White Paper

Markets Served
Data centers

Strategies for design

600V large modular UPS for critical power applications

Executive summary

Today's transformerless UPS systems are significantly smaller and lighter than isolation transformer-based systems, plus they are more efficient and reliable, and offer better power performance in a variety of applications. However, designing 600V UPSs can be challenging in several respects, from safety to fault handling to efficiency. Yet, 600V is popular due to the reduction in current required to support a given electrical load. In Canada, 600V is often required and is also used in the U.S.. In this paper, we consider various methods of providing a state-of-the-art UPS product in an environment where 600V is the preferred operating voltage. The goal is to be able to provide higher power distribution capacity and lower copper costs (versus 480V) and still capitalize on sophisticated features like the Energy Saver System (ESS) and Variable Module Management System (VMMS), which add reliability via reduction of mechanical complexity while lowering power costs. As a result, a compromise may be struck between older isolation transformer UPS technology and modern transformer-free designs that provides good value and maintains high reliability and extremely efficient operations. The user receives the benefit of compact size and weight, along with significant power and cooling cost savings, freeing up capital for other revenue-generating data center activities.

This white paper discusses the technical considerations for "native 600V," transformerless, and autotransformer UPS systems and details the advantages they may offer.

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Choices for 600V UPS design

Traditionally, the input and output voltage of a UPS were set via a transformer. The UPS input transformer may step the utility voltage up or down to provide the optimum voltage to the UPS rectifier electronics. The UPS output transformer acts to step up or down the raw inverter output voltage to match the user's requirement, typically 208V, 400V, 480V, or 600V. In fact, either an isolation (or "iso") transformer or an autotransformer may be used to perform these voltage transformations. However, a transformerless UPS has neither an input nor an output transformer. These modern UPSs have been designed to operate without the need for voltage transformation on the UPS input and output. Their rated voltages, however, have been limited to 208V, 400V, or 480V, ignoring the need for 600V in a significant number of applications. Thus, the UPS choices for the designer are native 600V (transformerless) or transformer-based. We will consider both of these.

Native 600V UPS design considerations

A native 600V UPS would have the immediate advantage of eliminating the traditional input and output transformers, saving on physical footprint, weight, and heat losses, i.e., efficiency. However, a native 600V design would require several new or modified subsystems, compared with existing 400V and 480V machines.

It would require significant redesign of all the power converters, and other related circuitry:

- 1800V IGBT transistors are required. (Reliability and switching speed may be compromised versus today's 1200V devices)
- Sensing and internal surge protective devices would all change to higher voltage
- Filter capacitors would be changed to higher voltage ratings, affecting mean time before failure MTBF
- Power train modifications would likely increase losses, reducing system efficiency

For the above reasons, particularly the likelihood of reduced efficiency, a native 600V UPS has been considered a less attractive option than simply using an existing 480V UPS product, and changing the input and output transformers to provide the 600V input and output required. That being said, the other benefits of transformerless design remain attractive and compelling.

Transformer-based 600V UPS design

There are two choices with a transformer-based UPS product. The UPS could use traditional iso transformers, or smaller and lighter autotransformers. The iso transformer UPS could be produced with minimal modification to an existing 480V UPS, but there remain significant drawbacks in both performance and efficiency compared with transformerless machines. Thus, an attractive option is to take a transformerless UPS at 480V, and add input and output autotransformers to achieve the required voltage without the burden of larger, heavier, less efficient iso transformers. The autotransformer UPS has the advantages of both transformerless and transformer-based solutions.

These advantages and benefits are described in the following sections. First, contrasting iso transformers and transformerless, and then comparing iso and auto transformer-based products.

A brief history of transformerless UPS technology

First appearing at lower power levels, transformerless UPS designs have been around for two decades. A vast majority of designs below 300 kVA are now transformerless, meaning the UPS does not contain power line frequency magnetics (transformers or inductors). This transformerless design trend encompasses even higher power levels because power line magnetics are both material and labor intensive. On the other hand, the high frequency power processing needed is technology intensive. In general, advances in technology mature sufficiently to support improved value to the customer without sacrificing needed reliability. Once that point is reached, the technology-intensive design becomes the preferred value leader. Technological advances have had a similar impact upon switch mode power supplies such as those used in servers, storage and networking gear.

Transformerless UPSs: A growing trend

At higher power levels reaching above 30 kVA and now as high as 1200 kVA, the challenge is to switch high currents rapidly at high voltages without high losses or excessive peak voltages. Over the last decade, high power IGBTs have matured enough to allow conversion frequencies of 10 kHz and above without large sacrifices in efficiency at these higher power levels. In addition, some creative control strategies permit further reduction of switching losses to the point where the transformerless UPS is superior to an older technology UPS when measured in terms of system efficiency.

Comparison of iso transformer and transformerless UPSs

Feature	Iso transformer-based UPS	Transformerless UPS
Weight and size		Typically 25 percent less weight and 40 percent smaller footprint
Efficiency	90 to 93 percent	92 to 97 percent
Energy-saver mode	Less efficient, slow to transition	99 percent efficient, 2-millisecond transition time
4-wire output availability	Yes	Yes
Separately divided source	Not when on bypass	Not when on battery
Support for high-resistance ground (HRG) sources	Yes, with reduced HRG benefit	Yes, with HRG fault tolerance preserved
Reliability (MTBF)	Lower	Higher, due to lower component count
Ability to limit fault current and mitigate arc flash	Good	Better, due to faster detection and isolation (not slowed by output impedance)
Generator compatibility	Requires larger filter, contactor and generator	Allows closely sized generator and both reduces part count and raises efficiency by not requiring a 12-pulse rectifier or input filter

Understanding the use of autotransformers in series with a transformerless UPS

Many transformerless UPS systems domestically and internationally are designed around a certain operating voltage. To meet the market need of different operating voltages, manufacturers of UPS modules use transformers on the input and output of a native 480V UPS module to achieve the operating voltage of the overall system required. The new operating voltage could be 600V, for example. The incorporation of an autotransformer into a native 480V UPS design increases overall reliability since a proven design is being used and reduces cost of parts due to increased volume. The use of autotransformers helps to decrease cost and footprint while achieving maximum efficiency of the UPS module including the transformers, without compromising on the overall system voltage requirements and design.

An autotransformer (sometimes called autostep-down transformer) is an electrical transformer with only one winding. The "auto" prefix refers to the single coil acting on itself and not to any kind of automatic mechanism. In an autotransformer, portions of the same winding act as both the primary and secondary sides of the transformer. (In contrast, an iso transformer has separate primary and secondary windings that are not connected). The autotransformer winding has at least three taps where electrical connections are made. Since part of the winding does "double duty," autotransformers have the advantages of often being smaller, lighter and cheaper than typical dual-winding transformers. Other advantages of autotransformers include lower leakage reactance, lower losses, lower excitation current, better input power factor, and increased KVA rating for a given size and mass. Negatives for using autotransformers include no cancellation of third and higher order harmonics, but a properly designed rectifier will cancel these electronically.

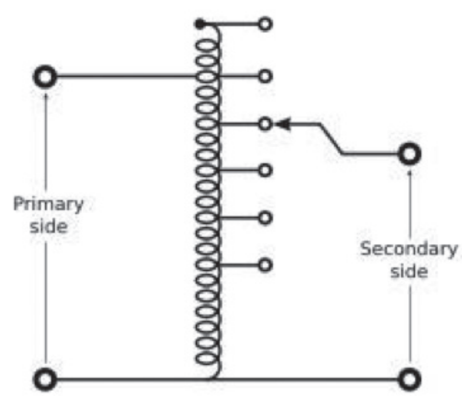

Figure 1. Schematic of autotransformer.

High resistance ground with autotransformers

Eaton transformerless UPS modules, as an option, are designed with the capabilities to sustain loads where the source used a high resistance ground (HRG), and incorporated autotransformers without any difficulties. Customers will not need to wire a neutral conductor to the UPS per US NEC250.186 code. If the site uses a dual source, where each source is a separate HRG, the UPS will function properly, but the factory should be notified if this is the case so appropriate circuitry can be included.

Comparing autotransformers and iso transformers in UPS systems

Autotransformers typically provide a slight efficiency loss in most system cases, estimated at one percent. The larger isolation transformer design typically also provides an efficiency loss at two percent or more. Due to the decreased cost, smaller footprint, increased KVA, lower overall losses, reduced effect on overall transformerless UPS system, and better efficiency ratings than isolation transformers, the autotransformer makes a better suited transformer for voltage transformations in UPS module systems.

Autotransformer advantages versus traditional iso transformers:

1. **Smaller size and weight** (30 percent).
2. **Lower core and heat losses** (1 percent per transformer).
3. **Improved input power factor** (.99 versus 0.9) for generator interface.
4. **Lower output impedance**, providing better transient response and faster fault detection and response.
5. **No magnetization delay**, allowing the fast transitions that are hallmarks of operating modes like Eaton's ESS and VMMS.

Autotransformer UPSs are not all equal

Autotransformer UPSs offer many advantages over iso transformer-based systems, but they're not all the same. Decision-makers should insist on the following characteristics when selecting an autotransformer UPS for their mission-critical applications:

1. **Low size and weight.** Autotransformer UPSs should be significantly smaller and lighter than iso transformer-based products, and not only because they don't contain a bulky transformer. The UPS should also feature compact magnetics (such as inductors, chokes and ferrites) as well as airflow improvements that minimize the size and weight of heat sinks and reduce the number of fans required for cooling. Note that in addition to saving space, these enhancements improve mechanical reliability.
2. **Ability to operate from grounded wye and even HRG sources.** The proper handling of the neutral should be described clearly in the installation documentation. Special attention should be paid to upstream and downstream fault performance, and the UPS should be able to feed 4-wire loads, such as 208/120V and 400/230V.
3. **Short transition times from high-efficiency to conventional operating mode.** Since the autotransformer UPS doesn't need to magnetize an output iso transformer when transitioning between high-efficiency and conventional operation, an autotransformer UPS should be able to complete the transition in about 2 milliseconds. Greater than 10 mSec transition times may cause problems for downstream static switches or the supported IT equipment itself.

Conclusion

The transformerless power train with small and lightweight filter inductors, high performance IGBTs in both inverter and rectifier, and advanced control strategies can bring improved performance and value. Compared to iso transformer-based UPS, a transformerless UPS is typically only 25 percent the weight and occupies 60 percent of the footprint. Full load efficiency can reach 95 percent and above. With these new benefits, this technology-intensive design has become the preferred UPS construction. The transformerless UPS, with its characteristics mentioned herein, using autotransformers to provide voltage transformation for 600V sources, will allow customers to meet current industry-leading efficiency requirements and reduced footprints with minimal cost increase.

Appendix: Iso transformer versus transformerless UPS

Benefits of transformerless UPSs versus legacy designs

Figure 2 illustrates the basic schematic of the legacy and transformerless technology UPS powertrain. A phase-controlled rectifier, while efficient and cost-effective, produces large harmonic input currents and reduced input power factor that is unacceptable at many sites and incompatible with some generators. Large input inductors and harmonic filters are needed to bring the harmonics down to 5 to 10 percent total harmonic distortion (THD) and power factor (PF) up to >0.99 PF. These components add cost and weight and increase footprint, while the large numbers of capacitors reduce mean time between failures (MTBF). In addition, they do not hold THD down and PF up over a wide load range. They are typically effective only above 60 percent of full load. At light loads below approximately 40 percent, the input PF can actually become leading and will cause incompatibility with generators. The PF also varies with line voltage but is only specified at nominal line.

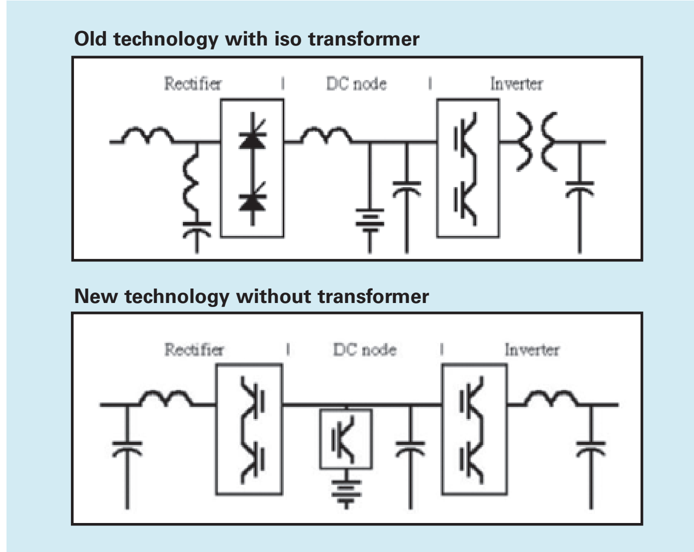

Figure 2. Simplified schematics of legacy and modern transformerless technologies.

As shown in **Figure 3**, the transformerless design with an IGBT rectifier inherently holds PF up and THD down from 10 to 100 percent load. It is highly compatible with generators and avoids the additional generator oversizing commonly required with an SCR. These superior input characteristics are maintained over the input voltage operating range.

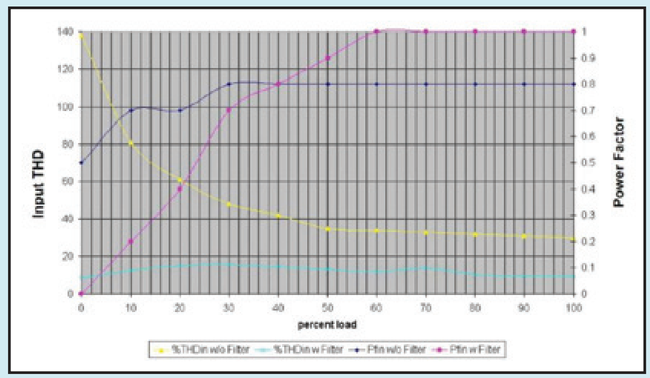

Figure 3. Typical input characteristics of legacy UPS designs.

THD and transformerless UPS designs

With regard to harmonic distortion, the severity level depends upon the particular application and location. For example, a 10 percent distortion component at a low frequency causes far less voltage distortion than one at a high frequency. Without adequate input filtering, a rapid di/dt (current spike) resulting from SCR firing can cause severe line voltage notching and interfere with adjacent equipment. In fact, it takes more than 14 percent THD before the input PF is reduced below 0.990 by the THD alone. (See **Figure 5**.)

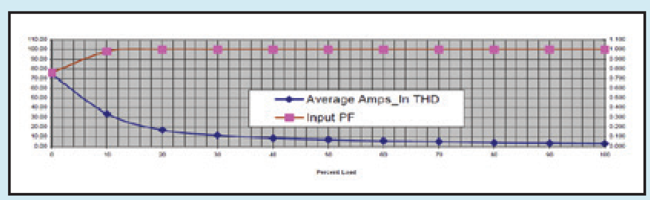

Figure 4. Typical input characteristics of transformerless UPS designs.

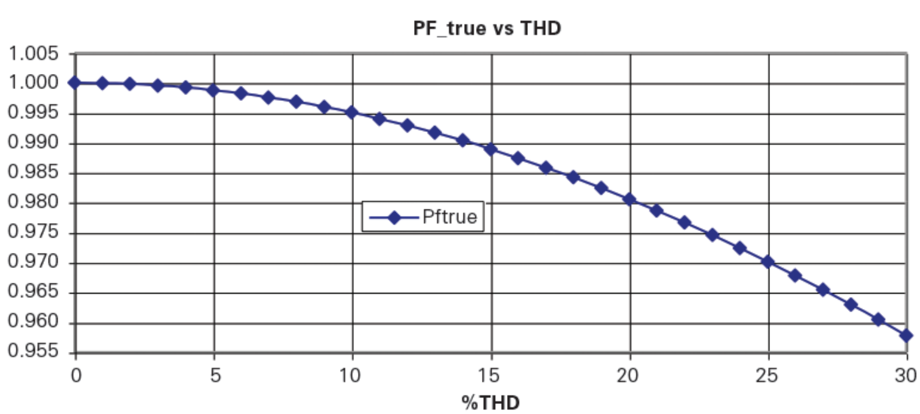

Figure 5. True power factor versus THD.

As seen in **Figure 6**, typical 6 SCR input current with 30 percent or more THD with di/dt limited by input inductors.

The higher switching frequencies used in the transformerless UPS allow the use of smaller filter inductors and faster response times with improved waveform integrity.

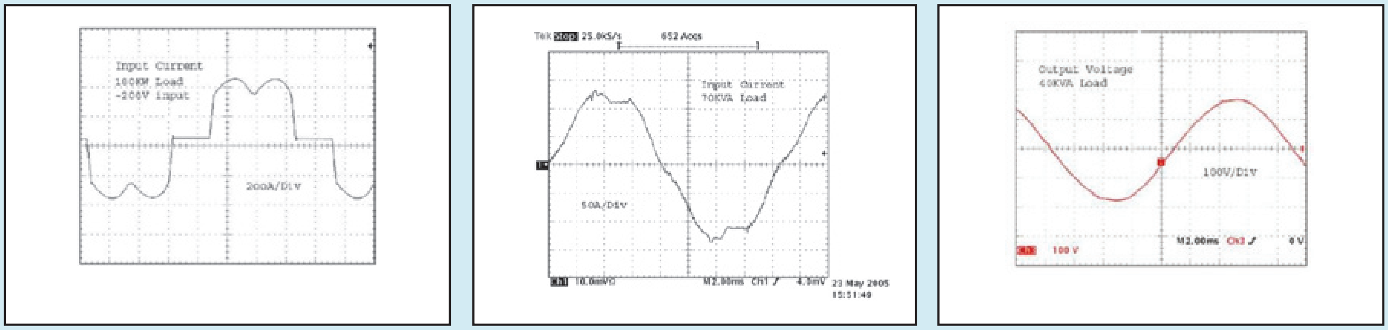

Figure 6. Typical input and output waveforms of a transformerless UPS.

The powertrain in **Figure 7** shows that an output neutral can be generated along with phase voltages without a transformer. While only three-wire input is needed for online operation, a neutral connection is needed to support bypass operation or phase-to-neutral loads. In the older UPSs, a Delta to Wye transformer is typically used to generate the output neutral.

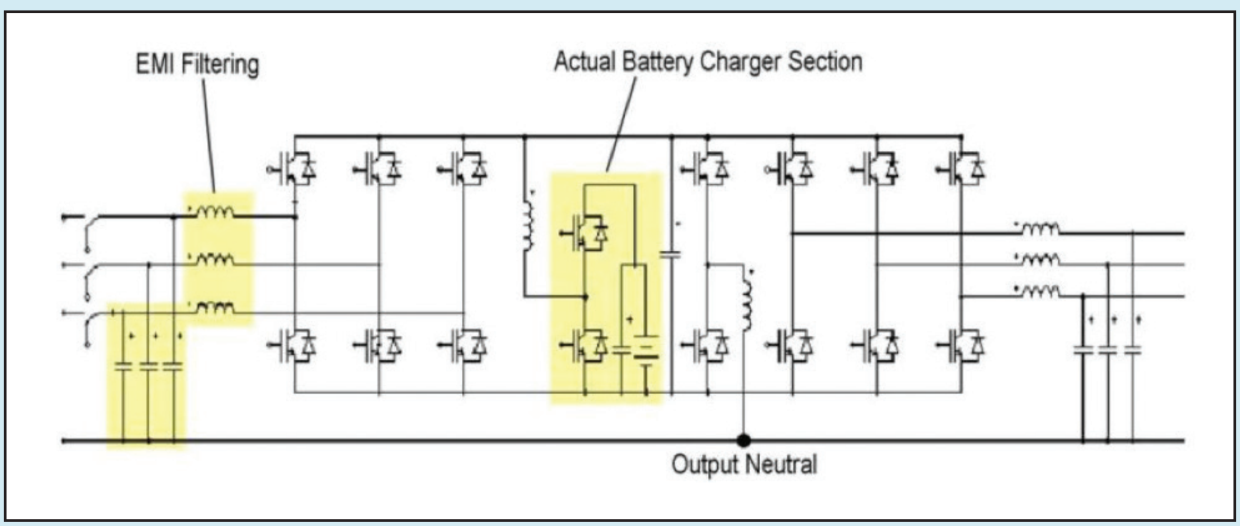

Figure 7. Powertrain that does not require transformers.

About Eaton

Eaton is a power management company with 2014 sales of $22.6 billion. Eaton provides energy-efficient solutions that help our customers effectively manage electrical, hydraulic and mechanical power more efficiently, safely and sustainably.

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