EPRI ELECTRIC POWER RESEARCH INSTITUTE

PHASE-EQ DYNAMIC PHASE-BALANCING TECHNOLOGY

Incubatenergy Labs 2020 Pilot Project Report

SWITCHED SOURCE

Startup

Switched Source

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Ameren

Hosts

EPRI and Ameren

Technology Solution

Utility distribution feeders commonly experience phase imbalance due to the use of single-phase laterals for loads like homes and small commercial customers. This creates the potential for voltage, thermal, or other operational constraints. Large clusters of rooftop solar, electric vehicles (EV), and other distributed energy resources (DER) introduced in a neighborhood can exacerbate imbalance issues. Utility deployment of voltage regulators helps mitigate one aspect of the problem but does not address the root cause. Localized upgrades via line reconductoring and phase rebalancing by manually re-tapping laterals require customer outages and may need to be repeated with load and DER growth.

This pilot project investigated the potential of Switched Source's Phase-EQ technology for mitigating phase imbalance in distribution systems. The Phase-EQ, an innovative technology for dynamic phase balancing using solid-state power electronics, is undergoing an initial utility demonstration in New York. It is designed for deployment along a three-phase feeder or at the substation on wye-configured 4-15kV distribution systems. The Phase-EQ measures the complex phase current and voltage and shifts power from one phase to another in real time to significantly reduce the local neutral current caused by imbalances. Resulting reductions in phase current and voltage imbalance can improve power system operations and customer power quality. Dynamic phase balancing also can increase circuit capacity to support additional distributed generation, as well as load growth.

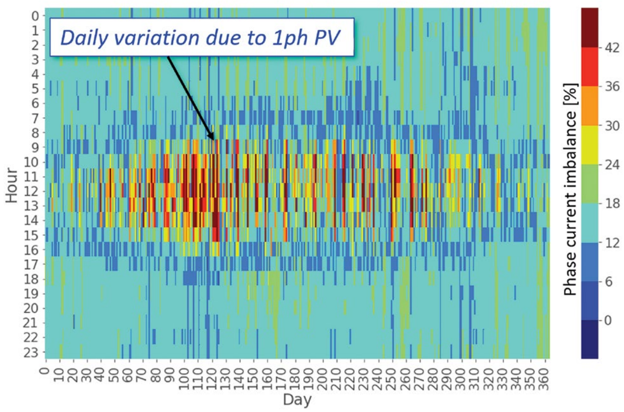
Challenge: Customer and Community Resilience

Phase-EQ device, ready for initial deployment

Project Overview

The objective of this collaborative demonstration project was to investigate the techno-economic benefits of deploying the Phase-EQ for dynamic phase balancing on distribution feeders. The project was divided into three components: (i) identifying the severity of phase imbalance issues, (ii) capturing the technical capabilities of the PhaseEQ device, and (iii) performing cost-benefit analysis.

Quantifying phase imbalance on distribution feeders is becoming increasingly important as single-phase loads grow and become more dynamic. Current utility practice may not provide a clear picture of the complexity of this issue. EPRI, Ameren, and Switched Source worked together to conduct power system modeling and simulation to better understand time-varying phase-level imbalances and the ability



Plot illustrating time-varying phase imbalance exacerbated by single-phase solar systems

of the Phase-EQ to mitigate these issues. This was performed using data from actual distribution feeders provided by Ameren and a device model provided by Switched Source. The cost-benefit analysis focused on assessing the different value streams associated with voltage optimization and reduced capital and operational expenditures.

Results & Learnings

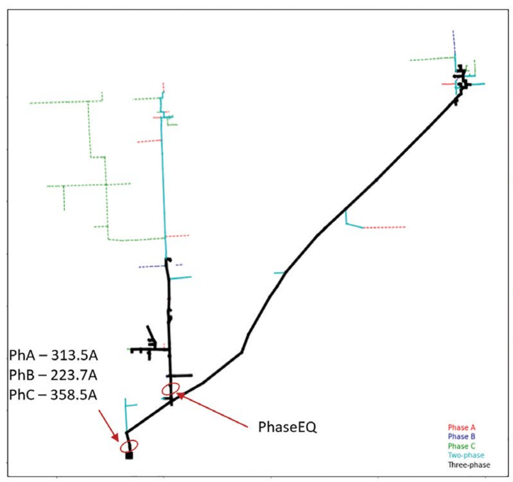
The first component of this project was to recognize and characterize the severity of phase imbalance on distribution feeders. Modeling and simulation results supported three key insights:

- **Phase imbalance is location-dependent:** Phase imbalance varies not only from feeder to feeder but also across the different sections of a feeder depending on the topology and load distribution.
- **Phase imbalance is time-varying:** Depending on the load composition (residential, commercial, industrial), phase imbalance may vary on a seasonal, hourly, or daily basis. Importantly, imbalance at feeder peak demand may no longer represent the worst-case condition.
- **Phase imbalance can be exacerbated by single-phase DER:** Technologies such as rooftop solar and EVs can increase the imbalance on feeders, which limits hosting capacity unless corrected.

The second component involved feeder-level modeling to investigate the technical capabilities of the Phase-EQ device. Different feeders and deployment locations were modeled and tested to assess efficacy, demonstrating that device performance depends on location and grid conditions. Through scenario testing and simulations, EPRI identified deployment criteria. The technology proved effective in reducing the neutral current due to phase imbalance, which in turn reduced the current imbalance and the voltage imbalance.

For a sample feeder and location, the table below compares simulation results (a) before deploying the Phase-EQ, (b) after deploying the Phase-EQ while operating with local measurement, and (c) after deploying the Phase-EQ while operating with remote measurements, in this case voltage and current at the feeder head. The Phase-EQ reduced the local neutral current caused by phase imbalance by 98.22% and the current imbalance by more than half. Leveraging remote measurements, the Phase-EQ also reduced the imbalance upstream of the device by more than half, decreasing the imbalance in feeder-head current from 25.07% to 11.60%.

The third component of this project was to investigate diverse potential value streams from deploying the Phase-EQ for dynamic phase balancing. Relative to traditional utility solutions, device capabilities and benefits were considered in five technical areas: balancing phase voltage, balancing phase current, enabling higher DER penetration, reducing neutral current, and improving feeder efficiency. Additionally, approaches to monetize each value stream were proposed.



		Before		Local Measurement		Remote Msrmnt	
		Mag.	Imbal.	Mag.	Imbal.	Mag.	Imbal.
Voltage @ phase EQ	PhA	0.9830		0.9797		0.9771	
	PhB	0.9926	**1.53%***	0.9884	**0.56%**	0.9875	**0.81%**
	PhC	0.9652		0.9875		0.9908	
Current @ phaseEQ	PhA	198.3		196.8		189.5	
	PhB	135.9	**31.04%**	167.6	**14.61%**	175.0	**14.96%**
	PhC	257.0		224.5		226.5	
Neutral Current @ phaseEQ		101.91		1.80	**98.22%**	27.18	**73.33%**
Feederhead current	PhA	313.5		311.7		304.2	
	PhB	223.7	**25.07%**	255.7	**13.97%**	263.2	**11.60%**
	PhC	358.5		324.1		325.8	
Neutral Current		115.5		23.27	**79.95%**	2.00	**98.27%**

(left) *Topology of a distribution feeder model highlighting the Phase-EQ location and remote measurement location; and* ***(right)*** *simulation results showing local phase voltage/current, neutral current at the Phase-EQ, and the phase current and neutral current at the feeder head*

TESTIMONIAL: Switched Source

Communicating the value of a new technology to busy industry stakeholders can be difficult. This EPRI-utility collaboration created a perfect environment to perform technical diligence and assess the techno-economic value of our Phase-EQ device. It drastically streamlined a challenging and typically lengthy process and provided us with a credible data set to use as a starting point with potential customers and collaborators moving forward.

TESTIMONIAL: Ameren

Across the industry, distribution system planning best practices identify and address potential phase imbalance situations. Ameren continuously evaluates and explores technologies and opportunities that help us mitigate reliability concerns in prudent, cost-effective, and innovative ways. This engagement helped Ameren reduce the R&D and time involved in exploring and evaluating the economic and technical viability of the Phase-EQ technology.

Deferral of capacity investments through balancing phase currents was found to be one of the most promising use cases for deploying this device. In addition, the Phase-EQ doubled the peak load reduction achieved by Volt-VAR optimization in some cases. Value stacking, aiming to capture multiple value streams from a single deployment, also improved the business case in certain scenarios.

As a modeling study, this project had inherent limitations that can be addressed in field demonstrations of the Phase-EQ. In addition, validating Switched Source's device model (available in CYME or OpenDSS) was considered outside the scope of this pilot, but third-party engineers have validated the model in previous projects.

Implications & Next Steps

This project demonstrates that the Phase-EQ provides utility planners with another tool for mitigating phase imbalance on distribution feeders to improve power quality and system operations, increase DER hosting capacity, and accommodate load growth. Results indicate that ideal host feeders are wye-configured, 11-15kV distribution feeders with significant phase imbalance on three-phase lines.

Applications where the Phase-EQ could be considered as a potential mitigation measure include feeders

- with phase imbalance above 10% at the feeder head,
- with imbalances that cannot be cost-effectively addressed by conventional approaches,
- with imbalances that need to be repeatedly addressed,
- where reconductoring—especially over a significant length—is proposed for an unbalanced three-phase line, or
- with a high concentration of single-phase DERs on a single-phase lateral.

Building on lessons learned from this study, Ameren has analyzed additional feeders to identify potential locations for a possible follow-on pilot involving field deployment and evaluation of the Phase-EQ.

Utilities interested in considering the Phase-EQ in system planning studies can reach out to Switched Source for access to the device model. In addition, EPRI and Switched Source are available to help evaluate potential device deployments from technical and economic perspectives.

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