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Situational Awareness in Large-Scale Electric Grids for Reactive Power Management

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***Abstract*—**Reactive power management requires situational awareness, especially when analysing research assessing the effects of high renewable generation or geomagnetic disruptions on the system.In order to give users doing and analysing power system studies a new and helpful tool to improve their situational awareness, this research presents the visualization technique known as VAR Ready Reserves (VRRs). To give users awareness of reactive power capability and dispatch over the course of a simulation or spatially, this visualization technique can be modified to demonstrate the dispatch, injection, and absorption capability of reactive power devices (such as generators, shunts, and SVCs) in either a chart view (VRR charts) or with an integrated system view (VRR GDVs).This study examines reactive power management industry standards, provides an overview of current visualization techniques, and uses a case study of a 2000-bus to illustrate the recently established VRRs.

Index Terms—Reactive power, Reactive power management, Situational awareness, Visualization

I. INTRODUCTION

An essential component in preserving the voltage stability of the power system is reactive power. Keeping voltage levels within reasonable ranges allows the system to supply active power to its users. Problems with voltage instability typically arise when a system that is under a lot of load has insufficient reserves of reactive power [1]. Therefore, in order to prevent potential voltage instability issues and even blackouts, power system operators need to be aware of reactive power and have proper management measures in place.

Reactive power resources can be added to the grid (either by injection or absorption) using generators and devices like shunts and static voltage compensators (SVCs). Even though operators try to avoid using switch shunts as much as possible, they might be employed to raise system voltages in post-contingency or routine situations. The response time for tripping or closing automatic shunts varies from 1 second to 15 minutes, as stated in the PJM operation manual [2].

To maintain and regulate system voltage within acceptable ranges under both conditions, Independent System Operators (ISOs) have developed their own reactive power management systems.

Normal and contingency conditions Reactive power reserves, for instance, are monitored by PJM utilizing real-time unit reactive capability data that is acquired from each generator owner or operator [3]. In order to maintain steady-state operating circumstances, this management scheme helps PJM operators and engineers to stay aware of each unit reactive power production and capacity inside the interconnection.The Electric Reliability Council of Texas (ERCOT) computes limiting factors, such as ambient temperature limitations throughout the unit's MW range and under/over-excitation limiters, to produce an updated reactive capability curve. As of right now, the leading and lagging reactive output's most restricting factors are taken into account [4]. To maximize the usage of reactive power control devices across a multi-hour period, such as shunts, generator voltage set points, and SVCs, ERCOT has created a Reactive Power Coordination (RPC) tool [5].In places where voltage instability is a problem, this tool helps to increase transfer capability and decrease the number of switching actions.

Certain rules for reactive power have been established by the Federal Energy Regulatory Commission (FERC) and ISOs in North America [2], [6]–[9]. These requirements are necessary to ensure proper management of the power systems. The minimum reactive power capability and voltage range requirements are shown in Table I. Generators must typically have a voltage range of 0.95 to 1.05 per unit and a 0.95 lag to lead power factor at the Point of Interconnection (POI). Depending on the machines' kind and voltage level, these limits may vary [2], [8].

	Power Factor Limit		**Voltage Range (p.u.)**
	Synchronous	**Non-synchronous**	
FERC	±0.95	±0.95	
ERCOT	±0.95	±0.95	0.95≤V≤1.05
PJM	+0.9/-0.95	±0.95	0.90≤V≤1.10
CAISO	+0.9/-0.95	±0.95	0.95≤V≤1.05

TABLE I: Reactive Power Requirements

A. *Motivation for Reactive Power Situational Awareness*

The significance of situational awareness in reactive power management is emphasized when taking into account the necessary research and advancements in generation technologies. It is possible for geomagnetic disturbances (GMDs) to raise reactive power demand and has the potential to introduce harmonics, which could cause reactive power resources to trip. This is a problem for grid planners and operators who are expecting a GMD because the availability of reactive power devices could alter unexpectedly.TPL-007-2 states that while designing a system, engineers in North America must investigate the possible effects of GMDs [10]. Given the substantial impact that GMDs can have on reactive power supply, interpreting the results of these investigations needs situational knowledge of reactive power. Power generating trends indicate that the integration of renewable resources into large-scale power networks is on the rise. The power electronics for the renewable generators provide reactive power support and voltage regulation, which emphasizes the need for continuous monitoring of reactive power availability and levels.

In order to improve reactive power situational awareness by making it easier to recognize the real-time condition of reactive power and capacity, this study reviews visualization techniques and develops a novel visualization tool. In order to improve reactive power situational awareness, this paper reviews visualization techniques and provides a new visualization tool that makes it simple to identify the reactive power and capacity status in real time. Section III presents a case study of reactive power management overtime and demonstrates the use of the situational awareness tools introduced and discussed. In Section IV, the work is summarized and prospective applications are discussed as the study comes to a close.

1. REACTIVE POWER SITUATIONAL AWARENESS TOOLS ARE DESIGNED FOR

Different types of studies environments. Certain tools offer reactive power awareness for individual generators; while others offer situational awareness for studies involving wide-area systems Reactive power situational awareness techniques often combine information from either shunts or generators independently. There have been situations where the reactive power requirements in various system zones have been substituted for situational awareness of voltage.

Graphs and Charts

The reactive power capability of generators is displayed using their reactive capability (or "D") curves for generator-level awareness [3], [11], [12]. This method works well for smaller systems or when taking generators into account inside a system's pre-defined zone of interest In order to incorporate individual generator reactive capability curves to a small system view, [13] displays the reactive capability aggregated zonally for a small system.

This method raises awareness of generators' reactive generation capacity from a broader perspective and may be applied more widely in situations where there is an imbalance in reactive power. Bar charts were used in [12] to manage post-study situational knowledge of the reactive power required from each generator in the system to enable SCOPF simulations

Integrated System Visualizations

Methods that combine the system diagram with reactive power visualizations have also been investigated. This is depicted in one line diagrams in [14], [15] as three-dimensional bars at the locations of generator reactive reserves. Geographic data views (GDVs) are icons that have been added to one line displays and maps more recently to offer extra system information, like shunt status or generators that are almost at their maximum for producing or absorbing reactive power [16], [17].Traditionally, these GDV indicators are placed geographically, however the arrangement can also be changed to make the most use of available display space. Examples of shunt relative location and dispatch status are shown in [16].

A. Voltage Visualizations

In order to display the bus voltages in the system for cases, system voltages are commonly depicted using a voltage contour [18]. This gives users visibility into the voltage level in different parts of the system and may identify locations where there are voltage problems and where reactive power dispatch may be able to stabilize the voltage.Visualising the state of the buses in the system based on how far away from voltage collapse is another way to indicate the need for reactive power to support the voltage. A surface map of the distance from voltage collapse is used in [19] to do this. [20] offers a voltage awareness application for the distribution system.

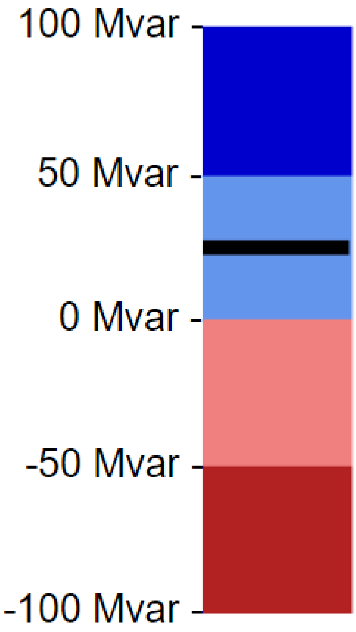


Fig.1: VAR Ready Reserve GDV

B. VAR Ready Reserves

This paper introduces VAR Ready Reserves (VRRs) to offer a tool to be leverage either in a chart view (as a VRR chart), or with an integrated system view (as a VRR GDV).VRRs incorporate available reactive power support from both generators and other reactive power devices. In chart form, there active power capability and dispatch is represented over a duration of time for a specific region of the system. VRRs are utilized to depict a portion of the reactive power resources that are accessible to the system when they are represented in GDV form. They do this by superimposing GDV icons over a system diagram. The region of the system may consist of user-defined regions or pre-designated zones, contingent on the system's size and the intended scope of research. The following informational layers are displayed by the VRR:

- **Level 1:** Online regional reactive power capability
- **Level 2:** Offline regional reactive power capability
- **Level 3:** Present regional reactive power dispatch

The available reactive power absorption and production capacities for committed reactive power devices, such as generators, shunts, and SVCs, are combined for Level 1 in the VAR Ready Reserve. Lighter hues in the centre of the VRR represent this. In Level 2, offline device reactive power capabilities are included in the VAR Ready Reserve.The upper and lower bounds for the reactive power capabilities within a system region are formed by darker colors in the VRR.Level 3 is the regional reactive power dispatch at a presentstate of the systemhe black line inside the VRR illustrates this. This paper uses a blue-red colour mapping, but you could use any high contrast colour mapping

Figure 1 presents an example of a VAR Ready Reserve GDVicon for a region in the system with 50 Mvar capability for online reactive power generation (indicated by the light blue),50 Mvar capability for absorbing reactive power using onlinedevices (indicated by the light red). Additionally, this region has 50 Mvar of reactive power generation capability with devices that are now offline (shown by the dark blue) and 50 Mvar of reactive power absorption capability with devices that are offline (shown by the dark red). As a result, the entire potential for generation and absorption of reactive power in the region is 100 Mvar. The black line in the VRR represents the net reactive power generation being dispatched in a sample scenario inside the sample region, which is roughly 25 Mvar. Because it combines the reactive power capacities of generators and other reactive power devices for each zone, this visualization technique is distinct. This situational awareness technique may be especially helpful for assessing the several courses of action available to alleviate voltage concerns in a study case because it presents this information in an integrated system view. For a region of study, a post-study analysis that takes into account the commitment of reactive power devices during the simulation can benefit from using a chart view to illustrate the VRR data.

CASESTUDY

A. *Scenario Description*

Since the information of actual electric grids is confidential and protected as Critical Energy Infrastructure Information (CEII), Texas A&M University has created synthetic electricgrids that are realistic in structure and function, but do not compromise CEII. These have been developed for various regions of United States' foot print and are available for research and educational purposes [21]. These synthetic grids are created based on public available data such as U.S. Census data [22] and generators' information that is available at Energy Information Administration website [23]. Reference [24]outlines fundamental steps for the creation of synthetic power system models including geographic loads, generators, Substations and assignment of transmission lines. More information about the general strategy for creating these networks may be found in [24]. Reactive power, transmission, and substation planning are all part of the broader procedure. Additionally, in order to produce realistic data sets, these synthetic grids are validated using validation metrics, which are significant, attributes of genuine grids [25], [26]. Geographic information about the system elements is one of these synthetic grids' key features. In order to generate load and renewable time series, as well as scenarios with different system operating conditions, the geographic information is specifically used [27]–[29].

In this work, ACTIVSg2000 [21] is the study tool. With 2,000 buses, 1,250 substations, 2,345 transmission lines, 1,350 loads, 544 generators, and 8 areas, this artificial grid is situated on the state of Texas. There has 100 GW of total generation capacity. The method outlined in [27]–[29] is used to create load and renewable time series.Although the generated time series are artificial, they have been verified using actual data [27]. This research will examine fluctuations in reactive power in more depth, focusing on August 11th, a high load day. In the simulation, the system load reaches its maximum at 3:00 PM, with a system load of roughly 66.3 GW.

Three visualization strategies are demonstrated ranging from graphical representation of reactive power levels to the VRRs introduced in Section II-D. Reactive power dispatch is precisely represented graphically in Figure 2, which offers insights into regional reactive power levels over time. Figure 3 shows VRR charts for the system's regions of interest, which shed light on how flexible reactive power levels can be over time. The VRR GDVs are displayed using a system-integrated visualization technique in Figures 4 and 5. These display the system's flexibility and reactive power level for certain regions during relevant times.

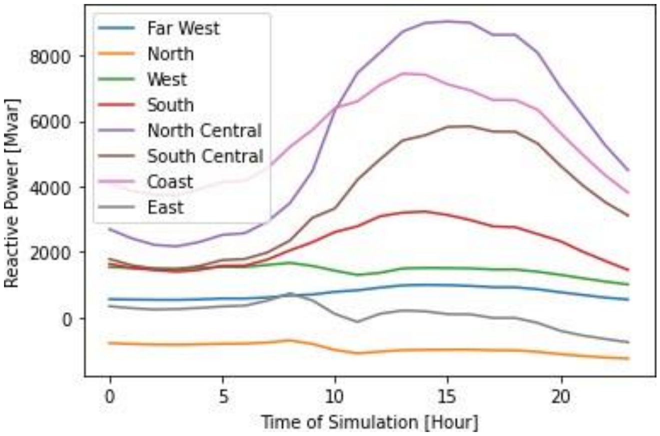


Fig. 2: Reactive power dispatch levels within each area of the case over the24-hour simulation window.

B. Results and Discussion

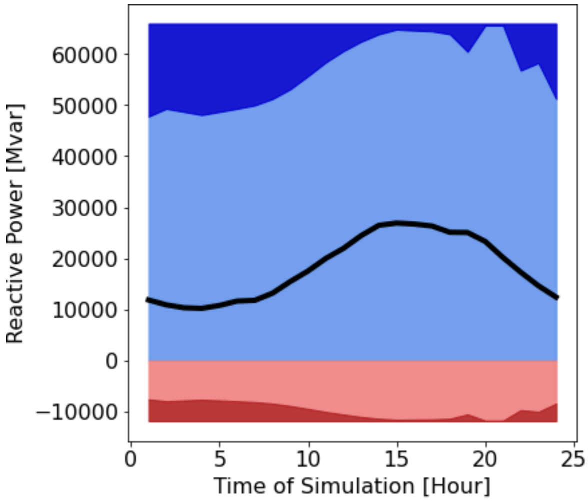
The reactive power dispatch for reactive power devices in each area for the duration of the simulation is shown in Figure

Every one of the eight system areas is shown. In order to facilitate the supply of the afternoon peak active power inside the system, the system's peak reactive power level peaks in the early afternoon. Throughout the experiment, each system region exhibits varying degrees of variance, with each showing shifts in reactive power levels around roughly 10:00 AM. The North, West, and East regions exhibit lower levels of reactive power injection (or higher levels of reactive power absorption) throughout this portion of the simulation, even if this equates to a net increase in reactive power injection for the case as a whole.Reactive power capability and dispatch are shown in VRR charts for various system regions in Figure 3, where online reactive power injection capability is shown by light blue, online reactive power absorption capability is shown by light red, and the total system's (online and offline) reactive power injection and absorption capabilities are shown by dark blue and dark red, respectively. The blackline denotes the net level of reactive power used within thecase over the 24-hour simulation window. Figure 3a shows anaggregation of the lines from Figure 2 as the black line and offers more details about the extent of adaptability of this dispatch level by showing the VRR's characteristics over time for the system as a whole. Overthe course of the simulation, there is great flexibility in there active power injection of the system as a whole. Changes in the status of reactive power devices can be seen with theamount of dark red and dark blue shown in the graph. Figures3b and 3c show the VRR charts for the North and Coast areas, respectively. The North area demonstrates a net absorption ofreactive power for the entire duration of the simulation, withnearly all of the online reactive reserve absorption capacitybeing used during the twelfth hour of simulation. The Coastarea has great flexibility in reactive power dispatch for all hours of the simulation.

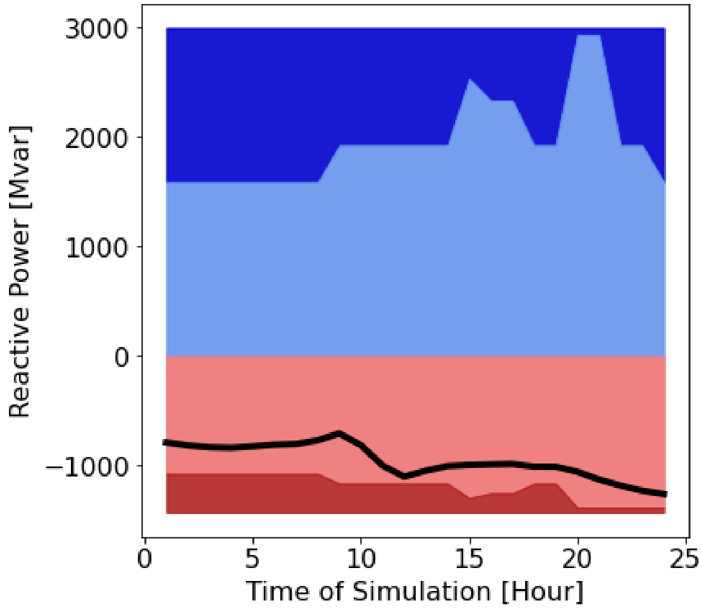
More information about the reactive power dispatch and availability for the system simulation at 2:00 PM and 3:00 AM, respectively, is given in Figures 4 and 5. These show how adaptable reactive power resources are for different system regions at one point in the experiment. Figure 4 shows that the East area in the example has the least amount of reactive power reserves online at 3:00 AM in the simulation .The other regions at this time in the simulation demonstrate a greater range of flexibility even though there are some reactive power resources offline in each area of the system. The VRRGDV sin Figure5 show that a majority of reactive power devices are committed with in the grid at this point in time which leaves the simulation with highly flexible reactive power support deployment. It is evident from the two figures that there has been a shift in the deployment of reactive power devices and the commitment of generators in each section of the system. This Visualization strategy enables the user to identify the regions of possible adjustments to reactive power levels within the system, which may be particularly useful when working with voltage issues in a more highly constrained system.

These visualization techniques are all appropriate for various uses. As a situational awareness tool, VRRs provide light on grid operations and unit commitment within a case. In addition, these can be used to validate synthetic power grid scenarios, plan future scenarios, create power system scenarios, and assess resilience or flexibility.

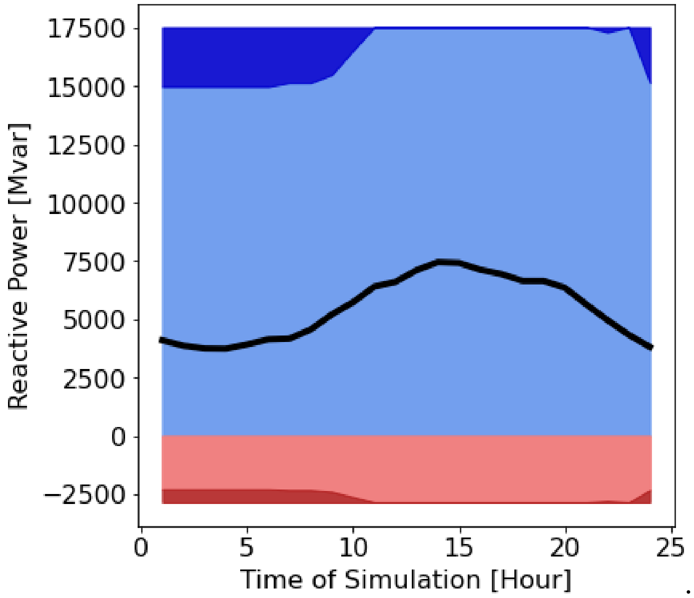
Both forms of the VRR offer a view of reactive power reserves and the flexibility of reactive power with in a region of the case. The VRR chart could be a useful tool for post-scenario analysis of a case's reactive reserves. Every tool, like any other, has uses for which it is more appropriate, therefore while choosing a situational awareness technique, keep the user and application in mind. The presentation of the flexibility of reactive power dispatch inside the case and the incorporation of the reserves from all reactive power devices in an area (including generators, shunts, and SVCs) is the unique perspective provided by both forms of the VRR in comparison to other visualization methodologies.



a) System-wide VRR chart



b) North area VRR chart.



c) Coast area VRR chart.

Fig.3: VRR charts for various regions of the system over the course of the simulation.

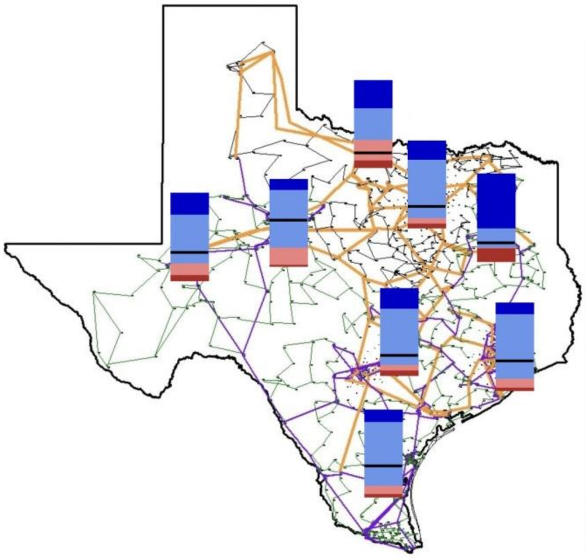


Fig.4: VRRGDV sat the simulation hour of 3:00AM.

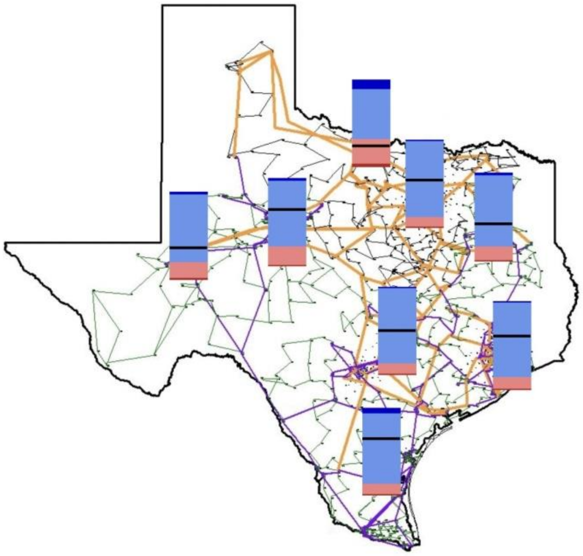


Fig.5: VRRGDV sat the simulation hour of 2:00PM.

CONCLUSIONS

In order to give users situational information of the availability and dispatch of reactive power devices inside a case, this article introduces VAR Ready Reserves (VRRs) in chart form and GDV form. Reactive power is reliably controlled in industry by defining reactive power management strategies based on voltage ranges and power factor.Thoserequirements are maintained by controlling generator set points and reactive power devices such as shunts and SVCs. Industry and academia alike have relied on a variety of visualizationstrategies to help maintain situational awareness of reactivepower levels within cases. There are advantages and disadvantages to each of the recognized visualization methods. Authors introduce anew visualization strategy, VRRs, for reactive power situationalawarenesstoaddresssomeoftheobservedlimitationsofexisting visualizations. VRRs present an aggregate visualization of the availability of reactive power resources (generators, shunts, SVCs)as well as present dispatch levels for a region of the case. These provide users a sense of how flexible the reactive power resources are in a particular area of the system. The VRRs can be used with VRR GDVs in an integrated system view, or with VRR charts in chart form. Combining VRR GDVs with other visualization tools, including voltage contours, is made simple. A case study illustrating the VRRs in chart and GDV form is provided, utilizing ACTIVSg2000. Future uses for this study could include validating synthetic grid scenarios, allowing for region flexibility in planning cases, or assessing planning cases with increased grid integration of renewable energy sources.

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