From Investments to Impact: Proving the Value of Grid Modernization through a Data-Driven Approach

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ABSTRACT

As the U.S. invests billions in grid modernization to address the rise of distributed energy resources (DER), growing demand, and extreme weather, evaluation methods for these investments remain underdeveloped. While energy efficiency and demand response programs have established evaluation, measurement, and verification (EM&V) protocols, grid modernization lacks standardized approaches. Some jurisdictions use inconsistent methods, while others skip evaluation entirely.

This paper explores various evaluation strategies, focusing on the Advanced Distribution Automation (ADA) and Monitoring & Controls (M&C) investments that were part of the Massachusetts Grid Modernization Program (GMP). Initially, the state mandated reliability metrics to assess the performance of ADA and M&C, but these metrics proved inadequate due to confounding factors like weather and storm hardening investments that also impact reliability metrics. In 2023, the regulator transitioned to a case study evaluation method that isolates device-level impacts from other variables.

The case study approach randomly selects devices and tracks how they were used to solve problems or achieve outcomes, comparing them to a scenario without the devices present. The method can prove the benefits of grid modernization investments by attributing avoided customer minutes of interruption (CMI) and faster emergency response to specific investments. The method also captures cases where the device mis-operated or failed to operate, highlighting opportunities for improved operation. Case study evaluation can be performed within a year of device deployment, unlike traditional methods which require several years of data accumulation. The paper outlines ways to apply case studies to grid modernization investments across the utility industry using streamlined benefit estimation techniques.

Introduction

As distribution utilities across the United States invest more than $50 billion annually[1] in grid modernization to address the accelerating deployment of distributed energy resources (DERs), rising customer demand, and increasingly severe weather events, the need for robust evaluation methods has become urgent. Grid modernization is widely recognized as essential for managing higher penetrations of intermittent resources such as wind and solar, and managing increasing demand from electrification and data centers which are driving up electric rates. Yet the evaluation, measurement, and verification (EM&V) frameworks that support these investments remain underdeveloped.

Unlike energy efficiency and demand response programs—where EM&V practices are well established—grid modernization lacks standardized evaluation protocols. Some jurisdictions have adopted ad hoc approaches, while others require no evaluation at all. This creates a critical gap for regulators and ratepayers: With the downward pressure on rates, how can investments be justified? How can the grid modernization investments be proven to effectively combat the issues they were intended to resolve? How can the impact of individual technologies be isolated within a broad portfolio of grid investments? And how can lessons learned be systematically captured to inform future deployments?

[1] U.S. Energy Information Administration (EIA) analysis published 2024 (URL: https://www.eia.gov/todayinenergy/detail.php?id=63724)

This paper offers a historical perspective on early efforts to evaluate grid modernization using traditional reliability metrics, particularly in the domains of distribution grid monitoring, control, fault location, and service restoration. It highlights the limitations of traditional reliability metrics in attributing performance improvements to specific investments.

The paper then introduces a novel case study approach pioneered by the Massachusetts Grid Modernization Program evaluation team at Guidehouse. The Massachusetts Department of Public Utilities (DPU) had mandated evaluation of ADA and M&C investments through traditional reliability metrics, but after inconclusive results in the early years of evaluation, approved a pivot to case studies as the primary method for evaluating ADA and M&C investments. The case study method addresses the shortcomings of traditional reliability metrics and enables evaluators to assess circuit-level impacts including the number of avoided customer minutes of interruption (CMI) resulting from specific grid modernization investments. Real-world case studies are presented, featuring both the benefits of grid modernization as well as improvement opportunities and lessons learned that emerged from analysis. Finally, ongoing efforts are outlined to streamline the case study approach and enhance its scalability for broader industry application.

What is Grid Modernization?

Grid modernization is the process of updating aging transmission and distribution grids to higher levels of functionality and efficiency using new technologies. It leverages digital two-way communications and microprocessor-based technologies for automated decision making on the electric grid, and in these respects is distinct from traditional investments in poles, wires and transformers. This paper focuses on investments in distribution grid monitoring, remote control, and automated restoration of service. The table below summarizes the common types of Monitoring and Control (M&C) and Advanced Distribution Automation (ADA) investments. M&C investments yield reliability benefits, operational efficiencies, and enhanced ability to integrate DERs and stabilize voltage on portions of the grid.

Table 1. Overview of M&C and ADA investments

Investment Type	Description
Monitoring and Control (M&C)	Remote near-real-time monitoring of current, voltage and other conditions on distribution circuits and substation devices, and remote-controlled operation of those devices. A common example is SCADA (supervisory control and data acquisition) at field devices such as reclosers and switches, and substation devices such as breakers or relays.
Advanced Distribution Automation (ADA)	Localized or centralized automation logic that is designed to rapidly isolate a ‘fault’ to a limited section of a distribution circuit, and restore other sections of the circuit via pre-programmed switching and reclosing actions.

Early Efforts to Evaluate Grid Modernization Investments

The American Reinvestment and Recovery Act (ARRA) of 2009 pioneered the use of case studies in demonstrating return on investment on taxpayer dollars. Branded the Smart Grid Investment Grant (SGIG) program, the U.S. Department of Energy catalyzed over $9 billion in public and private investment in smart grid[2] infrastructure across the United States[3]. The SGIG results evaluation revealed the complexity of deriving standardized, system-wide results across a 99-utility program within the first three years of deployment. Data collection, normalization, and aggregation proved challenging, and even when successful, much of the nuance—design decisions, operational insights, and customer impacts—remained hidden behind summary statistics. To address this, the SGIG evaluation team developed a series of case studies to spotlight specific utility experiences, highlight design trade-offs, and extract lessons learned. These case studies became a valuable complement to quantitative reporting, offering a richer narrative of grid modernization outcomes. Utilities and regulatory commissions nationwide have since used these case studies to inform investment decisions and to capture qualitative benefits such as improved customer satisfaction, enhanced data governance, better power quality, and more streamlined DER integration.

Challenges of Using Traditional Reliability Metrics for Grid Modernization Evaluation: Experience in Massachusetts

When investments in ADA and M&C were authorized by the Massachusetts DPU in 2018, reliability metrics were required to evaluate performance. Evaluation spanned three utilities implementing a suite of different technologies and with varying baseline levels of pre-existing grid modernization capability. The approved metrics were based on standard SAIDI and SAIFI indices, which are widely accepted in the electric industry and enshrined in the IEEE Standard 1366-2012[4]. The state-approved metrics required tracking the SAIDI and SAIFI performance over time of circuits receiving GMP-funded investments, and are shown in Table 2.

Table 2. 2018 State-approved reliability metrics

Metric	Description & Tracking
CKAIDI Metric	Compares the experience of customers on ADA-enabled and M&C-enabled circuits to the prior three-year average for the same circuits. Provides insight into how ADA or M&C can reduce the duration of outages. Tracks: • Circuit-level SAIDI (CKAIDI) for the program year • Three-year average SAIDI (CKAIDI) for 2015, 2016, and 2017 (baseline) • Comparison of current year SAIDI with the three-year average: AVERAGE(CKAIDI 2015, CKAIDI 2016, CKAIDI 2017) – Program Year CKAIDI. If result > 0 → positive impact
CKAIFI Metric	Compares the experience of customers on ADA-enabled and M&C-enabled circuits to the prior three-year average for the same circuit. Provides insight into how ADA or M&C can reduce the frequency of outages. Tracks: • Circuit-level SAIFI (CKAIFI) for the program year • Three-year average SAIFI (CKAIFI) for 2015, 2016, and 2017 (baseline)

[2] The industry term "smart grid" evolved into "grid modernization" but the terms are essentially synonymous. Aging and manually operated grid infrastructure can be *modernized* to produce a *smart grid*, characterized by remote communication and digital operation.

[3] U.S. Department of Energy, Smart Grid Investment Grants Program Final Report, 2016. URL: https://www.energy.gov/sites/prod/files/2017/01/f34/Final%20SGIG%20Report%20-%202016-12-20_clean.pdf

[4] IEEE 1366-2012: IEEE Guide for Electric Power Distribution Reliability Indices, published May 31, 2012.

Metric	Description & Tracking
	• Comparison of current year SAIFI with the three-year average: AVERAGE(CKAIFI 2015, CKAIFI 2016, CKAIFI 2017) – Program Year CKAIFI. If result > 0 → positive impact

During the first three years following the launch of the grid modernization program, sample sizes were too small to yield statistically significant insights from the average performance metrics. Nevertheless, it was critical to evaluate results in those early years, to identify opportunities for course correction and optimization ahead of broader rollouts. This is emblematic of a general issue in grid modernization, in that evaluation has to wait for larger-scale deployments before statistically significant results are possible. Grid modernization pilots are often limited to five or fewer circuits (as individual devices can be costly). By the time statistically significant results are possible, costs have been incurred and it is too late to adjust program design.

To offer early actionable insights, the evaluation team introduced case studies to complement the CKAIFI and CKAIDI metrics. Each year, twelve case studies were published to capture early evidence of improved performance and to identify operational adjustments that could enhance benefits. These case studies also uncovered instances where devices could have operated but did not, or where they could have been used but weren't. Such insights would have been lost in aggregate summary analyses.

The Massachusetts Grid Modernization evaluation experience highlighted three key challenges in using SAIDI and SAIFI to measure ADA and M&C performance, outlined below.

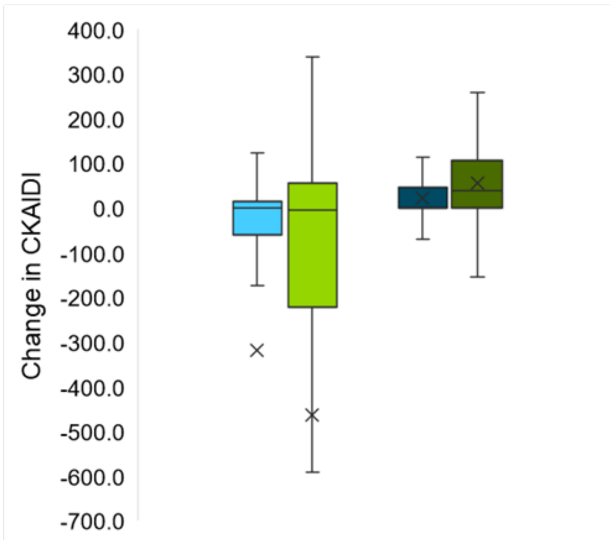
1) Attribution Challenge

Reliability metrics are affected by multiple overlapping drivers—foremost among them weather, but also other programs designed to improve reliability including undergrounding, vegetation management, storm hardening such as pole replacements, and operational process improvements, among others. When so many investments are intended to improve SAIDI and SAIFI metrics, it can be difficult to disentangle their individual contributions. For example, in Massachusetts, year-over-year variations in storm activity significantly impacted reliability metrics in performance year 2020 (see Table 2). While 2020 performance appeared worse than baseline, it remains unclear whether outcomes would have been even more severe without grid modernization. Conversely, in years when reliability improved (such as year 2021 pictured in Figure 1), attributing that improvement solely to ADA and M&C investments was equally problematic. Performance metric results were influenced by a wide range of external drivers, making it difficult to isolate the effects of the investments in question from other confounding factors.

Table 3. Reliability metric results in PY2020 relative to baseline for three participating electric distribution companies (EDCs). 2020 reliability on evaluated circuits was considerably worse than baseline[5]

	Number of M&C Circuits Evaluated	Metric	Baseline	PY2020
EDC 1	197	Weighted Average CKAIDI	106	233
	197	Weighted Average CKAIFI	0.93	1.16
EDC 2	25	Weighted Average CKAIDI	119	298
	25	Weighted Average CKAIFI	0.91	1.27
EDC 3	3	Weighted Average CKAIDI	66	135
	3	Weighted Average CKAIFI	1.06	1.61

[5] Massachusetts Grid Modernization Program Year 2020 Evaluation Report: Monitoring and Control (M&C) prepared by Guidehouse, posted on Massachusetts Department of Public Utilities Docket 15-120, 15-121 and 15-122 (Web URL)



	Change in System-wide CKAIDI w/ EMEs	Change in ADA CKAIDI w/ EMEs
Count	2,071	234
% No Change	35%	0%
Average Change in CKAIDI	-318	-463
Standard Deviation	1008	1198
Median Change in CKAIDI	0	-3

	Change in System-wide CKAIDI w/o EMEs	Change in ADA CKAIDI w/o EMEs
Count	2,071	234
% No Change	36%	0%
Average Change in CKAIDI	22	56
Standard Deviation	115	154
Median Change in CKAIDI	0	39

Figure 1. Circuit SAIDI (CKAIDI) metric performance results in PY2021 for one participating utility[6]. EME = excludable major events. Change in CKAIDI greater than zero indicates positive impact. CKAIDI without EMEs improved more for ADA circuits than for system-wide circuits. However, CKAIDI including EMEs worsened for ADA circuits more than for system-wide circuits, showing mixed results.

2) Control Group Challenge

The Commission sought to compare *grid-modernized* circuits against the remainder of the system, to discern differences in performance. However, many circuits across the system had already been upgraded with other modernization technologies, complicating the comparison. This reflects a broader industry reality: utilities often implement multiple capital programs simultaneously, each targeting reliability from a different angle. It is neither practical nor advisable to pause concurrent initiatives during grid modernization efforts. As a result, a pure control group remains elusive.

3) Evaluation of Non-Reliability Benefits

While ADA investments were targeted at reliability improvements, M&C investments were yielding a host of non-reliability benefits overlooked by reliability-focused performance metrics. In interviews with utility participants, non-reliability use cases became evident and merited an enhanced evaluation approach. These included situational awareness in emergency scenarios; avoided voltage violations during heat waves; avoided overload during contingency switching; avoided backflow and voltage issues on circuits with near-maximum DER penetration; increased efficiency through phase-balancing, and others.

Considering the challenges above, the participating utilities asked the Guidehouse evaluation team to propose alternatives to reliability metrics that would better capture the benefits of ADA and M&C performance. Guidehouse proposed a set of options to the regulatory commission including a statistical regression approach, an event-specific analysis approach, a case study approach, and an outage data-mining approach.

[6] (Web URL)

The commission's decision was a pivot to a case study approach. The case study approach initially complemented the state-approved SAIDI and SAIFI metrics and then came to supplant them entirely. The Massachusetts DPU ordered[7]:

- Discontinuation of SAIFI and SAIDI as performance metrics for M&C and ADA evaluation
- An increase in the number and types of case studies per evaluation period
- Inclusion of both normal weather and extreme weather conditions
- Special consideration of power quality, issues related to high DER penetration such as backflow, and circuits with worse-than-average reliability performance
- Inclusion of any cases where grid modernization devices failed to operate or mis-operated

The case study approach is outlined below, along with a set of sample case studies from Massachusetts .

The Case Study Approach

The case study approach involves selecting a random sample of devices and tracing how each was operated or utilized by the utility to address a specific challenge or achieve a desired outcome. The analysis then compares the observed scenario—where the Advanced Distribution Automation (ADA) or Monitoring & Control (M&C) device was present—with a counterfactual scenario in which the device were not present. This contrast allows evaluators to (1) isolate and quantify the benefit of the specific device, and (2) pinpoint ways to improve the configuration or utilization of the device to derive greater benefit in the future.

For example, evaluators may begin with a set of outage events over a year and investigate a randomly selected sample of outages on feeders equipped with M&C and ADA technologies. By examining outage location, cause, SCADA[8] data, switching logs, and distribution one-line diagrams, they estimate what the outage duration and extent (i.e., number of customers affected and total outage minutes) would have been without the ADA or M&C device present. This enables a direct derivation of avoided customer minutes of interruption (CMI) and reduced outage impact attributable to the equipment.

This method is particularly accurate for equipment with control capabilities—such as reclosers and sectionalizing switches—and requires only current-period data. It directly attributes observed outcomes to pre-authorized investments and also captures non-outage benefits, such as identifying overloads or voltage issues.

A few examples of case studies are summarized below.

Case Studies on Use of ADA and M&C During Outage Restoration

1) Underground Fault Detection to Reduce Outage Duration

One utility had replaced legacy underground oil-filled switches with modern fault-indicating switches. Legacy oil switches had no telecommunication or automation and could only be manually operated from inside the manhole. Before the upgrade, when a fault occurred, the circuit breaker would have locked open and the entire circuit would have lost power. In an underground circuit, there would be no way to know where the fault was. Crews would have had to enter one manhole after another, moving traffic and pumping water out, until the fault was found. Following grid modernization, when a fault occurred in 2022, the new switch automatically opened to 'isolate' the fault, thereby preventing an outage

[7] The Department Memorandum on Performance Metrics and Reporting was filed November 9, 2023 under Department dockets D.P.U. 21-80, 21-81, and 21-82.

[8] SCADA (Supervisory Control and Data Acquisition) is a system used to monitor the electric grid by collecting data from sensors, analyzing it, and enabling remote control of grid devices.

for many other customers on that circuit. Alerts were received from specific field devices and crews were dispatched to the manhole with that device, saving time. Once the crew determined the exact fault location, they requested remote switch operation to further isolate the fault to an even smaller set of customers. These efficiencies resulted in 40% fewer customer minutes of interruption than would have resulted from the same fault without grid modernization, as shown in Figure 2. As an improvement opportunity, the evaluation team recommended that the new switches be programmed so that only the switch closest to the fault should open. This would minimize the customer interruption impact even further and maximize the benefit of the investment.

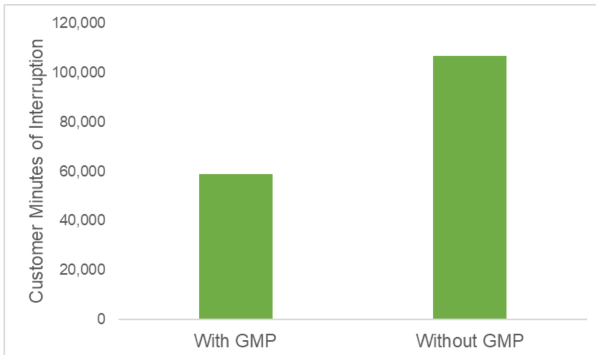


Figure 2. Savings in Customer Minutes of Interruption due to Massachusetts Grid Modernization Program (GMP) during an underground fault in 2022.

2) Performance and Customer Impacts of ADA

Case studies at another utility revealed that, out of over a hundred outage events surveyed as part of case study analysis on ADA circuits, ADA operated correctly over 90% of the time. For the case studies that had successful operations, FLISR restored customers in under one minute. This resulted in customers experiencing a momentary interruption instead of a sustained interruption. The evaluation team estimated that the successful FLISR operations improved CMI by over 50%. For unsuccessful or suboptimal operations, the evaluation team investigated causes and suggested corrective actions to improve future operations.

Case Studies on Using ADA and M&C during Public Safety Emergencies

1) Faster Storm Response

During a storm in 2024, a broken tree caused live overhead wires to fall on top of a fire truck. That circuit had previously lacked remote operation capability and crews would have had to travel to the site to manually deenergize the live wires. With SCADA investment, the utility was able to remotely deenergize the wires and quickly make the area safe.

2) **Fire Safety**

In 2023, when a pole-top device caught fire, the SCADA system sent an alarm within seconds to the dispatch control center. When the fire department called the utility, crews were already on their way. The timely indication of a circuit outage enabled the utility to dispatch personnel in a timely manner to respond to the emergency. As an improvement opportunity, the evaluation team recommended that if remote fault indicators had been present, the response would have been even quicker.

Case Studies on Using M&C to Avoid Overloads

1) Heat Wave Management:
During a heatwave when electric load is at its peak, distribution grid devices can approach their thermal carrying limits. Running a distribution feeder above its capacity for a sustained period is not advisable and can lead to equipment damage and outages. On June 18, 2024, a newly-installed M&C device sent load alerts to the utility control center. The feeder was already loaded at 90% of its normal current carrying capacity in normal weather conditions. The alerts, depicted in Figure 3, showed that starting at about 5:00 PM, current on A-phase (indicated as "PHA" in the middle column) began to approach the long-term carrying capacity of 290 amps, occasionally exceeding it for short periods of time. While the situation was manageable without necessitating action that evening of June 18, 2024, grid operators took action the following day when the temperature was equally hot. On June 19, 2024, grid operators took the preventative action of transferring a portion of the load to another circuit. Without near-real time grid situational awareness, this overage would have been difficult to detect in time.

TIME	TEXT	CATEGORY
06/18/2024 16:55:43d	(026) 26-09 4KV PHA AMP NRM Hi LIM EX 294.2 > Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:13:06d	(026) 26-09 4KV PHA AMP RET TO NRM 286.0 < Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:20:54d	(026) 26-09 4KV PHA AMP NRM Hi LIM EX 296.7 > Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:28:18d	(026) 26-09 4KV PHA AMP RET TO NRM 287.1 < Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:40:11d	(026) 26-09 4KV PHA AMP NRM Hi LIM EX 291.2 > Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:40:43d	(026) 26-09 4KV PHA AMP RET TO NRM 281.1 < Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:42:11d	(026) 26-09 4KV PHA AMP NRM Hi LIM EX 292.5 > Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:43:34d	(026) 26-09 4KV PHA AMP RET TO NRM 281.7 < Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:48:11d	(026) 26-09 4KV PHA AMP NRM Hi LIM EX 292.5 > Hi Lim: 290.0	P1 ANALOG
06/18/2024 17:49:39d	(026) 26-09 4KV PHA AMP RET TO NRM 287.4 < Hi Lim: 290.0	P1 ANALOG

Instances in which the A-phase exceeds the long-term carrying capacity of 290 amps are highlighted in yellow.

Figure 3. Guidehouse analysis of SCADA interval data

2) Peak Load Planning:

The evaluation team found that the actual load being served by a circuit in Massachusetts exceeded the feeder peak load recorded on the books of the utility's planning department. M&C device data recorded shortly after deployment showed that actual load exceeded the normal current carrying capacity of that feeder, as shown in Figure 4. Before M&C investment, this exceedance had gone undetected. The evaluation team recommended that the utility utilize M&C data to avoid overloads and determine if feeder upgrades are warranted.

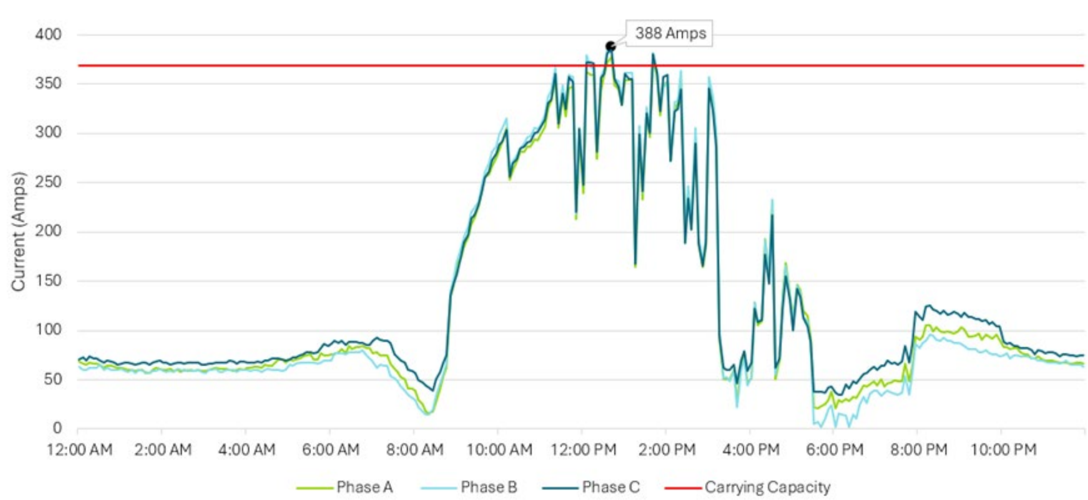


Figure 4. Guidehouse analysis of SCADA interval data and Peak Load Planning Documents.

3) Deferring Grid Upgrade Costs

One of the participating utilities used new M&C visibility to detect an imbalance on its distribution circuits. A distribution circuit comprises of three phases (A, B and C) and most customers are connected to one of the three phases. If equal customer loads are connected to all phases, the system is balanced and efficient. See Figure 6 for a schematic of a 'balanced' circuit. In reality, however, more customers over time get connected to one of the phases than another, and utilities don't have visibility into the load on each phase to detect the imbalance.

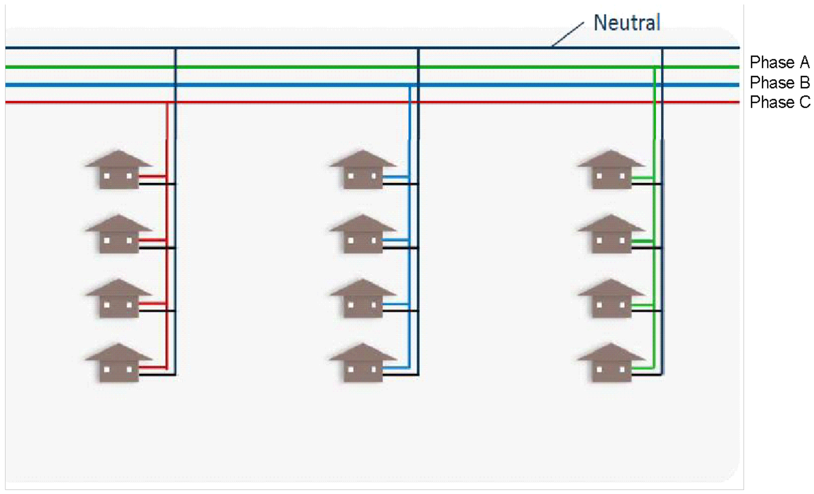


Figure 6. Schematic of customers serviced from a three-phase distribution line. Load on each phase is roughly balanced in this diagram (equal customers on each phase). Source: *Enerdynamics, The Electrical Distribution System*

The utility was expecting new customer load to be connected to one of its circuits. Existing records showed that the circuit was already at capacity, and costly upgrades were planned to accommodate new load. However, the new M&C device allowed the utility to monitor phase-level load. M&C data showed there was available capacity on one of the phases while other phases were heavily loaded. In this case, M&C improved this utility's system planning process and deferred costly upgrades. The evaluation team recommended the utility use SCADA data to verify peak loads at all M&C feeders to systematically improve system efficiency.

Conclusion and Applications to the Broader Electric Utility Industry

The examples above show that case studies offer several advantages to regulators and utilities in evaluating the benefits of grid modernization as well as discerning improvement opportunities and lessons learned. Unlike SAIDI- and SAIFI-based evaluation methods which require several years of data accumulation to get conclusive and weather-independent results, case study evaluation can be performed within roughly a year after grid modernization devices are commissioned. Case studies can also be used to evaluate grid modernization pilots, where statistical evaluation techniques are typically not feasible due to sample size limitations.

Case studies can be used to prove the reliability impacts of grid modernization investments by quantifying avoided customer interruption minutes directly resulting from specific investments. Case studies can also help discern non-reliability benefits of grid modernization including: (1) the benefit of grid visibility and situational awareness during emergencies; (2) avoided voltage violations such as during heat waves; (3) avoided overloads such as during contingency switching; (4) avoided backflow and voltage issues on circuits with near-maximum DER penetration; (5) increased efficiency through phase-balancing; and (6) successful resolution of customer voltage complaints.

The case study method requires a comparison of actual events with a counterfactual scenario of what would have happened without the devices in place. This can prove effort-intensive, and steps can be taken to streamline case study evaluation at scale to apply to large grid modernization deployments. The first approach is to draw a random sample from a dataset of device operations, such as main-line outages on a circuit over a year. Another approach is to scan event records over the evaluation time period to estimate the percentage of successful versus unsuccessful operations. This strategy yields an estimate of total savings in customer outage minutes attributable to the investments. Further streamlining of case study analysis using automated or AI-driven approaches is underway, including:

(1) Device data mining for ADA evaluation: Scan SCADA records of M&C and ADA devices over a few months or years to determine instances when they operated. For each time a device operated successfully, assume a preset benefit (reduction in CMI) to the customers within the section of the circuit where the device is located.

(2) Estimation of customer outage time saving: ADA events often unfold in steps, consisting of an initial momentary-outage step when an unaffected section of customers is restored, and a longer step when crews restore the smaller section where the fault has been isolated. Customer benefit analysis can assume that without ADA the first step would take at least as long as the second step, obviating the need for more detailed analysis and automating the time savings estimation process.

(3) Surveying for voltage and current violations: M&C device records can be screened for voltage readings and current readings that exceed thresholds for reliable operation. Checks can include voltages outside the regional bounds for consumer-level voltage, current readings that approach zero or negative due to high outputs from local DERs, or current readings that exceed circuit capacities or exceed the utility's own records of peak loading.