345KV SF_6-FREE CIRCUIT BREAKER PILOT PROJECT

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ABSTRACT

Like with many other utilities throughout the United States, and around the globe the future is in clean energy. At Eversource Energy, our company's vision is to lead our industry in sustainability, which is a critical element of our business today and into the future. To accomplish our target of being an industry leader in clean energy, Eversource has committed to making our operations carbon neutral by 2030. Many factors impact this, including the reliance on sulfur-hexafluoride (SF_6) gas as an electric insulator. Specific to this area, a focus needed to be placed on establishing aggressive emission reduction goals and the integration of SF_6-free high voltage equipment across our service territory. This paper will focus on the latter as Eversource will provide details on its carbon neutrality efforts, and its collaboration with Hitachi Energy to install the first of its kind, eco-efficient, 420kV EconiQ circuit breaker.

INTRODUCTION

Eversource Energy, New England's largest utility company, prides itself on delivering safe and reliable energy to approximately 4.4 million customers across Connecticut, Massachusetts, and New Hampshire. In addition to water and natural gas, its electric service territory encompasses 500 towns and over 13,000 square miles across all three states. To better serve the communities in which we live and work, Eversource self-imposed one of the most ambitious goals within the industry by committing to drive down greenhouse gas emissions and run carbon-neutral operations by 2030.

The path to carbon neutrality relies on the elimination and/or reduction of emissions across five key areas across the company, with the main one residing within electric business unit and being none other than the reliance on Sulfur-hexafluoride (SF_6). Eversource has made progress in reducing SF_6 emissions since 2019, through improved equipment maintenance and tracking, but it is recognized that further work needs to be done. So, Eversource embarked on a journey with one of its strategic partners in the industry, Hitatchi Energy, to research and pilot SF_6-free solutions such as the EconiQ product line.

EconiQ is Hitachi Energy's eco-efficient portfolio of equipment that utilizes technology that is free of SF6 gas, significantly reducing the carbon footprint throughout an asset's lifecycle [1]. Now more than ever, advancements such as this are needed to forge ahead toward a sustainable energy future and support utilities to transition to cleaner technologies.

EVERSOURCE'S CARBON NEUTRALITY GOALS & SF_6 EMISSION REDUCTION STRATEGY

Reducing carbon footprint and reaching neutrality goals requires significant effort as we continuously evaluate all areas and opportunities for emission reductions. Since 2018, a 25% overall reduction in greenhouse gas (GHG) emissions has been noted across all 5 key focus areas, proving efforts are yielding tangible results [2]. Eversources five (5) key areas are as follows:

- Line Loss
- Methane Emissions
- Our Facilities
- Our Fleet
- Sulfur-Hexafluoride (SF_6)

Reduction of Sulfur-hexafluoride (SF_6)

It is widely understood that SF_6 is the most potent greenhouse gas and is widely used as an electrical insulator in medium- and high-voltage electrical apparatus. In addition to improving its existing processes, Eversource created a focus group to plan how to achieve SF_6 reduction. This group identified two distinct areas of focus: 1) reducing the leakage of existing SF_6-filled equipment and 2) reducing the volume of SF_6 already installed on the Eversource electric system.

- **Reduce Leakage of Existing Equipment**
  - Implement improved methods to seal/repair or slow leaking equipment until appropriate maintenance can be performed.
  - Modify equipment practices to reduce emissions during equipment maintenance and installation.
  - Improve inventory and reporting practices.
  - Secure more accurate data management to identify system needs.

- **Reduce Volume of SF_6 on ystem**
  - Reduce the volume of new SF_6-filled equipment added to the system as part of system expansion/modifications (i.e. new equipment and facilities)
  - Replace existing SF_6-filled equipment with SF_6-free equipment via asset condition-based obsolescence replacement projects and programs.

Since 2019, Eversource has made significant progress in reducing SF_6 emissions through improved maintenance and gas inventory tracking, including a 17% reduction between 2021 and 2022 alone [2].

Table 1
Annual Target SF_6 Emission Rates

Target SF6 Emission Rates										
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1.0%	1.0%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.7%	0.7%	0.6%

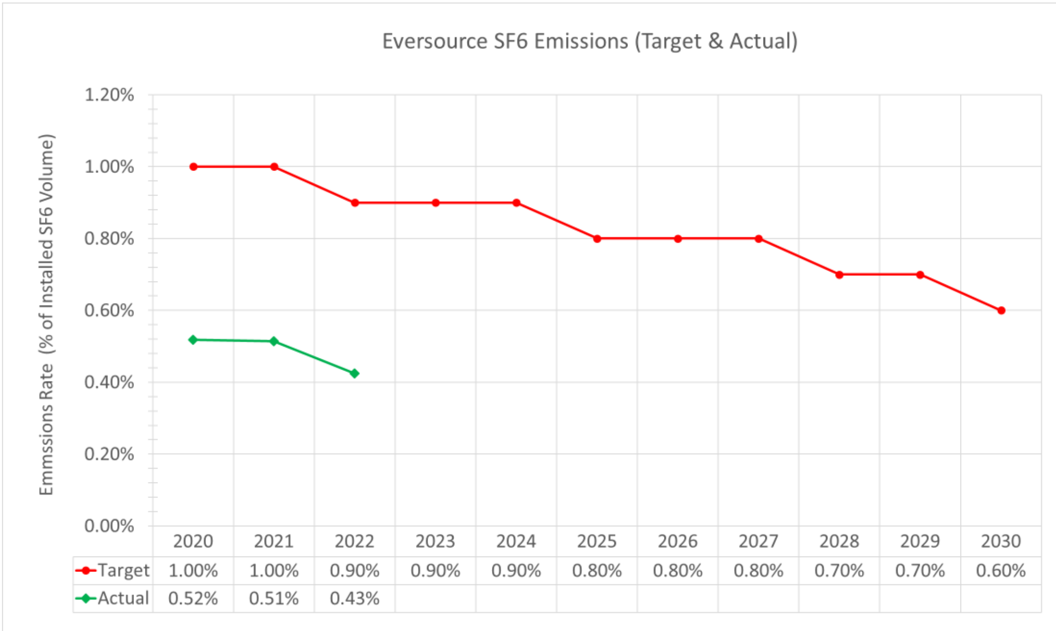
While there are opportunities for continuous improvement and advancement of maintenance practices, there will be a point of diminishing returns in emissions reductions. The continued operation of SF_6 insulated devices on the electric system inherently represents a perpetual source of emissions and, thus, is a significant risk in achieving aggressive carbon neutralization goals. As such, the only viable option for a long-term strategy that matched Eversource's ambitious carbon-neutrality goals required that SF6 be eliminated from high-voltage equipment.

The reduction and eventual elimination of SF_6-insulated devices from the system is a significant challenge, especially considering the imminent transmission system growth due to reliability-based upgrades, load growth due to electrification, and interconnection of clean energy resources.

The application of alternative SF_6-free equipment now looks like the obvious solution, but at the time Eversource entered into the pilot project with Hitachi Energy, there were no commercially available industry solutions that met both system operating voltage and fault duty specifications. Beyond the availability of the needed solution, the unknowns associated with the SF_6-free technology left many unanswered questions regarding the feasibility of applying this new technology to the system.

The size, weight, safety restrictions, operational limitations, monitoring/alarming needs, etc., associated with the potential SF_6-free solution were all unknowns that could ultimately impact substation design standards and operational practices. As such, the strategy considered brownfield and greenfield application as two distinct needs. As new design and construction could accommodate potential differences due to SF_6-free technology, greenfield applications were considered more flexible and thus a lower risk and lower overall priority in the SF_6 emission reduction plan.

Brownfield applications presented added challenges and constraints associated with the integration of new technology into an existing operating substation. Furthermore, as mentioned earlier, the presence of existing SF_6 insulated equipment represents an inherent risk of emissions. This risk is exacerbated by the fact that most of the existing installed fleet of SF_6-insulated equipment at Evesrouce does not meet current industry standard guaranteed leakage rates (0.5%), and compounded due to the trend of leakage rates of an aging equipment fleet increasing over time. Therefore, the long-term SF_6 emission reduction strategy regarded the development of a one-for-one replacement solution as a top priority.



SF_6 Emissions Target & Actual
Figure 1

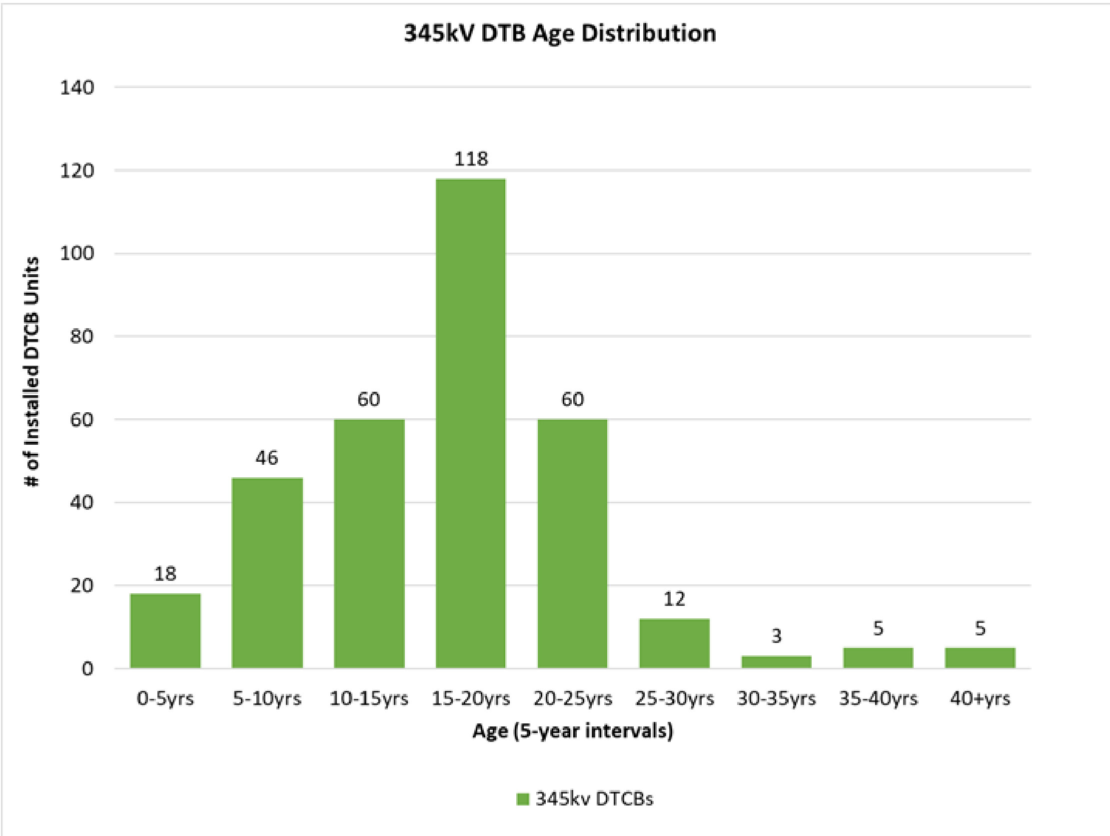
As mentioned above, results of the short-term strategy to reduce emissions exceeded the targets in the first three years following the development of the focus group. However, further reduction is expected to taper off. In the years remaining up to and beyond the 2030 carbon neutrality goal, maintaining the recent emission volume levels will be challenged by the risks associated with the aging fleet of SF_6 insulated equipment coupled with risks of system growth.

While continued system growth may lead to an immediate reduction of emission rates (% emission of total installed SF_6 volume) due to the added low-risk emissions volume of SF_6 to the system, it increases the risk of achieving reductions to the total pounds of SF_6 emission volume. In 2017, the Massachusetts Department of Environmental Protection (MassDEP) implemented mass-based SF_6 emissions limits as an amendment to the existing regulations limiting SF_6 emission rates. Although future regulatory changes are unknown, it is expected that Massachusetts and other states in New England will continue to implement more stringent SF_6 emissions controls. Considering that the rate of transmission system growth is likely to increase in the coming years, the risk of maintaining mass-based emissions targets is real.

Upon evaluation of existing assets, the need to focus on an SF_6-free alternative for dead tank circuit breakers was apparent. Eversource's transmission system has more than 1600 dead tank circuit breakers that contain 72% of the installed SF_6 gas volume. Furthermore, over 40% of the installed SF_6 volume is contained within circuit breakers at an age (15 years or older) where the risk of SF_6 leakage tends to increase. Therefore, identifying an SF_6-free solution to replace aging assets is essential for achieving and maintaining carbon neutrality goals.

Aging Fleet of 345kV Dead Tank Circuit Breakers

345kV dead-tank circuit breakers represent approximately 52% of the installed SF_6 volume on Eversource's transmission system across all operating regions. With age-based obsolescence and/or end of life for most of our fleet still 15-20 years away, an aging population represents a significant risk in achieving Eversource's carbon neutrality goals.



345kV Circuit Breaker Age Distribution
Figure 2

Currently, Eversource's asset strategy is based on equipment condition and the impact on system reliability, and as such, there is no mechanism for replacing SF_6 gas-filled breakers based on age and/or risk of leakage. Efforts to develop a broader asset strategy that incorporates regulatory and carbon neutrality goals are proceeding as necessary to support the implementation of SF_6-free solutions as they are identified and vetted.

HITACHI ECONIQ TECHNOLOGY

The Hitachi EconiQ portfolio is as an alternative solution for high-voltage equipment such as gas-insulated switchgear (GIS), gas-insulated lines (GIL), Dead Tank Circuit Breakers (DTBs), and hybrid switchgear [1]. New equipment is being designed and built in a similar manner and on a platform like their SF6 equivalent, allowing for easier retrofit or replacement of existing assets. Equipment has been fully type-tested to meet IEC and IEEE standards and specifications.

Table 2
Ratings of 420kV Breaker Using C4-FN Mixture [3]

Rated voltage	U_r	420 kV
Rated lightning impulse withstand voltage	U_p	1,425 kV
Rated switching impulse withstand voltage	U_s	1,050 kV
Rated power frequency withstand voltage	U_d	650 kV
Rated continuous current	I_r	5,000 A
Rated short-circuit breaking current	I_{sc}	63 kA
Rated short-time withstand current (3s)	I_k	63 kA
Rated peak withstand current	I_p	171 kA
Rated first–pole-to-clear factor	k_{pp}	1.3 / 1.5
Capacitive load switching	class	C2
Capacitive voltage factor	k_c	1.4
Rated capacitive currents	I_l, I_c	400 A
Shunt reactor current switching	Acc. to IEC 62271-110 and IEEE C37.015	
Rated frequency	f_r	50 Hz / 60 Hz
Mechanical endurance	class	M2
Electrical endurance	class	E2
Rated operating sequence	O-0.3s-CO-3min-CO or CO-15s-CO	
Operating temperature	-30 °C ... +40 °C	

Capacitive & Shunt Reactor Switching

The circuit breaker is based on reliable and well-proven gas circuit breaker technology using the puffer principle, adapted and optimized for the chosen gas mixture. The design covers both 50 and 60 Hz and both gas-insulated switchgear (GIS) and dead tank breaker (DTB) applications with the same interrupter. The main ratings are reported above in Table 2. To achieve maximum flexibility for application of the breaker in different countries, the test campaign covered both 50 and 60 Hz requirements and both IEEE and IEC standards [3].

Terminal Faults

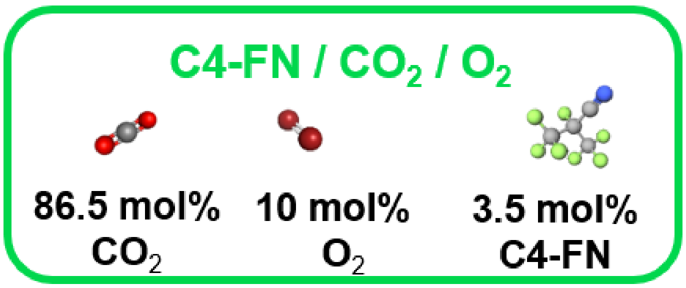
The SF_6-free 420kV circuit breaker passed all terminal fault tests for 63KA as defined by the IEEE and IEC standards. The tests were performed in a manner that permitted the requirements of both the IEEE and IEC standards to be met [3].

Short Line Faults

The breaker successfully cleared SLF75 and SFL90 test duties for 63kA, covering IEEE and IEC standards and the initial transient recovery voltage (ITRV) requirements (with less than 100ns time delay). During all type-tests, the breaker showed consistently very short minimum arcing times. This is mostly due to the adoption of reliable puffer technology, which is an important indication of breaker performance and clearing capability [3].

Use of the Eco-Efficient Gas Mixture

The EconiQ product line utilizes an eco-efficient gas mixture of CO_2 (carbon dioxide), O_2 (oxygen) C4-FN (fluoronitrile) as an alternative to SF_6. Similar to SF_6, C4-FN is a chemically stable, colorless, odorless, and non-flammable compound used in the gas mixture specifically for its insulating and interrupting properties.



Molecular Composition of Gas Mixture
Figure 3

The global warming potential (GWP) of the gas mixture used in the EconiQ is considerably lower than that of SF_6. Together with a lower gas density than SF_6, this would lead to a reduction of 99% in the CO_2 equivalent of the gas for the same volume (Table 4, below). Should a gas leak occur, the C4-FN will stay in the atmosphere for a much shorter time than SF_6 and will have a significantly reduced greenhouse effect compared to SF_6. This is visible through the characterization factors (GWP) provided in Table 3 below [3]. In summary, the contribution of the insulating gas to the carbon footprint of the circuit breaker is in effect eliminated.

Table 3
Material Properties of SF_6 Compared to C4-FN [4]

Category	Unit	SF_6	C4-FN
Atmospheric lifetime	years	1 000	34.5
GWP	GWP_{500} GWP_{100} GWP_{20}	29 000 24 300 18 200	835 2 750 4 580
Ozone depletion potential	ODP	0	0
Molecular mass	g/mol	146	195
Boiling point	°C (at 1 bar)	-64 °C	-4.7 °C

Table 4
CO_2-Equivalent of a 100m Three-Phase GIL when Filled w/ SF_6 or C4-FN Mixture [4]

Category	Unit	SF_6	**Exemplary C4-FN mixture** (3.5 % C4-FN / 10 % O_2 / 86.5 % CO_2)
GWP	GWP_{100}	24 300	391
Gas pressure	bar at 20 °C	5.3	9.1
Gas density	kg/m³	34	18.8
Gas volume	m³	32	
Gas mass	kg	1 090	602
Total banked CO_2-equivalent	t_{CO2eq}	26 400	236
CO_2-equivalent and reduction	-	100 % (reference)	**0.9 %** **-99.1 %**

EVERSOURCE COLLABORATION WITH HITACHI ENERGY

In August of 2022, Hitachi Energy published a press release announcing a collaboration with Eversource to install the first 420kV EconiQ circuit breaker. This announcement set the stage for both companies to take a major step toward their carbon footprint reduction and sustainability goals. The announcement also set the wheels in motion for an aggressive schedule in which engineering, design, manufacturing, factory acceptance, delivery, construction, installation, training, and equipment commissioning would occur in less than 18 months.

KEY MILESTONE TIME-LINE:

- ✓ NDA established between Hitachi Energy and ES 7/2022
- ✓ Received Proposal from Hitachi Energy 8/1/2022
- ✓ Hitachi Energy Press Release: published 8/31/2022.
- ✓ PO Issued to Hitachi Energy: 10/07/2022
- ✓ ES New Equip. Evaluation Team Kickoff: 11/16/2022
- ✓ Project Kickoff Meeting: completed 11/21/2022
- ✓ First Submittal of Physical DWGs (Hitachi): 12/02/2022
- ✓ Equipment Delivery: 6/30/2023
- ✓ Planned In-Service: Q4 2023 ***(Actual ISD – 12/20/2023)***

Overall Project Timeline
Figure 4

INSTALLATION & COMMISSIONING OF ECONIQ 420PM63-HA DTB

Eversource's criteria for this pilot project were based on six factors:

- The project needed to be an isolated 345kV circuit breaker replacement project.
- Project outage(s) needed to have minimal impact on the 345kV system.
- It needed to be installed in an existing position (i.e., could not be apart from a station expansion).
- It could not be installed in a reactive switching application (Eversource limitation, not based on breaker capability).
- The project schedule needed to align with Q4 2023 in-service date.
- It required authorized capital project funding through Eversource's Project Authorization Committee.

The equipment was successfully installed, without incident, between October and December 2023. Pre-construction and construction activities to ensure the site was prepared for the new circuit breaker included removal of the old circuit breaker, demolition of the existing foundation, installation of a new cable raceway, pouring of the new foundation, pulling and poising of new interface cabling and supplementary SCADA upgrades.

Site Preparation for New Concrete Footings
Figure 5

Installation of New Cable Raceway
Figure 6

Preparation of Interphase Cabling
Figure 7

Erection of New Breaker Frames
Figure 8

Four separate outages, including two 345kV lines and terminals, were required to obtain the proper working clearances and permissions necessary to perform the entire scope of work. Per Eversource procedure, the Field Engineering Project Test Specialist and team reviewed all IFC (issued for construction) prints, performed required write-ups, and created all test & commissioning plans ahead of the outages to ensure work started on time and commenced as scheduled.

Functional testing and final commissioning of the circuit breaker took place over eleven days, culminating with the successful energization of the circuit breaker on December 20, 2023. However, gas handling, sampling, and analysis needed to be completed before any testing could be performed.

Gas handling and filling was performed over three days, starting with the delivery of pre-mixed cylinders to the site. The cylinders were transferred into and stored on-site in a heated Conex container to keep the cylinders at/around 60°F. Similar to SF_6, the gas mixture needs to be kept at specific temperature and pressure to ensure it remains stable.

Gas Bottles in Heated Conex Container
Figure 9

Each phase required a total of 24 cylinders to fill to a rated pressure of 135psi. Additional actions were taken to accelerate gas filling including the warming and storage of cylinders as well as the evacuation and vacuum of adjacent poles being performed simultaneously.

Prior to transferring the gas into the individual phases, the contents of 12 cylinders were transferred into gas mixing equipment, provided by Hitachi Energy, on-site. The decision to perform the additional mixing came at the discretion and recommendation of Hitachi Energy to ensure the mixture was ideal before placing it in the breaker. The additional mixing took approximately 3.5 hours per twelve 12 cylinders. Transfer time from the mixing cart into the appropriate phase took approximately 2 hours. Before transferring the gas mixture from the mixing cart into each phase, the gas was analyzed for percentage of C4FN, O_2, CO_2, Moisture and CO. All measurements were within acceptable ranges. The gas was also tested and analyzed after it had a chance to acclimate within the breaker. All measurements were within acceptable ranges after all gas handling activities were completed.

The final Commissioning of the EconiQ circuit breaker was very similar to that of its 345kV SF_6 counterpart. Considering the equipment is built on a similar platform, all testing was performed on time due to Eversource's field test team's familiarity with commissioning and maintaining this type of equipment.

Major activities performed during this time consisted of the following:

- Point-to-point Wiring Checks (against schematics & three-line diagrams)
- Operating Mechanism & Interlocking Function Checks
- Circuit Breaker Timing & Travel
- Main Circuit Resistance (Ductor)
- Power Factor

Circuit Breaker - Before & After
Figure 10

CONCLUSION

Having an SF_6-free option for replacing high-voltage circuit breakers is a game changer for the utility industry. The installed SF_6-free equipment uses well-known operating mechanisms and is built on a platform similar to its SF_6 counterpart. This made the installation and commissioning phase comparable to what is typically experienced for equipment based on SF_6 technology. The evaluation of the new technology will include gaining operational experience and data collection to ensure that its performance is similar to SF_6 technology, as described in the 'Next Steps'.

Next Steps

Over the next two years, Eversource plans to pilot the 420PM63-HA circuit breaker to better understand its performance. During this time, periodic inspections, gas analysis, and maintenance, including functional and electrical testing, will be performed multiple times throughout the year to assess performance.

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- Marc Mellaly – Construction Representative; Eversource
- Craig Woodhouse – Construction Representative; Eversource

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BIOGRAPHIES

Brian Fluss is the Manager of Substation Technical Engineering for Eversource Energy, supporting Connecticut and Western Massachusetts. Brian has been in his role for over 2 years and with Eversource for just shy of 16 years. Throughout his career, he's held several positions but always found himself in an operationally focused engineering role. He's been involved with and supported substation apparatus ranging anywhere from 4kV-345kV however has always had a passion for high voltage circuit breakers. Brian received both his Bachelor's and Master's degrees from the College of Engineering, Technology, and Architecture at the University of Hartford in West Hartford, CT.

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