Visualization and Human Factors in Electric Power System Operation

Sushil Kumar Soonee, Devendra Kumar, Samir Chandra Saxena and Sunil Kumar

Abstract--**Optimal and effective operation of a large power system requires analysis of a huge amount of information by the system operators. In a large power system, it is a challenge to present the vast amount of data in a way, which assists the operators in assessing the state of the system and responding expeditiously. Restructuring of the power sector worldwide, the advent of new market mechanisms and the need to analyze various parameters and available security margins has made this challenge all the more formidable. These challenges are a prime mover for the continuous improvement and evolution of new visualization techniques. Effective visualization methods, techniques and tools are key to empowering the system operator and facilitating quick operator response under critical conditions. Internet and the development of new IT tools have added a new dimension for the power system operator. Analysis in real time and drill-downs into the data are required by the operator for a detailed investigation. Effective power system visualization capability is a strong motivating factor for the operator for improving his response and productivity. This paper describes the visualization methods, tools and techniques implemented and used by the Indian power system operator. Classical displays including single line diagrams, tabular displays, load curves, bar charts, pie charts, tie line interconnection diagrams, etc. have been discussed. New methods used more recently like multi-layered displays, macro visualization of a parameter over longer duration using zooming and panning, 3-D presentations, contours, data leveling, animation etc. and future methods such as GIS Maps are discussed. The human aspects and the ability of operators to comprehend and respond to the information presented to them in various formats are also discussed.**

Index Terms — **Cognitive, Diagnostic, Human Factors, Interactive, Visualization.**

I. Introduction

INFORMATION associated with power systems has traditionally been presented to the operator as numeric data on single line diagrams and by tabular list displays. This has been supported by a static mimic (map-board) display in the control center with dynamic data shown by different lights. This relatively simple approach has sufficed the requirements of vertically integrated utilities in the pre-reforms era. With the restructuring of the power-sector, high growth rate and integration of market forces, visualization techniques need to be reviewed and enhanced.

In a large power system, simulation and analysis involves modeling of complex power system elements and presenting them to the system operator. One is usually confronted with a huge amount of different information such as line loadings (MW and MVAR), bus voltages, generation, available transfer capability, scheduled and actual flows between control areas, etc. The list of variables becomes even longer with the use of advanced applications such as Optimal Power Flow (OPF), Contingency Analysis (CA), Available Transfer Capability (ATC) calculations, etc.

It is a challenge to present the vast amount of data to the operator in a way so as to facilitate quick assimilation and assessment of the situation and fast response by the operator. Effective visualization improves the ability of the operators to monitor, detect and correct the anomalous conditions in grid operation. Operator decisions and response time have a direct bearing on the day-to-day operation including the power markets such as day-ahead market, hour-ahead market and the real time market.

Electrically, India is divided into five regions namely the North, South, West, East and Northeast. Each region has its own regional control center equipped with a state of the art SCADA/EMS system monitoring data collected from the various RTUs. The no. of substations and the data points (analog and status) being monitored by the regional control centers are given in Table I.

TABLE I
Number of SCADA Data Points

Sr. No.	Region	Number Of		
		Stations	Analogs	Status
1	North	450	13180	37900
2	South	410	13000	22000
3	East	190	5500	16900
4	West	350	6000	16530
5	North-East	40	1400	4270
6	All India	1440	39080	97600

In addition to monitoring the data within the region, the operator is also required to monitor the inter-regional links, and to some extent the critical parameters of the neighboring regions. The northeastern region, eastern region and the

Sushil Kumar Soonee is with Power Grid Corporation of India Ltd and heading the Northern Regional Load Dispatch Center (NRLDC), New Delhi as Executive Director, (tel: 91-11-26852843,e-mail: sksoonee@gmail.com).

Devendra Kumar is with Power Grid Corporation of India Ltd. and heading the SCADA & IT group at NRLDC, New Delhi (tel: 91-11-26522093,e-mail: dkumarp@gmail.com).

Samir Chandra Saxena and Sunil Kumar are with Power Grid Corporation of India Ltd., SCADA & IT group at NRLDC (tel: 91-11-26522093,e-mail: saxena.samir@gmail.com / sunil.nruldc@gmail.com).

western regions have been integrated synchronously in the Central Grid. By mid-2006, the Central Grid would be synchronized with the Northern Grid. With this, the task of the operators manning the control centers would become all the more difficult and the visualization techniques become important. This paper attempts to study the power system visualization techniques used by the Indian grid operator with specific reference to the current techniques and the future requirements

II. Visualization Techniques

A. Tabular Presentation

The tabular format and the single line diagrams present the information in text and numeric format. Tabular displays constitute some of the most important type of displays used by the operators. They are the most frequently referred to displays. A wide variety of information is displayed in tabular format for the operators such as transmission line and ICT loadings, generations, voltages, schedule vs. actual values, frequency from different telemetered points, etc. as shown in Figure – 1. Detailed tabular displays pertaining to a particular control area are used as and when required by the operators. The texts on the displays use hyperlinks to lead to more detailed displays for the selected item. As a norm, the color used for displaying MW is green, MVAR in white or orange, KV in white and Hz in white. Figure – 2 shows the tabular display for a particular substation. An advantage of presenting information in the tabular format is quick location of the desired information by the operator. Computed information such as sums, angles, etc., are arranged in tabular formats for ready reference.

Fig. 1. Tabular Presentation SCADA Data

Fig. 2. Substation Tabular Presentation

B. Single Line Diagrams

The operators use single line diagrams interconnecting various busses to get an overview of the system. Single line diagrams display the most critical parameters and allow the operators to have a macro level view of the system. Numerical values of line flows (MW and MVAR) along with the direction of flow are indicated at both ends of the lines. The nodes indicate the bus voltages. The bus diagram for any bus can be obtained by clicking on the node of interest by the operator. Clicking on the neighboring nodes enables the operator to navigate throughout the region thereby obtaining a clear picture of the flows in an area with desired level of detailing. As a norm, the color of lines used for showing 800 kV network is yellow, 400 kV network is red, 220 kV network is green. HVDC is shown using the violet color and other colors are used for lower voltage level networks. The diagram uses firm lines of the appropriate color if the transmission line is in service. A dotted line is used to show a transmission line if it is out of service. Bus reactors are shown connected to the respective busses along with the MVAR. Hatched circles represent load busses whereas circles with the generator symbol represent generator bus. Temperature at a particular station is displayed in white color alongside the node and other weather data for that node can be obtained by clicking at the ‘sun’ symbol near the node. Clicking on the name of the control area opens a view-port containing the details for that control area. A single line diagram showing the super grid level network in the Northern Region is given in Figure – 3.

Fig. 3. Single Line Diagram

C. Bus Diagrams

Operators use the bus diagrams if detailing to the bus level is required in the real time operation. The bus view uses the text and numerals format placed appropriately on a substation bus diagram. It helps the operators identify flows into and out of a bus, giving both the magnitude and the direction of the flows. The bus diagram contains symbols representing busses, transmission lines, transformers, circuit breakers, isolators, and generators, shunt reactors, bus reactors and the appropriate data point shown numerically. The color scheme for the bus diagrams depends on the voltage level and for 800 kV is yellow, 400 kV network is red, 220 kV network is green. The bus diagram also illustrates the physical layout of the equipment in the substation to the operator i.e., how each element is connected to the other elements. A typical bus diagram used by the operators is given in Figure – 4.

Fig. 4. Bus Diagram

D. Control Area – Tie Line Representation

The control area – tie line representation is an important visualization means, which describes the system in terms of the control areas and the tie lines connecting them. The control area – tie line diagrams are important as they clearly indicate the control area's power exchanges with the neighboring area. This information is important to the system operator for economic reasons and for maintaining the security margins as usually limits are prescribed for the tie-line flows, this being one of the ways of safeguarding against potential operational problems such as high/low voltage, angular instability, etc. A diagram representing the regional level interconnection between the Northern Grid and the Eastern Grid is shown in Figure – 5.

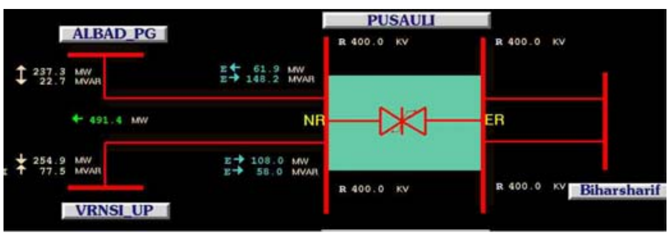

Fig. 5. Control Area – Tie Line Representation

E. Flowgates Illustration

A flowgate is a collection of transmission system branches. The lines comprising the flowgate are usually parallel paths for which a combined (total) limitation on the sum of line flows can be placed. In the Northern Region, the East-West flowgate comprises of the Rihand-Dadri HVDC Bipole, 400 KV Kanpur Agra, 400 KV Kanpur Ballabgarh, 400 KV Unnao Agra, 400 Kv Lucknow Moradabad and 400 KV Panki Moradnagar. A display has been made available to the operator showing the total flow on the line and the angular difference between the two busses as shown in Figure – 6.

Fig. 6. Flowgates Illustration

F. Multi – Layer Arrangement

A number of data needs to be displayed at any node apart from a lot of static information. Thus, the total volume of data being displayed becomes large and the view-port becomes cluttered with a lot of information. This reduces the ability of the operator to quickly comprehend the situation, assess it and respond to it. An effective way of overcoming this problem, which has been used by the Indian operator, is through using layered displays. In a layered display, the different values such as MW, MVAR, remote end values, voltages, line lengths, bus reactors, line reactors, angular separation, transformer values, different voltage level networks along with the values, bus summations, geographical boundaries, etc. are configured in different layers. The operator, depending on his requirement, can make the layers on the display visible or invisible through a menu selection. This packs a lot of information into a single display and eliminates the need to open different view-ports / displays for various kinds of information. An example of the layered display along with the menu options is shown in Figure – 7.

Fig. 7. Multi – Layer Arrangement

G. Graphical Views

The operators use a number of standard graphical views such as trend charts, pie charts, etc. The graphical presentation of data helps operators identify present and potential alarming conditions easily. Trend charts (line graphs) effectively represent the behavior over the past period say last 24 hours and are easy to configure for any parameter. Bar charts are used to display the UI rates in the Northern Grid and the Central Grid. Another bar chart indicates the frequency difference between the Northern Grid and the Central Grid and the inter-regional power flow along with the direction of flow. This is illustrated in Figure –8. Pie charts are an effective means of representing information. The can be customized in terms of color and size to suit operator needs (Figure – 9).

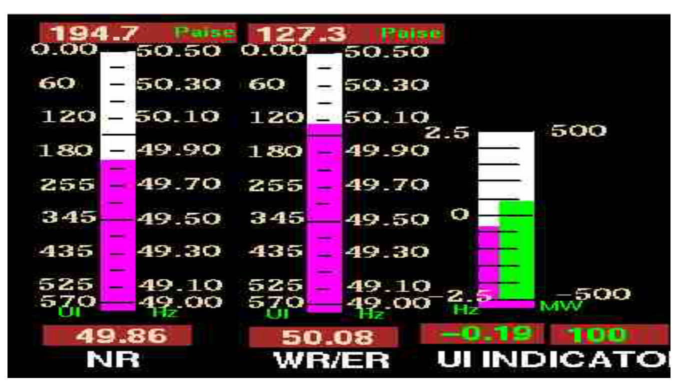

Fig. 8. UI Rates

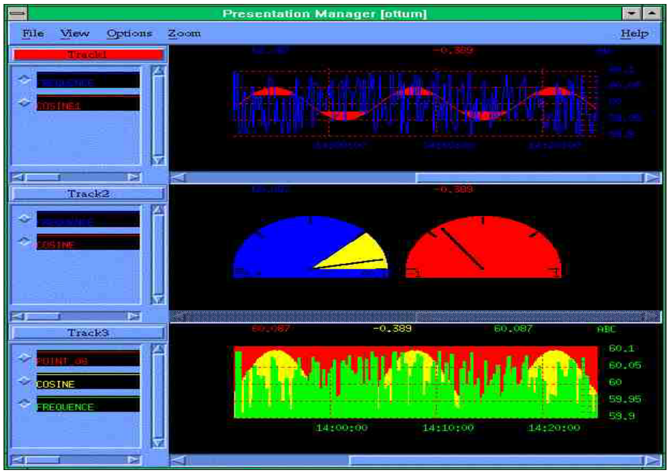

Fig. 9. UI Rates

H. Geographical Displays

Maps provide a power visualization tool to the operator. Geographical maps (approximate or to scale) have been superimposed with the transmission network. It is easier for the operator to locate information on a map and zoom in on an area of interest. A geographical display used is shown in Figure – 10.

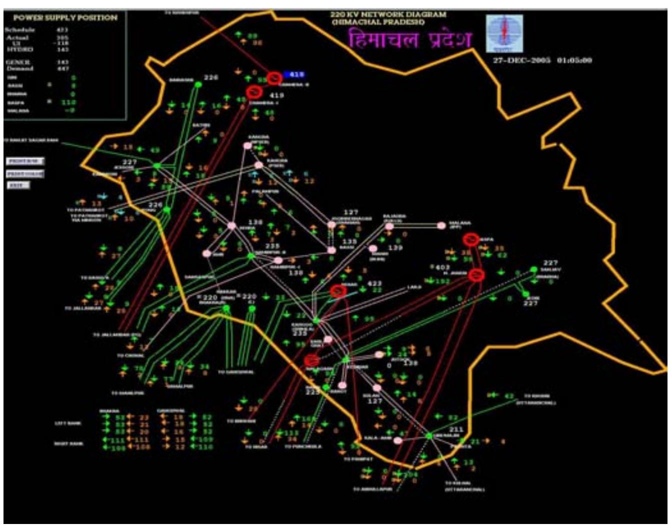

Fig. 10. Geographical Displays

I. Quality Tags

In all types of displays, the SCADA system modifies the displayed numeric value as per certain pre-set limits assigned for each telemetered value. Values violating the 'high' limit are shown as blinking and if the 'high-high' limit is violated, then the value is enclosed in a blue box and it blinks continuously to attract operator attention. On the lower side, the value blinks when the 'low' limit is violated and it blinks enclosed in a red box if the 'low-low' limit is violated. Each value has an associated quality flag, which shows the currency of the data. A value which is suspected to be incorrect is labeled 'S' and a value which has been replaced by the operator manually is tagged 'R'. The values replaced by the state estimator output are labeled 'E' and colored blue. These representations are essential to indicate to operator the confidence level to be associated with the data being displayed to him. The various kinds of quality flags associated with the measurands are un-initialized data, old data, bad data, telemetry failure, range violation, unreasonable, anomalous, manually replaced, state estimator replaced, calculated, maintenance mode, not in service, alarm inhibited, remote suspect, and remote replaced. The data is qualified as good or bad based on one or more of the above flag values.

J. Contouring

Contouring has been used very effectively to represent spatially distributed continuous data e.g., temperature. However, power system data is not spatially continuous for example, voltages exist only at busses. Thus to use contouring for power system data, virtual values must be assigned to the entire region. The operators have used contouring to represent the PU voltages and fault levels in the system. An illustration showing the PU voltages for the Northern Region is shown in Figure – 11 and fault levels for the Delhi system are shown in Figure – 12.

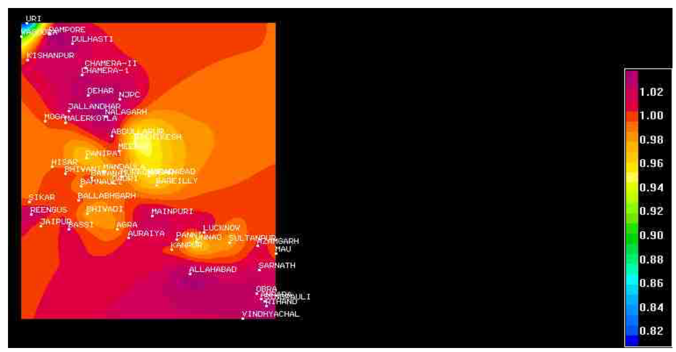

Fig. 11. PU Voltages in Northern Region

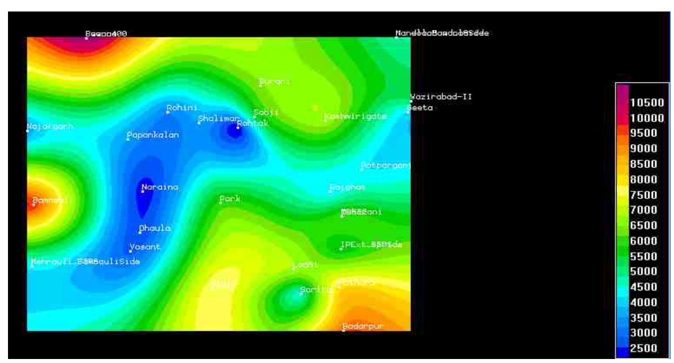

Fig. 12. Fault Levels in Delhi System

K. Three Dimensional Representations

Three-dimensional displays are useful and proven means of visualization. The grid operators use the 3-D displays to represent a desired parameter at five-minute interval over a longer period of say, a month. A 3-D representation of the demand in the Delhi control area is shown in the Figure – 13. As can be clearly seen from the figure, five-minute intervals are shown on x-axis from 1 to 288 and the dates are shown on the y-axis from 1 to 31. The magnitude is represented on the z-axis. This representation clearly brings out the peak (morning and evening) and off-peak (day and night) variation over a month. If this plotted over a longer period say six months or one year, seasonal patterns become eminent and easily identifiable. An added feature of this 3-D representation is the color contouring which enhances the display

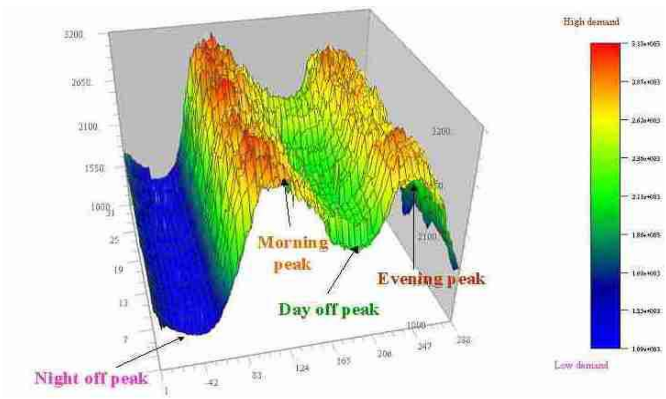

Fig. 13. 3-D Representation of Delhi Demand

L. Animation

Flow animation is another visualization tool, which has been used effectively. Line flows, when within safe limits are shown with a pre-designated line thickness of appropriate color (depending on the voltage level) as shown in Figure – 14. However, as the loading starts to increase, the line thickness increases to catch operator attention. Another popular technique of line flow animation, though not used in the Indian scenario, is through the use of animated arrows. As the line loadings increase, the size of the arrows and their speed of flow increases thereby attracting operator attention. Circuit breaker symbols appear filled when closed and vacant when open.

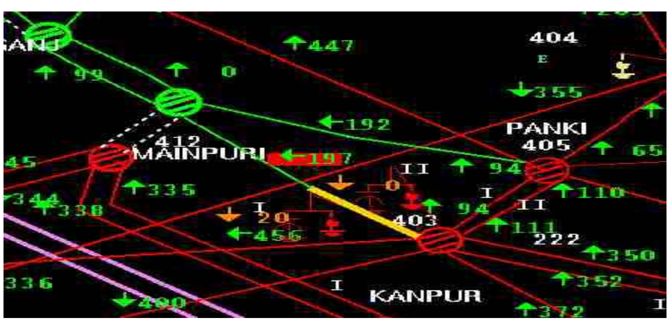

Fig. 14. Animation

M. Rooms

Each operator in the control center has his own perception, ways of visualizing and understanding different situations. The concept of "*one-size fits all"* does not hold true for the grid operators. When in shift, the operator is fully responsible for all his actions. Most operators thus have their own preferences while visualizing and assessing power system data for monitoring and making decisions. In order to enable operators to exercise such individual preferences, operators use the concept of "*Room*" in the SCADA system. A *room* is defined as a collection of view ports in which different kinds of displays such as tabular displays, single line diagrams, bus diagrams, trends, bar charts, etc. can opened and arranged as per the operator's choice. The use of rooms to customize and personalize displays gives flexibility to the operator and brings out his creativity. The very fact that he has designed the displays gives the operator a feeling of ownership and provides motivation to perform at his best. To create a room, the operator opens the desired displays in different view ports and saves them as a room. Whenever the designated room is called up, a pre-configured set of view ports with the desired layout opens. Thus, each operator can have an individual room, which can be opened with a single click.

N. Zooming and Panning – Online and Offline

The single line diagrams allow the operator to pan the view-port and focus on a desired area. Zooming allows the operator to drill down and investigate the network to the desired level of detailing. These features are being used effectively in the present SCADA system.

With offline data, this technique has been successfully applied in the form of scroll charts with zoom and scroll facilities to display any parameter e.g., a particular voltage or line flow for a longer duration such as over a month. As an illustration, Figure – 15 below shows the demand met in Northern Region and the frequency at five minute intervals for the whole month of November – 2005. Data leveling controls the amount of information at each level of zooming.

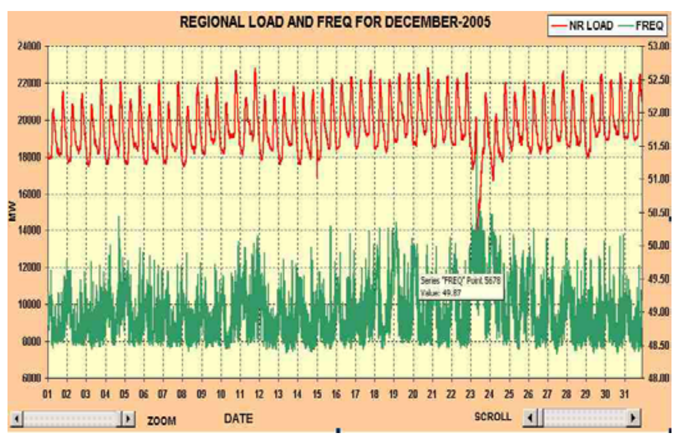

Fig. 15. Zooming and Panning

O. Alarms and Exceptions

The number of data points being monitored in the system is very large. Alarm and alerts must be effectively displayed to alert the operator of the anomalous conditions in the system. SCADA exception lists are also used to display the exceptions to the operator. The various ways of presenting the SCADA exception lists are the analog list, status point list, time ordered list, communication equipment list, single station list, station ordered list, RTU, topology, etc. This is shown in Figure – 16.

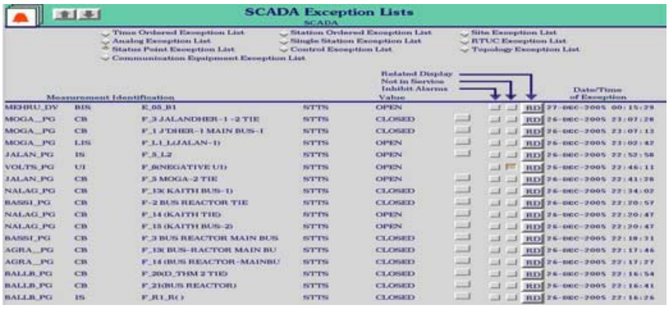

Fig. 16. Alarms and Exceptions

P. Market Visualization

The electric power industry worldwide is undergoing changes – deregulation and rapid restructuring and Indian Power Sector too is going through the same processes. The advent of Availability Based Tariff, UI mechanism and Open Access in Inter-state Transmission has added a new dimension to the system monitoring by the grid operators. The operator has to continuously monitor the available transmission capacities and the pool price. Unlike markets in developed countries, the real time market in India is relatively simpler to monitor. This is so as only the system frequency and the UI rate, both of which are common knowledge, need to be monitored not only for his region but the neighboring region also. However, the security margins in the system need to be monitored rigorously.

III. Human Factors

The visualization techniques used in any system should be cognitive i.e., they should be recognized and understood by the operators easily. The techniques should motivate a two-way interactive approach with the operator. Visualization provides the operator with the necessary inputs regarding the prevailing system conditions, which must be acknowledged by the operator followed by suitable corrective action. The prime requirements are speed and accuracy in identification and resolution of the problems. Information desired by the operator should be reachable easily in just a couple of clicks. This has become all the more important as due to various pressures on the operator; he neither has the time nor the inclination to manipulate complex windowing capabilities and be bogged down by the huge amount of data in unmanageable displays.

The benefits of color-coding are well documented in the human factors literature. Colors can be used to highlight certain areas of the displays requiring immediate operator attention thereby reducing the search area for the operator and facilitating easy identification of the problem area. It is a well established and documented fact that interpretation of color codes occurs during perceptual processing of information whereas, interpretation of numeric values comes later and with more effort. Hence interpretation of color-coded information occurs much faster as compared to the numeric processing e.g., color contouring identifies the low voltage pocket more easily than numerically presented data. There are however, limitations and costs associated with the use of colors. The number of colors that can be used is limited by the human judgment ability. Normally five to six colors are used effectively. A cost to the use of colors is that a natural hierarchy of colors does not exist, which enables the operators to judge whether one color is greater than or less than in value to another. Inadvertently, colors may also hide useful information from the operator by overlapping, blending, etc.

Based on the complexity of the situation, a trade-off is required to be made between color-coding and numeric presentation of data. The objective of color-coding is to quickly identify the worst violations thereby allowing the operator to acknowledge and respond to the situation with speed and accuracy. However, in other less critical situations, color-coding generally results in lower accuracy and slower speed of response by the operator as compared to numeric displays. It is because of these reasons a combination of the two is used in the Indian conditions.

IV. Conclusion

Visualization is a vital tool for enabling and empowerment of the operator. Visualization tools and techniques provide the vital inputs to the operator for assessment of the situation and taking remedial measures. The focus is on identification and resolution of the problem with speed and accuracy. Data converted into information must be presented to the operator in a meaningful way, which facilitates easy comprehension, assimilation of the existing situation and quick response. It is in an emergency or contingent situation that the real importance of the visualization tools is felt as compared to the peacetime scenario. The visualization tools and techniques available today are adequate to meet the operator needs. However, as the system size grows, complexity increases and market forces become dominant, the present visualization tools and techniques would become inadequate. These must be reviewed continuously and most importantly, operator feedback should be considered while implementing any new features.

Restructuring of the electricity sector is creating a need for new and innovative visualization methods for representing very large amounts of power system data. A Dispatcher Training Simulator (DTS) (or other such advanced applications) can be used for simulation studies and training operators. Visualization and analysis of the results of advanced applications such as Contingency Analysis, Optimal Power Flow, etc. is extremely important considering the large volume of data. As the complexity and the size of the power system continue to grow, it would be necessary to adopt advanced visualization techniques such as virtual environment to interactively visualize the large amount of power system data.

Migration of power systems world wide from vertically integrated utilities to a de-regulated regime has resulted in the evolution of various visualization techniques. Visualization of the power system is an art and is undergoing continuous refinement.

V. Acknowledgement

Authors are grateful to the power system fraternity and the POWERGRID management for the encouragement. The views expressed in this paper are those of the authors and not necessarily of the organization they belong to.

VI. References

[1] D.A. Wiegmann, A.M. Rich, T.J. Overbye, Yan Sun, "Human Factors Aspects Of Power System Voltage Visualizations, Proceedings of the 35th Hawaii International Conference on System Sciences – 2002.

[2] Spence L. Clark, Jill Steventon, Ralh D. Masiello, "Full-Graphics Man-Machine Interface for Power System Control Centers, IEEE, 1988

[3] T.J. Overbye, Jamie D. Weber, "Visualization of Power System Data"

[4] T.J. Overbye, D.A. Wiegmann, A.M. Rich, Yan Sun, "Human Factors Analysis of Power System Visualizations", Proceedings of the 34th Hawaii International Conference on System Sciences – 2001.

[5] T.J. Overbye, Raymond P. Klump, Jamie D. Weber, "A Virtual Environment for Interactive Visualization of Power System Economic and Security Information"

[6] Y. Sun, T.J. Overbye, "Three Dimensional Visualizations For Power System Contingency Analysis Voltage Data", IEE APSCOM 2003 Conference, Hong Kong, November 2003.

[7] Ray Klump, David Schooley, Thomas Overbye, "An Advanced Visualization Platform For Real-Time Power System Operations"

[8] Thomas J. Overbye, James D. Weber, "Visualizing the Electric Grid", IEEE Spectrum, pp. 52-58, February 2001.