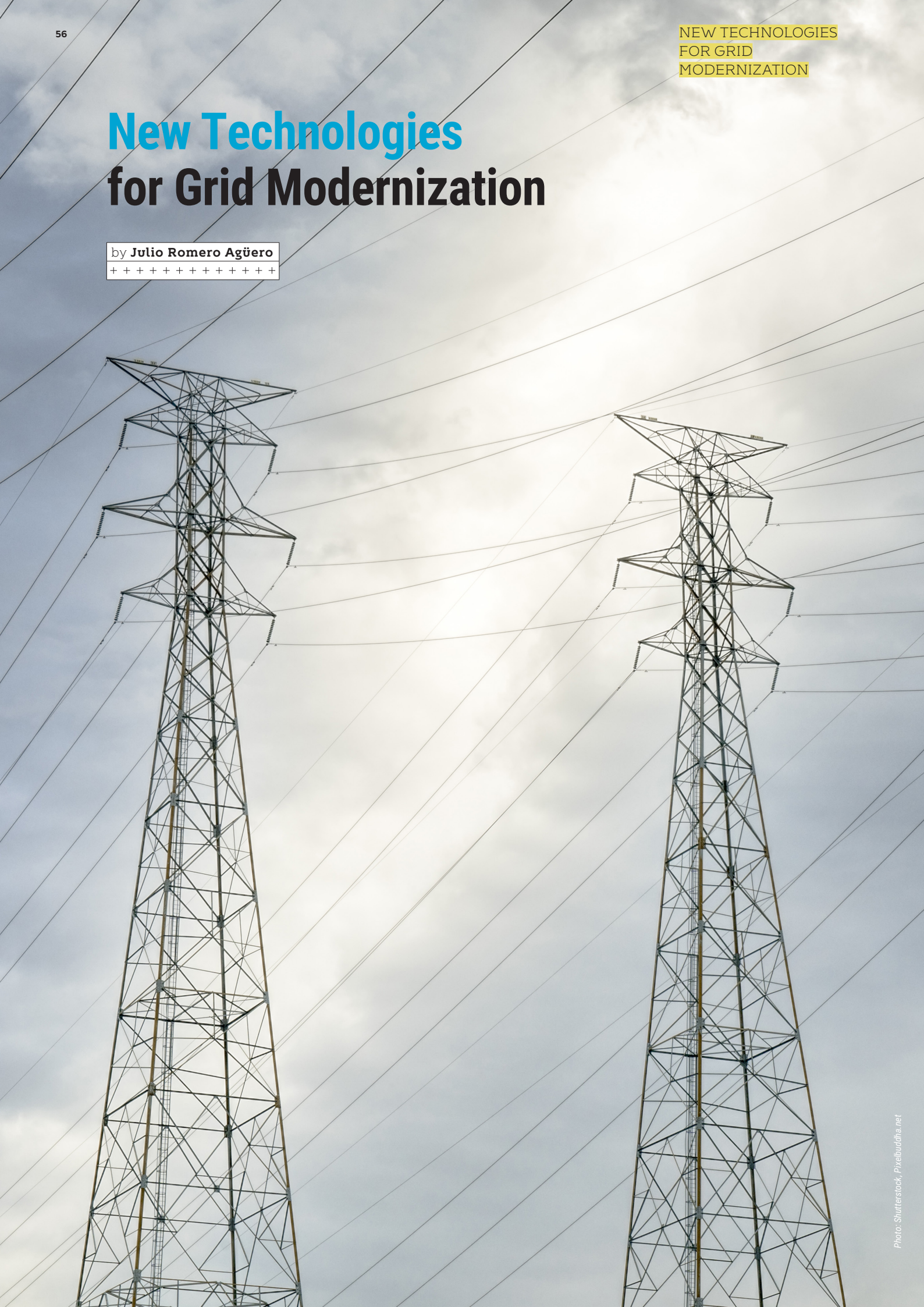


New Technologies for Grid Modernization

by **Julio Romero Agüero**

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The electric power industry is experiencing an unprecedented evolution driven by multiple important trends. For instance, in transmission systems, there is growing interconnection of renewable generation and retirement of fossil fuel power plants. In distribution systems, there is increasing integration of distributed energy resources (DER), particularly solar photovoltaic distributed generation, and electric transportation, as shown in Figure 1 and Figure 2, respectively. Key trends also include the adoption of energy storage, particularly battery energy storage systems (BESS), and the proliferation of data centers.

Additionally, customers have growing expectations regarding reliability, resilience, and power quality due to society's increasing dependence

on the digital economy. This is particularly challenging given the vulnerability of power distribution systems (particularly overhead lines) to disruptions caused by more frequent and severe climate-related events (e.g., hurricanes, winter storms, wildfires, etc.) and major events in general, as shown in Figure 3.

Finally, there is an increasing need for considering the interaction effects between transmission and distribution systems, such as reverse power flows through distribution substations caused by DER integration. The complexity to design, plan and operate power delivery systems is increasing rapidly, particularly given the unbalanced nature of distribution systems, this is conceptually illustrated in Figure 4.

Most urban and suburban feeders are natural candidates for implementation of closed-loop operation to mitigate voltage increase and fluctuation issues and facilitate DER integration, since their topology is generally meshed, and their operation is radial.



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Figure 1
Cumulative Solar Installations (U.S.)¹

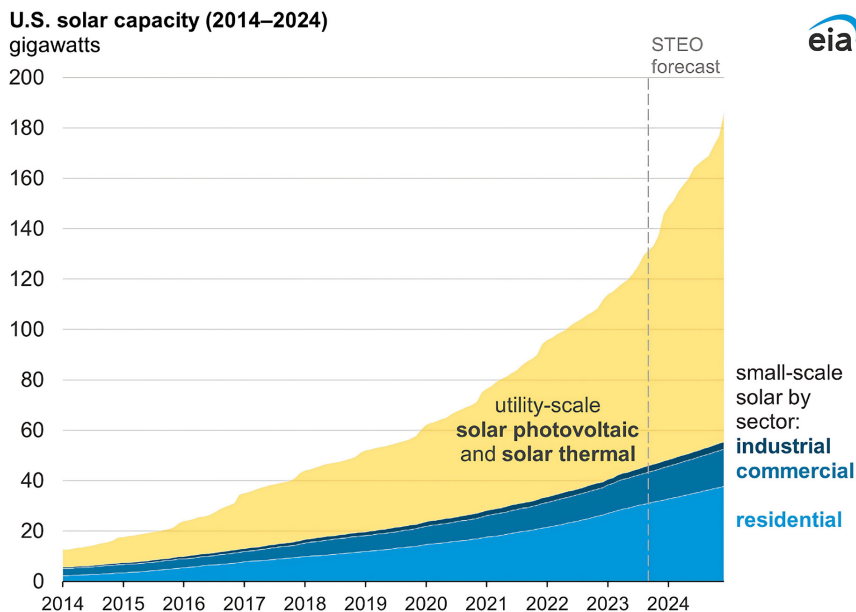


Figure 2
Total Monthly EV Sales (U.S.)²

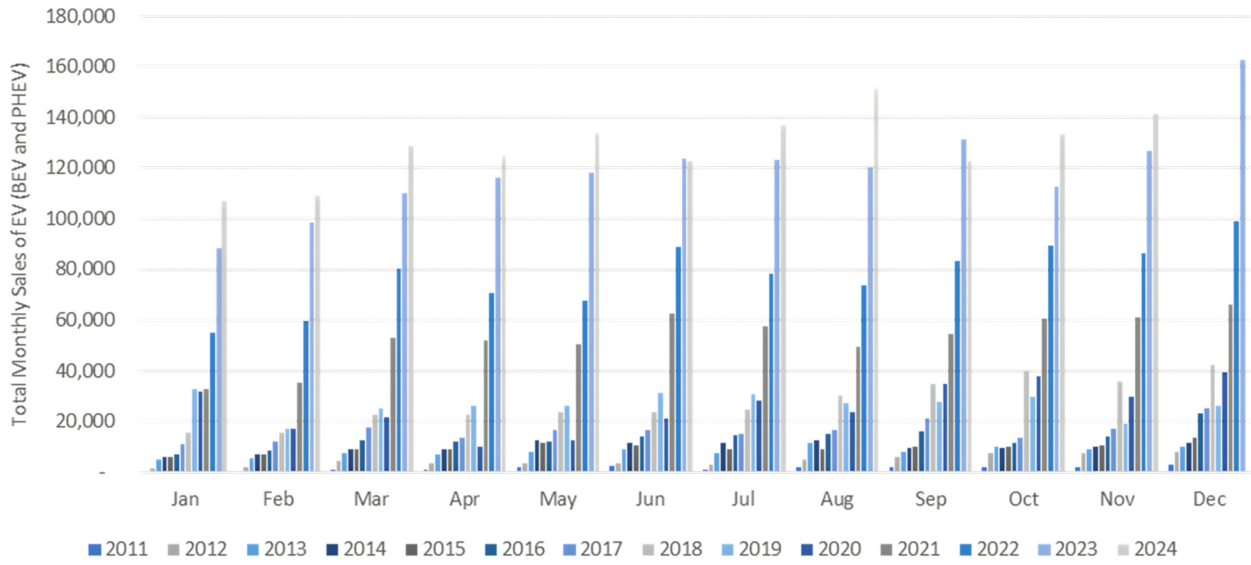
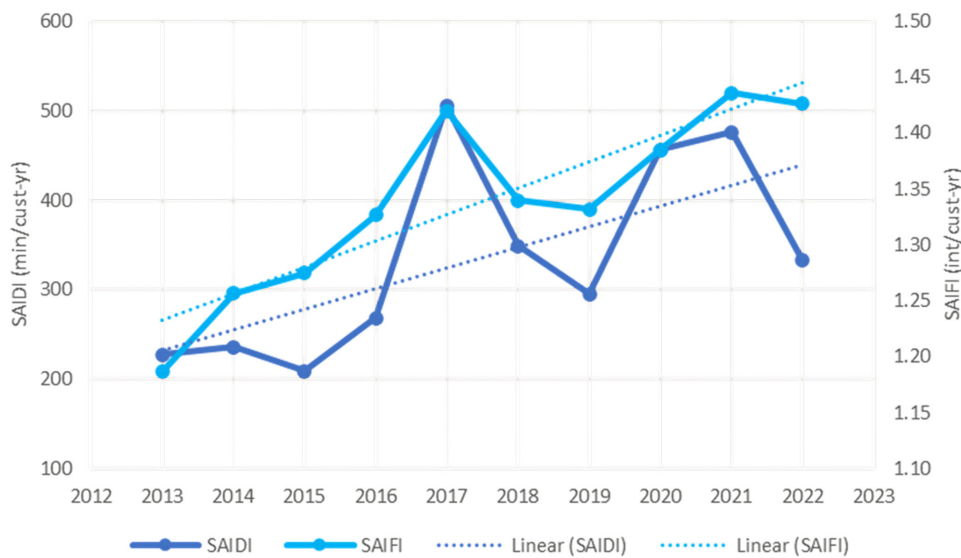


Figure 3
U.S. Reliability Indices with Major Events (IEEE)³



SOP are a distribution application of flexible alternate current transmission systems (FACTS), which are a family of power electronics devices that allow controlling transmission and distribution line voltages, currents, and power flows.

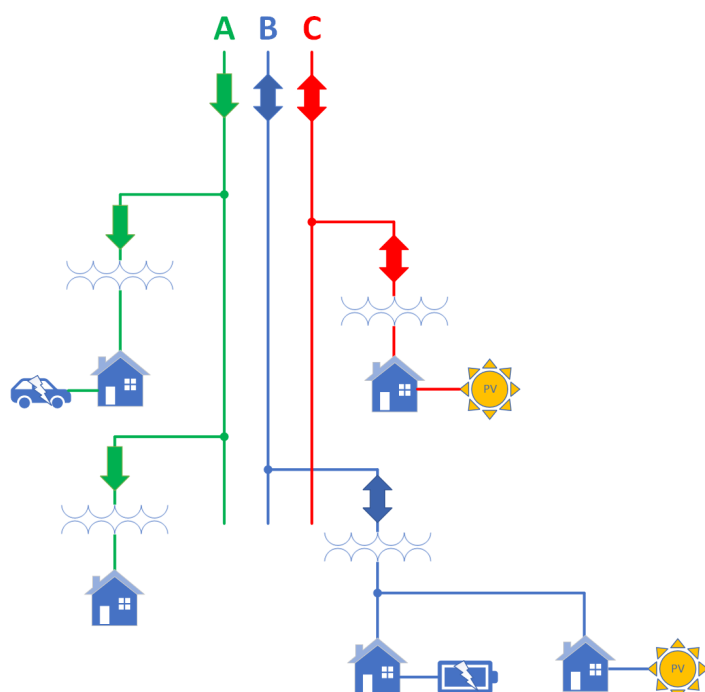
Addressing these challenges requires modernizing distribution systems to enable real-time operation, predictive analytics, and advanced planning applications. This requires, among others, the deployment of advanced technologies, the upgrade of foundational infrastructure, the implementation of efficient processes, and the training and recruitment of workforce with new skillsets.

SOP benefits include continuous and dynamic power flow control between neighbor feeders and substations, deferral of investments in capacity increase, improved reliability and resilience, increased DER hosting capacity, and power and energy loss reduction.

Over the last two decades there has been significant deployment of advanced technologies, particularly in distribution systems, examples include:

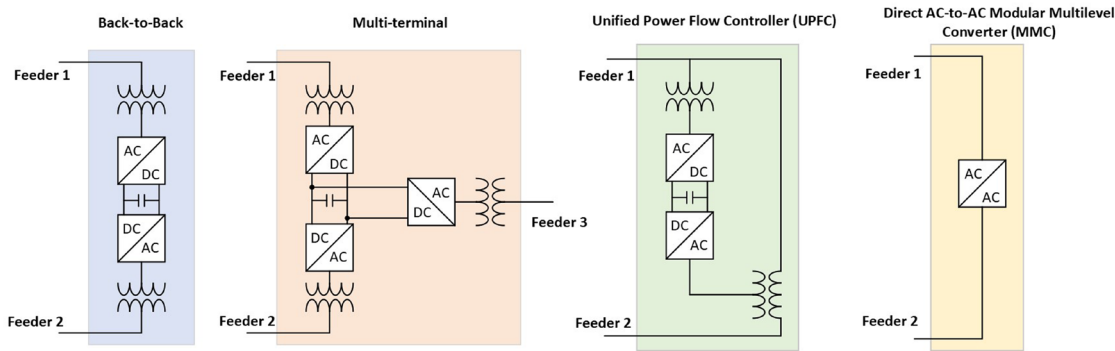
- Advanced metering infrastructure (AMI)
- Digital relays and intelligent grid devices (e.g., reclosers, capacitor banks, and voltage regulators with microprocessor-based controllers, voltage and current sensors, etc.)
- Distribution automation applications (e.g., fault location, isolation and service restoration – FLISR, volt-var optimization – VVO, etc.)
- Telecommunications infrastructure (e.g., optic fiber cable, remote terminal units, etc.)
- Advanced distribution management systems (ADMS) and DER management systems (DERMS)
- Smart inverters, microgrids and virtual power plants

Figure 4
Conceptual example of the increasing complexity to operate and plan distribution grids due to the adoption of DER and EVs



- **Phase A** supplies customers with traditional loads and electric vehicles (EV), current flows downstream
- **Phase B** supplies customers with battery energy storage systems (BESS) and photovoltaic (PV) distributed generation (DG)
 - Current may flow in the downstream (forward) or upstream (reverse) direction, depending on PV and BESS installed capacities, real-time output, and BESS operation mode (charging or discharging)
- **Phase C** supplies customer with PV, current may flow downstream (e.g., at night-time) or upstream (e.g., at daytime) depending on PV capacity
- In a high penetration scenario, each feeder and substation may supply hundreds or thousands of PV, BESS and EV. PV output can fluctuate significantly and rapidly due to cloud cover changes and some EV may operate in vehicle-to-grid (V2G) mode and inject power to the grid
 - Phase current and power flow magnitude and direction can change often, there may be violations of voltage and loading (planning) limits, voltages may fluctuate, imbalance can be an important problem, there may be total harmonic distortion (THD) issues, etc.

Figure 5
SOP Topologies



While significant progress has been made, the challenges introduced by the transformation of distribution feeders from largely passive and static radial lines into active and dynamic networks requires greater adoption of these technologies, along with the introduction of new technologies and alternative operation modes of distribution feeders. In this regard, this article discusses the utilization of soft-open open points (SOP) to enable closed-loop operation of primary (medium-voltage) distribution feeders. This concept can help mitigate the

impacts caused by the adoption of variable renewable generation and electric vehicles (e.g., voltage fluctuations, voltage increase and decrease, asset overload, etc.) and allow for greater and more efficient utilization of existing asset capacity (e.g., lines and transformers). This can help increase DER and EV hosting capacity, optimize reserve capacity, and therefore, improve reliability and resilience. This includes deferral of capital investments for capacity expansion, which can address, to some extent, concerns regarding grid modernization affordability.

It is worth noting that non-radial operation of distribution feeders is already utilized in some urban distribution applications (e.g., downtown areas of large cities) to attain premium reliability levels (e.g., spot networks, secondary networks, etc.). However, in suburban and rural areas, operation of distribution feeders is largely radial. Most urban and suburban feeders are natural candidates for implementation of closed-loop operation to mitigate voltage increase and fluctuation issues and facilitate DER integration, since their topology is generally meshed, and their operation is radial. This means that these feeders usually have multiple normally open points (NOP) with neighbor feeders that allow for reconfiguration and load transfers during outage management and restoration, and to address load growth needs. Generally, switches and reclosers with open status are deployed on those NOP to facilitate these activities.

SOP are a distribution application of flexible alternate current transmission systems (FACTS), which are a family of power electronics devices that allow controlling transmission and distribution line voltages, currents, and power flows. FACTS devices are increasingly being applied to distribution systems, for instance, static synchronous compensators (STATCOM) and low-voltage static var compensators (SVC) have been used to facilitate the integration of DER in distribution systems. SOP are deployed⁴ in NOP of distribution feeders to control power flows between neighbor feeders and substations. SOP functions during normal operation include addressing asset overloads, voltage regulation (low/high voltage violations), reactive power compensation, and current/voltage imbalance.

During abnormal conditions (e.g., during or after faults), SOP can isolate faults and support post fault supply restoration⁵. SOP benefits include continuous and dynamic power flow control between neighbor feeders and substations, deferral of investments in capacity increase (e.g., via peak shaving), improved reliability and resilience, increased DER hosting capacity, and power and energy loss reduction.

SOP topologies include a) two back-to-back voltage source converters (VSC) connected through a common DC link, b) multi-terminal VSC, c) distribution-class unified power flow controllers (UPFC)⁶, and d) direct AC-to-AC modular multilevel converter (MMC)⁷, as shown in Figure 5.



Figure 6 shows a conceptual example of an application of SOP to address distribution system issues. This figure shows two neighbor feeders with a planning limit of 4 MVA (this is the maximum amount of power that the feeder should deliver safely under normal operating conditions) and a NOP with a switch or recloser. Two scenarios are presented:

- In the first scenario (traditional), the annual peak demand served by the first feeder is twice that of the second feeder, this can be due to several factors, including the specific load profiles, load density, and number of customers served by each feeder. In this first scenario, there is no power flow through the NOP, since the switch or recloser is open, hence, the NOP serves as a boundary between both feeders. There is a need for capacity increase in this first feeder to serve future load growth and to host load transfers from the second feeder (reserve capacity) during outage management and restoration.

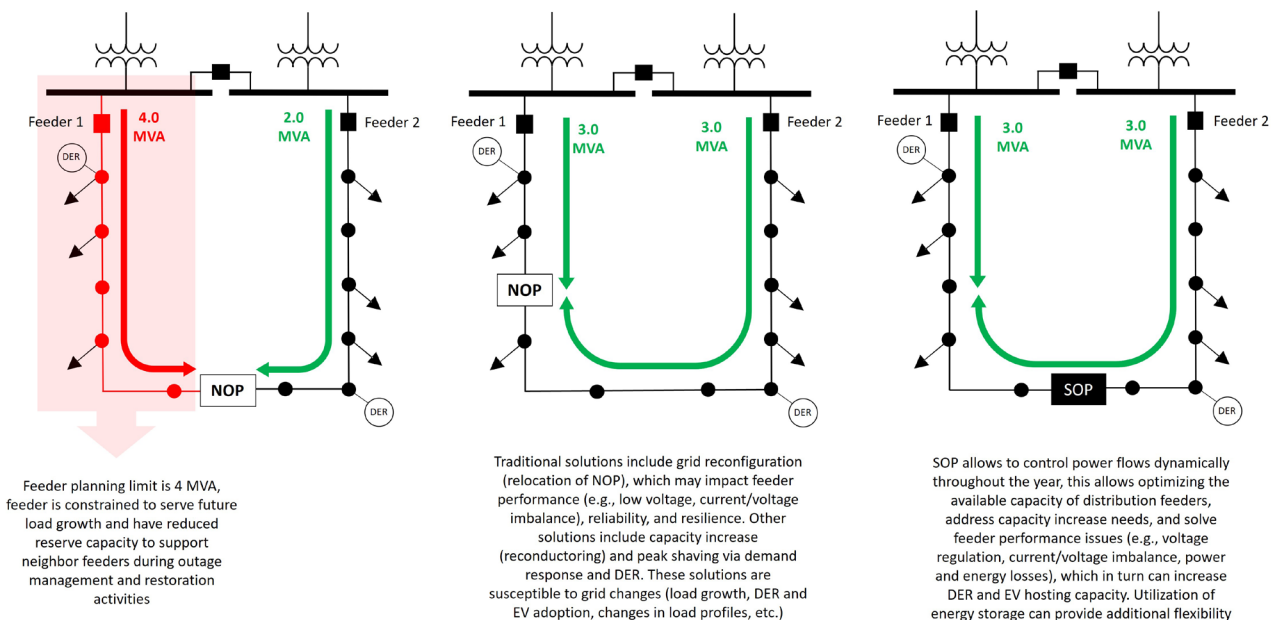
An alternative is to move the NOP to distribute the total peak load (6 MVA) evenly between both feeders (e.g., 3 MVA each), assuming both demands are coincident, i.e., they happen at the same time of the year. Moving the NOP may require changing the status of existing devices from open to close and vice versa, or the installing new devices on Feeder 1. NOP relocation would change feeder topologies (one feeder would be longer than the other), which could impact their reliability and resilience, and overall performance.

For instance, a longer feeder may have greater voltage drops, this could lead to temporary low voltage violations at feeder ends. Moreover, relocation of the NOP may impact current and voltage imbalance, which varies over the year, i.e., although current and voltage imbalance may be adequate during peak demand, it may exceed planning limits during other times of the year. Additionally, future changes in annual peak load (e.g.,

due to DER and/or electrification adoption) will change the optimal NOP location. In summary, the key challenge with this type of scenario is the largely static nature of NOP, which represents a limitation for the increasingly dynamic nature of distribution feeder power flows.

- In the second scenario (flexible), both feeders are operated as a closed loop and the SOP allows for controlling the power flow exchange between both feeders dynamically (like a valve in a hydraulic system). This capability can be used to balance demands, which solves the capacity issue in the first feeder. This can be implemented when needed, for instance, during a few hours or days every year (e.g., summer peak demands) or during outage management and restoration or temporary reconfiguration scenarios without the need to relocate the SOP. Moreover, SOP have the capability to perform this function for each individual phase of the feeder, which cannot be accomplished by a traditional NOP.

Figure 6
Example of Application of SOP for Closed-Looped Operation of Distribution Feeders



Examples of real-life deployments include the Active Response project by UK Power Networks (London, UK), which implemented SOP technologies on medium and low-voltage distribution feeders⁸.

DER and EV adoption are leading to increasing impacts on radial feeders. These impacts can be alleviated by a combination of conventional and advanced technology solutions. As DER penetration increases, distribution engineers are left with less options, even advanced technology solutions are bounded by the physical limitations of existing radial feeders. Closed-loop operation enabled by SOP represents the next step in the evolution of the distribution

system towards a highly efficient and flexible grid. Its advantages include improved voltages profiles, capacity utilization, reliability, and resilience, and more efficient operation. It also requires more complex protection systems, more robust equipment, and updated planning and operations philosophies. Since the technology required to overcome these issues is already available, the industry is encouraged to consider closed-loop operation as a viable alternative to achieve the goals set by the energy transition. A concerted effort is required to decrease technology costs of distribution-class FACTS devices, explore real-life applications, and enable greater adoption of these solutions.

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