Future State Visualization in Power Grid

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***Abstract*—Electrical utilities are faced with a challenge of processing large amount of data and presenting operators with optimal amount of information, which identifies the essential and critical state of the grid. The data have to be in form, which can be easily consumed by operators and easily associated with functional and geographical knowledge of the grid. Most of the visual presentations in power systems are focused on real-time and historical rendering of information. In modern electrical utility environment, it is becoming important to visualize the information predicted for the future state of the power system. The software development work was performed in a large electrical utility of USA in order to enhance visualization of future power system state. The implemented features encompass advanced future state monitoring, transmission reliability index, dashboard, global system wide alarms, and rendering of the forecasted weather and power system state data on GIS maps.**

Keywords—visualization, GIS, map, power, reliability index, situational awareness, future, forecast, weather, violation, overload.

I. Introduction

The Energy Management System (EMS) is employed in electrical utilities for monitoring, control, and data analysis to ensure high reliability of grid operations. EMS provides real-time assessment of the current state of the power system and the effect of potential contingencies. The network security assessment functions in EMS are executed automatically on a periodic basis or triggered by the occurrence of pre-specified events. The essential results of the network security analysis are provided as lists of voltage violations, overloads, and instabilities, which may occur in case of contingency occurrence. The basecase for performing security analysis is usually derived from real-time state estimation at the current time point. The assumption is that the state of power system for the future time point when contingency takes place is the same as the current state of the power system. However, (n-1) “what-if” contingency analysis is certainly oriented on evaluation of the electrical state of the power system at a future time point when that contingency actually may truly take place, not the current time point. Thus, there can be an essential time gap between the basecase used by contingency analysis and the time when contingency actually happens, which may lead to inaccurate analysis if the state of the power system changes fast. The predictive analysis [1] was proposed to create the basecases for the near future states of the power system using planned outages, load, generation, and weather forecasts. The predictive security analysis provides results, which are more realistic for future “what-if” scenarios. The improved situational awareness allows grid operators effectively address the predicted voltage violations and overloads, which might not be even “visible” for traditional contingency analysis using only the current time point basecase.

There are well-established standards and advanced visualization designs [2], [3] for presenting results of real-time analysis in EMS, but displaying a future time state of the power system has not been yet developed, because predictive analysis is a relatively new territory for electrical utilities. The objective of this paper is to discuss possible alternatives of visualizing and monitoring the future state of electrical grid with detailed analysis of predicted results. The Geographic Information System (GIS) allows user to dynamically capture, analyze, and display geographically referenced information available in electrical utility [4]. For a long time, The GIS systems have been successfully used in distribution systems, and the interest to GIS presentation of transmission system is also currently picking up in the utilities. GIS delivers global viewing of all power system’s components displayed on the map with the ability of zooming on any particular geographical area of the network that needs to be examined in details. GIS software provides a built-in capability to display temporal datasets, visualize it through time, and animate the time enabled data on geographical maps. These features make GIS a good fit for displaying future states of power system on the maps. However, in order to accomplish the rendering of EMS applications’ solutions in GIS, the EMS data need to be periodically transferred to GIS database.

This paper describes a new visualization of future state grid assessment developed at Ameren, which is a large US electrical utility with a net capacity of 12,000 MW and 7500 miles transmission lines. The look-ahead analysis was developed as an application enhancement in GE Alstom’s EMS [1], and visualization of near-future estimation is a customized application based on ESRI’s ArcGIS.

II. Monitoring Future State on EMS Dashboard

The monitoring of future state in EMS has been accomplished through a dashboard, which displays global and essential information on the current and future states of the power system.

Predicted trends of violations can provide a basis for comparative evaluation of violations’ significance for operations. The dashboard display (Fig.1) provides a graphical presentation of the projections and trend analysis with advanced visual notification of deteriorating electrical conditions. The near-future time frame is set to the total of one hour with 15 min 15 min study intervals, i.e. 15 min, 30 min, 45 min, and 60 min look-ahead time points. As a matter of fact, the forecasts and subsequent look-ahead solution results are more accurate for a short time outlook and may deviate significantly for the future analysis beyond 2 hours, especially, if a power system's state changes fast in case of adverse weather conditions.

Two essential bar charts are shown on the dashboard: normal and emergency violations. For simplifications only ten worst violations are plotted. Also, two graphs monitoring future prediction are shown on the dashboard: total branch violation and total risk index. The total branch violation is the sum of violation percentage delta values over 100% (i.e. for 135% and 123% violations, only 35% and 23% values are summed up) to avoid unnecessary accumulation of 100% for each violated value. The parallel dashed line shows the alarm threshold value, which is a configurable parameter.

The red bell on the dashboard appears only if the Look-Ahead analysis raises a future state alarm. The objective of the alarm summary is to identify the future system conditions, which are significantly different from the real-time time point. The future state alarm summary can be viewed by clicking on the bell, which result in a popup display with the details of all alarms identified in the current execution cycle of Look-Ahead analysis. The following conditions will result in the alarm:

1) A new branch violation of the emergency line rating has been identified by Look-Ahead analysis. Only new emergency violations should result in the look-ahead alarm. If emergency violation has already occurred in the real-time, then this particular violation does not need to be included in the Look-Ahead alarm summary as it has to be dealt in the current time point.
2) The total branch violation of the normal line rating is above the configured threshold.
3) The total risk index, which is based on combination of contingencies' severity and probability is above the configured threshold.

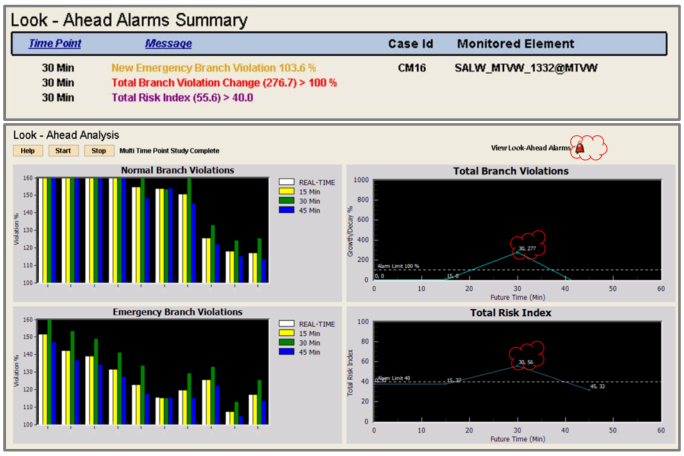

Fig.1 Monitoring of critical future state indications

The dashboard with plots and trends enhances situational awareness and provides a possibility of monitoring the adverse conditions developing in the power system. The operator's attention is drawn only to a "future global problem" through synthetic alarm identification [1]. However, the alarms, plots and even details of the violations do not provide global topological perspective that can be visualized on one single screen and be helpful in making fast operational decisions.

In order to evaluate and monitor the overall grid's "health", a transmission reliability index is introduced to combine the information on the system loading and violations to characterize the stress on power system reliability. It is assumed that a power system with no voltage violations and loading of all transmission lines below a user-defined S_o limit has the reliability index equal to the maximum value of 100. Any deviation from that normal operations reference point reduces the transmission reliability index by a certain calculated value. The following calculation is proposed as a measure for the transmission reliability index I_R based on the essential component factors affecting transmission reliability with appropriate small weight multipliers *a*, *b*, *c, d, e*.

$$I_R = 100 - (a_1 I_1 + a_2 I_2 + a_3 I_3 + a_4 I_3 + a_5 I_5) \qquad (1)$$

It is possible to extend the reliability index calculation with other components, e.g. voltage stability, transient stability, available reactive support, deviation from interchange schedule on tie-lines, available reserves. However, the objective of this implementation was a development of relatively simple calculations, which can be easily monitored in each cycle of real-time state estimation and *(n-1)* contingency analysis.

The I_1 component determines the power grid's loading stress relative to transmission capacity. The threshold value S_o is selected below 100%, which corresponds to the normal transmission line rating. The I_1 component is calculated for *n* transmission lines composing the grid, and the sign function *sgn* filters out the summation only for the lines where the actual loading S_i is greater than user defined S_{oi} limit in percent.

$$I_1 = \sum_{i=1}^{n} \frac{(S_{io} - S_i)}{2S_{oi}} [1 - sgn(S_{oi} - S_i)] \qquad (2)$$

The I_2 component determines thermal limit violations in basecase as a combination of total number of normal limit violations N_i and total number of emergency limit violations M_i. The corresponding weight multipliers b_i and c_i are selected for each voltage class. The total number of voltage classes is *k*. High voltage classes form a transmission system backbone and are more important for ensuring grid reliability.

$$I_2 = \sum_{i=1}^{k} (b_i N_i + c_i M_i) \qquad (3)$$

The I_3 component determines voltage violations and is composed of high limit and low limit violations with appropriate weight multipliers d_i and e_i for each voltage class.

$$I_3 = \sum_{i=1}^{k} (d_i H_i + e_i L_i) \qquad (4)$$

where H_i and L_i are total numbers of high and low voltage violations for a particular voltage class in basecase.

The I_4 component determines thermal limit violations in all studied contingencies as a combination of total number of normal limit violations NC_i and total number of emergency limit violations MC_i. The emergency violations have higher importance than normal violations, and therefore have higher weight. The corresponding weight multipliers b_i and c_i can be assumed the same as in formula (3). The effect of contingencies' violations on assessment of reliability is lower than basecase's violations, which is weighted accordingly through a_2 and a_4 coefficients in formula (1).

$$I_4 = \sum_{i=1}^{k} (b_i\, NC_i + c_i MC_i) \quad (5)$$

The I_5 component determines voltage violations and is composed of high limit and low limit violations. The corresponding weight multipliers d_i and e_i for each voltage class can be assumed the same as in formula (4). The effect of contingencies' violations on assessment of reliability is lower than basecase's violations, which is weighted accordingly through a_3 and a_5 coefficients in formula (1).

$$I_5 = \sum_{i=1}^{k} (d_i\, HC_i + e_i LC_i) \quad (6)$$

where HC_i and LC_i are total numbers of high and low voltage violations for a particular voltage class in all studied continencies.

III. TRANSFERING DATA FROM EMS TO GIS

There are different means of providing EMS data to GIS. The most common one is the use of intermediary database that can store EMS data and then make it available to GIS. One of such examples is OSIsoft PI, which is a real-time data historian application with efficient time-series database. The PI application records data from EMS into compressed time series database and can make that data available to other applications like GIS. However, it is more efficient to directly feed GIS database from EMS. A special adapter called DBeam was developed at Ameren to process and transfer EMS data to GIS database. Without any programming effort a user with system administrator privileges can configure online the selection of EMS parameters for displaying in GIS. The information from the populated GIS' database tables is assembled in database "views" as the ready-to-use data source for maps. The source for these tables and views can be from any EMS application, e.g. State Estimation, Stability Analysis, or Automatic Generation Control. DBeam uses Application Programming Interface (API) and captures the user defined EMS variables and transfers them to GIS database at a user defined frequency. DBeam adapter can run on any server where API client is installed. Thus, the GIS' database tables and relevant views are periodically updated with the EMS real-time data and the results of look-ahead analysis, and subsequently the data from the views are rendered on the GIS maps.

IV. MONITORING FUTURE STATE IN GIS

The GIS provides enhanced monitoring capability of all electrical components on an overview with different layers that can be switched on and off on demand. The implemented global visualization encompasses transmission line overloads, high and low voltage violations, and scheduled transmission line outages and innages. The current and future weather conditions provided by ESRI weather services are displayed on the geographical map to indicate the storm conditions, lightning activity, and precipitation, which may adversely affect the situation in the power system and increase the probability of outages. The inclement weather, and especially the transitory thunderstorm activity with lightning strike density can be factored into the assessment of the situation in the grid and operators' decision-making process. The evaluation of transmission lines' outage probability is very important for monitoring the future state of the power system, because it determines the priority focus of potential forced outages and increases situational awareness.

The formula for calculation of transmission line outage probability P is based on the linear approximation of a probability increase from statistically "normal" value to 1 depending on the loading of the transmission line:

$$P = \begin{cases} 1 & S \geq S_{max} \\ WP_o + \frac{1-sgn(100-s)}{2}(1 - WP_o)\left(\frac{S}{50} - 2\right) & S < S_{max} \end{cases} \quad (7)$$

where S is transmission line loading as a percentage of the power flow over the normal line rating, P_o is history based statistical probability of line outage during normal weather conditions, W is weather index, and $WP_o<1$.

It is assumed that at S_{max}=150% loading, a transmission line will trip, and therefore, the outage probability for that loading is equal to 1. The outage probability between 100% and 150% of line loading is a linear interpolation between two points. Most of studied contingencies are usually associated with one or several transmission line outages, and the probability of these contingencies can be calculated based on formula (7) and basic statistical operations for managing multiple probabilities.

The weather index represents a composite weather intensity factor that affects probability of outages. Storm's mean or maximum reflectivity, area of storm intensity, vertically integrated liquid, and probability of hail are some of the most essential parameters of storm activity that determine the danger of damages to the ground objects like transmission towers and lines. Severe Storm Indexes (SSI) are usually available from weather service providers and may vary in a range from V_{min} to V_{max} for different storm activities. In order to provide a simple weather ranking (e.g. from W_{min}=1 to W_{max}=10), the SSI value V can be scaled from the range [V_{min} , V_{max}] to the weather index value W in the range [W_{min} , W_{max}].

$$W = \begin{cases} 1 & \text{for } V \leq V_{min} \\ W_{min} + \frac{(W_{max}-W_{min})\,(V-V_{min})}{(V_{max}-V_{min})} & \text{for } V > V_{min} \end{cases} \quad (8)$$

Similar to reliability index I_R in formula (1), the mean value of outage probabilities for n transmission lines in the grid can provide another measure of the overall power system stress from the potential outage perspective:

$$I_P = 100 - \frac{100}{n}\sum_{i=1}^{n}(P_i - P_{oi}) \quad (9)$$

When all line outage probabilities are equal to their historical based statistical probability P_{oi} , the I_P is equal to the maximum value of 100. As line loadings increase or weather conditions sufficiently change to affect outage probabilities, the I_P decreases to indicate the deviation from estimated normal reliability conditions. Indexes I_R and I_P can be combined together in one index, but monitoring them separately provides an opportunity to estimate "forecasted" and probabilistic contribution, which has a degree of uncertainty and the actual real-time conditions. Monitoring of I_R and I_P indexes provides simple global system state assessment and serves as indication of the current and projected future state of the power system. The trending of the reliability indexes can provide an additional benefit of analyzing their rate of change, which is important during inclement weather conditions, fast load changes, occurrence of many switching and disturbances in the grid.

The visualization of estimated state of the power system is presented on geographical maps using tabs for real-time and each near-future time point of 15 min, 30 min, 45 min, and 60 min as shown on Fig.2. The transmission line overloads for base cases and contingencies are displayed in red color. The high and low voltage violations are displayed as red and blue triangles at the geographical location of the station associated with the violation. The basecase violations are assumed to take priority compared to *(n-1)* contingencies, and it is important to distinguish at a glance basecase and contingency violations on the maps. Therefore, basecase violations for all real-time and future time points are shown in solid color, and contingencies are shown with a low intensity color, or can be displayed using a color-coded transparency. The particulars (e.g. full/abbreviated name, address, telephone number, etc.) of substation or power plant can be displayed in a popup window as shown on Fig.2.

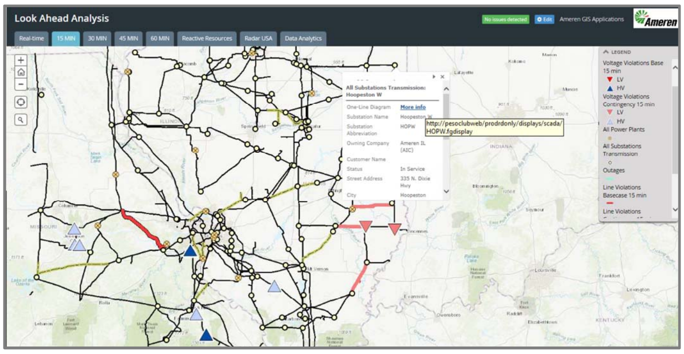

Fig.2 Rendering outages, overloads and voltage violations on GIS map

The look-ahead analysis provides a capability of calculating risk index of each contingency based on the severity of the violation and probability of the outages defining the contingency [5]. That probability calculation takes into account the actual transmission line loading and weather conditions in the area estimated for the future time point. The risk index of contingency may establish the contingency's operational importance, which can be used to identify the priority of violations associated with contingencies on the maps.

All deenergized lines are indicated on the geographical map with dashed green highlight. In addition to already outaged lines, it is also important to present the scheduled outages on the geographical map in order to give an instant overview of the transmission facilities that are likely to become soon unavailable. The developed application identifies the planned outages by dashed blue line (Fig.3) and also shows the remaining number of minutes to the scheduled start time of the outage. The outages are scheduled well in advance, sometimes months ahead of current time. Therefore, the outage indication appears on the geographical map only if the outage start time is within the two hour forward looking time window. Similar identification is provided for innages in green dashed color and number of minutes remaining to the scheduled time of innage.

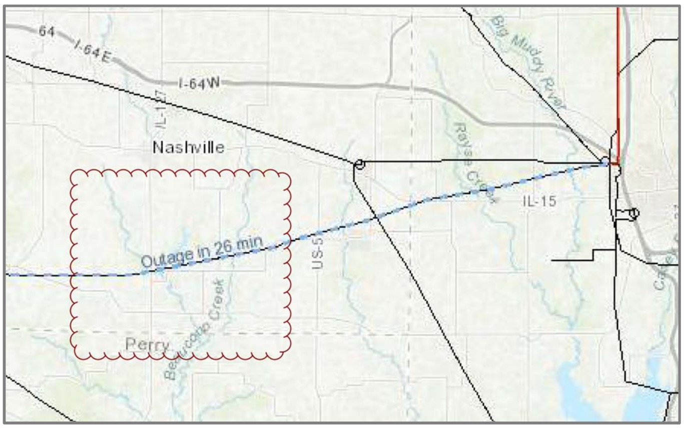

Fig.3 Monitoring line outages

The pulse-Doppler radar provides current and forecasted weather information to display storm activity, its intensity and motion, along with various parameters such as temperature, wind speed, precipitation. Modern weather radars are mostly pulse-Doppler radars, capable of detecting the motion of rain droplets in addition to the intensity of the precipitation. The weather conditions are provided by weather services and can be displayed as radar mosaic images in the form of snapshots or in animated motion on geographical maps as shown. The density of lightning strikes from the lightning detection network (Global Lightning Dataset - GLD360), can be also displayed as a separate GIS layer with 8km by 8km spatial resolution and 15-minute time period. In addition to weather radar, various data analytics are employed for detailed examination of future state prediction and data correlations, including outage probability, violations severity, and risk indexes. The superimposition of forecasted weather and the predicted electrical state of the power system (Fig.4) enables operators with advanced data analysis tools. The background maps and visibility of all layers are user configurable.

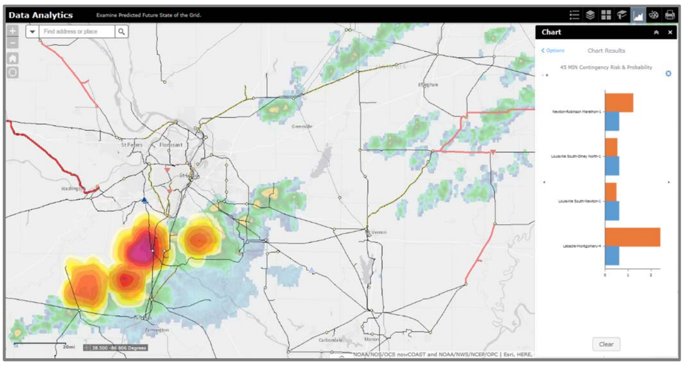

Fig.4 Data Analytics with charts and weather information

The rectangular widgets at the right top of the application screen provide capability to configure the map and layers, view the charts, show any data details, and print on demand. The developed data analytics allows an operator to manually select any part of geographical map and generate detailed information relevant to the selected area. For example, it is possible to approximately identify (using a free drawn line, ellipse, or rectangle) an area on the map with a highly inclement weather conditions based on the radar visualization. The large yellow and orange colored contours on Fig.4 represent very intense lightning density regions. Operator can select the area affected by intense lightning activity, and then evaluate on bar charts the calculated outage probability and risks for the overloaded (or all energized) transmission lines in that focus area. The analysis can be performed in the real-time or for the future time points to identify the highest outage probability in user-selected areas or for the whole power grid.

Similar to radar animation, the forward-looking prediction of future grid state can be animated and presented through the playback visualization of the events that are estimated for the next hour (Fig.5). Such animation can help to visualize the progressive dynamic of events on the map synchronized with weather conditions, especially during storm conditions when there is a large amount of information displayed on the maps. It is useful to have a capability of increasing transparency of weather layer for the heavy storm conditions in order to lower the intensity of vivid storm colors and bring to the map's foreground the electrical problems in the grid that operator has to address. Then, both weather and network security violations can be visible and correlated on the same global overview.

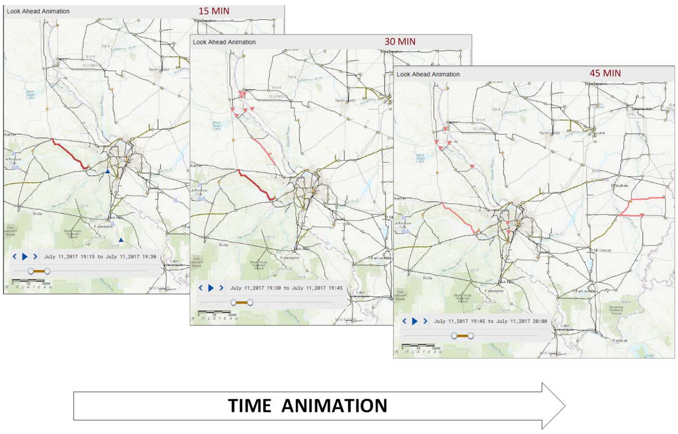

Fig.5 Animation of predictive analysis

The ability of correlating different information on geographical map provides a decision support basis for managing the grid operations. For example, in addition to voltage violations displayed on the geographical maps for future time points, it is very useful to provide the available reactive reserves, e.g. capacity banks, shunts, synchronous condensers, SVC, which are located at substations. Voltage violations are usually best remedied through application of reactive regulation, which is electrically, and in most cases geographically, close to the location of voltage problems. Therefore, a quick visual association of reactive resource availability in the geographical vicinity of voltage violation can be very helpful in the resolution of voltage problems, especially if their detection is predicted by for the near future time points.

The pie chart symbols on the map (Fig.6) represent reactive resources: green color for compensation, brown color for charging. Light beige and light green identify the amount of reactive resources, which is still not used, but is available at the station. If all reactive resources at a station are fully available, then the pie chart is presented as a circle filled entirely with only one color. Thus, green and beige filled circles indicate the switched off reactive reserves, which can be made available on demand. The stations without any reactive resources and without any availability of reactive resources are not displayed at all on the map in order to avoid clutter and distraction. Voltage violations are shown as blue and red triangles indicating low and high voltage violation. The pop-up window provides the essential information about station parameters and location. Also, the one-line diagram with detailed information (i.e. breaker statuses, flows, and voltages) is accessible via a hyperlink "More info" in the pop-up window (Fig.2 and Fig.6).

The geographical presentation of reactive resources does not replace optimal power flow analysis, but it improves the situation awareness for voltage management and provides geographical options for available reactive reserves in the vicinity of violations. For example, a low voltage violation is likely to be remedied by switching on capacitor banks or switching off reactive shunts, which are electrically close to the violation. Unlike line overloads, there is a short time for resolving dangerous low voltage violations, because they may quickly unfold into voltage collapse. Therefore, addressing voltage violations well in advance of their occurrence and in the context of estimated reactive reserves is an important advantage of the predictive analysis and future state visualization.

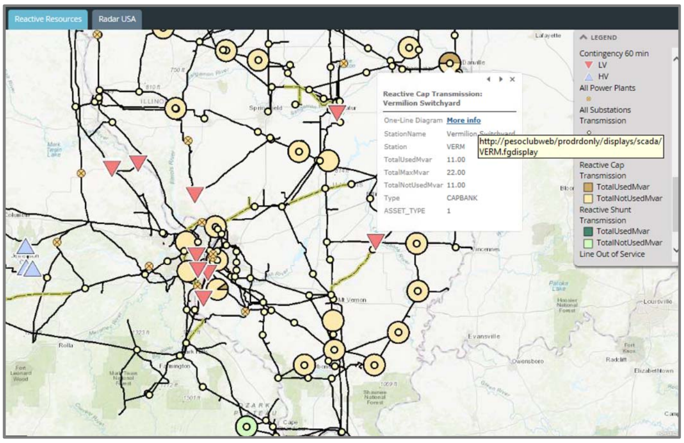

Fig.6 Reactive Reserve and Voltage Violations

Real-time and near-future time predictions of voltage profile can be examined in details through geospatial analysis for any user-selected area defined by a geometrical shape, e.g. rectangle, ellipse, circle, free hand curves and polylines. The voltage profile analysis can be applied either to the selected geometrical shape or to the entire power system network on the map. The stations with voltages above (or below) threshold are identified on the map by a blue round circle symbols in the selected area on Fig.7. The detailed information for each station is displayed in the summary list on the right, and user can be navigated to the station location from that list by clicking on each item in the list.

More sophisticated calculations and correlation analysis are considered for further development:

1) Data mining based on the detailed analysis of electrical characteristics and their correlation with local weather, geography, and other data sources internal to the grid.

2) Use of geographical analytic to correlate the power system conditions with the information from external domains available outside the grid, e.g. wild fires, significant accidents, large social events.

3) Tracking storm activity, dynamically identifying most vulnerable equipment, and performing *(n-2)* look-ahead analysis for the high intensity area of the storm.

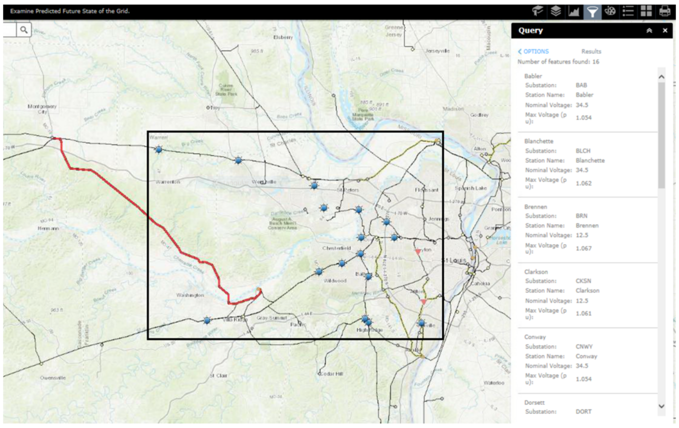

Fig.7 View stations with voltages above or below user-defined threshold

It is also recognized that there are many other promising areas of GIS implementation and spatial analysis in transmission and generation systems, which include: asset management, reserve management and ancillary services, contouring of stability analysis results, monitoring of renewable resources and weather, fault location and isolation, system restoration, electrical market operations.

V. Conclusions

Grid operators usually rely on EMS network security applications using current state of the power system. However, monitoring and control of the grid can significantly benefit from analyzing and visualizing future states of the power system with global overview of all violations for near-future time points. For the future state evaluation, it is important to identify the alarms and violations, which are new or significantly different from the ones already visible in the current time. The paper proposes characteristics like transmission reliability index, total risk index, probability assessment, and overall future state assessment alarming, which can be used to effectively monitor, track and trend the real-time and near-future health of the power system. The implementation of the proposed future state analysis in the electrical utility for real-time operations proved that geographical presentation and developed data analytics can provide important visualization enhancement and subsequently improve situational awareness. The introduction of GIS time enabled layers provides a global visual perspective that helps grid operators to identify major future anomalies, and subsequently, either mitigate or establish a better readiness for the situations that are likely to occur in the next hour. The flexibility of displaying maps with geographically referenced security violations, along with available reserves in the power system, and weather conditions, create the decision support basis for efficient management in emergency situations. Sometimes these future emergency situations may not be apparent in the real-time, but are detected by look-ahead analysis and clearly distinguished and presented in GIS as potential future events with estimated values.

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