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Voltage Optimization

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ACRONYMS

ADMS	automated distribution-management system
DERMS	distributed energy-resource management system
DOE	U.S. Department of Energy
EMS	energy management systems
ERCOT	Electric Reliability Council of Texas
FACTS	Flexible Alternating Current Transmission Systems
IBR	inverter-based resources
INL	Idaho National Laboratory
PDC	phasor-data concentrators
PMU	phasor measurement units
ROCOF	rate of change of frequency
SCADA	supervisory control and data-acquisition
STATCOM	STATic synchronous COMpensators
SYNCON	SYNchronous CONdensers
WAM	wide area monitoring systems

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VOLTAGE OPTIMIZATION

1. INTRODUCTION

Voltage optimization refers to a volt-var optimization technique which was originally designed to minimize energy consumption and improve end-use efficiency on the distribution system. This reduces source voltage at a substation, which lowers generation demand, reduces system losses, and improves system stability. This has been the conventional implementation of voltage optimization: focusing on regulation of voltages throughout the distribution system via coordinated adjustments of load tap changers, line-voltage regulators, switched shunt compensation, and the targeted placement of new shunt compensation. These methods have received increased focus following a growth in distributed-energy resources (DERs) interconnecting at the distribution level, given their developing capability to participate in voltage regulation. This is paired with the intermittency challenges they pose, load imbalances, and voltage fluctuations. Voltage optimization has long been an area of extensive research within the distribution system, with various strategies and philosophies demonstrating a range of effects. The conventional focus on the distribution system owes to the typical operation of transmission systems, which assumes firm local resources and flows strictly from generation resources to loads. The strategies employed in distribution have also been optimized for this typically radial configuration and operation of the distribution system.

The grid, as a whole, has seen a shift towards disparate utility-scale renewable sources interconnecting to the transmission system, which represents a more mesh connected network. These resources have non-firm generation characteristics that depend on atmospheric conditions, which has led to a transmission system in which loading has become less regulated over time. Broadly speaking, renewable generation has three defining characteristics: (1) it typically interfaces with the power system thorough full or partial power converters, referred to as inverter-based resources (IBRs), (2) it provides power in intermittent intervals, and (3) it is not dispatchable, meaning that the renewables' electric output cannot be provided on demand. The primary topics of concern for these technologies with regard to grid stability is that these IBRs are primarily grid following devices, meaning that they require a sufficient grid reference to ensure stable operation. The decentralized nature, typically remote from load centers like large cities, paired with the intermittency of power delivery makes the regulation of transmission-system voltages complicated in a way that was not a historical consideration. These new system configurations can carry certain operational risks; one leading concern that occupies many grid operators' thinking is the regulation of system voltages as loading trends and resource availability vary throughout the day.

2. WHAT AFFECTS VOLTAGE STABILITY?

2.1 Impact of High IBR Penetration on Voltage Stability

Several regional electric grids within the United States have seen significant adoption of variable renewable resources. In the modern system the majority of these resources are frequently IBRs. Some areas, such as the American Southwest, the Texas Panhandle, and the Great Plains, have seen a high penetration of these types of IBRs. These resources not only interconnect at high levels in areas of renewable-resource availability (i.e., strong sun, consistent winds), but they have also offset the retirement of conventional rotating generation resources, such as coal or nuclear power plants. IBRs, at least those that are currently connected to the grid as of 2024, conventionally function using grid following control schemes. These control schemes require a voltage and frequency grid reference to inform their operation. In absence of these grid measurements, the IBR controls can tend towards unstable operation. Historically, conventional power plants with high inertia from the spinning mass of the rotor have acted as the source of these grid references. Disturbances in close proximity to these conventional generators allow the inertia of the rotating mass to offset the grid disturbance and retain what is conventionally referred to as a stiff grid. As these conventional resources retire from the system, the sources of grid stiffness become more remote, leading to the development of weak portions in the grid.

The definition of a weak grid is one that demonstrates a high sensitivity to changes in power flow in the area (dV/dP or dV/dQ), a low short circuit ratio (high impedance in the area), and a low inertia constant. Grid weakness can create feedback loops in IBRs that are connected in the area as they are sources for power injection into the grid. If IBRs seek a grid reference to inform the balance of the active and reactive power that they inject, then they can find themselves governing their own operation, which introduces a feedback loop to grid response. This is exacerbated because IBRs have fast, high gain controllers that govern the functionality of their power electronics and see relatively high impedances connecting these resources to the grid. These conditions can force instability into the operations of the resource and can lead to unit tripping, voltage flicker or other power-quality issues, potential human-safety concerns, and damage to equipment. A weak grid assessment example has been provided in Figure 1.

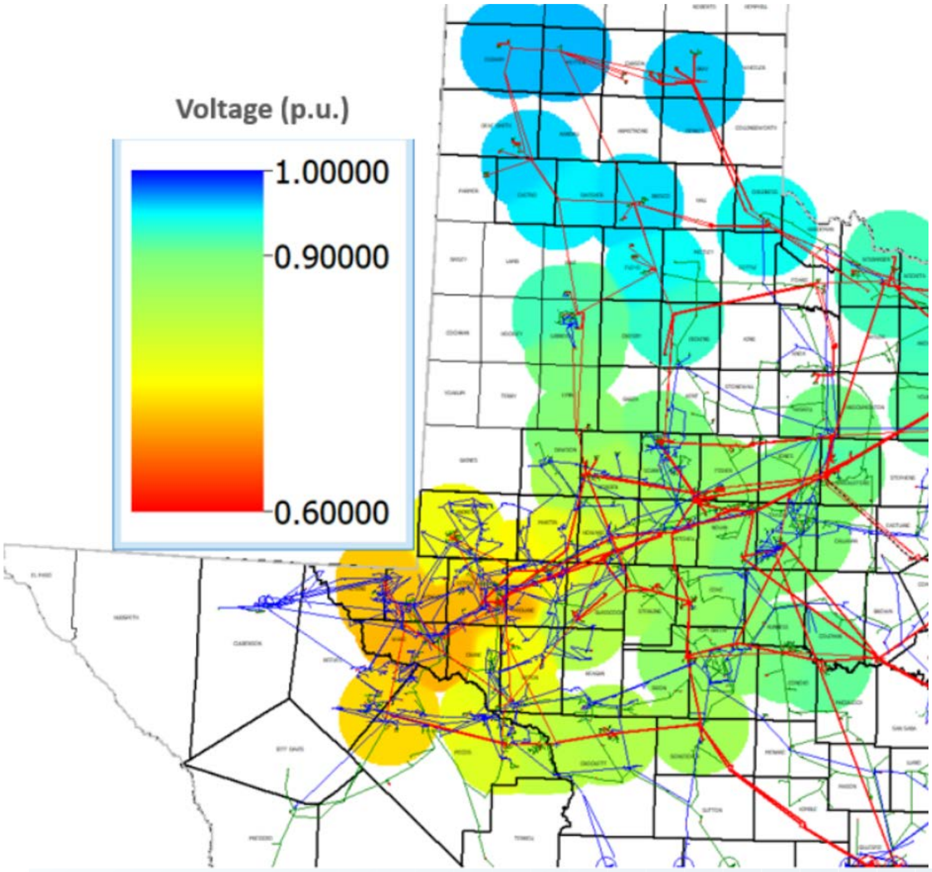

Figure 1. Weak grid presenting as a voltage-dip-sensitive area within the Electric Reliability Council of Texas (ERCOT) region, with its high IBR penetration[a].

Weak grids also depend on transmission system topology because portions of the system may indicate sufficient grid strength when all local lines are in service, but when a line outage occurs, the local system can develop sensitivities which compromise the stability of local IBRs. Typical mitigations to these conditions are curtailment orders applied to the IBR to minimize the influence that the resource has on local operating conditions, or can be provided by the implementation of transfer trip-protection schemes to disconnect the IBRs from the system under known topology configurations that have been identified in the planning stages.

Under such a configuration, the aggregate effect can lead to interaction among sites[b], driving sub- or super-synchronous oscillations[c] and reactive-power exchanges. These can cause

a C. Danielson. 2023. "ERCOT Assessment of Synchronous Condensers to Strengthen the West Texas System." ERCOT.

b L. Fan, Z. Miao, S. Shah, P. Koralewicz, and V. Gevorgian. 2023. "Solar PV and BESS Plant-Level Voltage Control and Interactions: Experiments and Analysis." IEEE Transactions on Energy Conversion 38(2): 1040–1049.

c L. G. Meegahapola, S. Bu, D. P. Wadduwage, C. Y. Chung, and X. Yu. 2021. "Review on Oscillatory Stability in Power Grids With Renewable Energy Sources: Monitoring, Analysis, and Control Using Synchrophasor Technology." IEEE Transactions on Industrial Electronics 68(1): 519–531.

operational risks that directly impact local generation facilities and risk propagation to the local system. Situations have been observed under which reactive power exchanges resulted in one resource being forced to operate at its capacitive limit while another was forced to its inductive limit. Depending on the capabilities of these resources this can force them to operate outside of their voltage limits resulting in both resources experiencing voltage protection operation events[d] that impact system stability and resource adequacy.

One solution for this configuration would be to remove the risk of common-node conflicts for clustered resources and, instead, implement an adaptive zonal-division method. This expands from local control to a zonal perspective and uses a wide-area closed-loop coordinated voltage and reactive control scheme. This aggregates several plants within the zone and schedules them to control a pilot node, or a central point in the zone, rather than targeting regulation of the high side of the facility or common point of interconnection with the transmission system. Voltage-droop control of a given renewable resource can minimize the risk of these facilities interacting and exchanging reactive power with one another through a process which involves designating zones and assigning resources to them. Zones are weakly coupled through a high interzonal impedance, meaning interzonal interaction is minimized and identification of the control node is generally located at the electric center of the defined zone. One of the benefits of this control method is that it allows for systems to be operated closer to their capacity limits by optimizing voltage support for the local zone. This also acts to better regulate the production and consumption of reactive power within the zone, which prioritizes reserving transmission capacity for active power transfers.

Lack of advanced technologies and techniques have required employing conventional solutions requiring a reliance on dynamic reactive power sources such as synchronous generators, SYNchronous CONdensers (SYNCON) or STATic synchronous COMpensators (STATCOM). These devices have recently grown in popularity as they were used to mitigate stability issues that developed in regions seeing high levels of IBR deployment. More information on SYNCONs, STATCOMs, and other shunt connected Flexible AC Transmission Systems (FACTS) can be found in the white paper, "Shunt Connected FACTS Devices and Synchronous Condensers." It should be noted that there is no specific level of IBR penetration that causes these issues to develop; rather, these issues are influenced by system topology and are dispatch dependent. These issues can easily develop in situations where a large level of active power is being produced by renewable resources that are weakly connected to the local grid through a high¬-impedance route such as in a radial topology. Under such configurations, feedback loops can result in local instability that propagates to the larger system, especially for grid-following inverter-control functionality. An acute example of this is the phenomenon known as subsynchronous control interaction, where a wind farm can be radially connected to a series capacitor. Resonant exchanges of energy between the wind farm and the series capacitor can result in fast-developing oscillations that have damaged

d B. Ryan, C. Mouw, C. Sifontes Lopez, et al. 2022. "Transmission-Level Multi-Facility Coordinated Voltage Control for the Integration of Inverter-Based Resources into a Weak Grid." CIGRE US National Committee, Grid of the Future Symposium.

both wind turbines and series capacitors in the past[e]. This is a single example and not inclusive of all configurations that can present concern.

Coordinating the voltage control between sites to prevent excess reactive-power flow and competing voltage control can mitigate such concerns. Reduced switching operations is a byproduct of this coordination and is caused by the reduced Var (reactive power) exchange. This implementation can reduce the requirement for heightened system-operator focus on local voltage issues that can develop due to topology and resource-dispatch issues. This is not a limitation on system-operator capability; rather, it is an issue with the response-time requirement to mitigate these issues when they develop being far faster than the 15–30 minutes that system operators conventionally allocate to address issues.

Under these configurations, voltage-droop control has not been observed to provide a sufficient control method for systems with low grid strength, complex interconnections, or potential combinations of these issues. Voltage-droop control functions properly with individual generators and facilities, but as more renewable resources are connected to the grid, interactions perpetuate and force undesired performance. These dependencies are exacerbated due to the variability present with such renewable resources as wind and solar, which can see rapid availability changes, requiring the local grid to compensate for this intermittency.

As mentioned previously, voltage-droop control is a valid control philosophy in many situations, but this manner of coordination is required to allow for resources to control their own interconnection points and avoid the risk of interaction with neighboring resources as they seek to control a single common node. When operating in voltage-droop control, resources have a significantly faster response time to sudden voltage change problems and calls for the requirement to regulate interaction between resources which would otherwise have no visibility on what their neighboring resource is doing.

2.2 Impact of Load Diversity on Voltage Stability

Sensitivities can develop in areas with high concentrations of industrial facilities and large electric loads or areas with high residential loads where cooling systems largely consist of single-phase air-conditioner units. If these regions also happen to be areas that have seen heavy penetration of variable energy resources, then power-quality issues can develop and cause damage to loads and trigger protection operations which disconnect the load from the system. These sensitivities have developed at an accelerated pace recently due to the distributed interconnection of large data centers that require a level of voltage stability to continue operating and avoid nuisance protection tripping. Various regions are examining performance expectations or requirements that may be attributed to these loads in order to ensure grid reliability.

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e D. Kidd and P. Hassink. 2012. "Transmission operator perspective of Sub-Synchronous Interaction." PES T&D 2012, Orlando, FL. pp. 1-3.

3. WHAT ARE THE MITIGATION SCHEMES?

3.1 Voltage Control at Transmission Level

Voltage control at the transmission level has traditionally involved the coordinated adjustment of transformer tap positions to match seasonal settings for de-energized tap-changer transformers, and reliance on switched shunt settings to regulate voltages on systems under different demand conditions. Generator owners and operators participate in this regulation effort by setting local automatic high side voltage schedules that the generation facilities maintain to a relatively fixed point. This operation is combined with local and supervisory control and data-acquisition (SCADA) transmission-level switched shunt devices to provide local voltage regulation.

Generators and FACTS—elements capable of providing fast reactive-power responses to disturbances in the system—are typically operated in voltage droop control to ensure they do not force reactive oscillations between electrically close power controllers as they act to meet a scheduled voltage setpoint. Voltage droop functions by coupling the amplitude of the point of interconnection voltage to the reactive output of the controlled element, which creates a local control loop. Under weak grid conditions (i.e., radial topology, low reactance to resistance ratio, or stronger real power-voltage coupling), this loop can degrade system stability. This occurs due to the dependence of the output of the interconnected resource that holds a greater influence on the measured reference voltage at the point of interconnection with the grid. This acts to exacerbate the feedback loop by allowing the resource output to directly influence its operation. For example, strong real-power voltage coupling can lead to voltage instability as real power fluctuates. System operators use reactive power as the element and voltage as the reference when optimizing for voltage stability.

3.2 Wide Area Monitoring Systems

Synchrophasors were introduced to the system following the development of phasor measurement units (PMUs). These devices have a sampling rate faster than conventional SCADAs or energy management systems (EMS), which allows them to provide closer to real-time monitoring on grid dynamics and stability. Typical PMUs have sampling rates on the order of one or two samples per cycle, and pairing them with geospatial and time-synchronizing capabilities allows for the development of a wide area monitoring systems (WAMS). WAMS are used to monitor, protect, and implement control schemes to regulate system performance. To construct a WAMS, PMUs are installed at locations across a transmission system, which provide a distributed perspective on coordinated system dynamics at the referenced sampling rates. PMUs monitor voltage/current magnitude and angle, frequency, and rate of change of frequency (ROCOF), based on the data collected from one or more primary sensors like current and potential transformers. PMUs can provide measurements in two performance classes, either P or M class. The P class is typically used for protection and control purposes, which requires fast response and minimum delay. The M class is typically used for measurements in the present of out-of-band signals, which require greater precision[f]. PMUs can be configured to provide real- and reactive-power measurements, sampled measurements, and Boolean status. PMUs can feed into phasor-data concentrators (PDC), which can then provide inputs and observability for local- or centralized-control operation to optimize system performance. These systems can be used to monitor wide-area status and flag stability concerns that can trigger automatic or system-operator action. Typical WAMS applications include voltage/frequency instability detection and control, system stress/robustness/damping detection and control, reliability margin detection and control, etc.

Various WAMS architectures are possible, with a range of performance considerations and communication-system bandwidth concerns. The most typical WAMS architectures are centralized, decentralized, and distributed. In centralized WAMS architectures, PMU data are collected and transmitted to a central PDC, at which time alignment and data concentration of all received PMU measurements are processed and stored. The concentrated data are used for analytics and visualization. Decentralized WAMS architecture has a monitoring area subdivided into multiple small areas, and PDCs control these areas locally using the local measurements. Local controllers are connected to one another when there is a need to solve larger-area problems. Distributed WAMS architecture is a blend of centralized and distributed controls, with a division of responsibilities, which has the effect of centralized control with decentralized execution. Local PDCs are situated at the substation or regional level, and a master PDC is located at a central control station. PMUs within a local area send phasor data to their local PDC, which is connected to the master PDC at the central control station. Distributed architecture's primary impact is the flow of information because local PDCs can process raw PMU data in a manner that is supervised and controlled by the master PDC. All three architectures require various levels of communication bandwidth, with the centralized architecture requiring the highest raw PMU data from the system. All are funneled to the central PDC. WAMS architecture selection is generally dependent on the targets of data analysis, data required for analysis, the source of data, the location where data analysis needs to be performed, and the location where enactment of action needs to be completed.

3.3 Coordinated Control of Various Reactive Power Devices

The above-mentioned methods, as well as conventional SCADA-driven, automated, or operator actions, can be used to maximize reactive-power margin at generating units. This is conventionally done to maintain reactive-power margin of units, targeting the operation of units near unity power factor, where possible and practical, with a focus on reducing active- and/or reactive-power losses. Generators must be coordinated with local shunt reactive devices to target this optimal power-flow configuration. This is done to best maintain dynamic reactive margins for the system in the event of disturbances to ensure that reactive power is available to support voltage recovery as reactive power and voltage stability are largely local issues.

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f IEEE/IEC International Standard – Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems - Measurement

3.4 Undergrounding Initiatives

Another trend that will impact regional sensitivities is the placement of transmission and distribution lines underground. In some areas, this is done as a method to mitigate such climate risks as the impact of rising ambient temperatures, wildfire, and high winds. The largest impact of moving electric infrastructure underground, beyond cost, is an increase in capacitive-line-charging current that has been defined as the Ferranti effect. This undergrounding initiative will work to shift voltage schedules across a system and increase the total amount of reactive power that is present in a system. This means that more miles of underground conductor will deliver larger amounts of reactive current into the system, increasing transmission- and distribution-system voltages. This effect is especially pronounced when systems are experiencing lightly loaded scenarios, which increases the need for additional types of voltage-regulating equipment to be installed on the system.

3.5 Voltage Optimization at the Distribution Level

For completeness, and to further distinguish how voltage-optimization techniques vary depending on the connectivity of the system, the following has been included as a summary of the current state of voltage optimization at the distribution level. These implementations can employ a centralized intelligence system that is either standalone or tied to an automated distribution-management system (ADMS) or distributed energy-resource management system (DERMS). The primary concern for distribution is not only the medium-voltage delivery levels, but potentially the secondary-voltage drops that are less standardized and have fewer real-time information feeds available to provide to a control algorithm. ANSI C84.1 allows for the point of delivery normally to be at 114 V on a 120 V base, which has to be split between medium voltage and service (secondary transformer line-to-line voltage) connections to the end customer. Few utilities map their systems down to the meter, including service drops. Therefore, an assumption of the worst case voltage drop has to be applied, which is typically in a range of 4–6 V. Most utilities focus on the conservation voltage-reduction benefit that voltage optimization can provide—i.e., obtaining passive savings by lowering voltage closer to the actual designed ratings of equipment. This provides efficiency that would not be there if the utility delivered serviced loads at higher voltages. Other use cases can include cost per installed kVAR, cost per kW/h saved for energy efficiency, loss improvement from real and reactive-power flows, deferred generation costs, avoided generation costs, capital deferments, and voltage support for other reliability programs like fault-location isolation and service restoration (FLISR). Voltage optimization at the distribution level is a flexible tool which can be used by the utility to provide higher-quality service. Moving forward, smart inverters and curves[g] can be thrown into the resource mix, but this effort is still developing due to the regulations around curtailment of real-power flows from rooftop solar sources. This would play into the role played by DERMS, with some vendors having already developed a volt-VAR-watt optimization product.

g K. Prabakar, A. Singh and C. Tombari. 2019. "IEEE 1547-2018 Based Interoperable PV Inverter with Advanced Grid-Support Functions." 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL, pp. 2072–2077.