A ROADMAP FOR DEVELOPING REAL TIME DISTRIBUTION SYSTEM SIMULATION TOOLS FOR THE SMART GRID

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ABSTRACT

Development of distributed generation, energy efficiency and demand-side management measures, economical and technical constraints to meet the performance targets fixed by the regulatory bodies are just some of the new challenges facing distribution system operators in the Smart Grid development context. Simulation capabilities are playing a major role in the distribution business improvements needed to meet these new objectives. For instance, simulation is providing support to develop the functionalities associated with the self-healing grid concept.

This article describes a roadmap for fast simulation and modeling tools applied to distribution systems. A survey of key industry experts was conducted to identify the main drivers for improving simulation and modelling functionalities and to determine the most likely path that evolution will take. The results of this roadmap are intended to provide a high level view of the functionalities that will be needed in the next 10 years to enable Smart Grid operation. These functions will be enabled by developments in various technical areas, providing solid foundations to build on. This roadmap identifies technological gaps and new software/hardware solution needs, It is focused on the future developments in these areas.

INTRODUCTION

Distribution network operators are facing new challenges such as the direct consequences of the liberalization of the electricity market and the preparation for a sustainable future. Regulatory bodies are now established and are playing a major role in the interaction between the different actors of the system. They fix power quality targets that network operators have to balance with their economic issues (investments, maintenance, and operation) to improve their own efficiency. The development of distributed generation, which was formerly considered by network operator as a constraint, is now also seen as a potential resource for network and global system operation. Energy efficiency and demand-side management measures are becoming increasingly important and network operators have to deal with them and use them, if possible, to maintain the power reliability and equilibrium for the global system.

All these elements are taken into careful consideration by network system operators as new challenges and they are changing their processes and visions to take advantage of progress in technology and research to integrate these new stakes. Simulation capabilities available to the operators play an important role in these improvements by providing new perspectives on network operation with new possibilities for "what if" analyses and on network development with more accurate models.

In order to support these developments, the "Fast Simulation and Modeling" (FSM) project of the EPRI IntelliGrid Consortium is developing the concept of a suite of tools designed to provide the mathematical foundation and a high performance "look-ahead" capability for a self-healing grid – one capable of automatically anticipating and responding to power system disturbances while continually optimizing its own performance. DFSM tools provide aid in decision-making by permitting an operator to optimize grid operations as well as predict grid behavior based upon historical and real time data.

The approach taken by IntelliGrid is not to develop products but to use software and equipment solutions available today and identify new software and hardware solutions needed in the future. All tools would work in an integrated and open environment to achieve the functions necessary for FSM. For instance, EPRI is in the process of structuring the Distribution System Simulator (DSS) software system as an open source software that can be the basis for advanced simulation tools. This software development is also being coordinated with a Department of Energy effort to develop an open source platform called GridLab-D. These tools are particularly designed to incorporate distributed resources and demand response as part of the normal operation of distribution systems.
The first stage of this work has developed functional

requirements and cost-benefit analysis. It has also been documenting the lessons learned from these new features by applying them in demonstration projects.
The second stage of this work will contribute to the integration of the many components that form this open platform. One important stage in this plan is to create a roadmap of these advanced functions.

OBJECTIVES AND APPROACH

The objectives followed through this effort are intended to provide a concise overview of the FSM functionalities identified in the first stages of FSM and propose to the electric industry the first roadmap of these functionalities in the next 5 and 10 years. This work complements the functional and technical requirements of the Distribution Fast Simulation and Modeling tools with a clear picture of the main drivers for change and their expected impact on the key components of Fast Simulation and Modeling tools.

The main questions that are addressed in this roadmap are:
(1) What will be the main drivers for evolving grid operation and planning both for transmission and distribution operation?
(2) How these drivers will shape the basic need of FSM functionalities?
(3) What functionalities will come in the next 5 years?
(4) What functionalities are likely to appear in the next 10 years?
(5) What are the main paths of the evolution of these functionalities?

A survey of some of the main experts of the industry was conducted to identify the main drivers of simulation tool evolution and to measure the most likely evolution of the Fast Simulation and Modeling functionalities. A synthesis of the answers received was compiled and shared with the participants of the study during a workshop where a first draft of the roadmap was presented and discussed.

Based on these materials, a first step is to identify the scenarios of evolution for networks by taking into account the most important drivers of evolution highlighted by the survey and classify them to build scenarios. In a parallel way, some analysis needs to be made on the key functionalities in order to develop a short list of those which appear to be the most critical for the evolution of the system. The next step is to unify those two results by forecasting how the key functionalities will evolve within the evolution scenarios based on a qualitative analysis on the way the drivers may impact the functionalities. As a complementary step, a review of the way FSM capabilities can provide a substantial contribution to the evolution process needs to be assessed for each of the functionalities. Based on these elements an analysis to identify possible common contributions can then be performed, last step before the creation of the roadmap itself.

FSM FUNCTIONNALITIES

FSM functionalities are resources that achieve operational functions for end-use applications. The diagram in Figure 1 presents this integrated view of the DFSM functionalities as identified in the previous stages of the project.

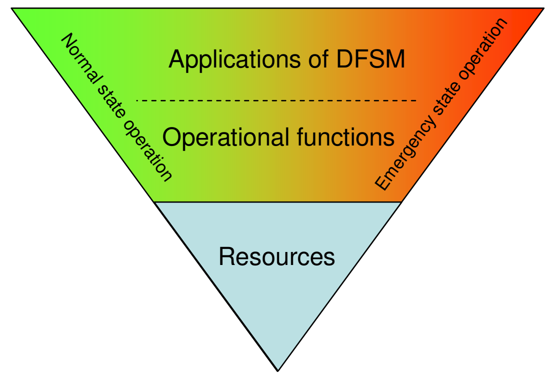

Figure 1: DFSM functionalities

The triangle shows the broad end-use application of DFSM (Expansion planning, Maintenance scheduling, Market management, Scheduling and dispatch, Security management), the necessary operational functions (Fault location and isolation, Grid reconfiguration, Voltage and reactive power control, Protection relay coordination) and the resources needed to achieve them (algorithms, modeling, simulation, visualization).

Real-time operation has very different constrains and requirements depending if the system runs in normal state or in emergency/recovery state. Normal state operation implies preventive actions, with a longer time response and mostly can be automated. The transformation of this mode of operation could aim to be on 'autopilot' with minimal human intervention. The associated functionalities are presented in Table 1.

Emergency/recovery operation implies the application of pre-defined sequences combined with human decision-making that cannot be easily automated, at least at the beginning. Ultimately, some of key functionalities that fold into these categories would be transformed to automatic actions and so become part of 'normal state operations'.

Transmission operation and distribution operation are not alike. Many differences could be pointed out: the size of the network handled by tools, the time response and the risk associated with the area covered, the differences of responsibilities in itself (load/generation balancing for instance). So these two sectors of the electric delivery should have their need addressed specifically.
On the other hand, many similarities exist in distribution

and transmission operation: similar basic responsibility (fault isolation and grid reconfiguration even if the resources are not the same), tools that rely on the same principles (load flow, performance indicators …). Several expected changes in grid operation might also change this distribution of roles among transmission and distribution thus narrow the distance between the two sectors. Examples of factors that are in favor of that argument include increased penetration of distributed generation at distribution level, appearance of active distribution network, multiplication of advanced monitoring technologies on the grid and ubiquitous communication infrastructure for both transmission and distribution grid.

Normal applications	DFSM Functionalities
Expansion planning	Planning tools, Load/generation economic modeling,
Maintenance scheduling	Integrated database, System modeling, Optimization of settings for local and coordinated controls
Market management	Electricity price forecasting: price simulation, volatility and performance analysis
Scheduling and dispatch	Load modeling, Modeling of margin and assessment of limits
Security management	State estimation, Contingency analysis, Look-ahead analysis, Aggregation of resources, Integrated advanced monitoring, DER Monitoring and Control
Fault location and isolation	Load forecasting, Pre-arming optimization of remedial action schemes
Voltage and reactive power control	Optimization of settings of controls, Equipment and system modeling

Table 1: Normal state applications

FSM ROADMAP

Industry survey and workshop

In order to create a roadmap for FSM functionalities, a survey has been conducted to collect an assessment from the industry of the need and priority of the FSM components. Three main sections composed the questionnaire (1) Drivers for FSM, (2) Transmission FSM functionalities, and (3) Distribution FSM functionalities. The survey was sent to 63 individuals that represented 34 utilities, 9 vendors, 2 Independent System Operators, and 16 R&D entities or consultants. The survey was sent by email and calls were made to most of the individuals to explain the purpose of the survey and verify that the material was properly received and understood.

Fifteen individual answers to the survey were collected representing 11 electric utilities, one Independent System Operator, one vendor, one consultant and one research organization.

After this survey phase, a workshop was organized in Palo Alto on July, 26th 2007. The objectives of this event were to (1) present the results of the survey on FSM functionalities, (2) share views on the priorities that the industry should tackle in the next 10 years in regard of FSM capabilities (for both T&D), and (3) develop a first version of FSM roadmap for T&D operations.

A total of 28 representatives attended the workshop including 12 utilities, 7 research companies, 4 universities, 3 vendors and 2 consultants. In order to meet its objectives, the workshop program was structured around both technical presentations and brainstorming sessions. The discussions and technical inputs resulting from the brainstorming sessions yielded very good materials for defining and reviewing the roadmap on the evolution of the T&D functionalities for the next 5 to 10 years. Some discussions on the next steps and activities provided very good guidance to the project, including: (1) concrete implementation of functionality (incremental approach), (2) identification of gaps in the state of the art, and (3) valuation of system reliability, the business case, and data needed.

Key distribution functionalities

The objective of this process is to make a short list of the most important functionalities to consider in the analysis based on the industry survey. The survey results for the Distribution Fast Simulation and Modeling functionalities clearly indicates a strong correlation with the importance of the functionalities and the effort needed in a 5-year time frame. The resulting functionalities to consider for the distribution systems are the following:

- Fault location and isolation
- Substation reconfiguration
- Load forecasting and modeling
- Contingency analysis and visualization
- Look-ahead analysis and visualization
- Volt/Var control at substation
- Protective relay coordination
- Intelligent alarms
- Circuit reconfiguration including islanding
- State estimation

Drivers of evolution

The survey and workshop results allowed the identification of the most important drivers that the electrical networks will have to cope with in the coming years. They are:

- Transmission and distribution operation closer to the thermal, mechanical and electrical limits: this reflects the difficulties and barriers to developing new transmission network capacity, the need to manage the congestions on transmission and distribution networks and identify solutions that could defer investments.
- Increased use of Intelligent Electronic Devices: more and more sensors will be made available by vendors to monitor the network state in both transmission and distribution areas such as phasor measurement units or advanced meters.

An additional driver not ranked among the most important is the increased penetration of Distributed Energy Resources. However, depending on the context of regulation and/or governmental orientations, it could have a strong impact on the way the distribution and transmission networks will operate in the future. In order to reflect this element, this driver was classified as a differentiation driver to be taken into account in the process of defining the scenarios of evolution on a mid-term basis.

The workshop participants reach consensus on another driver that was not initially listed in the survey: The coordination of Transmission & Distribution operations, which can be considered as cross-cutting issue allowing system wide efficiency of distribution or transmission operations. It can be applied to most of the Fast Simulation and Modeling functionalities such as state estimation or fault location and isolation.

Building scenarios

The characterization of the main drivers identified will define the 5-year evolution scenario (the red scenario) and can be assessed by the following assessments:

- Transmission and distribution operation closer to the thermal, mechanical and electrical limits
    - Operator must have an accurate assessment of the state of the network (condition, risks, …)
    - Operator must have forecasted alternatives and scenarios to react to contingencies
    - System must react autonomously with reflex controls to mitigate fast phenomena
- Increase use of Intelligent Electronic Devices
    - Energy management systems must handle data from various sources (coming from thermal, mechanical, electric sensors) in an integrated manner and make it available to simulation tools
    - Processes and practices to operate grid must adapt to the new resources and capabilities of the system

The differentiation drivers can then be used to define alternative 10-year frame evolution scenarios depending on the way their associated characterization will evolve:

- Increased penetration of Distributed Energy Resources: differentiation can be made on the way the capacity of Distributed Generation and Distributed Energy Resources will grow, following the historical trends for a given area or meeting the objectives in terms of installed capacity. At this stage, this evolution is closely dependent on non technical issues and will rely mainly on governmental or regulatory orientations which can evolve in time. The scenario associated with a growth of DG and DER installed capacity meeting the governmental targets is identified as the green scenario.
- Coordination of Transmission & Distribution operations: differentiation can be made on the information exchange and automated coordinated actions level. The scenario associated with the significant enhancement of these two aspects is identified as the blue scenario.
    - Improve information flow to better prevent and predict the grid state and events (real time, planning, maintenance) in the exchange of information between system operators
    - Improve the number of planned coordinated actions in order to react faster to various unexpected events

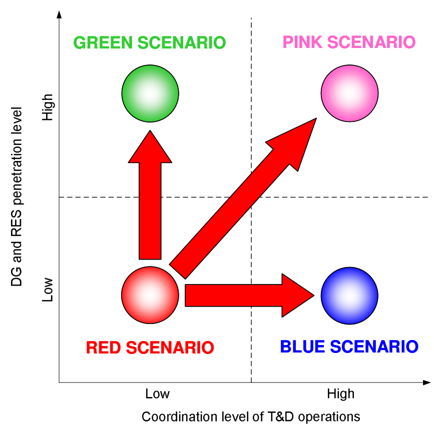

Figure 2: Identification of the scenarios

Evolution of the key functionalities

In order to identify the functionalities that are the most critical no matter which scenario is considered, it is necessary to assess qualitatively and quantitatively the impact of a given scenario on the functionalities. This step will be achieved by assessing qualitatively the impact of the scenario and then define a ratio for each scenario based on this assessment applied to the corresponding survey score. Figure 3 presents the impact of the scenarios on the distribution key functionalities.

Once this analysis has been achieved, each functionality needs to be characterized depending on the way it will be impacted by each scenario (equally, with small or strong differences). This step will be achieved by the calculation of the Behavior Compliance Parameter for each of the functionalities and defined as follow:

$$BCP_f = \frac{Average(SR_i) - AverageDeviation(SR_i)}{Average(SR_i)}$$

(SRi represents the forecasted Survey Result evolution for the functionality f in the red, green, blue and pink scenarios)

This parameter will be equal to 1 if the behavior of the functionality remains the same no matter which scenario is considered. Figure 4 presents the results for DFSM. The highest ranked functionalities will then be selected to achieve the roadmap process and define the contribution of Fast Simulation and Modeling to improve their development. They are the following:

- Load forecasting and modeling
- Contingencies analysis and visualization
- Look-ahead analysis and visualization
- Grid reconfiguration including islanding
- State estimation

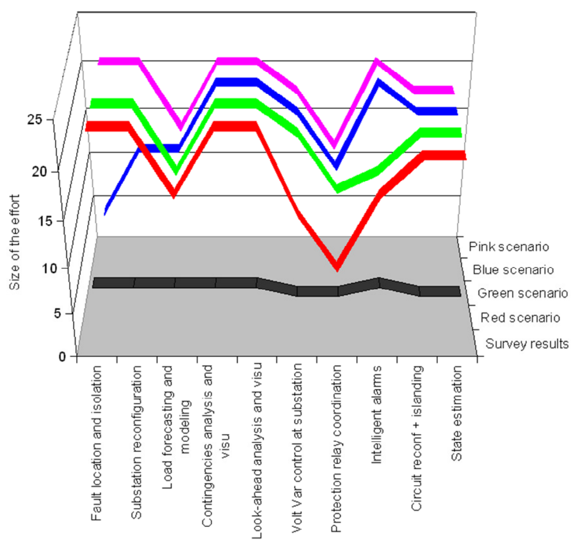

Figure 3: Scenario impact on the DFSM functionalities

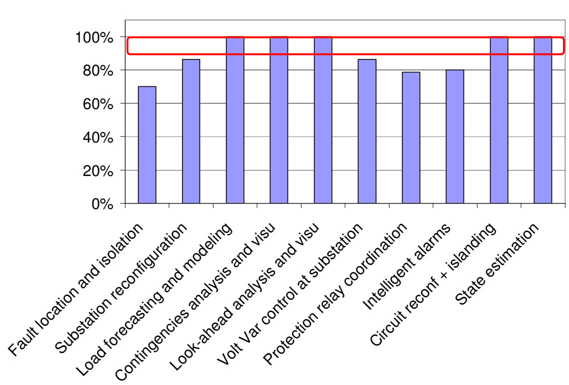

Figure 4: BCP values for each functionality

DFSM Contribution

This section presents for each of the identified functionalities the present state of the art and 5- and 10-year projections for the future state of the art. It also identifies the contribution that activities in the field of Distribution Fast Simulation and Modeling could bring to support these evolutions.

Grid reconfiguration

- State of the art: Grid reconfigured manually or remotely by operator based on experience, some grid reconfiguration local controls deployed
- Evolution in five years: Grid reconfiguration scenarios suggested to operator by modeling and simulation tools
- DFSM contribution: Enhance existing algorithms (load-flow) to integrate results from other applications and use more dynamic models based on real time data; Provide accurate results that will help the operator making decision with the maximum elements available
- Evolution in ten years: Grid reconfiguration scenarios take into account demand-side management and distributed generation
- DFSM contribution: Integration of real time information and forecast associated to DER production and DR issues (dynamic models, quick calculation steps); integration of the information coming from the transmission side to help finding the most reliable solutions.

State estimation

- State of the art: Distribution state estimator at early stage of research and development
- Evolution in five years: First prototype of distribution state estimator in control center
- DFSM contribution: Large amount of data coming from different sources (AMI) management and integration (architecture to retrieve data and make it available to DSE software); new algorithms for taking advantage of all the measurement available in order to go to a state solver instead of state estimator
- Evolution in ten years: Distribution state estimator as an option in distribution management system
- DFSM contribution: Algorithms integrate DER measurement and models; integration of dynamic models including DR capability; exchange of information between control centers and high level information exchange with the TSO level.

Look-ahead analysis and visualization

- State of the art: Handful of look-ahead analysis projects (based on load-flow); look-ahead taken into consideration in daily planning using simple assumption
- Evolution in five years: Several look-ahead analysis projects (based on load-flow); simulated look-ahead

tested in daily planning

- DFSM contribution: Look-ahead analysis correlated to the first state estimation prototypes : definition of the information to be exchanged
- Evolution in ten years: First look-ahead analysis calculation linked to state estimator tested
- DFSM contribution: Need perform the analysis faster because of the increasing number of parameters to deal with; the link between state estimation results and look-ahead analysis is clearly established; look-ahead algorithms integrate DER models variations; define a model to simulate the transmission level behavior and a way to exchange results.

Contingencies analysis and visualization

- State of the art: Contingencies analysis based on operators experience
- Evolution in five years: Minor evolutions in contingencies analysis: first modules available
- DFSM contribution: Evaluate different algorithms to perform these analysis with as much detailed models as possible and connect to the first state estimator prototypes for data exchanges
- Evolution in ten years: New computer-aided contingencies analysis solutions for distribution operation
- DFSM contribution: Integrate the impact of DER on the system in the algorithms with suitable models; define the structure and nature of information to be exchanged between different simulation area in order to take into account the induced effects and provide high level results

Load modelling and forecasting

- State of the art: Load models based on types of customers, weather forecast
- Evolution in five years: Detailed load models and loss forecasts (Figure 5) calculated based in most cases on real energy consumption (AMI), specific models and profiles added on demand-response behavior
- DFSM contribution: Enhancement of the existing load models including more detailed electrical behavior and other characteristics (economical, risk) thanks to AMI data integration; integration of algorithms to deal with new data available and definition of the results
- Evolution in ten years: Load models and forecasting based on real-data with precise profile including various rates/demand-response schemes; high accuracy (example 10 min error lower than 1%)
- DFSM contribution: Define dynamic DER detailed models that would include time-based, frequency-based behaviors and DSM management; definition of a high level precise model layer (including uncertainties evaluation) to exchange information between transmission and distribution systems; define dynamic detailed models that would include time-based, frequency-based behaviors and DSM management as well.

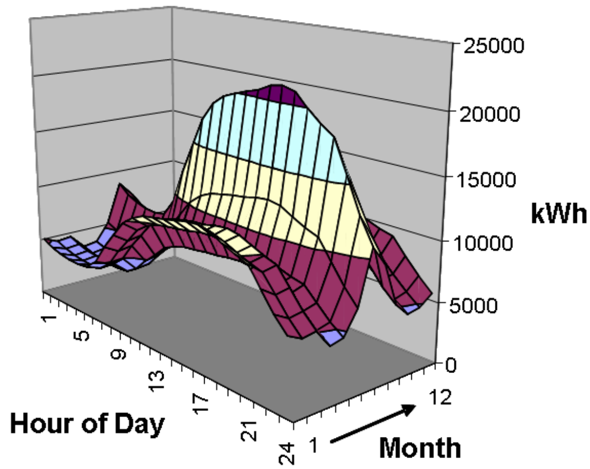

Figure 5. Annual energy loss shape from 8760-hr load modelling

Roadmap

Figure 6 presents the aggregation of the previous results in the form of a roadmap for Distribution Fast Simulation and Modeling tools. The resources part is derived from the common characteristics and elements identified in the different DFSM contributions analysis.

CONCLUSION

The development of Fast Simulation and Modeling functions is key to support the self-healing characteristic of the Distribution Smart Grid. This paper has identified the most critical functionalities needed and their foreseen development in the future years with the support of Fast Simulation and Modeling projects.

The objective of this roadmap exercise is to provide a vision to indicate what new functionalities are to be developed by vendors to answer the forthcoming needs.This work also helps to coordinate the efforts among worldwide research organizations and utilities in the Smart Grid deployment efforts currently being done. Examples of such coordination activities are:

- EPRI Intelligrid – EDF R&D common efforts to develop distribution state estimation concept, prototype and deployment conditions,
- Pacific Northwest National Laboratory coordination efforts among the GridLab-D simulation platform which focuses on expanding the scope of existing models to all power system business areas and on combining engineering and economic market models.
- EPRI Distribution System Simulator (DSS) software being released in open source community coordinated with Department of Energy Research project being

conducted by Enernex NexPower to develop an open source integration platform based on standard and open interfaces for distribution simulation tools.

Naturally, this approach is anticipating standardization efforts that will keep applications open to data exchanges. This roadmap is not intended to provide a static vision for the evolution of simulation tools and activities and will be updated on a regular basis to refresh the state of the art and foreseen perspectives associated with the functionalities that will provide self-healing capability to the future distribution networks.

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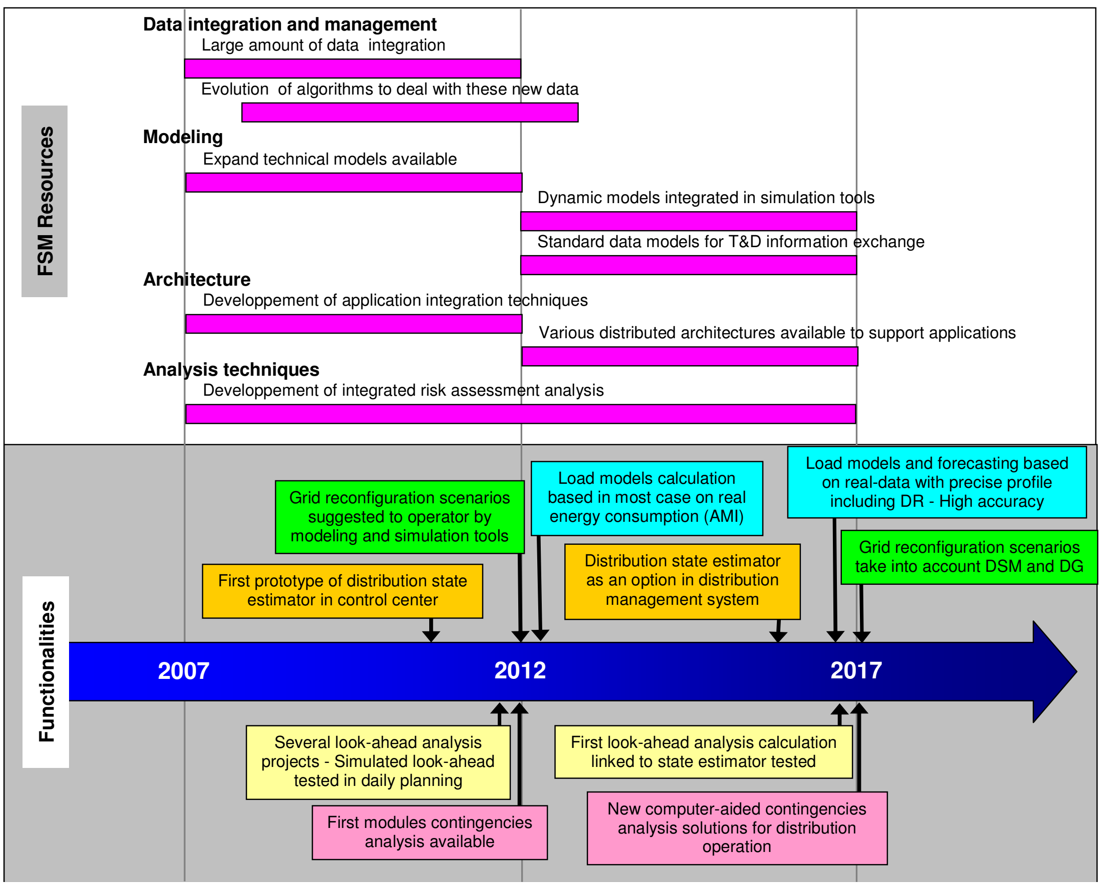

Figure 6: DFSM Roadmap