Fast Simulation & Modeling System - Technical Requirements Assessment Study

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INTRODUCTION

One of the most significant technical programs led by the Electricity Innovation Institute (E2I) is the Consortium for an Electricity Infrastructure for a Digital Society (CEIDS) program. CEIDS is a unique and far-reaching alliance of a diverse group of stakeholders (domestic and international utilities, federal and state agencies, and information technology companies) that has established the goal of transforming today's electric infrastructure, from the generator to the device consuming the energy, into an intelligent infrastructure for the future. (See www.e2i.org for a more detailed description of the CEIDS vision, mission, and program.)

One of the four major strategic goals of CEIDS is development of the technologies necessary to achieve the transformation of the current electricity system into a sustainable, adaptive, and self-healing electricity system for the future. Achievement of this goal entails a system that is capable of reconfiguration and self-restoration in response to a multiplicity of changing conditions: market-driven operational decisions in the generation and transmission sectors, external threats to system stability (weather, man-made risks), shifting distributions of loads, generation sources, and available transmission capacity. This dynamically adaptable electricity grid has been characterized as a "self-healing grid". Such a self-healing grid will require an architecture permitting substantial integration and coordination of functions affecting one another, e.g. communications and transmission control. The superposition of these dynamically changing externalities in an integrated architecture quickly leads to the conclusion that a self-healing grid will need large-scale automation and wide area monitoring to reach the necessary level of adaptability.

Large-scale automation implies several key enabling technologies: independent software agents capable of a combination of autonomous and coordinated actions, ability to predict system behavior on multiple geographic scales and time domains based on current or anticipated conditions, and availability of data sampled varying frequencies over wide areas. Consequently, the capability to model and simulate system behavior based on real-time data fast enough to anticipate changing system conditions is essential to support multiple automation/control capabilities. The purpose of the Fast Simulation & Modeling (FSM) system project is to develop this capability. Achievement of this goal hinges on a dynamic, real-time or faster-than-real-time simulation.

E2I intends to solicit proposals on development of the FSM system via a Request for Proposal (RFP). However, definition of the necessary capabilities of the FSM system is complex and must consider several aspects of current electricity system operations and planning. Therefore, E2I has conducted a study to evaluate current knowledge, relevant past research, and operating experience to thoroughly assess critical technical capabilities for the FSM system. This study will be made available to all organizations interested in responding to the RFP discussed above.

This study does not comprehensively define detailed technical requirements for the FSM system. Rather, it identifies critical capabilities and issues that must be addressed in subsequent definition of detailed technical requirements in the FSM system development project. The scope and new capabilities planned as part of the FSM system will inevitably require assumptions regarding other technologies and capabilities (e.g. sensors, data availability, data visualization tools, data communications and telemetry capabilities and standards, etc.) It will therefore be necessary to carefully identify all such assumptions and interfaces with other systems to capture implied requirements for other infrastructures. Many of these requirements will be vital input to other CEIDS projects addressing these areas.

Approach

This study approached the problem of identifying key technical capabilities for the FSM system through consideration of several perspectives:

- Existing approaches to state estimation currently in use in utility companies.
- Experience in development of complex, real-time simulation systems in other industries.
- Experience in utility generation and transmission operations and planning.
- Results of past research on different aspects of electricity grid stability, reliability assessment, operations & management, and modeling.

A wide range of organizations and individual experts were contacted and interviewed in depth to ensure a thorough identification of the most important technical capabilities necessary for a successful FSM system. Independent assessments the existing state-of-knowledge were also conducted. The issues emerging from these efforts were discussed and evaluated with technical advisors from the organizations funding the CEIDS program. In this study, the results of all of these discussions and investigations have been distilled into a core set of technical capabilities that must be addressed in any response to the RFP discussed above.

Conclusion

An effective FSM system that enables the self-healing grid as envisioned in the CEIDS program will require not only unique simulation and modeling capabilities itself, but will also require development of other key technologies and more robust infrastructures: new approaches to data and dynamic system visualization, and much more extensive wide-area grid monitoring. As the FSM system is developed, the project will have to coordinate closely with other CEIDS programs addressing visualization and communications.

The scope of the FSM system is daunting, yet it is an essential technology if the adaptive, self-healing grid is to be realized. Therefore, a highly structured, phased development approach to development will be necessary. The development process will have to provide for frequent interaction with key stakeholders in the electricity industry. Successful development and implementation will also depend on identification of sponsoring utilities who will actively participate in the FSM project.

While a number of viable alternatives to the precise nature of the project structure and phasing can be visualized, it is clear that the overall project approach will require at least three major phases (see Figure 1):

1. Definition of the technical requirements (engineering, computing, and validation)
2. Development of the FSM system for critical applications
3. Enhancement of the FSM system for other key applications

Phase 1 emerges from the conclusion that the full scope of technical requirements should be developed considering the breadth of the FSM system's application to ensure an effective and feasible integrated design. It is also essential to establish the criteria by which the fidelity and limits of the FSM system will be evaluated in concert with key industry stakeholders prior to actual development.

Phase 2 is based on the conclusion that a focused development of the FSM simulation "engine" geared to support the most critical one or two applications (see Figure 1) will result in earlier delivery of a useful FSM system. A more focused development will identify key issues and streamline further development and expansion of the FSM system to support other applications.

The final phase could in fact be several, based upon a logical separation of the remaining applications to be supported by the FSM system. For example, the optimization, automated control, and market model integration areas each entail substantial and different modeling needs and could be treated in separate phases.

Key Capabilities supported by FSM

Development Milestones	*Real-time security assessment*	*Operational generation/ load balance analysis*	*Inter-area power flow analysis*	*Power flow optimization*	*Generation dispatch optimization*	*Automated control/ recovery*	*Integration of market models*
Technical Req'mts. Document							
Computing Architecture (data, hardware, software)							
Software Verification & Validation Plan							
Prototyping							
Software Design Document							
Software Development							
α testing							
β testing							
Final testing							

Figure 1
Key Elements of FSM Development Project Structure

2
KEY TECHNICAL CAPABILITIES TO BE SUPPORTED BY THE FSM SYSTEM

The FSM system is envisioned as a dynamic simulation and modeling engine that can be used to analyze a range of time domains and system topologies in support of typical electricity grid operations, management, planning, and coordination activities. The key technical advance needed from the FSM system is more accurate time-domain simulation of power system dynamics – this entails analysis such time-sequenced power flow simulation with slow, discontinuous dynamics. Therefore, this study is organized from two perspectives: capabilities deriving from consideration of (1) the needs of grid management activities and (2) needs and capabilities implied by the computing capabilities expected for the FSM system. Inherent in this discussion is inclusion in the FSM system of capabilities to model time-dependent quantities and behavior, which implies features capable of modeling different phenomena at different levels of time resolution.

It is clear that there are some critical activities that will require new or improved capabilities to support the adaptive, self-healing grid concept envisioned by the CEIDS Master Plan. This study refers to these activities as "applications" in the sense that they represent different applications of the modeling and simulation capabilities to be provided by the FSM system. While not necessarily comprehensive, the following applications must be effectively supported and enhanced by the FSM system to be developed:

- Security assessment
- Operational generation/load balance analyses
- Inter-area power flow analyses
- Power flow optimization
- Generation dispatch optimization
- Automated control/system recovery
- Interface with market analysis models

The nature of these applications suggests a natural division in considering potential requirements for the FSM system in supporting them. Security assessment and load balance analyses are transmission operations oriented applications, and many of the most critical issues today revolve around these applications. Power flow analyses and optimization, and generation dispatch optimization are generally off-line, static analyses that affect planning and operational practices and procedures. Automated control/recovery and market modeling integration are new and generally unrealized capabilities; consequently, new issues will arise in creating and implementing these capabilities. Key issues associated with each of these applications are discussed below. Figure 2 provides an overview of the key performance dimensions of the FSM system in relation to different applications. Table 1 provides an overview of typical timescales for power system phenomena and actions.

Key Performance Parameter	*Real-time security assessment*	*Generation/ load balance assessment*	*Inter-area power flow analysis*	*Power flow optimization*	*Generation dispatch optimization*	*Automated control/ recovery*	*Integration of market models*
Time-step granularity	1-10 sec	10-100 sec	Static	Static	Static	0.01-0.1 sec (protective system actions) 0.5 sec–min. (stability, voltage control actions)	20-60 min. (market update)
Scope of Visualization	Control area	Multiple control areas	Reliability regions, multiple control areas	Multiple control areas	Reliability regions, multiple control areas	Multiple control areas	Reliability regions, multiple control areas
Primary Users	Reliability/ security coordinators	Control area operators	Planners	Planners	Control area/ transmission operators	Control area/ transmission operators	Control area/ transmission operators

Figure 2
Key Performance Dimensions of FSM Simulation Scope

Action/operation	Time frame
Wave effects (fast dynamics, lightning caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability Augmentation	Seconds
Electromechanical effects of oscillations in motors & generators	Milliseconds to minutes
Tie line load frequency control	1 to 10 seconds; ongoing
Economic load dispatch	10 seconds to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized & what is not)	Steady state; on-going
System state measurement and estimation	Steady state; on-going
System security monitoring	Steady state; on-going
Load Management, load forecasting, generation scheduling	1 hour to 1 day or longer; ongoing.
Maintenance scheduling	Months to 1 year; ongoing.
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact, etc.	10 years or longer

Table 1
Multi-Scale Time Hierarchy of Power Systems

2.1 Transmission Operations Applications

Security Assessment

Security assessment is an ongoing activity in day-to-day transmission operations. Several constraints must routinely be considered: thermal limits, voltage stability limits, available capacity, economic requirements, etc. Typically, system design has been based on assumption of failure of one critical component (i.e. N-1 criteria). However, events resulting from N-2+ failures either have to be anticipated and simulated to enable preventive actions or procedures, or they have to be analyzed in real-time. Integrated real-time modeling and simulation of multiple types of constraints under varying normal and failure conditions is needed. The ability to identify critical loads and/or generators whose behavior drives system stability under various conditions is needed. These capabilities are likely to require modeling to a lower level of topological detail than typical in existing steady-state EMS state estimation models, i.e. modeling down to the feeder breaker level. Other key security parameters that should be modeled/simulated by the FSM system include:

- Protection device settings and automated protection schemes
- Islanding schemes and associated device settings
- Varying levels of energy storage (both quantity and location)
- Model primary, secondary reserve levels
- Model/simulate load shedding schemes
- Interface with EPRI Community Activity Room (CAR) security assessment system.

<u>Operational Generation/Load Balance Analyses</u>

While historically this issue is largely addressed through short and mid-term planning analyses and by long-term system design, two new dimensions pose a dynamic, real-time analysis challenge. One issue is that many generators operate in more complex ways according to economically driven criteria, and often these actions can be contrary to system security interests. The second issue is the expectation that more sophisticated control by customers of their electricity load driven by real-time pricing (particularly in the commercial and residential sectors) will create new dynamics in the load curve. Real-time simulation and modeling of these dynamics (frequency, voltage, power flow, load forecasting) will be needed to support transmission operations. Other key new or existing operational parameters that should be modeled/simulated by the FSM system include:

- Dynamic behavior of distributed energy resources
- Voltage control commands/actions
- Choose the optimal generators for support in unbalanced situations
- Remedial actions and relay actions that may occur following occurrence of an initial contingency

- A convergence "index" that provides an assessment of the quality of the convergence of the load flow model. This "index" should also be related to potential for voltage stability issues.

For both of the transmission operations applications discussed above, several generic considerations arise:

- An assessment is needed of where deterministic vs. stochastic solutions are optimal. Probabilistic outputs with uncertainty would substantially enhance ability to later evaluate FSM system performance vs. verification and validation criteria.

- Key challenges to probabilistic analysis will require clearly defined assumptions in the FSM system design: nature of available transmission fault line data, fault probabilities as a function of weather variables.

- Additionally, FSM system compatibility via the EPRI Common Information Model (CIM) with existing major energy management systems (EMS) is a necessity for the FSM system. The FSM system should be able to accept steady-state data from EMS state estimators (where appropriate) in implementing the dynamic modeling cited above.

- Ability to vary portion of system modeled and portion of system modeled as boundary conditions in order to find a model scale at which calculations converge.

2.2 Planning Applications

The overall context of these applications is analyzing long-term electricity grid dynamics and equilibria at varying levels of topological detail. Typically, these analyses are performed off-line. The FSM system needs the capability to support these analyses. It is envisioned that new capabilities introduced by the FSM system would include probabilistic modeling of the location and effects of projected load, generation, transmission assets and distribution assets. It is expected that advanced modeling capabilities developed for the transmission operations applications cited above would be applicable to and valuable for planning applications. Other key planning parameters that should be modeled/simulated by the FSM system in support of one or more of the applications below include:

- Model inter-area power flow commitments.

- Analyze optimal transmission capacity usage.

- Analyze optimal configurations for average load and peak load conditions.

- Optimal reactive power compensation

<u>Inter-Area Power Flow Analyses</u>

Transmission planning requires assessment of power flows between security areas and reliability regions. This assessment requires analysis of system dynamics at this level of topology. New benefits anticipated from the FSM system are identification of possible sets of destabilizing conditions via simulation and more complete identification of key transmission assets posing constraints under normal operations scenarios.

Power Flow Optimization

Power flow optimization entails identifying conditions necessary to optimize efficiency of energy transfer across the transmission system. This entails maximizing efficiency of transfer capacity on transmission lines and minimizing losses. The anticipated benefit of FSM to this problem is ability to simulate and determine optimum deployment of generation resources, particularly distributed energy resources (DER), to create conditions closer to the optimum. Combined with appropriate visualization, the FSM system supporting this application can provide a valuable reference for transmission operations priorities.

Generation Dispatch Optimization

Planning development of generation and coordination/dispatch of existing generation resources is an ongoing activity. New challenges emerging in this application include planning, deployment, and analysis of impacts of distributed energy resources (DER) and establishment of planning criteria based on analysis of market-driven generation behavior. The goal remains maximum system efficiency and reliability, but with the capability of modeling effects of these new challenges. Other key generation optimization parameters that should be modeled/simulated by the FSM system include:

- Generation planning
- Unit commitment
- Economic/market dispatch

2.3 New, Adaptive Applications

Automated Control/System Recovery

Ultimately, the goal of the CEIDS program is to achieve an adaptive, self-healing grid. This overall goal translates to much more automation in terms of system diagnosis, control, and recovery following disturbances. Once development, testing, and experience is gained with the FSM system in its support of current grid management applications, it is envisioned that the FSM system can be enhanced to provide the simulations and data needed to complement field data to enable a higher degree of automated and more distributed intelligent grid control and remedial actions. The FSM system will need the capability to accumulate historical data and compare to simulations to identify distinct sets of operational conditions in which an unambiguous, technically acceptable automated control strategy can be defined and implemented. Other key automated control parameters that should be modeled/simulated by the FSM system include:

- Automated voltage control device settings

- FACTS device settings and actions. FACTS modeling will ultimately require instantaneous value, RMS value, and eigenvalue analysis.

Interface with Market Analysis Modeling/Simulation

Market rules (pricing, auctions, etc.) and gaming strategies by market participants introduce a new dimension of criteria for deployment and operation of grid assets (generation, transmission). The effects of variables such as wholesale energy pricing trends, volatility, transmission access pricing, auction methods, etc. will have to be addressed. Historically, ancillary services are rarely included in market models. Inclusion of ancillary services in market modeling and analysis should be supported by the FSM system. In addition to the timeframes outlined in Figure 2, day-ahead modeling is a critical timeframe for market operations.

It is envisioned that use of independent software agents may be a valuable strategy in modeling the heuristics associated with these effects. The FSM system will ultimately have to interface with or incorporate market models to fully simulate their effects on physical operations.

3

KEY FSM ISSUES: COMPUTING STRATEGY AND ARCHITECTURE

The FSM system will be a complex, layered system of data structures and input, modeling/simulation, and output/visualization/reporting modules. It is critical to consider the optimal architecture of this overall system prior to detailed design. A critical underlying consideration is the degree of distributed vs. centralized computing in the system software design, hardware architecture, and data architecture. For illustration purposes, an example high-level architecture might be as depicted in Figure 3. Key capabilities and issues associated with selected aspects of the computing strategy and architecture are discussed below.

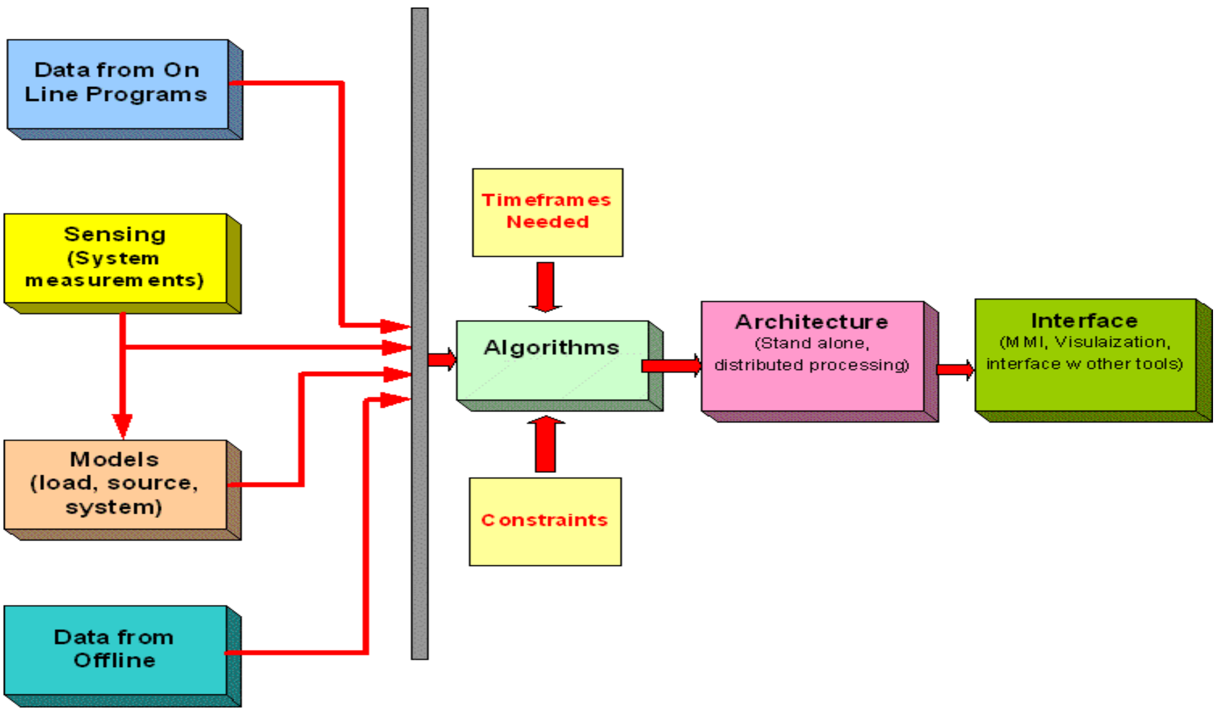

Figure 3

A Possible High-Level Computing Architecture for the FSM System

3.1 Modeling/Simulation Software Architecture

- A significant challenge to developing a robust and sustainable FSM system is development of a flexible design that maximizes adaptability to changing computing technology.

- Approaches such as abstract object modeling will have to be considered to allow integration/interface of the FSM system with other systems developed by different developers at various points in time using various languages and different class models.

- The software architecture design should consider facilitation of verification testing (e.g. classical methods like multiple design walk-throughs, code walk-throughs, and code analysis.)

- Compromises will need to be made between data access rates, modeling fidelity, and required simulation performance in order to operate within decision cycle time constants. This implies that decision cycle time constants are a key technical requirements metric.

- In terms of distinct characteristics and requirements for simulation, it may be useful to consider develop the architecture in terms of different types of simulations to be performed by the FSM system:

  - closed loop, non real-time simulations;

  - real-time simulations used to feed data to larger decision processes involving humans, other software, and/or other hardware;

  - "look-ahead" simulations used to support real-time decision processes.

3.2 Software Technologies

3.2.1 Distributed simulation techniques

Distributed simulation techniques such as High Level Architecture (HLA) design can be a significant enabling technology linking real-time data and simulations.

3.2.2 Adaptive software agents

- This technology should be considered in FSM system design for a number of reasons: modeling complex system dynamics at multiple levels of resolution, modeling dynamics driven by heuristic behaviors, and modeling new, adaptive characteristics planned for automated system control and recovery.

- Determination of rule sets can be extremely labor-intensive. Development of heuristic reasoning models is an ongoing research area.

- It is essential that the FSM system, where heuristic technologies like adaptive agents are used, include features allowing a clear reconstruction of the reasoning on which a result is based.

- Heuristic technologies, when used, should include defined constraints on behavior based on established limits.

3.3 Data Architecture

3.3.1 Technical/Engineering Data Sources

It is essential that input data assumptions and requirements be clearly identified since wide area measurement and monitoring requirements are implied. Additionally, in terms of dynamic simulation, particularly security assessment, capabilities for time stamping of data and preventing inappropriate mixing of data taken at different timeframes are important. Data types likely to be required by the FSM system (note that sensors for some measurands are not always widespread or available):

- Voltage, dV/dt

- Frequency, df/dt

- Phase angle/phasors

3.3.2 Data Acquisition

- The scope of the FSM system modeling will likely require data from multiple organizations. Data security and confidentiality capabilities will be important in ensuring cooperation in sharing data.

- Telemetry assumptions require consideration of security, bandwidth requirements, and use of existing communications infrastructures and protocols. In particular, assumptions for telemetry from distributed energy resources and Independent Power Producer (IPP) generation resources need to be defined.

3.3.3 Data Storage

Data should be stored in formats independent of the specific elements of the FSM system. This principle will simplify the addition of new tools, and minimizes the data management requirements for the FSM system.

3.3.4 Data Visualization

- The basis of data aggregation and visualization capabilities for the FSM system should include consideration of aggregations necessary to facilitate existing operational and planning decision processes.

3.3.5 Data Communications

- DNP3 is the standard communications protocol for remote terminal units (RTUs), but many old RTUs have proprietary protocols. The challenge is conversion of old RTU to DNP3 without loss in data accuracy and control/functionality. FSM system assumptions regarding this issue will need to be clearly defined.

- FSM system design and assumptions should be consistent with the EPRI Universal Communications Architecture (UCA).

- FSM system assumptions about compatibility/incompatibility with other communications protocols should be clearly defined (e.g. TCP/IP, ICCP, Alstom Inter-Site Data (ISD) protocol, IEC TC 57 61970 High Speed Data Access (HSDA), IEC TC 57 61970 Generic Data Access (GDA))

4

KEY FSM ISSUES: VERIFICATION AND VALIDATION

Determination of the Validation & Verification (V&V) requirements is essential prior to development and concurrent with definition of the FSM system technical requirements.

4.1 Validation

For purposes of this study, "validation" refers to validation of the accuracy and fidelity of the modeling and simulation results produced by the FSM system. Validation of the FSM system presents some important issues to be considered:

- Criteria for what constitutes "validation" will need definition at the same time technical requirements are identified, and before any development occurs. References for validation would include successful simulation of historical grid events, comparison to existing contingency analyses, and retrospective analyses of grid planning vs. actual events.
- An appropriate combination of technical parameters needs to be defined as the basis for quantifying the engineering performance of the FSM system vs. validation criteria. Each technical requirement should be clearly connected to one or more validation criteria.
- It will be essential to develop, evaluate, and confirm validation criteria and strategies with domain experts (e.g. transmission operators, contingency/security analysts, planners). This will be necessary in addition to this same extent of coordination during execution of V&V testing.

4.2 Verification

In this study, "verification" refers to demonstration that the FSM system operates as designed. It is essential that the verification test requirements for the FSM system carefully test limiting conditions for the models and simulations used in light of the complex dynamics that will be simulated. These limiting conditions need to include those which test limits of any rule-based or heuristic software modules within the FSM system