Substation Solutions & Power System Dynamics

Introduction

The Biden-Harris administration targets 100% clean electricity by 2035 and ambitious plans to cut greenhouse gas emissions to half by 2030, reaching net zero by 2050. As a result, the US power grid is anticipated to experience a significant shift from conventional power generation to renewable energy resources, distributed energy resources (DER), and electrification of the transport sector and nearly 3 TW.

To achieve 100% clean electricity, the US power grid must double its renewable generation capacity by 2030. This ambitious target poses a considerable challenge, as the US's existing power transmission infrastructure is already congested and doesn't have the capacity to integrate renewables as required. Currently, the renewable and storage interconnection queue stands at around 2.6 terawatts (TW)[1]. To cater to the interconnection queue, the US power grid must expand its transmission capacity by 1.3 TW (2.5%) annually, posing a great challenge to capital expenditure. Although, in the US, 20 new high-capacity transmission projects have entered the construction phase, which will add approximately 20 GW of transmission capacity by 2030, it will still be insufficient as the interconnection queue is anticipated to increase as well over the years.

Moreover, the Department of Energy expects a surge in annual DER additions from 2025 to 2030, including 20 GW to 90 GW of demand capacity from EV charging infrastructure and 300 GWh to 540 GWh of storage capacity from EV batteries. Additional demand from datacenters is expected to reach 60GW over the same period.

As a response to these challenges, U.S. electric utilities are turning to the automation of distribution feeders and substations.

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This strategic shift addresses existing issues and significantly improves grid resiliency, reliability, and system visibility.

Distribution Feeders and Substation Automation

Concerns over resilience and reliability have pushed electric utilities and in turn federal regulators to act in promoting automation of distribution feeders and substations.
An example of this can be seen with the Smart Grid Investment Grant (SGIC) program under the American Recovery and Reinvestment Act of 2009 (ARRA) funded the installation of 26 distribution automation projects. Similarly, recent initiatives such as the Grid Resilience and Innovation Partnerships Program (GRIP) and the Grid Innovation Program have further accelerated the trend toward automation of distribution feeders.

Moreover, automation at distribution is gaining traction among electric utilities to increase the reliability and resilience by maintaining the critical grid parameters, including achieving voltage stability, active and reactive power balance, and frequency regulation, which are being impacted by the proliferation of renewables and DERs. Similarly, electric utilities are opting for substation automation solutions by widely

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deploying SCADA (Supervisory Control and Data Acquisition) to remotely de-energize critical equipment during flooding, preventing catastrophic damage that could require weeks to repair or replace.

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Technologies Under the Spotlight

There are several advanced grid technologies available of which we'll focus on: Dynamic Line Rating (DLR), Voltage/VAR optimization (VVO), and substation automation.

Dynamic Line Rating to Tackle Renewables Interconnection Queue Challenges:

To tackle concerns related to the interconnection queue, electric utilities and federal initiatives, such as the Federal-State Modern Grid Deployment Initiative, aim to accelerate improvements to the U.S. electric transmission and distribution network.[2] A significant component of this initiative is the deployment of dynamic line rating (DLR) technologies which optimizes the power capacity of transmission lines in real time by considering factors like weather conditions and line temperatures.

This enhances the efficiency and utilization of existing grid infrastructure, reducing congestion and supporting the integration of more renewable energy sources.

The application of grid-enhancing technologies, including DLR, has offered substantial benefits to electric utilities in the US. For example, in the Kansas and Oklahoma portion of the Southwest Power Pool (SPP) grid, combining topology optimization, dynamic line ratings, and power flow control devices significantly reduced congestion. This combination more than doubled the existing headroom for interconnecting renewable resources, adding 3.7 GW of capacity with a payback period of only six months.
This $90 million investment is projected to yield $175 million annually in reduced production costs, highlighting the economic and operational benefits of adopting such advanced technologies.
Key examples of DLR deployment in the US include:

- Since 2022, PPL Electric Utilities has integrated DLR into real-time and market operations, using sensors to optimize transmission line capacity and enhance reliability.[3,4]
- Great River Energy is implementing the largest DLR project in the country by installing numerous sensors to boost grid efficiency.[5]

Diamonds are Paper's Best Friend

Volt/Var Optimization to Perform Voltage and Reactive Power Regulations

VVO is an example of a distribution automation system that increases the efficiency of the electricity delivery system and improves service to end-user customers by performing voltage and reactive power regulation under increasing load and DER integration scenarios.[6] VVO works by adjusting the voltage levels and reactive power flows in real-time or near real-time based on system conditions and operational requirements. It involves deploying advanced control algorithms and smart grid technologies to dynamically adjust voltage set points, control capacitor banks, and manage voltage regulators. By optimizing voltage and reactive power flows, VVO helps to minimize line losses, improve power quality, and extend the lifespan of electrical equipment.[7,8]

1 https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_1.pdf
2 https://www.whitehouse.gov/wp-content/uploads/2024/05/Federal-State-Modern-Grid-Deployment-Initiative-Principles_formatted.pdf
3 https://insidelines.pjm.com/dynamic-line-rating-activated-by-ppl-electric-utilities/
4 https://news.pplweb.com/2023-07-11-PPL-Electric-Utilities-first-of-its-kind-innovation-improves-reliability,-reduces-costs
5 https://heimdallpower.com/heimdall-power-launches-largest-dynamic-line-rating-project-in-the-u-s-with-great-river-energy/
6 https://www.ilsag.info/wp-content/uploads/SAG-ComEd-VO-Presentation_11-15-23.pdf
7 https://cleanenergygrid.org/wp-content/uploads/2014/08/Integrated-Volt-VAR.pdf
8 https://www.pnnl.gov/available-technologies/voltvar-optimization

Installed Base Renewables Capacity Needed for USA's 100% Clean Energy Target by 2030

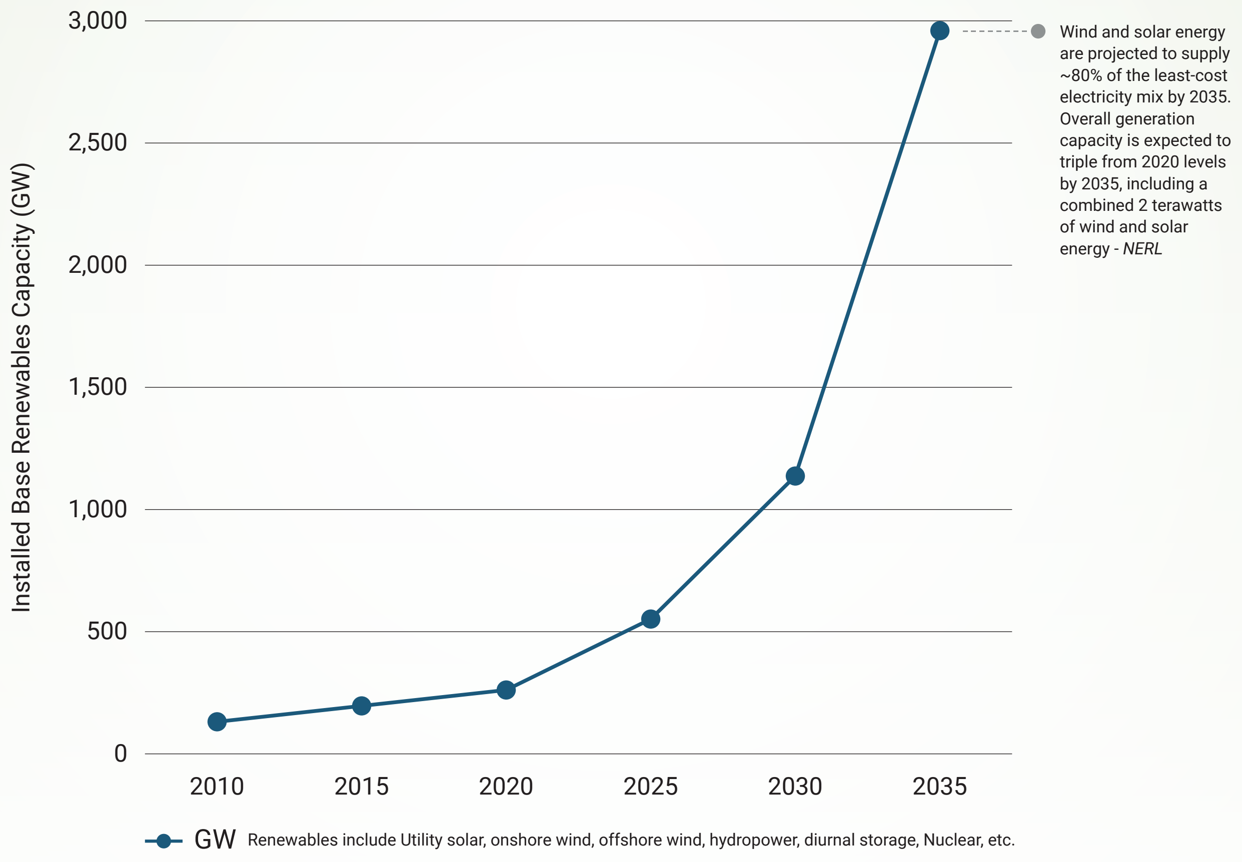

Figure 1: US's Pathway to 100% Clean Energy Targets, Source: PTR Inc.

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In the US, Electric utilities have implemented VVO for over a decade; for example, Duke Energy Progress of North Carolina has also installed VVO systems at 315 substations, while Duke Energy Florida has installed VVO systems at 262 substations.

Substation Automation to Cater to the Massive Adoption of EV Charging Infrastructure and Renewables

Substation automation integrates advanced control, monitoring, and communication technologies within substations to enhance operational efficiency, reliability, and responsiveness. It enables utilities to remotely monitor and control various substation equipment and processes, such as circuit breakers, transformers, and voltage regulators, using SCADA systems and intelligent electronic devices (IEDs). In the US, around 35% of the substation automation market is derived from the distribution sector, followed by the transmission sector, accounting for 25%.

Electric utilities across the US increasingly turn to substation automation to effectively manage the surge of EV charging infrastructure and renewable energy integration. For instance, Southern California Edison (SCE) has implemented advanced automation technologies in its substations to accommodate the growing number of EVs and solar installations in its service area. By deploying intelligent monitoring and control systems, SCE has enhanced grid reliability and efficiency, which is crucial for handling the variable nature of renewable energy sources and the unpredictable charging patterns of EVs. This proactive approach ensures stable power delivery and supports the transition towards a cleaner energy future.

Key Features and Adoption Status of Distribution and Substation Automation Technologies

Technology	Adoption Status	Key Features	Grid Issues Addressed
Substation Automation	Mature Technology	• Real-time remote monitoring and control • Advanced protection and control • Automated fault isolation switching operations • Seamless integration with renewable energy sources	• Manual fault detection and isolation • Unbalanced loads and power demand fluctuations • Grid stability and reliability issues due to proliferation of renewables
Volt/Var Optimization	Emerging Technology	• Real-time Monitoring and Control • Automation of legacy equipment (capacitor banks, voltage regulators, and tap changers) • Data analytics and predictive maintenance • Integration with existing SCADA system	• Voltage fluctuations and instability due to variations in load and DER generations • Power losses due to inefficient reactive power management • voltage and reactive power control challenges under high renewables scenario
Dynamic Line Rating	Emerging Technology	• Real-time monitoring and data acquisition based on sensor • Predict the line's capacity under varying environmental conditions and forecasted loads • Integration with grid management systems (existing energy management systems and SCADA)	• Transmission line congestion • Impact of the intermittent nature of renewables on the grid, such as fluctuations in power flows, challenging static line ratings • Operational flexibility and grid reliability issues

Figure 2: Key Features and Adoption Status of Distribution and Substation Automation Technologies, Source: PTR Inc.

In recent years, electric utilities have been integrating VVO into the already adopted substation automation solutions to manage the grid operations better and perform regulations of critical parameters under high-density DERs and renewables regions. A few key examples include Duke Energy, which has deployed VVO and substation automation to improve grid reliability and efficiency. At the same time, Ameren Missouri uses VVO as part of its Smart Energy Plan and leverages substation automation for grid modernization.

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Rising Winds Will Lift All

PTR expects all three technologies covered to grow significantly over at least the next decade as both utility-scale and behind-the-meter DERs continue to develop. Major utilities have planned the following just to name a few:

- PPL Electric Utilities intends to extend its DLR technology across more transmission lines to enhance grid reliability and efficiency further.
- Great River Energy plans to increase its DLR deployment to improve the grid's capacity and operational efficiency.
- Duke Energy and Ameren are committed to expanding their VVO and substation automation projects to support renewable energy integration and overall grid performance.
- Utilities like NextEra Energy, Exelon Corporation, Entergy, Xcel Energy, and National Grid are planning significant investments in substation automation to modernize grid infrastructure to improve real-time data analysis.

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The ambitious decarbonization goals necessitate this comprehensive transformation of the power sector, with a strong emphasis on renewable energy integration and transportation electrification. Automation of distribution feeders and substations has emerged as a critical strategy to tackle the inherent challenges of enhancing grid resilience, reliability, and efficiency. Advanced technologies like Dynamic Line Rating, Volt/VAR optimization, and substation automation will address current grid constraints while paving the way for a more flexible and adaptive energy infrastructure. Continued adoption and expansion of these technologies by utilities will be essential in supporting the U.S. in achieving its clean energy targets, ensuring a sustainable and resilient power grid for the future.

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Michael Sheppard Mike has 16 years of market research experience designing numerous research practices from scratch while leading over 50 bespoke projects with Fortune-500 companies. In 2016 he co-founded Power Technology Research (PTR) and has since launched new research practices in solar, storage, battery, and e-mobility. In addition to building and growing partnerships, he currently focuses on research around regulation and de-carbonizing efforts. In 2020, he co-founded Matos, an intelligence automation company focused on providing powerful AI-driven tools for the market research sector. In 2023, this business was acquired by PTR. Prior to founding PTR, he spent 8 years with iSuppli/IHS Markit in various analyst and consulting roles where he covered a broad range of sectors including mobile, renewable power and electricity transmission and distribution (T&D).
In his last role, he led the power technology consulting group. He is an expert on the PV industry and having performed numerous competitive dynamics and opportunity assessment projects, covering upstream, downstream, and supply chain topics. In 2008, he obtained a Bachelor's of Science in both Financial Services and in Corporate Finance from San Francisco State University. (sales@ptr.inc)

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