U.S. DEPARTMENT OF ENERGY

Advanced Transformers Workshop Report

United States Department of Energy

This report was prepared by DOE's Office of Electricity (OE) as a collaborative effort by OE, Oak Ridge National Laboratory (ORNL), and the National Energy Technology Laboratory (NETL).

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Executive Summary

The US Department of Energy (DOE) Office of Electricity (OE) Advanced Transformers Workshop was hosted at the National Energy Technology Laboratory (NETL) in Morgantown, West Virginia, on May 23–24, 2023. The goal of the workshop was to identify the technology gaps and opportunities associated with transformers, and other potential substitute and supporting technologies. The workshop was organized into five panel sessions—(1) transformer specifications, procurement practices, and tech-to-market requirements; (2) advanced transformer design and materials; (3) transformer manufacturing perspective/industry best practices; (4) solid-state transformers; and (5) transformer advanced features (e.g., flexibility, modularity, scalability)—and two breakout sessions that focused on the benefits and limitations of power transformers and distribution transformers, respectively, and discussed the challenges and paths to achieve advanced transformers. More than 65 attendees participated and self-identified as being from various organizations: utilities (17), manufacturing (14), federal agencies (14), national laboratories (12), academia (4), and research institutions (4).

This document reports the panels and breakout sessions. The presentations of each panel are summarized, and the Q&As are briefed. The discussions from the two breakout sessions are also summarized.

US DEPARTMENT OF ENERGY OFFICE OF ELECTRICITY ADVANCED TRANSFORMERS WORKSHOP REPORT

Table of Contents

I. Agenda

Tuesday, May 23, 2023

8:00 – 8:30 AM	WORKSHOP REGISTRATION CONTINENTAL BREAKFAST
8:30 – 8:50 AM	WELCOME AND INTRODUCTION Dr. Brian J. Anderson, Director, National Energy Technology Laboratory – Welcome, safety and logistics
8:50 – 9:10 AM	KEYNOTE PRESENTATION Gil Bindewald, Acting Principal Deputy Assistant Secretary, Office of Electricity
9:10 – 9:20 AM	CURRENT LANDSCAPE & WORKSHOP GOALS Michael Pesin, Deputy Assistant Secretary, Office of Electricity
9:20 – 9:40 AM	TRAC AND AGTS PROGRAM OVERVIEW Andre Pereira, Program Manager, Office of Electricity – Workshop & TRAC overview Fernando Palma, Program Manager, Office of Electricity – Workshop & AGTS overview
9:40 – 10:00 AM	NETWORKING BREAK

Utilities Perspective Session

10:00 – 11:15 AM	PANEL 1 : UTILITIES TRANSFORMER SPECIFICATIONS, PROCUREMENT PRACTICES, AND TECH TO MARKET REQUIREMENTS Moderator: Michael Pesin, DOE Kyle Stechschulte, P. E., Staff Engineer, American Electric Power (AEP) Michael Lamb, General Manager, ET Operations & Maintenance, Dominion Energy John Arp, Chief Engineering and Grid Operations Officer, Rappahannock Electric Cooperative (REC)

Short-Term Transformer R&D Opportunities and Challenges Session

11:15 AM – 12:15 PM	PANEL 2: DESIGN, INSULATION MATERIALS, WINDING DESIGN, ADV MATERIALS ETC) Moderator: Brian Rowden, ORNL Kristie Armstrong, Technical Projects Manager, ERGON Jagan Devkota, Senior Scientist, NETL Kevin Biggie, Innovation Manager, Weidmann Group
12:15 – 1:15 PM	LUNCH BREAK
1:15 – 2:30 PM	PANEL 3: TRANSFORMER MANUFACTURING PERSPECTIVE/ INDUSTRY BEST PRACTICES Moderator: Fernando Palma, DOE Chad Eckhardt, Chief Commercial Officer, ERMCO Zachary Weiss, Engineering Manager, WEG Transformers Chins Chinnasamy, Distinguished Fellow, ORNL
2:30 – 3:00 PM	NETWORKING BREAK

Medium- to Long-Term Transformer R&D Opportunities and Challenges Session

3:00 – 4:00 PM	PANEL 4: SOLID STATE TRANSFORMERS (SSTS) Moderator: Joao O. P. Pinto, ORNL George Mantov, Chief Technology Officer, Solid State Power LLC Jack Flicker, Technical Staff, Sandia National Laboratories (SNL) Ram Adapa, Technical Executive, Electric Power Research Institute (EPRI)
4:00 – 5:00 PM	PANEL 5: TRANSFORMER ADVANCED FEATURES (E.G., FLEXIBILITY, MODULARITY, SCALABILITY) Moderator: Andre Pereira, DOE Enrique Betancourt, Technical Manager, Prolec GE Deepak Divan, Professor and Director of Center for Distributed Energy, Georgia Institute of Technology Parag Upadhyay, Electric Machines, Transformers & Electromagnetic Expert, Anduril Industries
5:00 – 5:10 PM	SUMMARY AND WRAP-UP

Wednesday, May 24, 2023

8:00 – 8:45 AM	CONTINENTAL BREAKFAST NETWORKING
8:45 – 9:00 AM	INTRODUCTORY REMARKS/DAY 2 OVERVIEW Gil Bindewald/Andre Pereira/Fernando Palma
9:00 – 11:00 AM	BREAKOUT SESSIONS Breakout session A—Power Transformers Breakout session B—Distributions Transformers
11:00 AM – 12:00 PM	WORKING LUNCH TRANSPORTATION Randy Staley, Edward Moving & Rigging
12:00 – 12:20 PM	POWER TRANSFORMER BREAKOUT BRIEF-OUT
12:20 – 12:40 PM	DISTRIBUTION TRANSFORMER BREAKOUT BRIEF-OUT
12:40 – 1:00 PM	CLOSING REMARKS Andre Pereira & Fernando Palma
1:00 – 3:00 PM	OPTIONAL LAB TOUR

II. Panel Session Briefs

There were five panel sessions discussing five different topics related to advanced transformers. Each panel had one moderator and three panelists from DOE, manufacturers, utilities, national laboratories, and other research institutions, including universities. Each panelist presented for 15 to 20 minutes. In the sequence, a Q&A session was carried out with questions from the audience and the moderator.

PANEL 1: Utilities transformer specifications, procurement practices, and tech-to-market requirements

Moderator: Michael Pesin, DOE

Panelists: Kyle Stechschulte P.E., Staff Engineer, American Electric Power (AEP)
Michael Lamb, General Manager, ET Operations & Maintenance, Dominion Energy
John Arp, Chief Engineering and Grid Operations Officer, Rappahannock Electric Cooperative (REC)

This panel provided a utility-sector perspective on the current transformer landscape and opportunities moving forward. The following are some of the key takeaways of this panel:

- One of the goals of the utility sector is to leverage the total life cycle cost and value of major equipment as effectively as possible. To accomplish this, the strategy is to (1) standardize equipment; (2) catalog item minimization to achieve efficiency in designing, stocking, and sparing; (4) ensure equipment reliability to minimize maintenance tasks and extend maintenance intervals; and (5) provide equipment that minimizes assembly, commissioning, and testing.
- Recommendations to maximize industry output include having well-established standards, long-term vendor contracts, multiple vendors capable of providing similar designs, and well-managed order volumes.
- Some of the key challenges facing the transformer sector are (1) multiple disruptions to supply chains in recent years due to the COVID-19 pandemic, Russia–Ukraine war, etc.; (2) price increases due to raw material price increases, large volumes of equipment procurement with price-escalation clauses, and material/labor cost indices; and (3) significant increases in power transformer needs.
- The extended lead times for major equipment and materials have resulted in some utilities increasing inventory and safety stock levels, identifying additional suppliers, slot allocations from strategic partners, and improving forecasting of future project material needs. Other challenges include the very limited number of large power transformer factories in the United States, mineral oil supply constraints due to increased demand, transportation system (marine, rail, and heavy haul) stress due to global transformer demand, lack of adequate resources for assembly, oil fill processing, and site acceptance testing.

- One of the panelists highlighted that technical specifications, collaborative work between the supply chain and area-of-domain technical teams, and supplier quality are key to succeeding against the aforementioned challenges in the transformers industry and further described an innovative way to achieve success with a three-tier approach (i.e., small, medium, and large power). In the first tier, transformers with the primary side up to 60 kV is supplied by manufacturers based in the United States. In the second tier, voltages ranging from 115 to 230 kV on the primary side are supplied by manufacturers from Mexico, Taiwan, Germany, and the United States. In the third tier, voltages above 345 kV on the primary side are supplied from the Netherlands, Germany, Croatia, and Japan. The risks are managed per tier group based on the designs (core and shell forms), geopolitics, currencies, suppliers, and long-term relationships and partnerships.
- Some of the technical specifications that are highly standardized and continually updated based on lessons learned include, not are not limited to, loss evaluations, electrical ratings, detailed component (core, winding, lead support, and tank) design requirements, manufacturing process requirements (especially for winding stabilization and final clamping of the core and coil), standard components, control cabinets, monitoring systems, paint coatings, and gaskets.
- Lastly, one of the panelists highlighted the importance of better understanding the demands of the grid moving forward and identified how the grid is affected by electric vehicle (EV) charging using chargers levels 1, 2, and 3. For instance, the panelist identified that the demand from level 3 chargers is approximately 4 times higher than from air conditioner systems, which are considered one of the largest building loads. Furthermore, the panelist identified that for a realistic case in which 1 EV charger was added, 12 more transformers were required in addition to other changes in the feeder. For a maximum case, 4 EV chargers were added, and 76 more transformers and changes in the feeder were required, including additional installation protection equipment.

Panel Q&A

In addition to the items presented and discussed by the panelists, other issues were raised during the Q&A section. Below are some of the points made by the panelists:

- Manufacturing capacity is limited, whereas the demand for transformers is increasing.
- Mineral oil availability is limited.
- Labor availability is limited for both manufacturing and installation points.
- Availability of accessories and tap changers (automatic and manual) is limited.
- Standardized transformers are needed despite the utility sector’s reluctance to deviate from their own standards.
- Utilities load distribution transformers (DTs) typically around 80% load at rated temperature.
- Current peak demand is about as high as in the past but has longer duration, which affects thermal management.
- One positive new function of transformers is the ability to take significant overload.
- With EVs penetrating the market, there will be no nighttime cool-down cycle, so being able to ensure high utilization for longer periods during hot weather is also desirable new functionality.

PANEL 2: Advanced transformer design and materials (e.g., core design, insulation materials, winding design, advanced materials)

Moderator: Brian Rowden, ORNL

Panelists: Kristie Armstrong, Technical Projects Manager, ERGON
Jagan Devkota, Senior Scientist, NETL
Kevin Biggie, Innovation Manager, Weidmann Group

The focus of this panel was the design and materials innovation for advanced transformers. The following are some of the key takeaways of this panel:

- The primary transformer mineral oils and esters (dielectric fluids) properties for consideration include insulation properties, cooling properties, viscosity, pour point, flash point, and freedom from corrosive sulfur for oxidation stability.
- Mineral oil is derived from crude oil, whereas synthetic esters are targeted as a more environmentally friendly alternative with less fire risk but are limited by the number of available suppliers. Natural esters are also available, have lower fire risk, and are more environmentally friendly than mineral oil, although concerns exist regarding deforestation. The esters are particularly good for environmentally sensitive applications such as offshore wind turbines, subsea equipment, wildfire prevention, and congested city areas with fire safety concerns.
- Additives should be minimal or minimized to the extent possible.
- Dielectric fluid is used as a diagnostic tool for power transformers through dissolved gas analysis (DGA).
- The new diamond pattern–enhanced (DPE) cellulose-based insulation provides higher thermal class, better dielectric performance, faster drying, and faster impregnation of dielectric liquids. The primary driver is improving the thermal class to 130°C (compared with Kraft paper, which can range from 105°C to 120°C) while minimizing the cost increase, though the relative cost of the solid insulation is approximately 2% of the transformer cost.
- Because of the increased thermal class of 10°C, a transformer's lifetime is extended while maintaining the same rating as Kraft paper with average 65°C winding temperature. Evaluating the electrical design based on 75°C or a dual temperature rating (65°C/75°C average temperatures) can increase the power level for the same footprint or allow smaller transformers to carry higher loads with reduced size and weight.
- The primary application for wide-bandgap and ultrawide-bandgap semiconductor devices is to drive high-frequency switching to increase efficiency and power density for technologies such as EVs and high-frequency converters.
- At higher frequencies, Fe-Si alloys do not perform as well as other materials used in wide-bandgap and ultrawide-bandgap devices, but soft magnetics can magnetize and demagnetize must faster, which can increase the energy density, though energy loss must be managed. Higher frequencies can significantly reduce the passive size and weight of the devices compared with traditional 50/60 Hz applications.
- A major share of the soft magnetics market is currently covered by grain-oriented electrical steel (GOES) and non-oriented electrical steel (NOES). Tailoring the magnetic

composition will help to develop new magnetic materials tailored for lower energy loss and higher power ratings. This can be done through base-composition modifications, new chemistries, or atomic-level optimization. For traditional electrical steels, some property improvements can be made with better control of the Si properties to minimize redesign.

Panel Q&A briefs

In addition to the items presented by the panelists, other issues were raised during the Q&A section, including the following:

- Cost is the limiting factor preventing some new technology from penetrating the distribution transformer market.
- DGA can still be used with new materials such as esters; however, there may be some subtle changes to DGA that are being evaluated by IEEE committees. Solid insulation is still a cellulose-based material, so the aging processes have not changed.
- The DPE material can be damaged just like existing systems and designs if the temperature is overloaded beyond 75°C. (Traditional utilities experience about 2% loss of life in reliable overloaded conditions).
- The amorphous core materials can be nanocrystalline to potentially reduce core losses by use of a single material and by creation of more grain sites.
- The DPE material can be leveraged in existing transformer designs to increase the thermal limit and extend operational life without a new design. This provides longer life and more resilience to overload conditions.
- Renewable materials such as esters can be used for improved sustainability and lower emissions to support existing designs and when paired with the DPE solid insulation can improve the thermal limit even further.
- The diamond shape of the DPE material is a paper epoxy coating to be applied and cured later, creating channels between the dots to allow moisture drawn in by the cellulose to escape to improve the drying process.

PANEL 3: Transformer manufacturing perspective/industry best practices

Moderator: Fernando Palma, DOE

Panelists: Chad Eckhardt, Chief Commercial Officer, ERMCO
Zachary Weiss, Engineering Manager, WEG Transformers
Chins Chinnasamy, Distinguished Fellow, ORNL

This panel provided a perspective from the manufacturing sector, and examples of industry best practices. The key takeaways from the panel are as follows:

- Industry strategies include sourcing materials domestically for transformers, leveraging multiple technologies, understanding the demand for finished goods, and understanding foreign entrants.
- One way of handling the shortage of components is to control the vertical supply chain, widening the breadth of acceptable suppliers on specs.
- Technologies based on existing materials could be revisited and modified to accommodate future materials, and the development of new soft magnetic materials may influence transformer design.
- New methods for manufacturing existing materials or new soft magnetic electrical steels with superior electromagnetic properties must be developed and introduced into the traditional transformer manufacturing process.
- Some of the main challenges in manufacturing transformers are (1) material availability concerns, (2) labor availability and retention, (3) renewable growth (new untested technology), and (4) change and growth in loading.
- In some instances, material availability is not an issue as some industries develop good relationships with suppliers and customers, have stable and predictable usage, forecast well, and communicate thoroughly and in advance.
- Renewable growth is causing unexpectedly high harmonics, and cyclical loading profiles are causing stresses on transformers. To address these issues, attention is being given to core shielding, increased cooling, re-evaluation of internal and external transformer connections, and redesign of new 600A HV bushing.
- The change and growth in loading on the grid are causing more cyclical loading and higher overall percentage loading, pressure change, heating at connection points, and hotter operating temperatures. The present response to these issues is the evaluation of tank pressure withstand, electrical connection withstand, and cooling.
- Compared with the conventional grain-oriented and non-grain-oriented approaches to manufacturing electrical steels, additive manufacturing (AM) could be a disruptive technology in the transformer market.
- AM could potentially enable the building of complex components and devices with a material layer by layer without being limited by tools and molds.
- In a potentially new AM method to manufacture transformers, complex structures can be printed more easily, which can result in weight savings, reduced manufacturing time, eliminating scrap waste, addressing supply chain issues, allowing for mass production

and end-to-end AM solutions (powder to part), and can enable the creation of multimaterial devices.
- The development of high-Si steels using the conventional method can reduce the humming noise of transformers and improve performance.

Panel Q&A briefs

The most important items discussed during the Q&A session were the following:

- One of the major AM producers has successfully created transformers in the 10–13 kVA range on a laboratory scale. This achievement along with the existing expertise in developing Hilbert-type transformer cores makes designing transformer cores using AM feasible.
- AM has been used to create axially laminated transformers with air core structures, demonstrating its potential as a viable solution for future transformer development.
- Compared with conventional methods of manufacturing transformer cores, AM shows great promise as a more scalable and cost-effective option, particularly for large-scale production. However, AM technology for transformer development is still in its early stages, and thus significant research and development efforts are necessary to further its capabilities.
- Among the main problems that the transformer industry is facing are supply chain issues, having local producers for all types of transformers, and long lead times.

PANEL 4: Solid-state transformers

Moderator: Joao O. P. Pinto, ORNL

Panelists: George Mantov, Chief Technology Officer, Solid State Power LLC
Jack Flicker, Technical Staff, Sandia National Laboratories (SNL)
Ram Adapa, Technical Executive, Electric Power Research Institute (EPRI)

This panel discussed state-of-the-art solid-state transformer (SST) technologies as well as gaps and industry perspectives of these technologies. The main discussion outcomes were as follows:

- The technology currently used in transformers today is very similar to the transformer technology used in 1885 (i.e., the transformers today are about 140 years old). Changes in supply and demand patterns are stressing the distribution electric grid, leading to more equipment on the distribution lines and increasing costs and complexity. For instance, in addition to substations, lines, and transformers, Volt-VAR control is also needed in many cases for proper operation of the feeders, tap changers, sensors, capacitor banks, and voltage regulators.
- The current technology is changing with SSTs, which are power electronic converters and high-frequency transformers used to step voltage up or down. Because voltages and currents can be controlled by the converters, SSTs can perform much more than only step-up and step-down functions. Improvements in semiconductors enable SSTs to perform all functions as reliably as conventional transformers.
- SSTs can provide savings in energy, distributed energy resource (DER) interconnects, vault and pole upgrade costs, and installation costs and footprint; integrate EVs, DERs, and storage without additional hardware; and eliminate more than 50% of losses incurred by EV chargers, among other advantages. Furthermore, SSTs are natural candidates to be hubs for virtual power plants. SSTs also provide other benefits such as standardization, reduced size and weight, and oil elimination. They are the cornerstone device for advanced distribution automation.
- SST technology has clear start and end points, but the pathway from one to the other is not clear. The start point is the low-cost, robust, low-performance conventional transformers, and the end point is equipment that can provide complete nodal control, interconnection of asynchronous grids, and arbitrary active power/reactive power (P/Q) control and can allow for creation of a network of SSTs. The three intermediate phases to reach the end point of SST technology were identified as:
    - **Phase 1 (within 5 to 10 years).** The SST value proposition is developed to define the minimum necessary functionality, to identify the achievable benefit of using a single isolated SST, and to evaluate the possibility of augmenting conventional SSTs. The value proposition should define the operational envelop that will help to choose the circuit architecture from among topologies such as single-phase AC-AC dual active bridge, single-phase type IV, and single-phase AC-AC triple active bridge. Among the criteria for topology determination are support for bidirectional power flow, reactive power sourcing and sinking capabilities, input and output voltage phase-angle requirements, support for cascaded output

configurations, voltage source operation, compatibility with grid-forming control strategies, and number of semiconductors.

- **Phase 2 (within 10 to 20 years).** For this phase, the value proposition is already clearly defined, and lower-cost SSTs with increased performance are achieved. So, in this phase, codesign that simultaneously considers materials, devices, and systems will be able to couple system needs with device abilities, drastically shorten learning cycles, translate device improvements to system improvements, and maximize the impact of materials innovation in end-use application. This will overcome the fundamental materials and control challenges that have limited SST implementation.
- **Phase 3 (after 20 years).** High-voltage (HV), high-power SST topologies are achieved based on modular SSTs using modular power-electronic building blocks. Methods to improve units already in the field must be developed, or reduced performance must be accepted.

- The most popular topology is currently the conventional SST with HV switches, multiple windings, and multiple converters with inputs in series and outputs in parallel. Although it is the most popular, this topology has issues such as input voltage balance, high voltage offset of the phase-connected module, and multiple small transformers each with 95 kV basic insulation level.
- A new topology has been developed in which an HV converter with switch modules parallel drives the transformer primary, which uses a single high-frequency transformer and has natural input voltage balance, reduced voltage over the HV winding, and susceptibility to partial discharge/corona. Furthermore, it has simple medium-voltage (MV)/low-voltage (LV) isolation, and conventional control for MV tolerances does not affect the input balance. However, this topology requires high-quality MV capacitors.
- The core needed technologies for reliable LV and HV (high-power) SSTs are a new state-of-the-art power electronic topology; new HV, high-current power semiconductor devices; and interoperability with open communication architecture.
- Some SST product spin-offs are emergency extra-high voltage (EHV) and recovery transformer replacement, among others.
- The Intelligent Universal Transformer (IUT) is a special SST whose low-voltage side supplies customers with AC and DC loads. One of the benefits of the utility side is the control of the power factor to unity. IUT replaces the conventional Cu- and Fe-based bulky distribution transformer with modular power electronics technology. Its modularity allows flexibility should the user require a different voltage or power level. It was developed in cooperation with multiple institutions and showed numerous advantages over conventional transformers. Is it being commercialized.
- Currently, the SST market is more focused on traction applications than utility applications because of benefits achieved from SSTs' high power density, but the advances for the traction industry sector can potentially be leveraged for utility applications.

- The challenges related to SSTs are higher costs, lower efficiency, and lower reliability than conventional transformers. Additionally, SSTs have 66% shorter lifetimes because of the power electronics converters and can be more vulnerable to cyber security threats.

Panel Q&A briefs

The Q&A section of this panel raised the following points:

- Regarding reliability, SSTs can be made to last a very long time, but the cost may be prohibitive.
- The presentations indicated that making SSTs modular is beneficial because then components can be replaced or upgraded as needed. Although reliability is a factor, the presentations indicated that other benefits such as control and adaptability should be considered for the overall evaluation of SSTs.
- Technological issues are not the biggest concern regarding SSTs; rather, cost and reliability are the driving constraints.
- SST efficiency can be improved to surpass conventional transformer efficiency (above 97%) by decreasing switching losses and implementing new technologies, among other measures, but doing so requires further development and funding.
- A Q&A participant suggested that a different name for SSTs that reflects its other functionalities should be considered. Other names have been suggested in the past, such as solid-state power substation and solid-state controllable substation, among others.

PANEL 5: Transformer advanced features (e.g., flexibility, modularity, scalability)

Moderator: Andre Pereira, DOE

Panelists: Enrique Betancourt, Technical Manager, Prolec GE
Deepak Divan, Professor and Director of Center for Distributed Energy, Georgia Institute of Technology
Parag Upadhyay, Electric Machines, Transformers & Electromagnetic Expert, Anduril Industries

Desirable advanced features for advanced transformers were the main topic of this panel. The main points, outcomes, and discussion topics from this panel were as follows:

- Large power transformers (LPTs) are one of the most critical components of the transmission and distribution grid. As a relatively vulnerable asset, these transformers are susceptible to extreme weather events and exposed to vandalism and attacks. The challenges for owners are replacing failed units in a short period of time (typical lead time is 1 year or more) and minimizing management cost (number of spares, voltage, rating, impedance).
- Today's available LPTs are not "flexible." They cannot replace each other unless identical, the production-per-design ratio is approximately 1.3, and a large spare inventory is required to ensure quick replacement times, resulting in high costs. Furthermore, current LPT technology cannot provide grid support, except for voltage regulation, so LPTs capable of providing other types of support are needed.
- The number of voltage levels for power transformers with high-voltage sides ranging from 110 to 500 kV is considerably large. Because of the high variability of transformer specifications, an inventory of spare parts would be very large and expensive. However, because transformers are the backbone of the grid, in natural disaster events they must be fixed promptly for quick power restoration.
- One of the panelists highlighted the need for modular, flexible, and resilient LPTs.
- One example of a flexible LPT was provided: a unit with a high voltage of 230 kV, low voltages of 115/138/161 kV, rated powers of 100/120/150 MVA, maximum capacities of 166/200/250 MVA, and impedance ranging from 4% to 14%. From this example, the flexible transformers concept has been proven by developing, demonstrating, and testing in the factory and in the field a full-scale prototype, a 165 kV, 60 MVA autotransformer with three LV ratings (57.5/69/80.5 kV) and an online adjustable impedance (4.3%–9.2%).[1]

- In the distribution grid, the phenomenon of reverse power flow affects the performance of the interconnect transformers. The operating power factor has also significant impact on transformer losses. The amount of impact on transformer life depends on the design of

[1] GE Research and Prolec GE Power Up World's 1st Large Flexible Transformer to Enhance the Resiliency of America's Grid | GE News

the transformer and operating conditions. If the reverse power flow is not restricted, then the interconnect transformer loses 25% of its life. The restriction of the power factor of reverse power flow can maintain the life of the transformer. Today's challenge is that the levels of increased (load or line-side) voltage and voltage harmonics caused by reverse power flow have mostly not been communicated or have not been considered in transformer specifications.

- To enable unrestricted, unconditional operation of transformers without loss of life, customized transformers are being developed based on system analysis and study. Transformer manufacturers have experience in design to resist operational stresses when the system characteristics are known. As an intermediate step to address already-installed units, digital technologies to monitor for load flow, total harmonic distortion, and primary and secondary voltage at the transformer can be installed to improve predictability of potential failures and increased aging characteristics.

Panel Q&A briefs

The following important topics were raised during the Q&A session:

- To increase transformer longevity, thermal life must be considered, and attention must be given to the dielectric design. Lowering the impedance can also help to extend the life cycle.
- To expedite the adoption of advanced transformers, it is important to guarantee their reliability. Systems that have fail-normal safeguards in place need to be created. That is, if the system fails, it needs to be able to maintain its functionality without power electronics.

III. Breakout Sessions

Following the panel sessions, the second day of the workshop focused on two breakout sessions that were organized by transformer type: power transformers and distribution transformers. A set of questions was prepared to help to guide the discussion, and each session had a coordinator to help to guide the discussion.

BREAKOUT SESSION 1—POWER TRANSFORMERS

QUESTION 1: What types of innovations would contribute toward streamlined and/or improved manufacturing processes related to power transformers?

SUMMARY OF DISCUSSION:

The identified innovations were:

- new manufacturing processes (e.g., hybrid additive manufacturing);
- prevention of moisture absorption by cellulosic insulation to improve dimension control, drying, and impregnation processes; and
- means to detect contamination on insulating materials to prevent EHV process failures.

Another big concern from industry was the physical security of the transformers. Among possible solutions are dry technology bushings at EHV levels, ballistic walls, tall fences, dikes, ballistic-proof panels to be placed in front of transformers, changing standards to allow for different materials (less valuable than Cu), and drones.

QUESTION 2: What type of innovation is needed to reduce costs in power transformers? (Cost reductions may be achieved through a variety of objectives including—but not limited to—material reduction, lower-cost components, efficient installation techniques, modularity, scalability, and flexibility.)

SUMMARY OF DISCUSSION:

Some of the innovations identified to reduce costs included the following:

- Flexible transformers to help standardize building automation
- On-site intelligent transformer assembly to reduce shipping and transportation costs
- Increasing the value that the transformer provides by incorporating new functionalities such as power flow control, congestion, and new transmission default
- Less costly and faster manufacturing of innovative transformer accessories to help decrease price and lead time (standardization could be an option)
- Improvements to the supply chain, mainly of Si steel (e.g., via electrification of Si steel manufacturing), to address shorting of the supply for transformer manufacturing caused by competition with other industries (electric cars)

QUESTION 3: What are some of the challenges related to the installation, inventory management, maintenance, and transportation of power transformers, and where could research efforts provide solutions to those challenges?

SUMMARY OF DISCUSSION:

- For the installation cycle, accurate estimation of moisture in insulation is important. Industry currently has different criteria that could be unified to save time while ensuring reliability.
- Modular stackable transformers can provide flexibility. This will require impedance control, which could be achieved using hybrid transformers. A module rating of around 10 MVA would be a good choice for series of parallel connections.
- Research could be done to promote ease of manufacture, flexible ratings (transformers need to meet many requirements), power flow control, and grid support.
- System costs versus unit costs could be analyzed. Newer advanced transformers can reduce system costs in the future.
- Not only initial cost, but also lifetime and durability of transformers must be considered. Thus, monitoring and predictive maintenance for lifetime management are desirable.
- The maintenance cost must be assessed for leak detection and identification of constantly failing parts (bushings, fans, etc.). Cost-benefit analysis could be performed to identify the proper time for retirement.
- Methods need to be developed for rewinding a unit, including identification of what parts can be reused (tank, core, etc.). Today it costs two-thirds of a new unit, and there are few rewinding service providers.
- Oil changes can improve the lifetimes of transformers, but preventive oil changes are neither technically nor economically viable, so research on condition-based oil change is needed to achieve reliable and cost-effective online monitoring of DGA.
- Normally, 20% of costs are attributable to the design (includes overhead, etc.). Standard designs will decrease transformer costs by almost 20%.
- Effort should be put into reducing assembly time to reduce the overall installation cost, which is currently $1,500 per day.

QUESTION 4: What key factors are needed to motivate adoption of flexible, adaptable power transformer designs across a range of transformer applications (e.g., physical dimensions and electrical performance)?

SUMMARY OF DISCUSSION:

- Flexible transformers also demand a certain level of flexibility from utility users. More inputs from utilities are required. So, data gathering from utilities should be conducted to help shape advanced transformer features.
- The grid is changing with PV, EVs, storage added, etc.; dynamic loss of inertia and stability are concerns. Power electronics can address these issues. However, the short lifetimes of power electronics (average of 20 years) would create issues for utilities. Research for longer-lifetime power electronics–based grid devices is required.
- Physical dimensions of transformers must be reduced using power electronics or new alloys.

- Advanced semiconductors and alloys should be developed.
- A new additive manufacturing approach or hybrid manufacturing should be developed.
- Grid forming and black start, among other functionalities, will be required soon in the grid. The group recommends that affordable and reliable hybrid transformers, SSTs, and other power electronics–based grid components shall be developed.

QUESTION 5: What type of innovation is needed to increase efficiency in power transformers?

SUMMARY OF DISCUSSION:

Participants noted that efficiency is not the key issue unless talking about SSTs.

BREAKOUT SESSION 2—DISTRIBUTION TRANSFORMERS

QUESTION 1: What type of innovations would contribute toward streamlined and/or improved manufacturing processes related to distribution transformers?

SUMMARY OF DISCUSSION:

- Standardization of transformer designs (from the materials to manufacturers to the utilities) shall be considered a priority by all parties involved. An entity outside the industry such as DOE or IEEE may need to help drive the change toward standardization. For engineering and new designs, some testing is unavoidable, so the overall number of designs must be reduced to address this area of concern. For standardization, the internal configuration of the transformers needs to be addressed to provide a base function model, which may drive some features such as internal fusing or arrestors under oil to alternate external bolt-on alternatives. Combination of a base model with external bolt-on features will require further definition of the required testing and manufacturing point at which that testing would need to occur to ensure the same level of performance of the final installation for the utility.
- Standardization could provide better forecasting and potentially shorter lead times, assuming the number of required component part numbers can be reduced. Standardization options must also consider that all manufacturers have different methods, shop configurations, and manufacturing techniques, so the standard base model concept may need to have some flexible boundary conditions.
- A concern with the standard concept for manufacturers relates to tooling, timing, and staffing for these designs to increase production capability for the current market, but if current supply chain constraints dissipate in the next few years, the utility sector may resort back to requiring its preferred suppliers and level of customization. Currently, if utilities can get a unit close to what they need in the required time frame, the industry will consider buying standardized transformers rather than wait the longer lead times. This could lead to an unwanted inventory of standard models or factories focused on building standard designs for which little market demand exists once the utilities industry is not in urgent need for units.
- Availability of labor was a major concern from many of the workshop participants as it can impede the ability to evaluate alternate materials or processes and new technologies.

This labor shortage is widespread, affecting general labor for internal-component and full-transformer manufacturing and engineering design at both the manufacturer and utilities.

- Furthermore, the connection point between manufacturing and commissioning needs to be better understood and addressed. The qualification and inspection process needs to be streamlined to see what is inside the transformer during testing. Transportation and on-site inspection requirements also must be considered when trying to use new designs and provide feedback to the manufacturers to strengthen the design, manufacturing, and upfront testing processes. Considering monitoring and sensing for field operations may enable better insight into what is going on inside the transformer during the testing and commissioning process.

QUESTION 2: What type of innovation is needed to reduce costs in distribution transformers? (Cost reductions may be achieved through a variety of objectives including—but not limited to—material reduction, lower cost components, efficient installation techniques, modularity, scalability, and flexibility.)

SUMMARY OF DISCUSSION:

- In general, retooling time savings associated with considering a standard design appears to be minimal for current transformer manufacturing.
- Distribution transformer cost is being driven by steel, core steel, oil, and copper demand around the world, creating a commodity environment to the prices. This results in prices rising every quarter with demand larger than capacity. Limited suppliers, particularly of core steel, creates further availability problems for domestic supply at any cost. For core steel, discussions pointed to the fact that it would take approximately 3 years to catch up on the current backlog even if all the needed raw materials were sitting at their docks today. There is also the concern that some core steel manufacturers are ramping up or making alternate products for higher-margin EV applications.
- Electrification for items such as EVs is only exacerbating the problem because it increases the need for transformers as well as the size classification of the transformers needed. It also affects the lifetimes and operational considerations for the transformers because EVs may extend the transformer operational time by charging in the off-peak time, which may affect the thermal cycling and down time of the transformer. This is also the case with other technologies such as rooftop solar.
- One option to help ease the problem would be to have less transmission and distribution voltages to help drive more standardization in the design and manufacturing phases. Designing options for multiple voltages may not be as helpful because of the sizing/cost tradeoffs.
- Consideration of process automation to help improve throughput and standardization would have to be driven by return on investment compared with capital expenditure. All aspects of the supply chain would have to be considered because it does not make sense to automate transformer manufacturing if an internal component cannot be supplied at the same pace. This customized automation would have to be considered, and several of these automation suppliers are severely backlogged supporting the EV, battery, and electronics industries, which may limit the options for the short term.

- The impact of component selection and performance variation needs to be considered for new innovation or restrictions to innovation. Currently, most manufacturers will put whatever is requested inside the transformer if the materials are available, but this has become more of an issue with all types of components from fuses to bushings. This customization or flexibility usually requires some level of design change to use the next available material. This substitution or a list of suitable substitutions needs to be investigated and agreed upon to provide some flexibility to make modifications to support alternate materials that have known performance with minimal to no impact on end use. The overall number of suppliers for components still needs to be a significant focus because disruption here will only further hinder transformer availability.

QUESTION 3: What are some of the challenges related to the installation, inventory management, maintenance, and transportation of distribution transformers, and where could research efforts provide solutions to those challenges?

SUMMARY OF DISCUSSION:

- The transportation of transformers is also a bottleneck because it is difficult to find enough freight haulers to transport them. There is an 18,000 lb per axle maximum for road weight in transport; the damage to the road surface increases significantly for every additional ton in weight. If transformers grow in size and weight because of larger kVA requirements or transition to heavier materials, this will have a significant impact on the number of transformers per load, which will require even more freight haulers and may have a more detrimental impact on highway infrastructure. As noted earlier, utilities are already phasing out traditional 15–25 kVA overhead transformers and 25–37.5 kVA pad mounts for larger transformers (50 kVA and above) going forward. This also factors into the oil supply chain because the tanks will need to be larger, requiring even more dielectrics. All of these factors affect the quality of the freight ride and mechanical stress on the transformers as well as the roads and bridges; thus, increased monitoring may be needed as these loads are moving along the route.
- The supply chain is also affecting items such as wood poles, which have increased in lead time from 1 week to more than 2 months. This presents a concern for increased electrification requirements in addition to increases in inclement weather events. As transformers get heavier and increase in volume, they will require new or more constraints on poles, and there are weight and size limitations that need to be considered for ingress and egress and overhead installations. At a certain point, installation will need to be done by cranes, which will constrain available equipment at the installation point in addition to trucking and storage.
- For new installations, new poles or pads can be accommodated, but refurbishing or upgrading existing infrastructure is difficult to support with the increased size and weight because of new standards, materials, or current supply chain availability.
- Standardization can be difficult even within a given utility due to regional differences. Some of the difficulty stems from how the grid was developed and old standards that have driven standard operating practices for decades. The same transformer needed for the Gulf Coast is too costly to be used in the Midwest because the Gulf Coast imposes environmental constraints such as saltwater exposure that require increased resiliency. More modular designs and manufacturing processes must be considered to provide

common options. Some manufacturers have experimented with a pick list, but the variety of components makes it difficult to prebuild. Also, the coil and core need to be protected from moisture, which makes them difficult to store.

- Distribution transformers have traditionally been run to failure with limited DGA oil samples for health monitoring, and then they would potentially be sold to some remanufacturing or recycling entity. During and after the pandemic, investigation into the cause of failure was increased to determine if the transformer is repairable at the utility lot to put back in service. In addition, remanufactured units are being purchased to meet the demand. Also, distribution transformers located at idle service areas where the dwellings may not be occupied are being brought back to the shop and put back in the utility lot for reuse.
- The impact of EVs has also had unintended consequences. If EVs are connected to the grid without the utility industry's knowledge, there is the potential for damage to the fusing that was not sized originally to handle this load. Also, voltage sag is introduced because of EVs, which can be helped with lower-impedance transformers; thus, secondaries may need to be replaced to address this issue. Some states are trying to pass laws that require the utility industry to be notified when an EV sale occurs and to be provided the address where the EV is registered.

IV. List of Participants

Last Name	First Name	Company	Organization Type
Divan	Deepakraj	Georgia Institute of Technology	Academia
Grainger	Brandon	University of Pittsburgh	
Mazumder	Sudip	University of Illinois, Chicago	
Nations	Mark	North Carolina State University	
A Issack	Ramadan	AEP	Energy Sector
Armstrong	Kristie	Ergon, Inc.	
Arp	John	Rappahannock Electric Cooperative	
Banunarayanan	Venkat	NRECA	
Benke	James	MEPPI	
Coe	Michael	American Public Power Association	
Horgan	Hunter	Moore Strategic Ventures	
Kelley	Stephne	Southern Company	
Lamb	Michael	Dominion Energy	
LeBlanc	James	GE Research	
Morgan	Tyler	Duke Energy	
Patel	Dipeshkumar	Eaton Corporation	
Safro	Sandra	The Edison Electric Institute	
Stechschulte	Kyle	American Electric Power	
Tedesco	Joseph	Hitachi Energy	
Urbanic	Raymond	Southwest Electric Co	
Valentin	Reinaldo	Duke Energy	
Bindewald	Gil	US Department of Energy	Federal Agency
Buric	Michael	US Department of Energy	
Christy	Eddie	US Department of Energy	
Dodrill	Keith	US Department of Energy	
Lemmond	Marc	US Department of Energy	
Messenger	Matt	US Department of Energy	
Mollohan	Brian	US Department of Energy	
Palma	Fernando	US Department of Energy	
Panos	Cody	US Department of Energy	
Pereira	Andre	US Department of Energy	
Pesin	Michael	US Department of Energy	
Romberger	Tyler	US Department of Energy	
Smearcheck	Shawn	US Department of Energy	
Yao	Qingnan	US Department of Energy	

Balan	Carla	ABB Electrical Control Systems	Manufacturing
Betancourt Ramirez	Enrique	Prolec GE	
Biggie	Kevin	Weidmann Electrical Technology, Inc.	
Eckhardt	Chad	ERMCO	
Gaytan	Carlos	Prolec GE	
Hodge	Quinton	Howard Industries	
Kernion	Sam	CorePower Magnetics	
Larison	Andrew	Hitachi Energy USA	
Lozano	Pedro	PROLEC GE INTERNACIONAL	
Mahajan	Kushal	Eaton	
Narawane	Aniruddha	Eaton	
Parkinson	Dwight	Eaton Corp	
Perigo	Elio	ABB	
Weiss	Zachery	WEG Transformers	
Chambers	Edward	US Department of Energy	National Laboratory
Chinnasamy	Chins	Oak Ridge National Laboratory	
Devkota	Jagannath	US Department of Energy	
Flicker	Jack	Sandia National Laboratories	
Ingram	Michael	NREL	
Lander	Gary	NETL	
Monson	Todd	Sandia National Laboratories	
Pereira Pinto	Joao Onofre	Oak Ridge National Laboratory	
Robinson	Clark	US Department of Energy	
Rowden	Brian	UT Battelle Oak Ridge National Laboratory	
Rumsey	Brayden	US Department of Energy	
Vaagensmith	Bjorn	Idaho National Laboratory	
Liu	Jingbo	Eaton Cooptation	Other
Orr	Paul	NEMA	
Wuenschell	Jeffrey	Leidos	
Adapa	Rambabu	EPRI	Research Institute
Cotton	Arthur	GE Research	
Ndiaye	Ibrahima	GE Research	
Upadhyay	Parag	Anduril Industries	
Jordanoff	Plamen	Solid State Power LLC	Small Business
Mantov	George	Solid State Power LLC	
Raghavan	Ajay	Palo Alto Research Center	
Staley	Randy	Edwards Moving & Rigging, Inc.	Transportation