A Data-Driven Approach to Interactive Visualization of Power Systems

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***Abstract*—Information visualization appears to be a promising technique for improving the business practices in today's electric power industry. The legacy power system visualization tools, however, restrict the visualization process to follow a limited number of pre-defined patterns created by human designers, thus hindering users' ability to discover. This paper proposes a data-driven approach to interactive visualization of power systems. The proposed approach relies on developing powerful data manipulation algorithms to create visualizations based on the characteristics of empirically or mathematically derived data. Based on this approach, a data-driven model exploratory tool has been developed to enable users to visualize the power system's physical/electrical configurations at various levels and from different perspectives. The conducted case studies have demonstrated that the data-driven approach could result in an interactive and user-driven power system visualization tool that fosters scientific understanding and insight, therefore unleashing the power of visualization.**

***Index Terms*—Common Information Model (CIM), data-driven, interactive visualization, one-line diagram, pattern matching, power system visualization, situational awareness, Smart Grid, visual analytics.**

I. Introduction

As Smart Grid technology becomes ubiquitous, there is a compelling need for new tools to assist power system operators and analysts to perform critical and complex tasks. Information visualization has proved to be one of the effective techniques for meeting the emerging business requirements. It involves visual representation of large-scale collections of information and use of graphical techniques to help people understand and analyze the data. More specifically, the technique relies on the creation of images, diagrams, and animations to promote the communication and interpretation, enhance the recognition of patterns, and perceptually monitor a large number of potential events. This technology, as demonstrated in the following two business-driven use cases, can be effectively applied to improve the business practices in today's electric power industry.

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Use Case 1: Operation of large power system has become increasingly complicated. For secure and optimal operation of a large transmission system, system operators in a control center must monitor and analyze large amounts of information from different sources and respond to problems before disruptions can arise. This challenge is further intensified by the realities of an aging workforce. Recognizing the urgency, Federal Energy Regulatory Commission (FERC) has recently recommended enhancement of situational awareness as one of the four priority applications in its Smart Grid Policy Statement [1]. In Europe, following the recommendations [2] by the Union for the Co-ordination of Transmission of Electricity (UCTE), European Network of Transmission System Operators for Electricity (ENTSO-E) is working on development of the European Awareness System that allows Transmission System Operators to share the information beyond their own areas of control and understand the evolution of the overall system. In the context of power system operation, situational awareness means understanding the current environment and being able to accurately anticipate future problems to enable effective actions. It can be accomplished by two correlated methodologies:

- supporting operators' abilities to maintain situational awareness by developing decision support analytical applications;
- timely presenting relevant information in a way that reduces cognitive demands on operators.

The emerging field of visual analytics, which combines analytical reasoning with interactive visualization, appears to be promising in addressing this requirement.

Use Case 2: To support power system operation, planning, and other business practices, engineers in a utility organization must analyze a large amount of information. For example, at BC Hydro, engineers need to analyze the neighboring utilities' network models to ensure that the external networks have been properly modeled in their Energy Management Systems (EMS). The traditional manual methods of data analysis, such as spreadsheets and ad-hoc queries, have proved insufficient to help analysts capture the patterns and insights from large and complex data sets. Experiences have shown that humans can absorb and analyze visual information much more quickly than they can absorb data in traditional presentation formats such as tabular displays [3]. Visual presentation of data facilitates information exploration and enables knowledge discovery. It makes it easy for utility analysts to discover the business intelligence that can be taken advantage of for improving the efficiency, saving the cost, etc.

Power system visualization is not a new concept. The related researches have been conducted for decades. A variety of power system visualization applications have been developed for different purposes, ranging from real-time monitoring to analytical result interpretation.

Traditionally, visualization of power system operation is provided by EMS designed to monitor, control, and optimize the performance of generation and transmission systems. Typically, EMS vendors provide tools for utility clients to design the graphical displays that show the real-time information and estimated data on the network diagrams to help system operators intuitively monitor the power system operating conditions at a control center [4]. Building and maintaining these graphical displays is quite labor-intensive. This is because transmission grids are large in size. Thousands of displays may be needed to monitor the details of the grid operation. The real problem of these visualization applications, however, lies in their designer-driven approaches. In these legacy EMS applications, visualization designers determine what should be of interest, and users are restricted to only viewing the visual representations pre-designed. While the pre-designed visualizations provide consistent system views familiar to users, the designer-driven approach has fundamentally restricted users' ability to explore and consequently to make effective and corrective control decisions [5].

The conducted investigation has revealed that the fundamental problem inherent in the legacy EMS visualization tools is resulted from their designer-driven visualization approaches, which significantly increase the cost of using these tools and restrict users' ability to discover. It is discovered that a data-driven approach will fundamentally overcome these shortcomings. A data-driven approach relies on developing powerful data manipulation algorithms to create visualizations based on the characteristics of empirically or mathematically derived data.

Recently, the data-driven approach to power system visualization has been investigated and consequently resulted in new control center visualization tools [5]. More specifically, researches have been conducted on dynamically creating power system visualizations using power system information along with geographic information imbedded in the power system model. The proposed "pseudo-geographic" approach enables geographically-based visualizations to be dynamically created to display the desired power system quantities over wide geographical regions. The approach also provides users with an ability to customize the dynamically-created displays to meet their specific needs.

While research conducted in [5] has resulted in significant progress in the field of data-driven visualization of power systems, its focuses have been put on displaying the data to facilitate interpretation of data and implementation of a software tool. This paper extends the research conducted in [5] with a more extensive investigation of the data-driven visualization approach and its potential applications in the electric power industry. The paper focuses particularly on applying various data-driven approaches for interactive visualization of power systems. As demonstrated in the use cases, exploratory data analysis requires a human analyst tightly in the loop to seek useful information from large volume of data. This generally corresponds to the capability of creating the visualizations dynamically in response to users' requests. A data-driven approach is well-suited for interactive visualization, because it enables visualizations to be generated on demand to display the underlying characteristics of the data. The approach puts the users rather than applications in the driving seats, enabling them to explore the information at a will of their own. It yields the power of visualization to users.

To demonstrate the potential of the proposed data-driven approach to interactive power system visualization, a case study has been conducted to build a user-driven model exploratory tool. Built upon Common Information Model (CIM), an open industry standard, the model exploratory tool enables users to visualize the power system's physical and electrical configurations at various levels and from different perspectives. A variety of data-driven techniques have been applied to auto-generate the high-quality visualization displays, such as query-driven generation of network diagrams and layout of the generated substation diagrams based on pattern matching, etc. Furthermore, by leveraging the latest-and-greatest information visualization technologies and open industry standards, the designed model exploratory tool is aimed to deliver a rich user experience and provide a standard-based visualization solution that can be seamlessly integrated with the existing utility information infrastructure.

II. Data-Driven Visualization of Power Systems

This section explores how various data-driven visualization techniques can be leveraged to address some emerging business requirements in today's power industry.

A. *Visual Analytics and Interactive Visualization*

During the last decades, advances in scientific and business data collection have generated a flood of data and information. Such volumes of data and information clearly overwhelm the traditional manual methods of data analysis, such as spreadsheets-based approaches. New methods and tools which can intelligently and automatically transform data into visual presentations to facilitate the knowledge discovery are the subject of the emerging field of visual analytics. Visual analytics is defined in [6] as "the science of analytical reasoning facilitated by active visual interfaces." It is motivated by the need to gain understanding of features, trends, and anomalies present in large and complex data set.

Visual analytics is a multidisciplinary field that includes many focus areas. One of these areas involves interactive visualization, which studies how humans interact with computers to create graphic illustrations of information [7]. The basic idea of interactive visualization is the integration of the human's outstanding capabilities of visual information exploration and the enormous processing power of computers to form a powerful knowledge discovery environment where both visual as well as analytical methods are intertwined. Most importantly, the user is not merely a passive element who interprets the outcome of visual and analytical methods but the core entity that drives the whole process.

B. *Data Driven: An Unrestricted Approach to Interactive Visualization*

One of the main characteristics of interactive visualization is the tight integration between human interaction and generation of visual presentations. Pre-defined visualization approaches provide limited interactivity, because these approaches restrict the information exploration process to follow a limited number of pre-defined visualization patterns created by human designers. This limits not only the expressiveness of a visualization approach, but also its applicability to different or similar visualization tasks.

Realizing this shortcoming, the research conducted has been focusing on seeking the state-of-the-art visualization techniques that are able to lift the restriction. The conducted investigation has revealed that a data-driven approach proves to be a generic and powerful technique to accomplish the established goal. This approach relies on developing sophisticated and powerful algorithms for manipulating the data under analysis and transforming it dynamically to feed suitable visualizations. A data-driven visualization uses empirically or mathematically derived data to formulate the visualization. In this case, a specific relationship between data values and the graphic elements is defined so that a graphic characteristic varies dynamically in some pre-determined fashion. This dynamical visualization approach enables users to explore at their own will, thus facilitating comprehension and discovery. Additionally, this approach formulates visualizations on-the-fly. It does not require a visualization design stage, thus completely eliminating or significantly reducing the cost for building visual displays.

C. Data-Driven Visualization of Power Systems

When applying the data-driven approach to support interactive visualization of a large, complex, and constantly-changing dataset, the tool designers must provide mechanisms to help users find and subsequently visualize the data that is deemed to be "interesting". However, it must be the users rather than the designers who define what the "interesting" data is. The focus of the investigation has been put on applying the proper data-driven techniques to address the emerging industry needs of power system visualization.

1) Query-Driven Visualization for Information Exploration: For different business purposes, engineers, planners, and other stakeholders in an electric utility must analyze various kinds of information. Interactive visualization facilitates this information exploration process and enables the knowledge discovery. However, as analyzed in the previous section, the pre-designed visualization tools lack user-driven interactive ability. Such a designer-driven visualization tool is just like a database providing none or limited query support. It significantly restricts users' abilities to explore and subsequently to discover. Users are the best information explorers. They should be the driving force of this exploration process. The conducted research has revealed that query-driven visualization proves to be an effective technique that can be leveraged to accomplish this goal.

Query-driven visualization, combining the data management technology and the data-driven visualization technique, enables users to limit the visualization to the "interesting" data. Users define the "interesting" data using formulated queries [8], [9]. Several factors contribute to the overall motivation for the query-driven visualization approach. As data grows larger and more complex, simply building larger, more scalable visualization systems produces a greater amount of output, which in turn increases the cognitive load on the viewers. In some cases, increasing the amount of visible output may actually hinder understanding. Similarly, with increasing data size and complexity, finding and displaying relevant data becomes increasingly important to foster scientific understanding and insight.

Query-driven visualization focuses on presenting "interesting data" in large, multidimensional collections of information. The technique provides design patterns for formulation of the "interesting data" definition, finding the "interesting data" quickly, and effective visual presentation of "interesting data". Query-driven visualization is well suited for performing analysis and visualization on datasets which are both large and highly complex.

2) Event-Driven Visualization for Situational Awareness: Operation of large power systems has become increasingly complicated. In a real-time operation control center, system operators are confronted with an enormous amount of information. The information that needs to be monitored and analyzed reside in different utility information systems. It is extremely difficult to interpret the diversified and discrete information within a short period of time to understand and anticipate the system operating conditions. An event-driven visualization tool will help system operators perceptually monitor a large number of events in a timely manner.

An event can be defined as "a significant change in state", or an extraordinary occurrence. For example, an outage on a transmission line is an event. The basic idea of event-driven visualization is to let users describe interesting aspects of the data by means of events and then adapt the visual representation of the data on occurrence of events [10]. The motivation of event-driven visualization is to shift the user into the focus by timely presenting relevant information, thus reducing cognitive demands on users.

The event-driven visualization technique involves three correlated parts: event modeling, event detection, and event presentation. In a general way, events can be described as special portions of a data set complying with certain conditions and constraints. Event detection is quite domain-specific. At its simplest form, it can be formulated as a condition or a constraint, such as "The transmission line flow (MW) exceeds seasonal ratings or limits of the equipment." Event presentations focus on visualizing events, rather than the data. It is fundamentally based on query-driven visualization with emphasis on presentation and illustration of events. The goal is to help users perceptually monitor abnormal events. In the above limit violation case, for example, in response to the detected event, a visualization display can be auto-generated to display the location of the over-limited transmission line and intuitively illustrate the limit-violation condition using graphical representations such as pie graph or bar graph, etc. Like most event-driven systems, an event-driven visualization tool relies on a publish/subscribe infrastructure for event detection and notification.

The event-driven visualization provides effective decision-support for performing time-critical tasks. It can be leveraged to enhance situational awareness in a control center environment, where system operators must timely monitor various kinds of events and respond to the problems before they deteriorate. However, simply creating visualizations to display events provides limited assistance, especially during an emergency when system operators at a control center may encounter an overwhelming number of events in term of alarms in their areas of responsibility. Because events are cascading in nature, a flood of resulting and redundant alarms may be introduced. A transmission line outage, for example, could cause over-limiting conditions on other lines, resulting in many over-limiting alarms. These alarms can be a source of confusion and distraction for operators, especially if the system events require immediate action. It has become clear that an analytical process is needed to identify the root cause of the alarms before presenting visualizations to operators. This analytical process, referred to as intelligent alarm processing, is designed to analyze the related alarms and extract the information that explains cause-effect sequences. Based on this event cause-effect analysis, visualizations can be created to shift the operators' focus on the root cause of alarms, such as transmission line outage, rather than distract them with the resulting side-effecting events.

3) Visual Data Mining for Knowledge Discovery: For decades, utility information systems have archived a huge amount of historical data for traceability and other purposes. Such information may contain hidden treasury. Based on mining of the historical information, discoveries can be made to promote the efficiency, optimize the operations, save the costs, etc. For example, based on the analysis of the historical feeder loading measurements, one can discover the patterns of loading changes, the so-called load forecast. The forecast loading patterns can be used to optimize the system operation. The traditional data analysis approaches, such as spreadsheet-based data analysis, provide little intuitions and tune to be too simple to be effective. There is an urgent need industry-wide for intuitive and sophisticated information analysis tools to enable knowledge discovery.

Data mining is the process of identifying new patterns and insights in data. As the volume of data collected and stored in databases grows, there is a growing need to identify important patterns and trends and act upon the findings. Insight derived from data mining can provide tremendous economic value, often crucial to businesses looking for competitive advantages and cost-saving strategies.

Visualization offers a powerful means of analysis that can help to uncover patterns and trends hidden in unknown data. However, visual methods cannot entirely replace analytic nonvisual mining algorithms. Rather, it is useful to combine multiple methods during data exploration processes. The new area of visual data mining focuses on the combination of visual and nonvisual techniques as well as on integrating the user in the exploration process [11], [12].

Visual data mining has proved to be a promising technique for enhancing the operational security and economy of power systems. Recently, Pacific Northwest National Laboratory has developed a tool to analyze phasor measurement unit (PMU) data for detecting abnormal behaviors of bulk power grids [13]. The tool relies on a data-driven technique to analyze large volume of time varying PMU data and calculate signatures or characteristics that can be used to identify typical patterns, atypical events, and precursors to a blackout or other undesirable event. The analytical results can be presented to domain experts graphically to enable them to gain insights and facilitate management of the grid. The tool also uses drill-down graphics to support the detailed investigations.

III. Case Study: Building a User-Driven Model Exploratory Tool

To demonstrate the potential of data-driven visualization, a case study has been conducted to build a model exploratory tool for multiple purposes in various utility organizations.

A. Objectives

For decades, the graphical notation of a one-line diagram has been widely used in the power industry. A one-line diagram is a simplified notation for representing a three-phase power system. It is used to graphically describe the network components and their physical/electrical connections. Traditionally, one-line diagrams are created by human designers. EMS and planning tool vendors normally provide tools for users to design these diagrams. Even with the help of these tools, it is very labor-intensive to build these diagrams, because a real-world power system may contain thousands of substations and a one-line diagram is needed for each of them. For a typical EMS project, a significant portion of the budget is spent on building one-line displays. It is also costly to maintain these manually-created one-line visual displays.

The objective of this case study is to build a general-purpose query-driven visualization tool that can automatically generate the high-quality one-line diagrams in response to user's query. This model exploratory tool was designed to support multiple business functions in an electric utility environment. Some of the identified business functions that have been put into practical use include:

- Facilitating power system model exchange—Utilities that exchange their operational/planning models can leverage this tool to understand different configurations of the power system in their neighboring utilities.
- Interpretation of analytical result—Analytical results, including planning, operational, marketing, etc., can be intuitively displayed on top of the generated network diagram to facilitate interpretation.
- Speeding up operator display building—For EMS display designers, this tool can perform the majority of the tedious work for them. All they need to do is simply adjust the auto-generated diagrams for better look-and-feel and then fix the adjusted to create operator displays.
- Assisting application development—A user-driven graphical tool will significantly facilitate development and debugging of network applications.

B. CIM-Based Model Visualization

Building a general-purpose model exploratory tool is a challenging task, especially in an electric utility environment. An electric utility organization normally maintains a variety of enterprise applications to automate business processes ranging from operation, planning, to management of assets, customers,

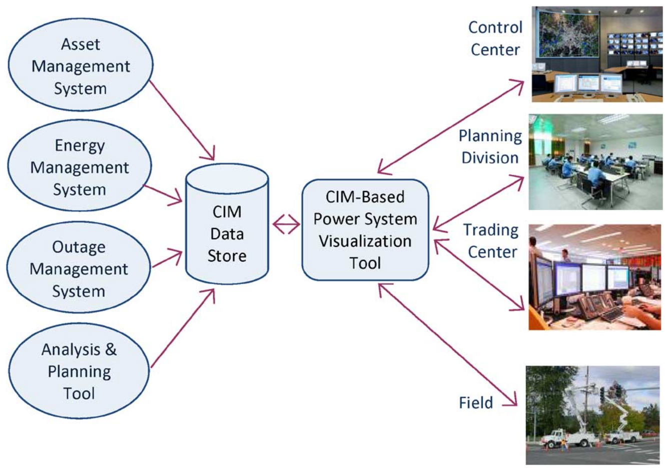

Fig. 1. CIM-based power system visualization.

outages, etc. These legacy applications, typically designed as discrete business functions, model a power system and its operation from their own business perspectives, resulting in a diversity of overlapped and sometimes conflicting information models residing in hundreds of incompatible formats. Building a general-purpose model exploratory tool requires heterogeneous information to be seamlessly integrated and intelligently organized.

To address the information integration issues in the power industry, the International Electrotechnical Commission (IEC) has been working on the specifications for interfaces to facilitate the interoperation of electric utility software from independent sources. A significant achievement of this effort is the creation of a CIM [14], [15]. The purpose of the CIM is to produce standard interface specifications for promoting information exchange and fostering collaborations among various utility enterprise applications.

Because CIM describes all aspects of a power system, it provides a standard-based semantic foundation for building a general-purpose model exploratory tool. One of the major benefits of a CIM-based model exploratory tool is its native interoperability. Because CIM is an open industry standard currently supported or to be supported by many utility information systems, a CIM-based power system visualization tool can be seamlessly plugged into the existing utility information infrastructure. Fig. 1 illustrates such a use case where a centralized CIM-compliant data store consolidates the information from various sources to feed a power system visualization tool designed for different stakeholders in an electric utility environment.

C. Data-Driven Auto-Generation of One-Line Diagrams

Auto-generation of a one-line diagram has been studied for many years [16], [17]. The focuses of these studies have been put on developing diagram layout algorithms. For example, three different layout diagrams have been investigated in [16]. The research has resulted in a Web-based application in the SCADA/EMS environment [17]. Typically, these one-line auto-generation studies and the resulting applications target for a particular type of audiences, such as system operators in a control center. The model exploratory tool is designed to address a more general issue: enabling users "see" structure in a graphed data set that is difficult or impossible to see in its raw form. Realizing that it is impractical to develop a one-fits-all algorithm that can auto-generate the one-line diagrams for different purposes, the research conducted has been focusing on applying various data-driven visualization techniques to auto-generate different types of one-line diagrams with emphasis on what the underlying data is.

The applied data-driven visualization technique involves presenting data by mapping the data to graphical elements and adapting the graphical elements to reflect the characteristics of the data. The key of this methodology is discovering the mapping and adapting patterns between the data and the graphical elements. Based on this discovery, various types of one-line diagrams can be generated to visualize the power system configuration and its operating condition. For example, a substation diagram can be created, showing the internal configuration within a substation where electric equipments are physically located and interconnected. The displayed equipment connection could be physical or electrical. In the latter case, the physical network connection (referred to as node-breaker representation) is simplified as an electrical configuration (called bus-branch representation) based on status of the switching devices. Other types of diagrams can also be derived from the network model to facilitate model exploration. A substation neighborhood diagram displays the selected substation and its connection to the neighboring substations. A line diagram illustrates how a transmission line connects two substations. Various types of solution diagrams can also be generated to interpret the monitored and analytical results. For example, flow limit diagrams highlight limit violating contingencies and interchange diagrams enable users to visualize the interchanges between two control areas.

To illustrate the applied data-driven visualization techniques, the remaining section will focus on two visualization algorithms: one for substation configuration diagram and the other for substation neighborhood diagram. While the methodologies for creating different types of diagrams may be different, they share the same underlying data-driven philosophy: generation of the diagram based on the characteristic of the data. In general, the problem can be formulated as: transforming a CIM-based model to a graphical representation and laying out the generated graphical representation in a way that facilitates interpretation. It can be accomplished using the following data-driven approaches.

1) Processing CIM to Support Query-Driven Visualization: In order to support query-driven one-line visualization, the underlying domain model, i.e., CIM, must be pre-processed. This will enable users to quickly find the information of interest. Specifically, the following processes are performed:

- Building model hierarchies and indexes: A practical CIM model is large in size. In order to allow users to conveniently and quickly visualize the data of interest, the CIM information is organized into different modeling hierarchies, which result in various navigation trees in the user interface, enabling users to explore the model from different perspectives. The hierarchy building is data-driven: i.e., the modeling hierarchies are created based on the internal relationships between entities. Furthermore, all of the modeling entities are indexed using a binary tree. This allows users to quickly find the information.

- Query support: To support the query-driven one-line diagram auto-generation, a query engine was developed to extract the relevant information from the model depository. It supports not only the generic query, such as "finding a modeling entity by ID or name", but also the complicated domain-specific ones, such as "finding all of the neighboring substations that are within two branches from the selected substation".

2) Transforming CIM to Graphical Representations: CIM describes all aspects of a power system, ranging from transmission, distribution, generation, to markets. Because CIM models the power system and its operation at fine granularities, a model transformation process must be applied to create the graphical model from the fine-granulated domain information model. This can be achieved by creating a logical view on top of the CIM-based information model. The created logical view transforms the fine-granulated CIM objects into reality-based graphical elements suitable for information rendering.

3) Laying Out Graphical Elements to Form the Diagram: The most challenging task for auto-generation of one-line diagram is how to layout the graphical elements in a way that facilitates interpretation.

a) Layout of substation configuration diagram based on pattern matching: Substation configuration diagram displays the equipments and their connections within a substation. Some substations contain hundreds of electric equipments and the physical connection configurations of these equipments could be arbitrary in theory. It is infeasible to develop a layout algorithm that could allow for all possible substation configurations.

The applied data-driven approach is based on the in-depth study of the real-world data. The goal is to discover the patterns and insights that can be used to layout the substation configuration diagrams. Although the substation equipment connection could be arbitrary in theory, there are a rich set of patterns that can be extracted from the human-designed substation one-line diagrams. These patterns fundamentally originate from the principles and philosophies of substation designing. Engineers do not design substation configuration arbitrarily. Instead they design substation configurations for specific purposes. These purposes result in many "configuration patterns" that can be leveraged for guiding diagram layout. Therefore, the problem of substation configuration diagram layout becomes a matter of "pattern discovery". More specifically, by studying human-designed substation one-line diagrams, the visualization developers extract dozens of substation configuration patterns, and then designed a layout for each discovered configuration pattern. At run time, the substation display builder engine will perform the following calibration processes to layout the substation configuration diagram:

- Overall Layout—The purpose of this process is to discover the "overall" layout pattern through a data clustering analysis. The process groups the graphical elements into hierarchical "Blocks" and places the Blocks based on the best-matching pattern.
- Block Layout—This process is designed to detail the Block layout, i.e., layout of the diagram within a Block. A rich set of template library has been built for this purpose. A sophisticated pattern-matching algorithm has been developed to identify the best-matching Block layout based on the network topology analysis within the Block. Fig. 2 shows a few samples of the discovered equipment connection patterns within a Block.
- Fine Tuning—The last process is to tune the generated diagram layout to enhance the diagram layout quality. For example, the positions of some graphical symbols and labels are finally adjusted to minimize overlapping.

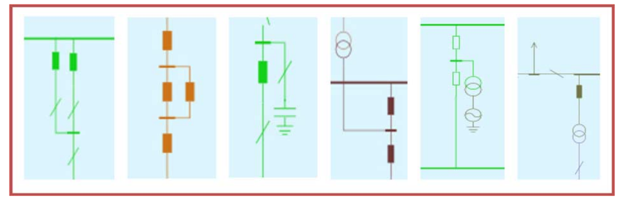

Fig. 2. Samples of equipment connection patterns.

The quality of the generated substation diagram layout has been tested using two reality-based network models, one containing about 1000 substations and the other containing more than 4200 substations. Fig. 3 displays one of these substations. Two independent tests were conducted to examine each substation diagram. Of all of the substations, about 94% of the diagrams passed the "high-quality" criterion, meaning no manual adjustment needed for visual clarity. The remaining 6% of the diagrams require users to adjust some parts of the diagrams by dragging-and-dropping the graphical elements.

b) Layout of substation neighborhood diagram based on force directed graph algorithm: Substation neighborhood diagram enables users to visualize a selected substation and the connections to its neighboring substations. The purpose of this diagram is to support the model exploration at a substation level. The diagram creation is user-driven. Users can specify the scope of the neighborhood diagrams, such as "displaying all of the neighboring substations that are within two branches". Furthermore, users can visualize the details of the selected substation through a popup or by navigating to the corresponding substation diagram.

While there are patterns for the layout of substation one-line diagram, layout of substation neighborhood diagram is practically arbitrary. Therefore, the pattern-matching approach does not apply here. The conducted study has indicated that a computer graph layout algorithm, called Force Directed Graph layout algorithm, can be applied for the layout of substation neighborhood diagram. This algorithm determines the position of each node in a graph by iteratively computing attractive forces between connected nodes and repulsive forces between all pairs of nodes. The goal is to find the "balancing" position for each node. Since the algorithm is based on physical analogies of common objects, like springs, the behavior of the

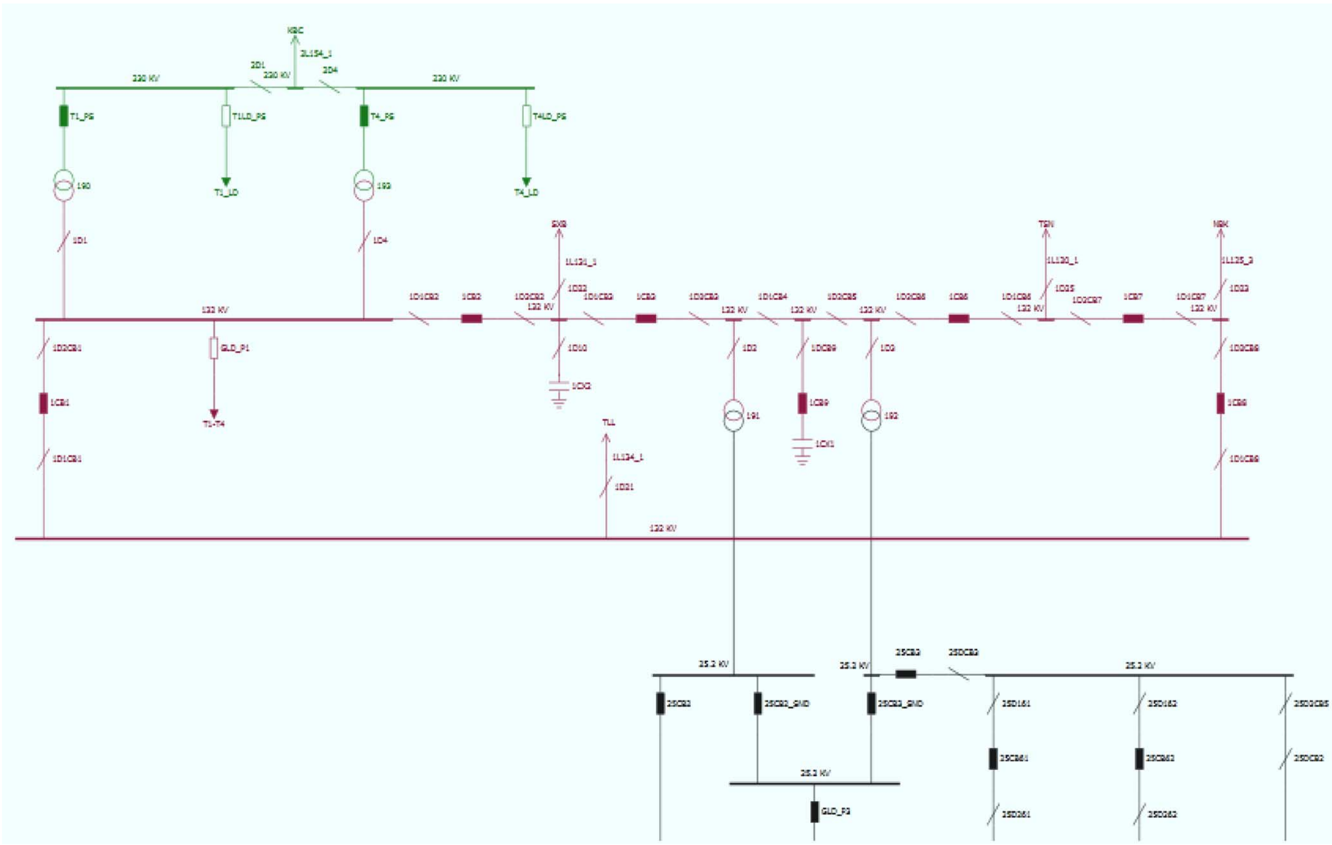

Fig. 3. Reality-based substation configuration diagram auto-generated.

algorithms is relatively easy to predict and understand, and the layout of the graph produces high level of clarity.

When applying Force Directed Graph layout algorithm, substations are modeled as “nodes” and connecting transmission lines are modeled as “edges”. The conducted experiment has revealed that the substation neighborhood diagram created based on this algorithm produces good quality: edge-crossing is minimized. This layout diagram is enhanced by modeling the “force” between “nodes” based on the line impedance values. Incorporating electrical distance in the layout process improves the quality of the substation neighborhood diagram, since it reflects the reality. Finally the quality of the layout is further improved by tuning the diagram layout based on some heuristic rules. Some substations positions need to be adjusted to minimizing cross-over and some labels need to be moved apart to avoid overlapping. Fig. 4 shows a substation neighborhood diagram with a popup displaying the detailed configuration of a browsed substation. Based on users’ suggestion, an interactive feature was later added to enable users to explore the substation neighborhood by expanding the diagram from the selected boundary substation one at a time. This interactive feature enables users to drive the visualization process at their will.

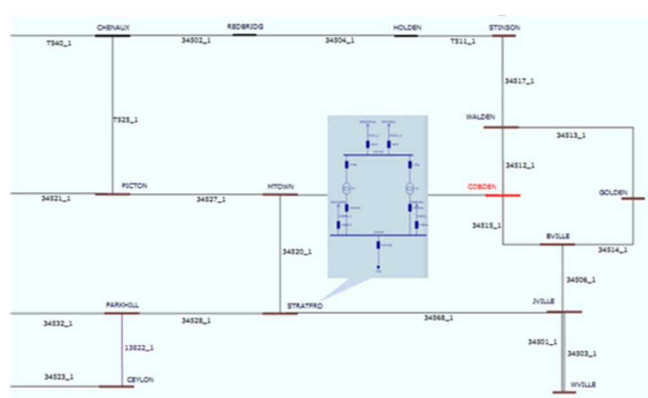

Fig. 4. Substation neighborhood diagram.

D. Implementation

The model exploratory tool is implemented as a distributed Web application, as illustrated in Fig. 5. Architecturally, it contains three tiers: a CIM-compliant data repository, a visualization server, and a Web browser based user interface (UI). The CIM data repository stores the model information extracted from various utility information systems. It could be a CIM-compliant database or a collection of standard CIM/XML files. The visualization server is a C++ application supporting Web Services. In response to users’ queries, it retrieves the model information from the CIM data repository, generates the graphical diagrams, and sends the diagram information to UI for rendering. The Web browser UI is based on Ajax,

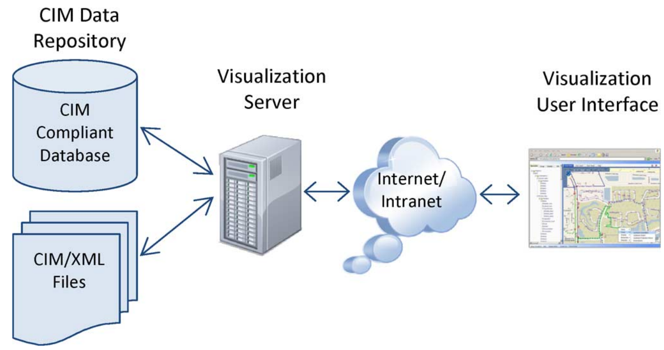

Fig. 5. Architectural overview of model exploratory tool.

a programming model for creating dynamical and interactive Web applications.

IV. Conclusions

Visualization is more than just displaying the data in a pre-designed format. A user-driven interactive visualizatixon tool will facilitate exploratory data analysis and enable knowledge discovery. This paper proposes a data-driven approach to interactive visualization of power systems. Application of the proposed data-driven approach has resulted in a model exploratory tool that has been practically used to address a variety of business needs in different utility organizations.

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