time and are associated with the spatial locations of the machine and their relation to the grid elements. 4D surface wave animation becomes a good candidate for their representation. Transient behavior can also be multi-scale, as in stiff nonlinear DAE systems [82].

10.3.3 Multi-Scale Spatial and Security Datasets

Aggregation of information is at the core of spatial dimension handling in electricity systems. Linear or nonlinear collapsing of a dimension is necessary to discover clustering at various levels. Existing methods to address spatial scales are currently based on multiple data arrays and object type conversion. Recent research allows electricity network multi-scale information to be dynamically aggregated at various levels using a single array. This has resulted in unified application solvers such as the unified power flow [58], which can solve operations models established at the node/breaker level or planning models aggregated at the bus/branch level. The technique uses dynamic object assignment to aggregate grid topologies of any complexity in a single object. Implementation is achieved through dynamic pointer reassignment in graphs, which allows generic handling of spatial data at different aggregation levels depending on the specific client or the granularity needed in a certain solution region. As an example, a combined Security-Constrained Unit Commitment (SCUC) application may start with zonal interface congestion management, but certain zones may be dynamically expanded to the nodal level depending on the solution state to address intra-zonal congestion at full distribution device detail. While these methods were originally designed for computational solvers, similar methods can be used to address multi-scale issues in visualization.

Within the security dimension, scenarios and contingencies are usually decoupled. This implies that contingency analysis must be repeated for every scenario. In this project we will be able to determine values in the relevant security space by utilizing two strategies:

a) Contingency coupling screening techniques to determine the combined effect of multiple event contingencies [60]. This allows double contingencies to be identified by exploring a small subset of the 2D security solution space, and
b) Injection sensitivities to model active power related patterns such as load or generation profiles including distributed wind.

Because active power injection and contingency sensitivities are close to be linearly related in well-conditioned systems, this method would allow using existing contingency information in the solution of new scenarios. In this manner only a small fraction of the contingency processing needs to be done for deeper dimensions. A two-order increase in computational speed is expected by using these techniques [61].

10.3.4 Multi-Scale Temporal Datasets

Temporal multi-scale visualization can be achieved by addressing query response time and screen space clutter over large datasets. To reduce clutter and make visualizations more informative, a temporal, multi-scale view of data via a hierarchical clustering method for parallel coordinates can be utilized [20]. The algorithms for MDMS pre-processing will be largely based on wavelet methods. Temporal scales can be studied by determining the natural frequencies of relevant components using frequency domain and wavelet transforms of input data, e.g., from wind generation, PMUs, etc. Wavelet transforms on massive historical data will allow us to perform dynamic dataset compression [62]. Multi-resolution methods play a key role on MDMS applications navigation [75-77]. The basic approach consists on making the resolution based on natural gradients in the datasets and on focus-dependent resolution [78,79].

10.3.5 Learning Visualization

The development of the MDMS visualization software is also tied to research opportunities in learning visualization —the process through which humans learn while immersed in complex visual analytics. The impetus for learning visualization is the overwhelming complexity of emerging behavior in real-time [21]. Learning visualization in operator training simulation environments can be studied in combination with slow motion techniques to study operator decisions that can be automated. A similar problem arises at the end user (commercial, industrial, or residential) who is interested in energy optimization and efficiency, but not in the intricate optimization and control processes required. Technology needs to be developed and deployed to free the user from the control and optimization details while providing loose directives to a more intelligent control system. Learning visualization in MDMS systems is essential to formalize machine learning and deploy embedded software for such downstream smart grid systems [22].

10.4 Visualization Applications

Visualization applications are developed to meet the functional and performance requirements of specific decision-making processes. The MDMS applications will be in an upper (application) layer of the visualization software from which the engine routines will be called. The application design and architecture assumes a level of engineering knowledge acquired by formal training and human aspects of the system operator or analyst. In the following we will describe four specific applications. These applications are highly critical for the industry and cover a significant portion of the possible functional requirements of MDMS visualization systems for electricity systems.

10.4.1 Forward-Looking Operation of Systems with Large-Scale Renewables

The problem of real-time operation of systems with significant penetration of renewable energy is characterized by temporal variability and uncertainty. Current forecasting errors are as high as 8% for 4-6 hours ahead [80,81], which is much larger compared to historical accuracy of short-term load forecasting (1.5-2.0%). This implies that large-scale renewable energy cannot be modeled as negative load as it was customary in systems with small penetrations. A significant variation of large-scale wind energy can result in balancing conventional units not being able to ramp fast enough to avoid operation of under-frequency relays and load shedding [2].

The visualization problem faced by the bulk system operator must be addressed, which needs to ensure reachability of secure generation dispatch objectives given uncertainty of wind production. Visual, early awareness of wind production deviating significantly from the forecasted values provide consistent mechanisms to induce the operator to take preventive control actions, e.g., dispatching fast conventional generation ahead of time, or calling critical demand response actions. The dataset complexity arises due to: a) the temporal scales involved in the optimal control actions, b) the relation of wind variability and balancing dispatch with transmission constraints and congestion, c) requirements to consider the security dimension warnings, and d) the underlying uncertainty of the problem.

10.4.2 Consumer Behavior and Demand Response Research

Demand Response is likely to become a key component for the smart grid over the next decade. Up to 45% of the expected smart grid benefits in the U.S. will result from demand response actions and, more generally, active end-user participation. From an end-user standpoint, demand response consists of adjusting when to use electricity and how much to use in order to minimize electricity costs. Customer applications that enable demand response could generate as high as $59 billion annually in the U.S. by 2019 [84]. Benefits related to demand response include shifting demand away from critical and daily peak demand periods, reducing overall energy consumption, and reducing needs for new power plants in the future, resulting in an avoided cost capacity. Dynamic pricing programs, where consumers decide whether and when to use energy based on a retail rate that changes over time, are very likely to expand. The development of such dynamic pricing requires design of the optimal price signals or time-differentiated electricity rates to maximize social benefits.

Visualization-driven data mining methods could be used to exploit massive amounts of customer data. Dynamic pricing and time-differentiated rate design will require comprehensive understanding of the datasets. Visual techniques can be used to represent: a) the temporal shifting and energy consumption reduction from baselines upon application of time-differentiated rates and their effect on the grid, b) the types of devices that are being used for demand response, and the correlations with consumer type, demographics, etc., and c) the temporal interplay of fast response loads such as TV, electronics, elevators, pumps, and devices with longer time constants such as water heaters and air conditioning. Multi-scale temporal visualization can be developed to study emerging behavior and identify relevant patterns for price design and broader energy and electricity policy objectives.

10.4.3 Real-time Visualization of PMU-detected Dynamic Oscillations

Wide-area monitoring, protection, and control is becoming increasingly important for improved power system operation [85,86]. Phasor measurement units (PMUs), samples the ac voltage and current waveforms while synchronizing the sampling instants with a global positioning system (GPS) clock. The potential applications of PMU measurements are numerous [87,88,89], including fast enhanced state estimation, detection of events and disturbances in the control area or outside of it, and detection of oscillations, which can include oscillations at frequencies outside the natural human perception range. Visualization will enable a) explore PMU datasets from wide-area monitoring systems, b) use frequency domain techniques for discovery of relevant behavior associated with disturbances and oscillation detection, and c) propose MDMS visualization that takes advantage of emerging PMU datasets.

PMU-enabled fast system stabilization and related phenomena can only be visualized in the 3D or 4D interface through temporal scaling. Slow varying phenomena can likewise be brought to natural human frequency.

10.4.4 MDMS Synchronization of Variable Renewables with Flexible Loads

The effects of temporal variability of renewable generation can be mitigated by coordination of variability with flexible loads and storage, in particular industry scale storage, PHEV, and deferrable loads, which include air conditioning, refrigeration, washing machines, controlled lighting, agricultural pumping, etc. In addition, energy storage devices can provide frequency regulation and reserve, increasing the number of ancillary services providers, decreasing the needed amount of reserve due to the fast response capabilities of power electronics, and absorbing renewable energy variability [V67]. Synchronization of renewables with flexible loads implies addressing multi-scale issues ranging from potentially the entire interconnection to aggregations of flexible loads ranging from utility level to parking lot and homes. Issues such as availability of stationary PHEV and controllability of deferrable loads capable of handling large renewable variations, as well as issues associated with visualization of the transportation system.

Figure 10.3: Conceptual MDMS visualization for coordination of renewable energy

Figure 10.3 above illustrates how a cloud system results in highly variable solar production in Southern Company footprint near afternoon commuting time. The Atlanta area exhibits potential problems due to loss of stationary storage (red contouring driven by aggregated security metrics). Variability absorption capabilities at 2x2 square mile resolution are illustrated in the upper 3D layer using cylinders (virtual generation). Fuchsia stacks are PHEV V2G energy, blue stacks are frequency regulation, green and yellow stacks are 5 and 12 minute PHEV cleared reserve.

11 Conclusions

This report determined that existing energy management systems are no longer sufficient to cope with the additional complexity and timescales introduced by new emerging technologies to the electric power grid. An overview of the current state of EMS and analysis applications was presented, and numerous technological requirements were identified. These requirements included the needs for unified data models, better numerical methods for solving power system problems, large-scale visualization platforms, seamless communications and data management, as well as interfaces that can exploit new computational hardware. These requirements must be met in order for the next generation of EMS to succeed the existing control and operation infrastructure so that the grid may continue to meet its objectives of optimal security at minimum cost.

Several seams discussed in this report arose from historical divisions of responsibility between functional groups such as operations and planning, usually determined by the considered timescales. As the lines between these timescales continue to blur, EMS applications need to be developed in conjunction with planning software so that they can leverage each other’s strengths. Similarly, there has been a historical division between transmission and distribution. These lines have already begun to blur, motivating the need for unified models that can be used across spatial scales.

Other seams discussed in this report arose from the use of outdated software and hardware. Traditionally the power industry has been slow to evolve since there is little incentive to adopt new technologies when they have the potential to lead to disastrous outcomes. Hence, the industry had adopted a risk-averse approach. Yet other fields like the computer industry are fast-paced and ever-changing with new break-through innovations every few years. While the power industry may never keep pace with the computer industry, it can still track their advances in areas such as parallel computing, visualization, data mining, optimization, and numerical analysis, and incorporate them whenever applicable and beneficial.

The manifold requirements and seams presented in this report will take years to fully address, but visionary and convening research organizations such as EPRI that are investing in new research in these areas will be well-positioned for the coming changes over the next decade.

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