MEDIUM-VOLTAGE, SOLID-STATE POWER TRANSFORMER WITH REDUCED WINDING VOLTAGE

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I. Introduction

The structure of the electric power grid hasn't changed significantly since Edison's time 140 years ago. However, the onset of Distributed Energy Resources (DER) on the supply side and Electric Vehicles, (EVs), storage batteries and increasing amounts of electronics usage on the demand side are fundamentally changing the dynamics of the power grid.

Industry and government efforts at modernizing the grid have been mostly incremental to date. Automation and switching, software and data management, grid edge and charging technologies appear to attract most of the research and investment attention. At the same time, one of the most ubiquitous elements of the grid—the Distribution Transformer (DT)—has not received nearly as much attention, even though there are over 50 million installed DTs in the US alone and they provide the very foundation of the distribution grid.

Although some work on the improvement of medium voltage distribution transformers has been conducted in the past, including the use of solid-state technology, most efforts remained at the laboratory stage and were limited mostly to research institutions.

Leveraging recent advances in power electronics which have driven up semiconductor reliability while decreasing cost, Solid State Power LLC has designed, patented and prototyped the world's first commercial-grade, medium-voltage, Solid State Transformer (SST). In doing this, SSP aims to reimagine the role of distribution transformers in the grid and not only address the challenging supply/demand dynamics at present but also provide a future-proof platform for building the grid of tomorrow.

II. Background

One of the main obstacles for the development of SSTs in the past was the lack of reliable, widely available and cost-effective high voltage semiconductors. This limiting factor has been reduced with the emergence of Wide-Band Gap semiconductors, which are currently available off the shelf for a rating of up to a few kilovolts. Despite the continuous increases in the levels of unit semiconductor voltage on the market, engineers still have to contend with the problem of converting primary voltage levels much higher than the voltage rating of the switching devices in the course of designing medium or high voltage SSTs.

Earlier efforts in this area cluster along three main approaches (see Figure 1):

A. A power converter with a single High Frequency (HF) transformer utilizing composite high voltage (HV) switches.
B. Multiple power converters utilizing multiple individual high frequency transformers.
C. Multiple power converter modules feeding a single multi-winding HF transformer.

Topology “A” is the simplest approach toward converting a HV power source using low voltage switches. It is based on a HV composite switch consisting of lower voltage semiconductors in series. A well-known converter topology is then utilized to convert the high voltage.

The composite switches in most cases use a topology named “Cascode” which was initially developed for vacuum tubes electronics. It has great performance in linear mode with two switches in series. However, the voltage distribution between multiple switches when applied to power converters is a challenge. Furthermore, with the “A” approach the voltage applied on the primary side of the HF transformer is equivalent to the peak input voltage. This leads to the primary transformer winding being vulnerable to various challenges associated with applying high voltage over a small transformer winding, including the corona effect.

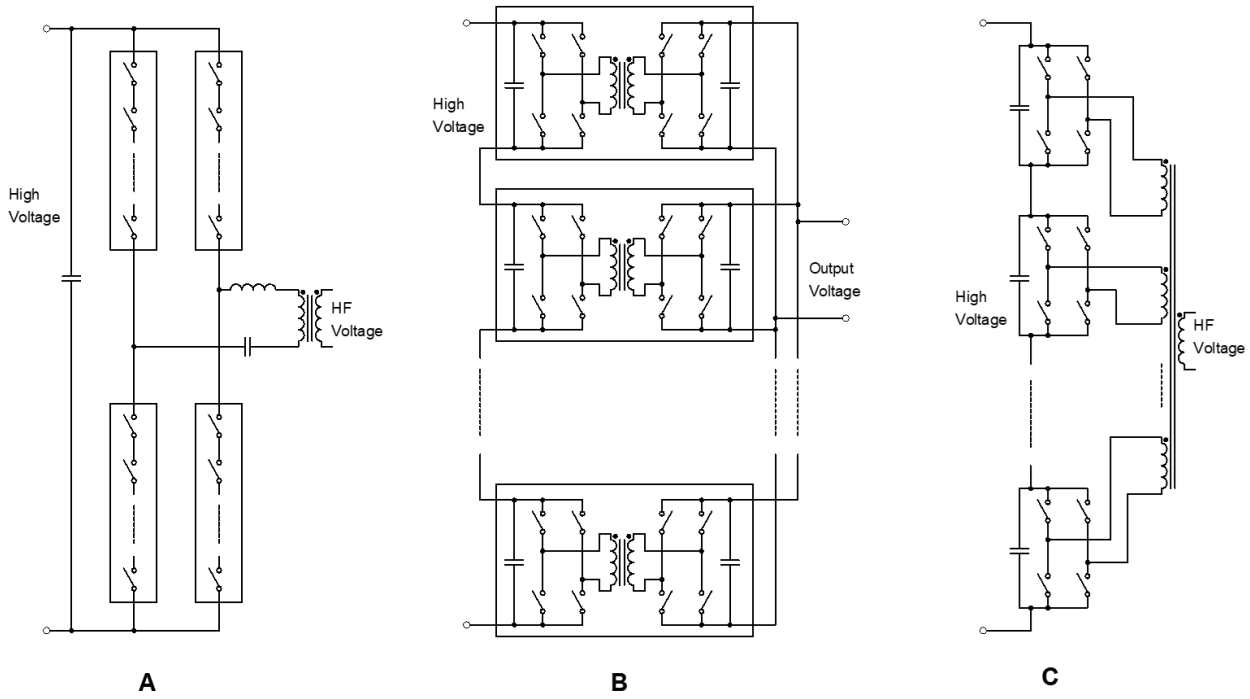

Figure 1 Prior Art

Topology “B” utilizes multiple conventional power converters with inputs in series and outputs in parallel. This is a very simple approach but it requires that multiple small high frequency transformers be used which is not always practical. The problem is worse in the case of a utility application in which a basic insulation level (“BIL”) of 95kV or higher is needed, because this type of isolation is difficult to achieve by a small size device.

Furthermore, the relatively small transformers operate with low voltage between their leads, while having a great voltage offset vs. ground. This makes them vulnerable to corona effect, which is harder to suppress on a multitude of small devices.

Balancing the voltage drops on the inputs of multiple converters in series is another challenge. There are solutions which can achieve a balanced operation but these may be vulnerable to extreme conditions which degrade reliability.

Topology “C” tries to deal with the issues listed above by connecting each output of synchronously operating power converters to separate windings on a single HF transformer. In this case the complexity of such a HF transformer becomes an issue as is also the need for equal magnetic coupling of multiple windings on a single transformer.

In addition, even though each individual winding operates with relatively low voltage between its two ends, high voltage is still applied between the primary windings which leads to problems with isolation and potential corona effect.

III. Solid State Power LLC Topology and Technology

Solid State Power LLC developed and patented a topology under US Patent 12,132,406 which reduces the voltage before applying it to the HF transformer. By utilizing voltage blocking capacitors as shown in Figure 2, the voltage on the HV side of the SST is divided by the number of the power converters and then applied to the primary of the HF transformer through the voltage blocking capacitors.

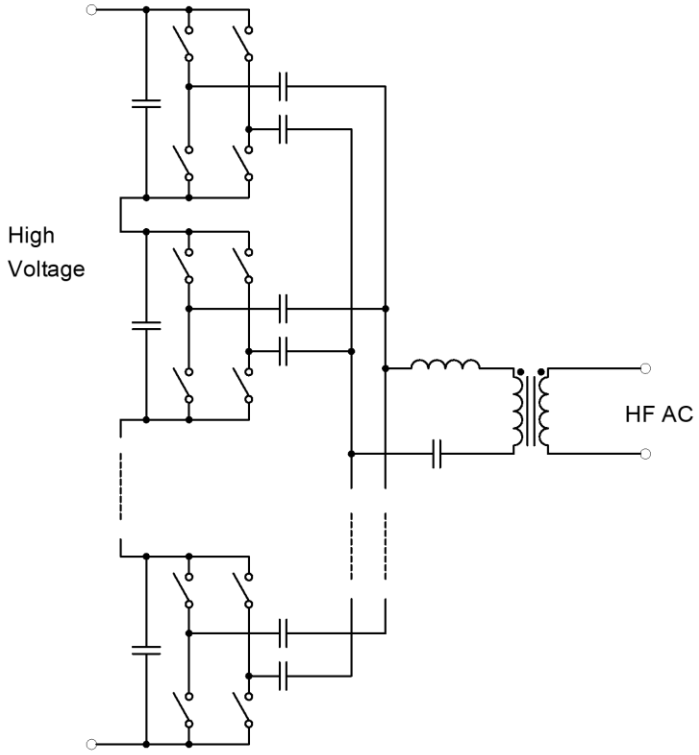

Figure 2. A HV converter with switch modules parallel driving the transformer primary.

Some of the advantages of this topology are:

- The voltage stress is applied over the Voltage Blocking Capacitors instead of affecting a more vulnerable part such as the HF transformer.
- The voltage drops on the primary sides of the serially connected power converters are naturally balanced during the circuit operation.
- A HF transformer with a single winding can be used, which greatly reduces transformer complexity.
- Natural bidirectional operation.
- The reduced voltage over the power transformer HV winding simplifies the isolation and makes it less vulnerable to HV specific issues such as the corona effect.

IV. Building and Testing Gen I 7.2kV, 25kVA Prototype

A prototype based on the topology shown in Figure 2 was built and successfully tested. A twelve-module approach was selected in order to deliver 25kVA, split 120 / 240 VAC, coming out of a standard North American 60Hz 7.2 kV AC distribution grid. Power semiconductors for the switches are 1,700V rated MOSFETs, providing enough voltage tolerance for the 7.2kV input voltage while also being cost effective and widely available. A photo of the prototype during lab testing is shown in Figure 3.

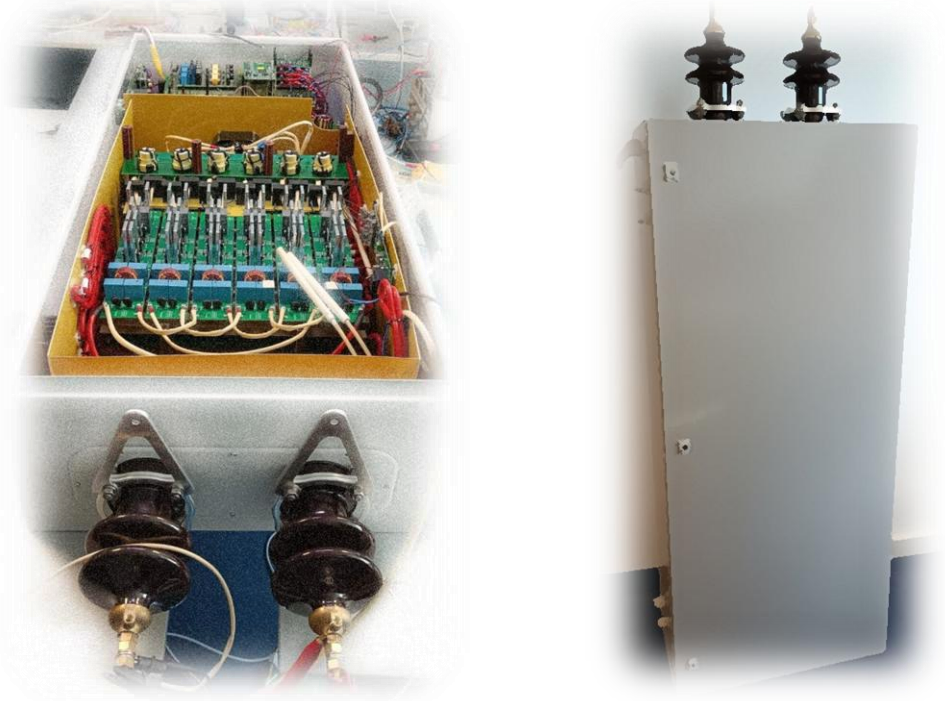

Figure 3. Gen I 7.2 kV 25kVA prototype

The successful testing of the prototype proved that the circuit shown in Figure 2 reduces the voltage on the HV winding of the HF transformer and naturally distributes and equalizes the voltages over the serially connected inputs of the power conversion circuits. It successfully steps down a single phase

7.2kV AC to 240 / 120 VAC. The built-in software voltage regulation keeps the 240VAC side voltage stable, compensating the voltage fluctuations on the 7.2 kV AC side.

The basic voltage waveforms at full power operation are shown in Figure 4. The dark blue waveform is the 7.2kV input voltage, while the red waveform is the high frequency voltage applied to the primary winding of the HF ferrite transformer. The light blue waveform is the 240VAC output of the solid-state transformer prototype and shows a clear, distortion-free, stepped down conversion of the input voltage.

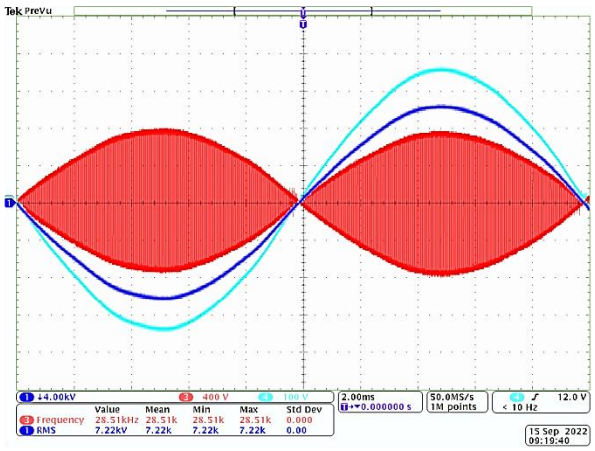

Figure 4. Example Gen I prototype's basic waveforms at full voltage and power

Common methods and off the shelf components and materials were used in isolating high voltage areas within the prototype.

In the next phase of development, SSP is scheduled to conduct field tests with one of its utility partners to gather additional customer feedback which will be incorporated, together with several major improvements, in the design of the pre-production Gen II SST.

V. Will SSTs transform the current power grid?

The development of the power grid toward a more flexible, smarter, safer and reliable network is gathering speed. A digital distribution transformer, driven by solid-state technology will put in place a platform which will further enable these developments. Some of the key benefits that the SST will provide include:

- A plug'n'play replacement for conventional DTs
- Integration of DC inputs/outputs to address growing DC supply / demand
- A smaller, lighter, and modular device reducing field servicing / crew costs for grid operators
- Inherent voltage regulation eliminating the cost of voltage regulators and tap changers
- Unity Power Factor Correction increasing network power factor and reducing the need for switched capacitor banks
- Integrated brownout / blackout protection reducing the need for UPS modules
- Inherent built-in monitoring and control enabling network optimization

In addition to performance benefits, a power grid based on SSTs provides considerable safety and environmental benefits, including:

- Absence of oil which eliminates spills, subsequent cleaning costs and fire/lightning hazards
- Increased crew safety due to smaller size/lower weight and modular architecture
- Reduced consumption of raw materials such as copper and iron by substituting them with silicon
- Reduced CO2 footprint

VI. Summary

Even though solid state transformer technology has advanced significantly since initial research started in the 1970s, it has been plagued by multiple issues which have prevented its commercialization in high voltage applications. Solid State Power's prototyped, patented technology addresses many of these issues which, coupled with recent advances in power semiconductors and components, enables the company to develop the first of its kind commercial-grade, medium-voltage distribution transformer.