ELECTRICAL GRID RESILIENCY VIA SOLID-STATE TRANSFORMER TECHNOLOGY

This project focuses on the development a novel circuit architecture to render AC–AC solid-state transformers (SSTs) competitive in real-world applications, and an analysis of how second-generation AC–DC–AC SSTs can address the problem of cascaded electrical outages. R&D activities span advanced modeling of the stabilizing effect of AC–DC–AC SSTs on the electrical grid, design and testing novel AC–AC SST circuit architectures subject to stringent efficiency and electromagnetic interference requirements, and independent third-party technoeconomic analysis of Sandia's proposed AC–AC SST architecture.

THE CHALLENGE

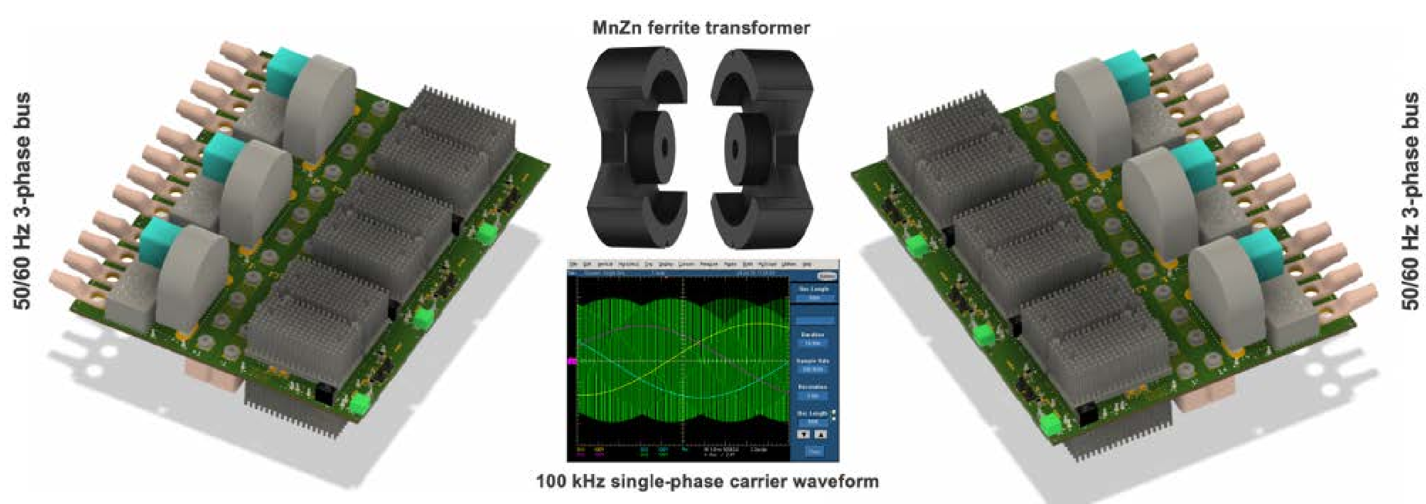
The electric grid comprises thousands of three-phase 60 Hz alternating current (AC) generators that must always be kept precisely synchronized in frequency and phase. This synchronization requirement makes large AC grids vulnerable to cascaded failures, such as the August 2003 Blackout that left an estimated 55 million people without electrical power. Such failures have been the result of unintentional events, but the grid is also increasingly vulnerable to cyberattack.

It has been hypothesized that replacement of conventional transformers with AC–DC–AC solid-state transformers that provide phase/ frequency decoupling would serve to arrest the propagation of cascaded outages. Although these devices. have been the subject of increasing research during the past decade, the high metal-oxide silicon field effect transistor (MOSFET)/insulated-gate bipolar transistor (IGBT) parts count, passive component burden, and efficiency penalties of prior art SSTs has prevented them from achieving market penetration.

APPROACH

From the standpoint of SST technology development, there are two major challenges. The first challenge is to devise a drop-in replacement for conventional AC–AC transformers that convincingly demonstrates the ability of emerging SST technology to compete with traditional wire-wound, steel-core transformers. This is an enormous challenge. Such first-generation SSTs must not only compete on price ($25/kVA) and efficiency (98%), they also need to meet stringent regulations for electromagnetic interference (EMI) and provide a path to unlimited power/voltage scaling.

Achieving acceptance of first-generation SST technology in the marketplace is required to accomplish the other major



Anatomy of a single LMI3-SST module

challenge, the development of next generation wide- and ultrawide-band-gap semiconductor switch technology required for second-generation AC–DC–AC SSTs. If first-generation AC–AC SST technology can gain a solid foothold in the market, the race will be on to mature MOSFET technology based on more advanced semiconductor materials, such as gallium nitride (GaN) and aluminum nitride (AlN). The much lower on-state resistance of such advanced MOSFETs is needed for AC–DC–AC SSTs to achieve necessary price and efficiency targets.

The goal of the hardware team was therefore to devise the first commercially viable circuit architecture for AC–AC SSTs subject to the limitations of present-day silicon carbide (SiC) MOSFETs and passive component technology. This led to the invention of Sandia's patent-pending "Low-Modulation-Index 3-phase Solid State Transformer" (LMI3-SST) technology, which is currently at Technology Readiness Level (TRL) 2/3. The hardware team has made a great deal of progress de-risking LMI3-SST technology through a series of ever more advanced prototype builds, and this work is now culminating in the construction of a 100 kW, 480 VAC, three-phase, AC–AC SST that targets an efficiency of 98%, a specific cost of $25/kVA, and full compliance with stringent EMI regulations. The ultimate goal is to construct a TRL 5 prototype LMI3-SST that can be used to engage industry through the Department of Energy's Technology Commercialization Fund (TCF) program.

The modeling team has developed dynamic component models for AC–DC–AC SSTs in GE's Positive Sequence Load Flow (PSLF) for the purpose of testing the frequency/phase decoupling hypothesis. These high-fidelity simulations have confirmed the benefits of phase/frequency decoupling of SSTs from the standpoint of mitigating cascading failures.

EXPECTED RESULTS

At the end of calendar year 2020, the hardware team will deliver the 100 kW, 480 VAC, three-phase, AC–AC SST described above, along with a battery of test data pertaining to transformer efficiency, EMI performance, and thermal management. While first generation AC–AC SSTs will not provide phase/frequency decoupling, they will serve to dispel skepticism about the ability of SSTs to compete in real-world applications. The creation of a viable market will stimulate much greater investment component technology. This not only includes MOSFETs based on GaN and AlN capable of meeting the more demanding on-state resistance requirements of AC–DC–AC SSTs. There will also be strong market pull for advances in soft magnetic materials and next-generation ceramic dielectric materials to improve handling of high-frequency ripple current.

EXPECTED IMPACT OF THIS RESEARCH

In addition to improving grid resiliency, additional benefits provided by the second-generation AC–DC–AC SST technology include phase/frequency decoupling, and neutralization of balanced reactive power, thereby reducing load on transmission lines providing increased operating margins. Various other improvements to grid resiliency can also be realized by either AC–AC or AC–DC–AC SSTs. For example, the construction of utility-scale transformers from series/parallel combinations of mass-produced, standardized SST modules will make deep inventory and rapid deployment of replacement transformers possible. Present generation utility-scale transformers can have replacement lead times of several months or longer. The net impact of cyberattacks, kinetic attacks, and extreme weather events will be determined in part by the agility with which we can replace damaged transformers. Lastly, coronal mass ejections (CMEs) represent a truly existential threat to an electrical grid based on conventional wire-wound steel-core transformers. The Carrington Event of 1859 damaged telegraphy equipment worldwide, and a more recent CME in 2012 of comparable magnitude missed intercepting the Earth's orbital path with a margin of nine days. The need to transition to solid-state transformer technology in the coming years is therefore very clear.

RESILIENT ENERGY SYSTEMS

Sandia's investment in this project is part of its Resilient Energy Systems portfolio of projects, coordinated R&D that addresses the resiliency of the nation's energy systems and other critical infrastructures to threats. This project provides both modeling and device research that can improve overall resilience to the nation.

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