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CIGRE US National Committee
2024 Grid of the Future Symposium

National Grid Pilot of Phase-EQ Technology

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SUMMARY

The increasing integration of renewable energy resources, electric vehicles (EV), and challenges posed by extreme weather events have necessitated the development of flexible solutions to enhance power quality, reliability, and distribution system capacity. National Grid (NGRID), tasked with maintaining reliable and quality service for its customers, leverages its Distribution Planning and Asset Management (DPAM) department to perform needs assessments and develop solutions, including area planning, load interconnection studies, and the integration of new technologies. This paper details the planning, implementation, and initial field results of a Phase-EQ pilot project conducted by NGRID to test Switched Source's Phase-EQ technology. The project involved key stakeholders: NGRID as the host utility, Switched Source as the Phase-EQ manufacturer, and RLC Engineering as a third-party power systems consultant.

The Phase-EQ is a power electronics device designed to mitigate imbalances in three-phase medium voltage (MV) distribution circuits by dynamically transferring power between phases. This technology reduces zero sequence current and improves power quality across the distribution network. Eaton's CYME software was utilized to model and evaluate the performance of the Phase-EQ technology within NGRID's distribution system. NGRID provided five candidate distribution circuits for evaluation, and two circuits were ultimately selected for a full-scale assessment. This paper covers multiple aspects of the Phase-EQ pilot, including the device's specifications, modeling, circuit selection, field results, and a benefits-cost analysis (BCA).

NGRID actively seeks innovative technologies to improve electric reliability, increase load capacity, and accommodate more renewables or distributed energy resources (DERs). The key findings of this project suggest that the Phase-EQ technology can enhance system capacity and power quality, offering a potential alternative to costly infrastructure upgrades. The initial field testing verified simulated results and the BCA indicated promising returns on investment.

KEYWORDS

Phase-EQ, Power Quality, Dynamic Phase Balancing, Non-Wires Alternative (NWA), Voltage Optimization, Energy Efficiency

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I. INTRODUCTION

The evolving energy landscape requires efficient and robust utility distribution systems capable of accommodating new challenges such as the integration of renewable energy resources (DER), electric vehicle (EV) adoption, and increased system resilience against extreme weather events. One of the challenges faced by utility operators is managing power imbalances in distribution circuits. These imbalances can arise from various sources, including uneven load growth, single-phase loads, DERs, EVs, and long single-phase laterals [1, 2, 3, 4]. Such imbalances can lead to increased operational and maintenance costs, reduced equipment lifespan, capacity constraints, and compromised power quality [1, 2].

Traditional methods to address power imbalances, such as load re-phasing, adding voltage regulators, deploying capacitor banks, or extending three-phase distribution lines, may require substantial capital investments, maintenance outages, and/or may not fully resolve the issues due to the dynamic nature of loads [4, 5]. More advanced solutions, such as Flexible AC Transmission Systems (FACTS) including Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM), offer some benefits but can be expensive and complex to implement [5].

Switched Source's Phase-EQ technology is a novel solution for dynamically correcting power imbalances in medium voltage (MV) distribution circuits. The Phase-EQ is a shunt-connected power electronics device designed to reduce zero sequence current by transferring power between phases, thereby balancing the upstream current flow. This real-time adjustment enhances power quality by reducing voltage imbalances and neutral current, improving overall system efficiency and reliability.

This paper outlines the Phase-EQ pilot project undertaken by National Grid (NGRID) to explore the potential of this technology in their distribution network. NGRID, in collaboration with Switched Source and RLC Engineering, identified suitable circuits for the deployment of the Phase-EQ device. Eaton's CYME software was utilized for modeling and simulation, providing insights into the potential benefits of Phase-EQ installations, such as enhanced system capacity and improved power quality metrics.

The following sections of this paper delve into the specifics of the Phase-EQ technology, including its design and specifications, modeling approach, and the criteria used for circuit selection and device siting. Additionally, the paper presents the results of the system studies, field verification, and a comprehensive benefits-cost analysis (BCA) that underscores the economic and technical advantages of deploying Phase-EQ technology in NGRID's distribution network.

II. PHASE-EQ DESCRIPTION AND SPECIFICATIONS

The Phase-EQ is a three-phase, shunt connected, power electronics device designed to reduce zero sequence current by redistributing power among the phases. By strategically managing power transfer between the phases, the current phasors are repositioned, and zero sequence current is decreased. This process reduces system imbalance and improves the overall efficiency and reliability of the system.

Figure **1** shows a series of phasor diagrams that provide an example of Phase-EQ impact on unbalanced phase currents. Moving from left to right, panel 1 shows an example of unbalanced current phasors. Panel 2 shows the phasor addition and the resulting zero sequence current (I_0). Panel 3 shows the Phase-EQ's counteracting zero sequence current injection, which results in the real and reactive power transfer between the phases. Panel 4 shows the resultant phase currents following the Phase-EQ's correction. Finally, panel 5 shows the post Phase-EQ phasor addition and how the shift in the current phasors results in the elimination of zero sequence current.

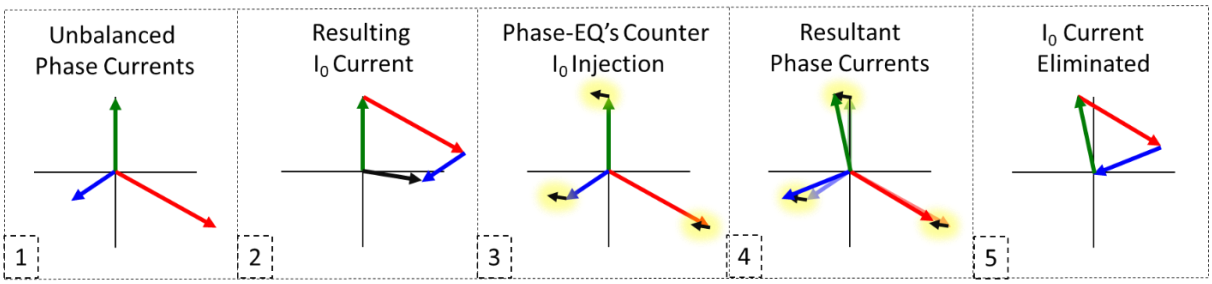


Figure 1: Phase-EQ Zero Sequence Reduction Example

The Phase-EQ's ability to reduce system imbalance can offer several core power quality benefits, including:

- Reduced neutral current flows upstream of the device
- Decreased current imbalance upstream of the device
- Reduced voltage imbalance across the circuit

These power quality improvements may translate into a number of other benefits, including:

- Enhanced performance of conservation voltage reduction (CVR) schemes
- Improved inverter-based resource (IBR) voltage regulation due to reduced voltage imbalance
- More balanced voltage regulator operation, increasing regulation capability
- Increased circuit capacity in the presence of phase imbalance
- Reduced operational expenditures (OpEx) by minimizing system rebalancing and lateral re-tapping
- Mitigated imbalance from DER and EV deployment
- Deferred need for costly upgrades like reconductoring, line rebuilds, or three-phase extensions

Regarding device specifications, the Phase-EQ is designed for MV applications up to 15 kV and is rated for up to 133 A of neutral current. The device dynamically responds to changes in system conditions and is capable of ramping up to full power output in less than 2 cycles. Additionally, the device can use local measurements or remote telemetry as input.

The Phase-EQ is a pad mounted device. Excluding the pad, the physical dimensions are 4 feet 1 inch in width, 11 feet 9.5 inches in length, 6 feet 0.25 inches in height, and it weighs approximately 9,000 lbs. Table 1 provides a summary of basic device specifications as well as an image of the device.

Table 1: Phase-EQ Specifications and Image

Phase-EQ Specifications	
Neutral Current Rating	133 A
Interconnection Voltage	15 kV 3-Phase
Power Rating at 15 kV	2 MVA
System Configuration	Wye, Wye-Grounded
100% Power Ramp	< 2 cycles
BIL Rating	95 kV
System Weight	~9,000 lbs
Operating Temperature	-40 ^{o}C to 50 ^{o}C
Enclosure	NEMA 4



III. PHASE-EQ MODELLING IN CYME

Due to the absence of a standard component for the Phase-EQ device within CYME, a model was created using standard equipment from CYME's library, coupled with Python device control scripts. The Phase-EQ is represented by three single-phase battery energy storage systems (BESS), which simulate the device's power transfer capabilities by adjusting real and reactive power on a per-phase basis. A Switched Source Controller, implemented as a black-box model in compiled Python code, processes input data such as voltage and current magnitudes and angles to calculate the appropriate device responses. A Python interface links the CYME model to the controller, capturing and transmitting voltage and current measurements to the controller and applying the resulting power commands back to the CYME model to update the single-phase BESS components. This integrated approach ensures that the simulation accurately reflects the Phase-EQ's impact on the distribution system, providing valuable data for the pilot project's evaluation and device siting.

IV. CIRCUIT IDENTIFICATION AND DEVICE SITING

The selection of circuits and the optimal siting of the Phase-EQ device were critical steps in the pilot project. This process involved identifying circuits that would benefit the most from the Phase-EQ technology and determining the best locations for device installation to maximize its impact.

Circuit Selection

RLC and NGRID collaborated on the methodology to rank candidate circuits for Phase-EQ deployment. NGRID applied this ranking system to 972, 13.2 kV, wye configured circuits, identifying about 19% (185 circuits) as potential beneficiaries. From these, five circuits were selected for more detailed analysis to identify a pilot location. A detailed analysis was conducted using CYME simulations to evaluate these circuits based on key metrics such as:

- Neutral Current: The magnitude of neutral current is a primary indicator of phase imbalance. Circuits with high neutral current were prioritized, as the Phase-EQ is particularly effective in reducing these currents.
- Voltage Imbalance: The percentage difference in voltage levels between phases can impact power quality and equipment performance. Circuits with high voltage imbalance were considered strong candidates for Phase-EQ deployment.
- Load Distribution: The distribution of loads across phases was analyzed to identify circuits where the Phase-EQ could redistribute power more evenly, thus improving overall system balance.

Device Siting

After selecting the circuit(s), the next step was to determine the optimal locations for the Phase-EQ devices. The siting process involved:

- Heat Map Analysis: Heat maps were created to visualize areas with high neutral current and voltage imbalance within each circuit. This analysis helped pinpoint sections of the circuit where the Phase-EQ would be most effective.
- Distance from Substation: The distance from the substation was also a factor, as the Phase-EQ's effectiveness can vary depending on its position relative to the substation. Ideally, the device is sited in areas with significant imbalance that are not too close to the substation, where phase balancing may be less challenging.
- Feasibility Assessment: The physical feasibility of installing the Phase-EQ at identified locations was evaluated, considering factors such as available space, accessibility, and existing infrastructure.

Figure 2 shows example heat maps used in the siting process for the pilot circuit as well as the chosen Phase-EQ installation location based on neutral current, voltage imbalance, and land availability.

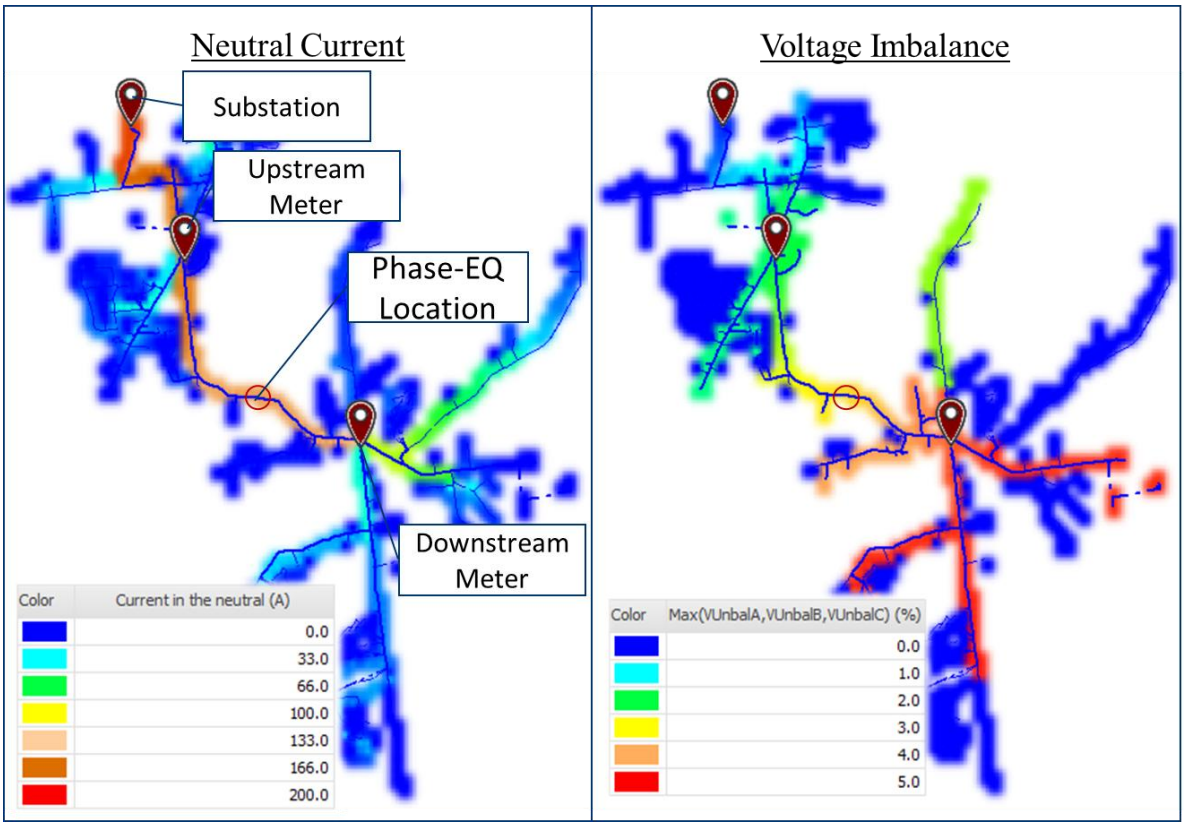


Figure 2: Example Heat Maps for Device Siting

The heat maps provide an easy way to visually identify potential device locations, aiming to select a site with relatively high neutral current and proximity to areas of higher voltage imbalance. Figure 2 shows the chosen pilot location, which strikes a balance between neutral current magnitude (around 148 A) and its proximity to areas of voltage imbalance. The careful selection of circuits and device location were important for the successful deployment of Phase-EQ in NGRID's distribution network. This strategic approach was designed to maximize the technology's benefits in enhancing power quality and system capacity.

V. SIMULATION RESULTS

The Phase-EQ's impact on the selected circuits was initially assessed through simulations using CYME. The simulations focused on evaluating the device's effectiveness in the following areas:

- Neutral Current Reduction: The simulations showed a significant reduction in neutral current across all tested circuits, indicating that the Phase-EQ effectively balances the system. This reduction is essential for minimizing losses and improving the overall efficiency of the network.
- Voltage Imbalance Mitigation: The Phase-EQ demonstrated the ability to reduce voltage imbalances, resulting in more consistent voltage profiles across the circuits. This improvement is critical for maintaining equipment performance and prolonging the lifespan of distribution infrastructure.
- Load Capacity Increase: By balancing phase currents, the Phase-EQ increased the circuits' load-carrying capacity. This enhancement allows for better utilization of existing infrastructure, potentially deferring the need for expensive system upgrades.

Figure 3 and Figure 4 provide a comparative look at the Phase-EQ impact on the feeder using heat maps of neutral current magnitude and voltage imbalance, respectively.

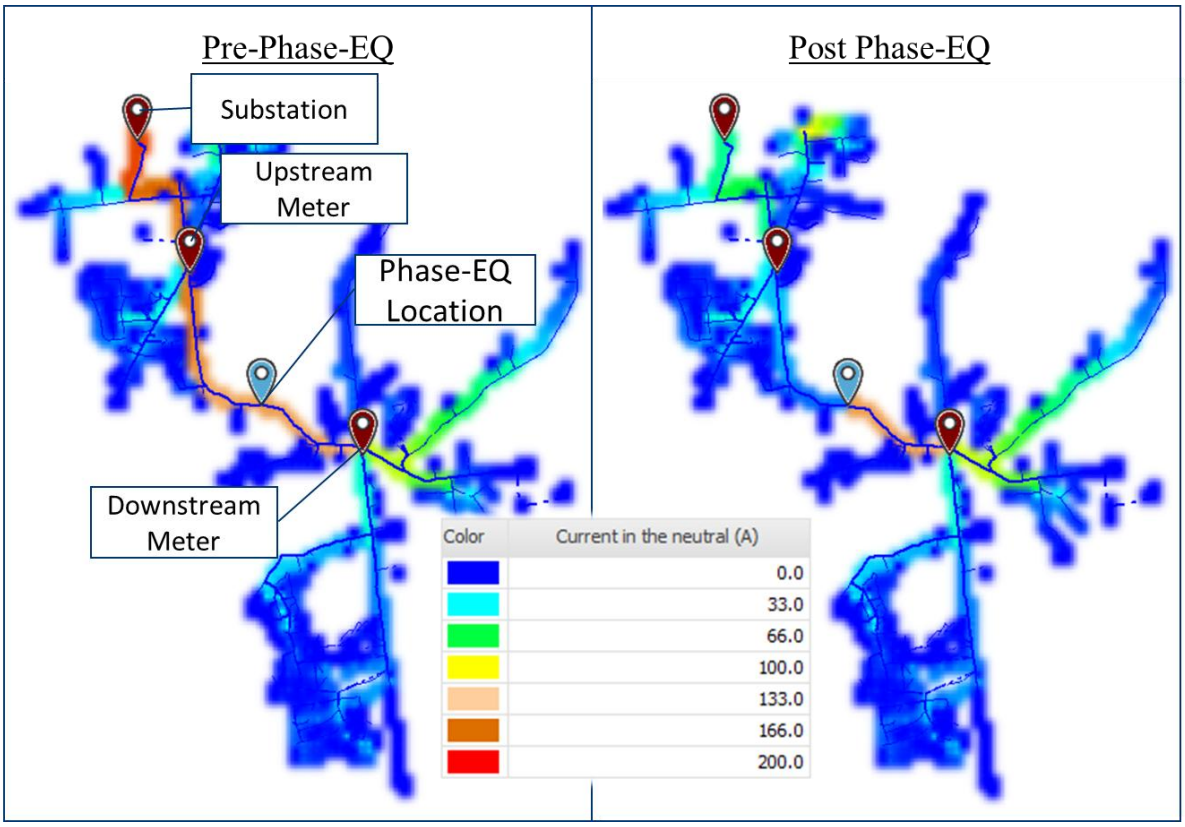


Figure 3: Neutral Current Heat Map: Pre- to Post-Phase-EQ

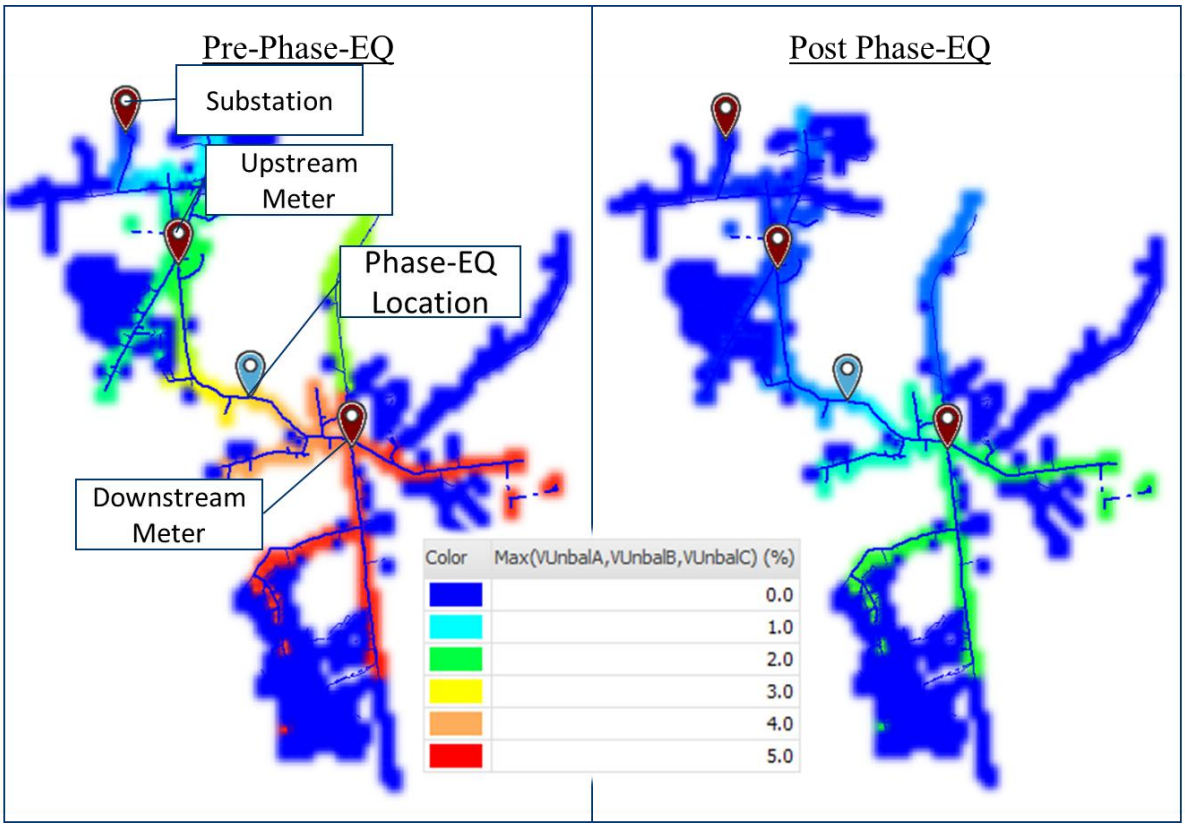


Figure 4: Voltage Imbalance Heat Map: Pre- to Post-Phase-EQ

As shown in Figure 3, the Phase-EQ reduces upstream neutral currents by approximately 130 A. Figure 4 demonstrates a circuit-wide decrease in voltage imbalance. The balancing effect of upstream phase currents reduces the maximum voltage imbalance on the circuit from 4.6% to 2.3%—a 50% improvement.

A capacity evaluation was conducted to determine the critical load level, which is the maximum load that can be accommodated before encountering voltage or thermal violations. Table 2 summarizes the results of this evaluation, comparing scenarios with and without the Phase-EQ.

Table 2: Simulated Load Capacity Increases Post Phase-EQ

Metrics	Monitored Point	Voltage Critical Load Level			Thermal Critical Load Level		
		Pre-Phase-EQ	Post Phase-EQ	Δ	Pre-Phase-EQ	Post Phase-EQ	Δ
Peak Load (kW)	Feeder Head	6,356	8,487	**2,131**	9,572	10,108	**536**
Max. $I_{imbal.}$ (%)	Feeder Head	30.2%	17.4%	**-12.7%**	30.6%	19.6%	**-11.0%**
$I_{Neutral}$ (A)	Feeder Head	127.9	47.9	**-80**	198.3	80.5	**-117.8**
Max. Thermal Loading	336.4 AL	63.9%	82.2%	18.3%	99.6%†	99.9%†	0.3%
Minimum Phase Voltage	-	95.0%*	95.0%*	0.1%	90.2%	92.7%	2.4%
Max. Voltage Imbalance	-	3.4%	2.2%	**-1.2%**	5.5%	3.2%	**-2.3%**

* The voltage critical load level was limited by circuit voltages hitting 95%.
† The thermal critical load level was limited by 336.4 AL backbone conductor reaching 100%.

The results show that the Phase-EQ increased the voltage-limited load capacity by up to 2,131 kW and thermally-limited load capacity by up to 536 kW. Additionally, the Phase-EQ improved both voltage and current imbalance and significantly reduced neutral currents upstream of the device.

VI. FIELD RESULTS

Field test data from June and July 2024 was analyzed to validate simulation results and assess the real-world performance of the Phase-EQ. The tests monitored four locations: the device itself, along with meters at the feeder head, an upstream recloser, and a downstream recloser. Data collected included:

- Feeder Head: Power flow, phase currents, phase voltages, neutral current
- Upstream Recloser: Power flow, phase currents, phase voltages, neutral current
- Phase-EQ: phase voltages, neutral current
- Downstream Recloser: Power flow, phase currents, neutral current

Historical voltage data was unavailable at the downstream recloser, complicating the validation of voltage profile improvements downstream of the device. Minor voltage imbalance improvements were noted upstream of the Phase-EQ; however, the device's impact typically diminishes closer to the substation where less voltage imbalance is observed. Additionally, peak imbalance levels did not occur during the field tests, limiting the assessment of this metric. Consequently, the primary focus in evaluating the field test results was on assessing changes in current imbalance and neutral current magnitude. Figure 6 and Figure 6 presents a plot of neutral current, current imbalance, and voltage imbalance for the week before and after the Phase-EQ installation at the feeder head and the midline upstream recloser, respectively. Figure 7 shows the neutral current flow immediately upstream and downstream of the Phase-EQ as well as voltage imbalance measured at the device. Note that the device is shunt connected, and only corrects the upstream imbalance. Therefore, this plot provides an excellent depiction of the Phase-EQ's local neutral current correction.

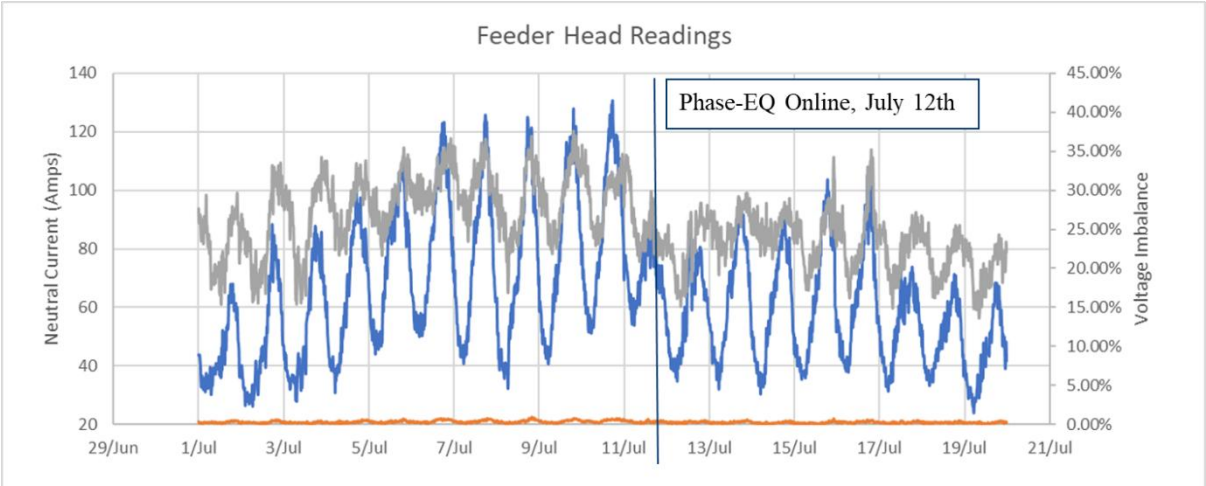


Figure 5: Feeder Head: Neutral Current (Blue), Current Imbalance (Gray), Voltage Imbalance (Orange)

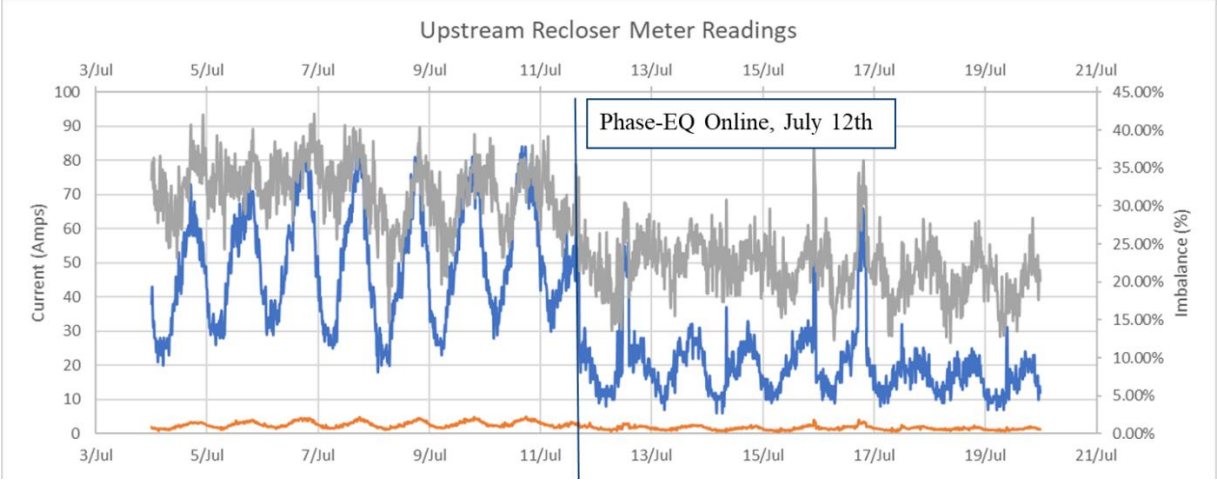


Figure 6: Upstream Midline Recloser: Neutral Current (Blue), Current Imbalance (Gray), Voltage Imbalance (Orange)

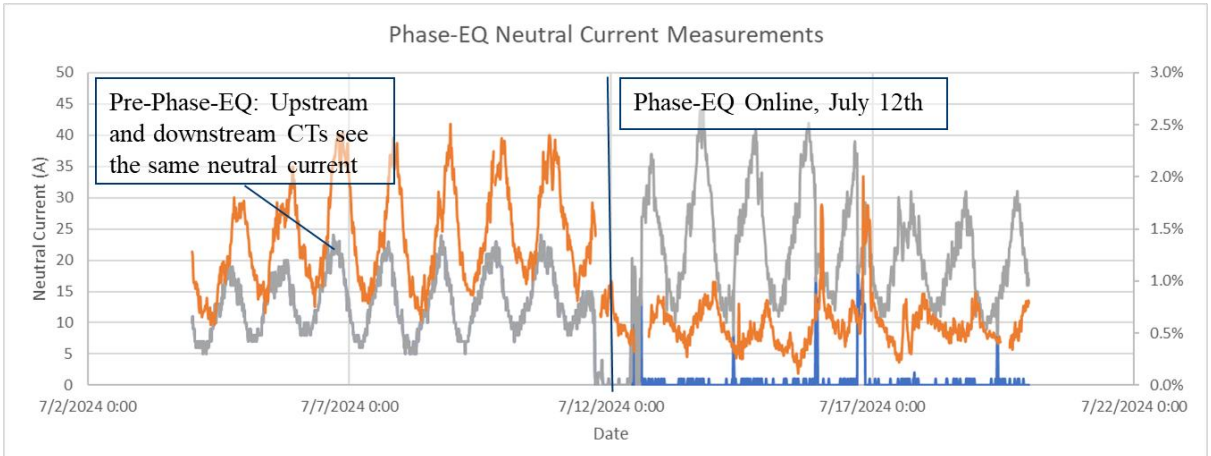


Figure 7: Phase-EQ CT: Upstream Neutral Current (Blue), Downstream Neutral Current (Gray), Voltage Imbalance (Orange)

As expected, reductions were observed in both neutral current and current imbalance. Voltage imbalance decreased slightly at the upstream locations with more noticeable decreases local to the device. Under the tested conditions, the Phase-EQ mitigated approximately 30 A of downstream neutral current and

reduced voltage imbalance from peaks of 2.5% to peaks of approximately 1.0%. It should be noted that additional load imbalance exists upstream of the Phase-EQ location, which explains why higher neutral current levels are observed at the upstream recloser and feeder head, despite the device resolving all local neutral current, as shown in Figure 7.

A secondary objective of the field tests was to validate the device's simulated performance. To do this, the distribution system model's load was adjusted to reflect the feeder conditions observed at 18:15 on July 18, 2024. Neutral current flow, a consistent metric across all meters, was used for comparison. Table 3 compares the simulated device performance with the field test data based on the July 18, 2024, 18:15 snapshot.

Table 3: Comparison of Simulated and Field Tested Results

Meter	Feeder Head	Upstream Recloser	Upstream Phase-EQ	Downstream Phase-EQ	Downstream Recloser
Simulated Results	67.8 A	23.0 A	1.6 A	32.7 A	33.1 A
Field Results	71.2 A	25.0 A	0 A	30 A	33 A

Small variations in phase current and voltages were observed, indicating slight differences in load allocation and the voltage profile. However, the expected neutral current reduction and associated impacts closely matched the simulated device performance, reinforcing confidence in the accuracy of the model.

VII. BENEFITS COST ANALYSIS

The BCA for the Phase-EQ pilot project assessed the economic and operational benefits of deploying a Phase-EQ device within NGRID's distribution network. The analysis compared implementation costs with anticipated benefits across seven key use cases, using National Grid's BCA Handbook and template tools to quantify these benefits. The Phase-EQ offers a range of applications beyond merely balancing power flow on a three-phase circuit, providing secondary benefits such as enhanced system reliability and deferred infrastructure upgrades.

The analysis assumed a 20-year lifespan for the Phase-EQ, with a maintenance cost of approximately $20,000 in year 11. The unit retails for $275,000, with an estimated installation cost of $50,000. The seven specific use cases considered are:

1. Capacity Only: Balancing phase currents to increase load-carrying capacity by 1,200 kW, eliminating the need for re-tapping projects four times over 20 years.
2. Upgrade Deferral: Deferring capital upgrade projects like feeder extensions or system voltage upgrades, resulting in over $500,000 in capital expense reductions and an immediate payback.
3. High Annual Imbalance: Reducing significant annual imbalances, leading to operational cost savings and improved system reliability, with increased load-serving capacity similar to the capacity-only scenario.
4. High Seasonal Imbalance: Mitigating seasonal load imbalances, particularly those caused by heating or cooling, with benefits akin to the high annual imbalance use case.
5. Power Quality Issues: Addressing power quality issues traditionally managed by slower or less flexible equipment, providing immediate payback while enhancing load-serving capacity.
6. DER Integration: Supporting DER integration by balancing phases and managing voltage and thermal limits, with immediate payback even without stacking benefits.
7. Volt-Var Optimization (VVO) Application: Enhancing VVO efficacy by 1%, offering a 6-year payback period even with minimal load-serving capacity increase.

The BCA results indicate that the Phase-EQ technology offers economic benefits, particularly in scenarios involving capacity increases, upgrade deferrals, and power quality improvements. Despite the upfront costs, most use cases exhibit a net present value (NPV) payback period between 5-6 years, well within the unit's 20-year lifespan. The Phase-EQ provides a variety of tangible OpEx and CapEx reductions and ancillary benefits such as increased hosting capacity and energy efficiency, beyond just neutral current reduction and voltage imbalance correction.

Figure 8: BCA Results

Metrics	(1) Capacity Only	(2) Upgrade Deferral Only	(3) High Annual Imbalance	(4) High Seasonal Imbalance	(5) Power Quality Issues	(6) DG Integration	(7) VVO Application
NPV Benefits	$681,552	$335,213	$489,018	$546,706	$1,010,018	$597,056	$523,625
*NPV Costs	$335,215	$335,213	$335,213	$335,213	$335,213	$335,213	$335,213
NPV Benefits Less Cost	$346,337	$0	$153,805	$211,493	$674,805	$261,843	$188,412
Years to Payback	6	0	6	6	0	0	5
* NPV cost assumptions: device retail price of $275k, an estimated installation cost of $50k, and a $20k maintenance cost in year 11, for a total cost of approximately $335k.							

Many utility planning processes address system issues reactively, only when specific thresholds are exceeded. However, the Phase-EQ offers proactive solutions with multiple payback periods in the 5-6 year range, making it a cost-effective option for enhancing system performance and reliability.

VIII. CONCLUSION

NGRID's Phase-EQ pilot, while on-going, has begun to demonstrate the technology's effectiveness in reducing imbalances within MV distribution circuits. Both simulations and field tests have shown that the Phase-EQ reduces neutral currents, ameliorates voltage imbalances, and improves overall power quality. These improvements can translate to increased load capacity and more efficient use of infrastructure. The benefits cost analysis conducted across seven use cases—such as capacity increases, upgrade deferrals, and power quality improvements—suggests potential cost savings and operational benefits. The analysis showed that most scenarios involving Phase-EQ implementation have a payback period of 5-6 years, which falls within the device's 20-year lifespan. This payback period, along with the device's capability to defer infrastructure upgrades while enhancing system performance, highlights its possible value for utilities.

In summary, the Phase-EQ provides a practical solution for managing phase imbalances, improving system reliability, and optimizing distribution networks. The results from the NGRID pilot indicate that the Phase-EQ has the potential to deliver meaningful benefits, suggesting that further evaluation and consideration of its wider adoption could be beneficial for the utility sector.

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