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Unlocking Capacity in Imbalanced Distribution Circuits with Phase-EQ Technology

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SUMMARY

Driven by extreme weather, the increasing integration of renewable energy resources and electric vehicles, among many other factors, the power industry has experienced an increased need of flexible solutions to enhance power quality and distribution system capacity. This paper describes the planning stages and simulation results from a Florida Power & Light (FPL) pilot project to install and test Switched Source's Phase-EQ technology. The pilot project involved three key parties: FPL as the host utility, Switched Source as the Phase-EQ manufacturer, and RLC Engineering (RLC) as a third-party power systems consultant. RLC was responsible for modeling and simulating the performance of the Phase-EQ, as well as assisting in identifying suitable locations for the device on FPL's distribution system.

The Phase-EQ is a power electronics device designed to reduce imbalance in three-phase, medium voltage (MV) distribution circuits. Rated for up to 133 A of neutral current, the Phase-EQ operates by dynamically transferring power between phases to reduce zero sequence current and, in turn, achieves a more balanced power flow across each phase. The benefits of this balancing process extend beyond the reduction of neutral current flows; it also mitigates current and voltage imbalance across the circuit, leading to improvements in power quality and system capacity.

To evaluate the efficacy of the Phase-EQ technology within FPL's distribution system, RLC Engineering developed a model within DNV's Synergi load flow software to help facilitate the system studies. FPL provided 240 candidate distribution circuits for evaluation. A scalable screening and ranking process was developed to narrow the candidate pool. Ultimately the list of 240 circuits was reduced to the top 10 candidates and a detailed system review was performed for this short list. RLC performed power flow simulations to evaluate system capacity with and without the Phase-EQ for four candidate circuits to better understand the benefits of the technology.

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This paper covers five aspects of the Phase-EQ pilot:

1. An exploration of Phase-EQ benefits and specifications.
2. The development of a Phase-EQ model within DNV’s Synergi load flow software.
3. A description of the process used to screen for candidate Phase-EQ circuits.
4. A description of the process used to site the Phase-EQ.
5. A description of the simulated system study results and capacity benefits.

As the energy sector continues to evolve, the need for innovative solutions will grow. This pilot study marks a significant step in addressing this need and offers valuable insights into the potential of the Phase-EQ technology. While further field validation studies are needed, the initial simulation results underscore the Phase-EQ's potential to boost distribution system performance, enhance power quality, and possibly defer costly grid upgrades.

KEYWORDS

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

I. INTRODUCTION

The development of efficient and robust utility distribution systems is crucial in the evolving energy landscape. However, effectively managing power imbalances remains a challenge for many systems. Power imbalances can have many sources, such as single-phase loads, distributed energy resource (DER) integration, electric vehicle (EV) adoption, long single-phase laterals, and uneven load growth, among others [1, 2, 3, 4]. These imbalances can increase operation and maintenance costs, decrease equipment life, prematurely push system capacity to its limits due to single-phase constraints, as well as create customer power quality concerns [1, 2]. Various approaches have been explored in the industry to address power imbalances, such as periodically re-tapping loads for phase balancing, adding voltage regulators or capacitor banks, using Flexible AC Transmission Systems (FACTS) [4, 5], such as Static Var Compensators (SVC) or Static Synchronous Compensators (STATCOM), and many others. However, these solutions can be financially demanding, may require periodic outages to customer service, and their efficacy can diminish over time due to the fluctuating nature of loads.

The Phase-EQ technology from Switched Source provides a novel solution that can dynamically correct distribution system imbalances. The Phase-EQ, a shunt-connected power electronics device, is designed to reduce zero sequence current and dynamically balance phase loading. By improving the balance in power flows across the distribution circuit, the Phase-EQ has the potential to reduce voltage imbalance, decrease the burden on the most limiting phases, and unlock additional capacity. The Phase-EQ's ability to quickly and dynamically respond to system changes and reduce system imbalance can have numerous benefits such as improving conservation voltage reduction (CVR) performance, improving inverter based resource (IBR) voltage regulation capability, and reducing operational expenditures (OpEx), to name a few. To better understand the benefits of the Phase-EQ technology, Florida Power & Light (FPL) is piloting the device on a number of their circuits. This paper describes the planning stages and simulation results from the FPL pilot project. The study involved three key parties: FPL as the host utility, Switched Source as the Phase-EQ manufacturer, and RLC Engineering (RLC) as a third-party power systems consultant. RLC was responsible for modeling the Phase-EQ, simulating device performance, assisting in the identification of suitable locations for the device, and analyzing and summarizing the results.

The following sections of this paper describe the Phase-EQ technology, including its specifications, how it was modelled, and its applications. Additionally, the paper presents an approach to identify circuits that would stand to benefit most from the Phase-EQ technology and a methodology to determine the optimal location for the device within a chosen circuit. Finally, the results of the post Phase-EQ capacity simulations are described, as well as conclusions from the planning portion of the pilot.

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, pane 1 shows an example of unbalanced current phasors. Pane 2 shows the phasor addition and the resulting zero sequence current (I_0). Pane 3 shows the Phase-EQ's counteracting zero sequence current injection, which results in the real and reactive power transfer between the phases. Pane 4 shows the resultant phase currents following the Phase-EQ's correction. Finally, pane 5 shows the post Phase-EQ phasor addition and how the shift in the current phasors results in the elimination of zero sequence current.

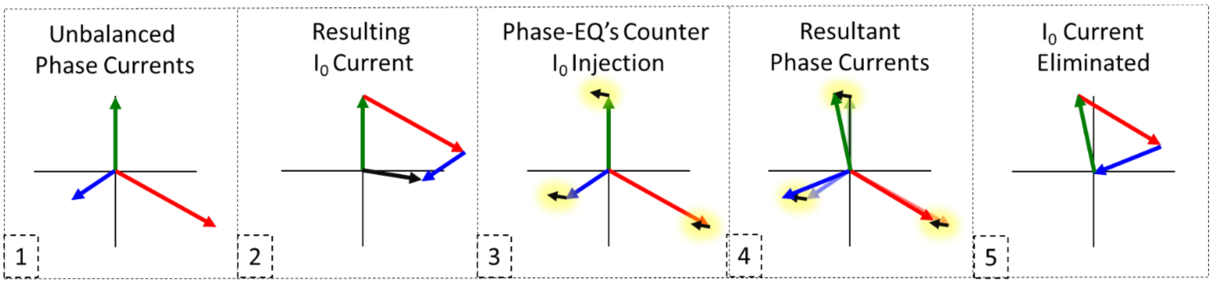

Figure 1: Phase-EQ Zero Sequence Reduction Example

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 CVR schemes
- Improved IBR voltage regulation performance due to dynamic voltage imbalance reduction
- More balanced voltage regulator operation, leading to increased regulation capability
- Increased circuit capacity in the presence of phase imbalance
- Reduced operational expenditures (OpEx) associated with system rebalancing and lateral re-tapping
- Mitigated imbalance from renewable energy resource and electric vehicle deployment
- Deferred need for expensive upgrades such as reconductoring, line rebuilds, or three-phase line extensions

Regarding device specifications, the Phase-EQ is designed for medium voltage (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 °C to 50 °C
Enclosure	NEMA 4

III. PHASE-EQ MODELLING IN SYNERGI

FPL uses DNV's Synergi load flow software for system planning purposes. To evaluate the efficacy of the Phase-EQ technology within FPL’s distribution system, RLC developed a model within Synergi to facilitate the system studies. The model consists of three main parts: a device representation in Synergi, a black-boxed Phase-EQ controller, and a Python interface between the Synergi model and Phase-EQ controller. Figure 2 provides a diagram and flowchart of the Phase-EQ implementation.

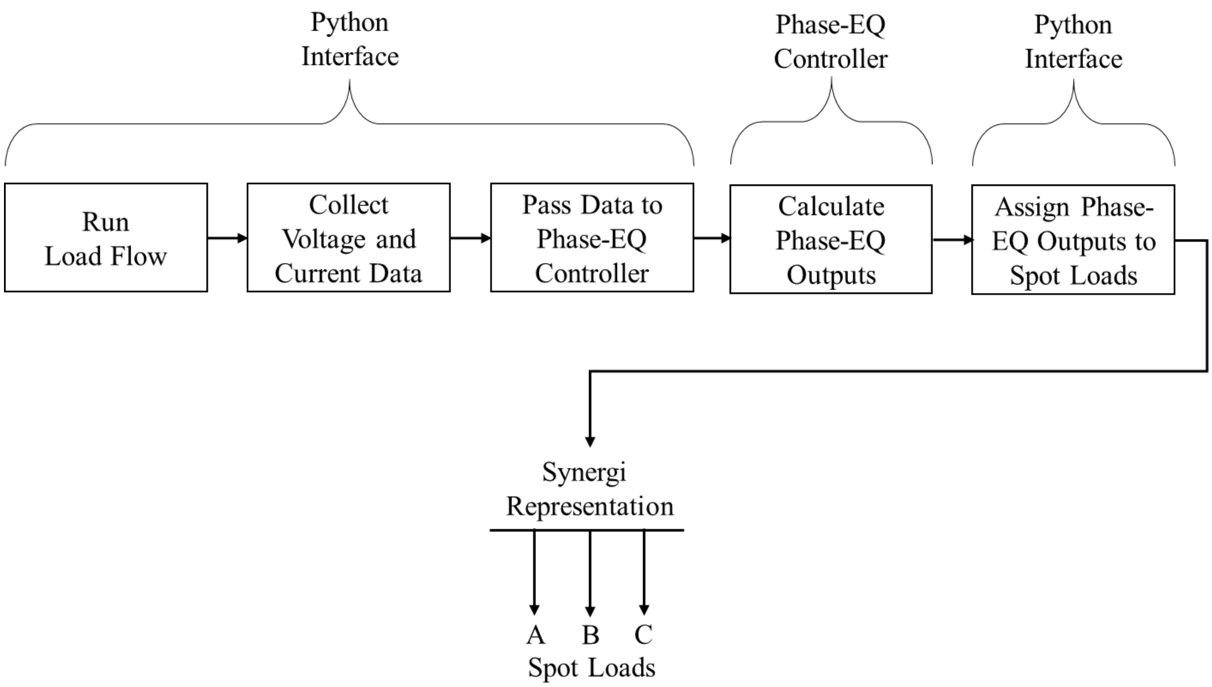

Figure 2: Phase-EQ Model

SYNERGI REPRESENTATION

As depicted in Figure 2, the device representation in Synergi was created using the built-in spot load component. Because the Phase-EQ exchanges real and reactive power between phases, the utilization of positive and negative, per phase, spot loads allowed for an analogous power exchange behavior. The spot loads were also conveniently accessible through Synergi's Python application programming interface (API), allowing for an automated approach.

SWITCHED SOURCE CONTROLLER

The Phase-EQ controller is a black-box model, developed by Switched Source, to accurately represent device performance. The Phase-EQ controller runs as compiled Python code and requires both voltage and current data, in the forms of magnitudes and angles, as inputs. The controller takes the voltage and current inputs, determines the appropriate device response, including accounting for device losses, and generates per phase real and reactive power commands as outputs.

PYTHON INTERFACE

The Python interface, created by RLC, has two main functions. Firstly, it captures and passes voltage and current measurements from the load flow simulation to the Phase-EQ controller as inputs. Secondly, it receives the real and reactive power output values from the Phase-EQ controller and assigns these to the spot load component. The interface was also responsible for iterating until the error between each load flow reached an acceptably low threshold.

MODEL BENCHMARKING

To ensure the Phase-EQ model was performing as expected within Synergi, RLC benchmarked against a previously developed device implementation within Eaton's CYME software. The CYME implementation leveraged a slightly different modelling approach, and used single-phase battery energy storage systems (BESS), instead of spot loads, to model the power transfer between phases. The BESS component was used within CYME because of the availability of custom python device control scripts, which exist for BESS but do not exist for spot loads. The device control scripts provided convenient "hooks" for embedding the Phase-EQ control scheme directly into CYME's solution architecture, enabling users to leverage more advanced functionality, such as time series analyses. To facilitate the benchmarking process, equivalent CYME and Synergi models were developed for a few distribution circuits based on system data provided by FPL. The benchmarking methodology was straightforward and consisted of three simulations to evaluate the Phase-EQ model performance:

1. Peak load with approximately 85 A of neutral current at the Phase-EQ location
2. Peak load with an artificial spot load added to increase the neutral current to 133 A, the device's maximum rating
3. Peak load with an artificial spot load added to increase the neutral current to 200 A, exceeding the device's maximum rating

These three scenarios were tested in both CYME and Synergi, and similar results were achieved, affirming the performance of the model.

IV. CIRCUIT IDENTIFICATION AND DEVICE SITING

The FPL Phase-EQ pilot involves siting five units with installation expected to be completed by the end of 2024. As part of the pilot's system study phase, FPL provided a collection of approximately 240 distribution circuits for analysis. This collection was viewed as a sample of FPL's broader system, and the assessment of these circuits provided insights into the scope of possible Phase-EQ applications. The collection of circuits included both 22.9 kV and 13.8 kV systems. The existing design of the Phase-EQ is limited to applications up to 15 kV; therefore, the pilot focused exclusively on the 13.8 kV systems. However, the 22.9 kV systems were not completely excluded. A number of 22.9 kV systems had sections stepped down to 13.8 kV and were thus eligible for Phase-EQ deployment.

RLC developed an automated, Python-based, approach to screen and rank the candidate circuits. Load flow simulations were conducted for all 240 circuits. Key metrics were then obtained for each circuit and the circuits were ranked based on expected Phase-EQ benefit. The metrics collected included peak load neutral current, percent current imbalance, feeder power factor, maximum voltage imbalance, and the number of sections at risk of experiencing voltages outside the 95% to 105% range. A 20-point system was developed to assist in the ranking and determination of candidate circuits.

The ranking system assigned scores to each circuit based on neutral current, voltage imbalance, and the number of high and low voltage violations. Additionally, two corrective factors were incorporated into the ranking algorithm to account for potential load allocation errors or situations where the Phase-EQ's impact might be reduced. The first factor applied a negative score to circuits with a power factor less than 90%, indicating potential inaccuracies in load allocation. The second factor reduced the weight of high or low voltage violations if the circuit exhibited low voltage imbalance, as the Phase-EQ's effect on such circuits would be limited. The automated script assembled the relevant metrics for each circuit and ranked them accordingly. The top 15 circuits were then scrutinized to identify issues that might disqualify them as candidates. This list was further narrowed down to 10 circuits, with FPL participating in vetting these circuits by reviewing historical data and results.

Upon identifying the top candidates, the methodology transitioned to determining individual device siting. Device locations were identified by performing load flow simulations under peak loading conditions, and studying neutral current and voltage imbalance across the candidate circuits. Heat maps representing neutral current and voltage imbalance were used to assist in positioning the Phase-EQ. Ideal device placement often coincides with areas of high neutral current and high voltage imbalance. Locations that tend to perform best have higher levels of neutral current and are typically situated one or more miles from the substation.

The Phase-EQ mitigates voltage imbalance levels by balancing upstream current flow and equalizing voltage drop across each phase. The influence of balancing phase currents generally becomes more pronounced with increased distance from the substation. Figure 3 provides two example heat maps: one representing neutral current (left), and the other showing voltage imbalance (right).

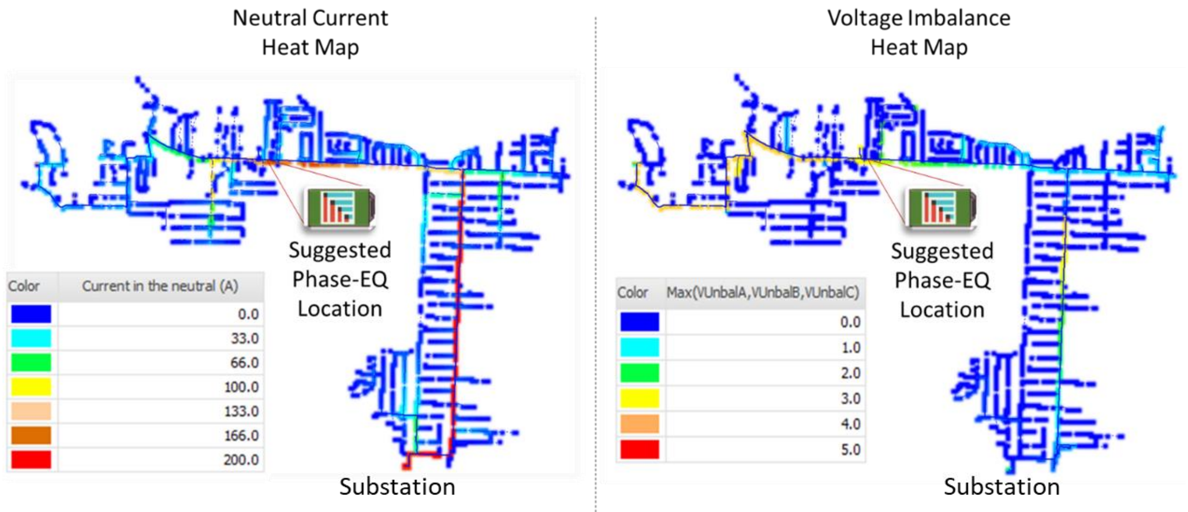

Figure 3: Device Siting Heat Map Examples

Figure 3 shows the suggested Phase-EQ placement, approximately 3.8 miles away from the substation. Note that the substation is located at the bottom of these system diagrams. This simulated example Phase-EQ location would be a good candidate due to its high neutral current (approximately 200 A) and high voltage imbalance (approximately 3%). Each circuit is unique, and there is not a specific neutral current or voltage imbalance number that should be targeted; however, a good guideline is to look for locations first with relatively high neutral current and then try to site as close to the areas of high voltage imbalance as possible.

Once RLC identified a general area from a system performance perspective, FPL surveyed the area to assess the feasibility of each location from a physical installation standpoint.

V. CAPACITY ANALYSIS RESULTS

RLC analyzed system capacity, which involved running simulations and evaluating each circuit's load carrying capacity before and after the addition of the Phase-EQ. This analysis included a comparison of results across four feeders. The main objective of these capacity analyses was to determine the extent of load that could be accommodated on each circuit without breaching thermal and voltage constraints. Each circuit was assessed under peak load conditions and the load was uniformly scaled up until either voltage or thermal constraints were met. For example, if a circuit's peak load is 400 A—100 A on A-phase, 125 A on B-phase, and 175 A C-Phase—then scaling this load up by 25% would equate to a 3-phase loading of 500 A with 125/156/219 amps on A, B, and C-phases, respectively. Figure 4 details the simulated capacity results with and without the Phase-EQ for Feeder A.

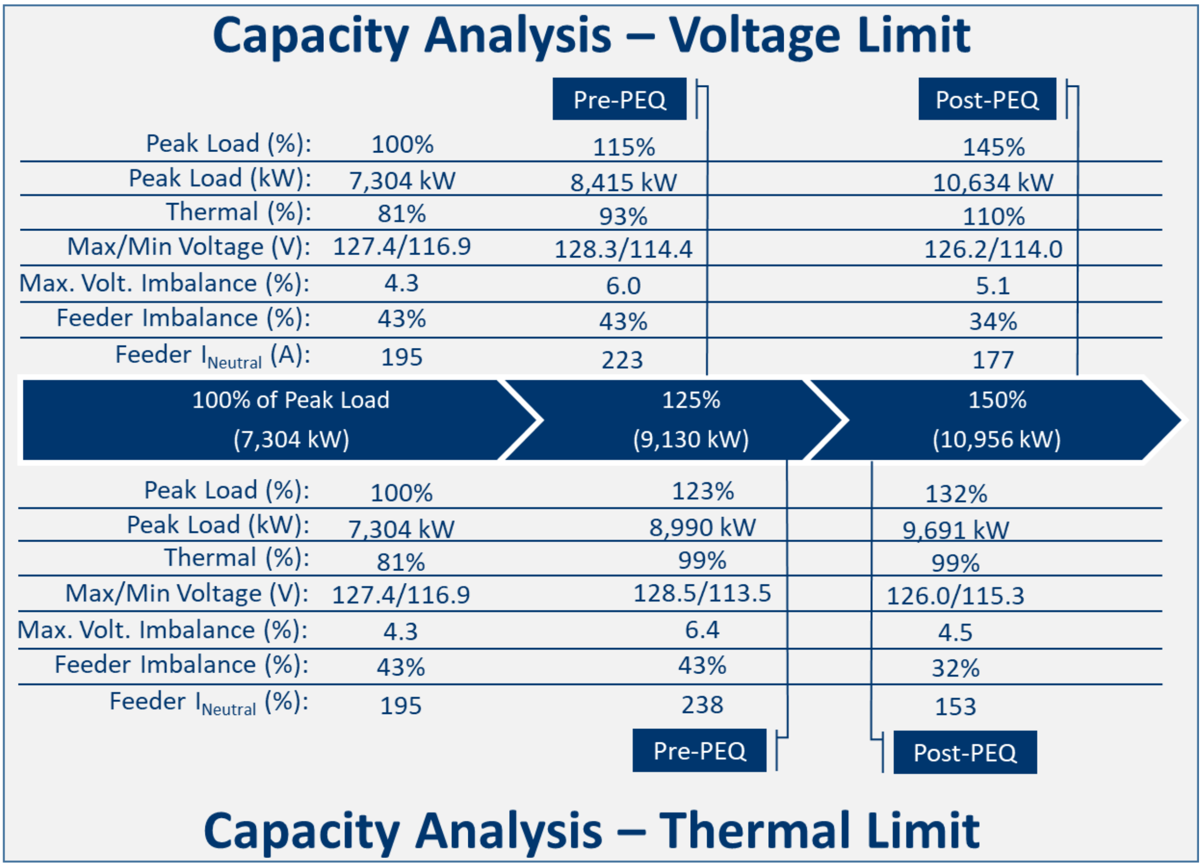

Figure 4: Feeder A Capacity Evaluation

The Phase-EQ increased the voltage limited capacity of Feeder A from 8,415 kW to 10,634 kW, a three phase power increase of approximately 2.2 MW (+26%). This was achieved by reducing the voltage imbalance on the circuit, which raised the systems lowest voltages, and allowed for additional capacity. Similarly, the thermally limited capacity of Feeder A was increased from 8,990 kW to 9,691 kW, a three phase increase of 701 kW (+8%). The thermal improvement is the result of the Phase-EQ reducing the loading on the most heavily loaded phase and redistributing it to the more lightly loaded phases. Additionally, it can be seen that after scaling the three-phase load to 145% of peak, the post Phase-EQ neutral current (177 A) remains below the existing system's feeder head neutral current (195 A).

Table 2 summarizes the simulated results of the capacity analyses for four different circuits, including Feeder A.

Table 2: Summary of Capacity Results for Four Circuits

Feeder	Voltage Limit				Thermal Limit			
	Without Phase-EQ	With Phase-EQ	Increase (kW / %)		Without Phase-EQ	With Phase-EQ	Increase (kW / %)	
A	8,415	10,634	2,219	26%	8,990	9,691	701	8%
B	7,349	7,951	602	8%	12,689	13,276	587	5%
C	17,858	19,336	1,478	8%	13,047	14,019	972	7%
D	12,687	13,123	436	3%	11,000	11,267	267	2%

The greatest improvements were observed on Feeder A, which had the phase EQ modeled relatively far away from the substation and experienced relatively high imbalance. Contrasting this, Feeder D was a 22.9 kV circuit, stepped down to 13.8 kV, which is where the Phase-EQ was modeled. While the Phase-EQ marginally improved system performance, Feeder D had a significant amount of available capacity and required a 150% load scale before reaching the pre-Phase-EQ voltage limit. The tail end of the 13.8 kV system was approaching voltage collapse in this highly loaded state. The Phase-EQ reduced the imbalance observed in the system; however, due to loads being heavily scaled and near voltage collapse, reduced benefits were observed.

VI. CONCLUSIONS AND FUTURE DIRECTIONS

The Phase-EQ is a three-phase power electronics device designed to facilitate balanced power flow in MV distribution systems. This paper explores the planning stages of FPL's pilot of the novel technology, and includes device specifications, an overview of how the device model was created, the process of selecting candidate circuits for device deployment, as well as simulated performance results. The results presented in this paper underscore several advantages the Phase-EQ may provide for imbalanced distribution systems. RLC's study results indicate an average voltage limited load capacity increase of about 12% was observed across the four circuits tested, primarily attributable to the reduction in voltage imbalance, which raised the lowest voltages on the system and reduced the highest voltages. Similarly, on average, the thermal capacity limit increased by 6% across the circuits tested. The most substantial improvements were found in scenarios where the Phase-EQ was positioned 1 or more miles from the substation. This optimal placement maximized voltage drop balancing, thus yielding increased improvements in voltage imbalance. The simulated results affirmed the efficacy of the Phase-EQ in promoting balanced and efficient power flow, resulting in increased load capacity and improved power quality. Beyond the quantitative improvements, the Phase-EQ also showed possible qualitative benefits such as more balanced voltage regulator operation and increased regulation capability, improved capacity for renewable energy and electric vehicle integration, and the potential for reduced operational costs associated with system rebalancing.

Looking ahead, future work will involve gathering field data to corroborate these simulated results. This step will continue to build on the work already done, creating a more complete picture of the Phase-EQ's role as a tool in the arsenal of modern power distribution system planning and operation.

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