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Comparing Transformer-free to Transformer-based UPS Designs

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Executive Summary

There is growing interest in using transformer-free UPS modules in higher power, three-phase mission critical power backup applications (e.g. 200 kW to 5 MW). However, many organizations are unclear about which architecture—transformer-based or transformer-free— is best suited for a particular application.

In general, transformer-based UPS systems are highly robust and excel at providing the highest capacities and availability while simplifying external and internal voltage management and fault current control. The latest transformer-free designs offer better efficiency, smaller footprint and improved flexibility while providing high levels of availability. Driven by data center designer demand, most leading UPS suppliers offer both topologies.

Presently, large transformer-free systems are constructed of modular building blocks that deliver high power in a lightweight, compact package. This modular design offers advantages when the timing of future load requirements is uncertain by allowing capacity to be more easily added as needed, either physically or via control settings. On the other hand, a modular design means higher component counts, which may result in lower unit Mean Time Between Failure (MTBFu) and higher unit service rates.

For high-power enterprise data centers and other critical applications, a state-of-the-art transformer-based UPS still provides an edge in availability. Transformers within the UPS provide integrated fault management and galvanic isolation as well as greater compatibility with critical power distribution system requirements that should be considered when designing a high availability UPS system. Technology developments and configuration options allow the latest transformer-based designs to operate at higher efficiencies compared to previous designs, making them more comparable to the transformer-free models in terms of efficiency.

However if operational efficiency, expansion flexibility or limiting UPS footprint are of paramount importance, and other appropriate measures are instituted to provide an acceptable level of availability, transformer-free technology may be the optimal choice. In general, 200 kW is a threshold below which the space, weight and cost advantages of transformer-free UPS systems outweigh the robustness and higher capacity capabilities of transformer-based systems. These under-200 kW applications can benefit from the high efficiency and excellent input power conditioning through active components offered by transformer-free designs. In addition, the scalability of a modular transformer-free UPS can help avoid over-provisioning while maintaining operational efficiency.

NOTE: The recommendations in this paper are intended for mission critical data centers based on North American standards and design practices. Conditions, practices, and regulatory considerations in other global regions may impact selection criteria.

Introduction

Transformer-free UPS products meet the need for lighter, more compact, highly efficient three-phase UPS systems in a market that has, until recently, been dominated by transformer-based UPS systems. This paper addresses the factors that should be considered when deciding between transformer-based and transformer-free UPS designs.

Both approaches use a double conversion process (Figure 1) to provide power protection for mission-critical applications. An input rectifier (Rect) is used to convert AC power to DC power to maintain the DC power storage source (Batt - battery) and power the DC-to-AC inverter (Inv). In turn, the inverter provides AC power to the critical load. In the event of an AC power outage, the inverter continues to provide conditioned AC power from the DC battery (or other energy storage system). Input and output switchgear (Swgr) and power distribution units (PDU) complete the basic power path to the IT loads (Rack).

The primary difference between the two technologies is in their respective use of transformers.

A transformer-based UPS may use a transformer before the rectifier and requires an isolation transformer after the inverter to derive the voltage being delivered to the critical load. Transformer-free UPS designs use power and control electronics technologies to eliminate the need for an isolation transformer as an integral part of the inverter output section. This is illustrated in Figures 2 and 6.

Advances in power semiconductors and control have also allowed PWM (Pulse Width Modulation) converter switching frequencies to increase, encouraging the use of IGBTs (Insulated Gate Bipolar Transistors) within the rectifier stage. IGBTs have been utilized within inverters for many years; higher PWM switching frequencies improve inverter overall performance.

Both approaches (transformer-based or transformer-free) can be designed to maintain adherence to key UPS power quality performance objectives, such as availability, maintainability and adaptability. However, an engineer designing a large data center needs to carefully consider the costs and benefits of utilizing one or the other technologies as they relate to the overall performance criteria of the facility.

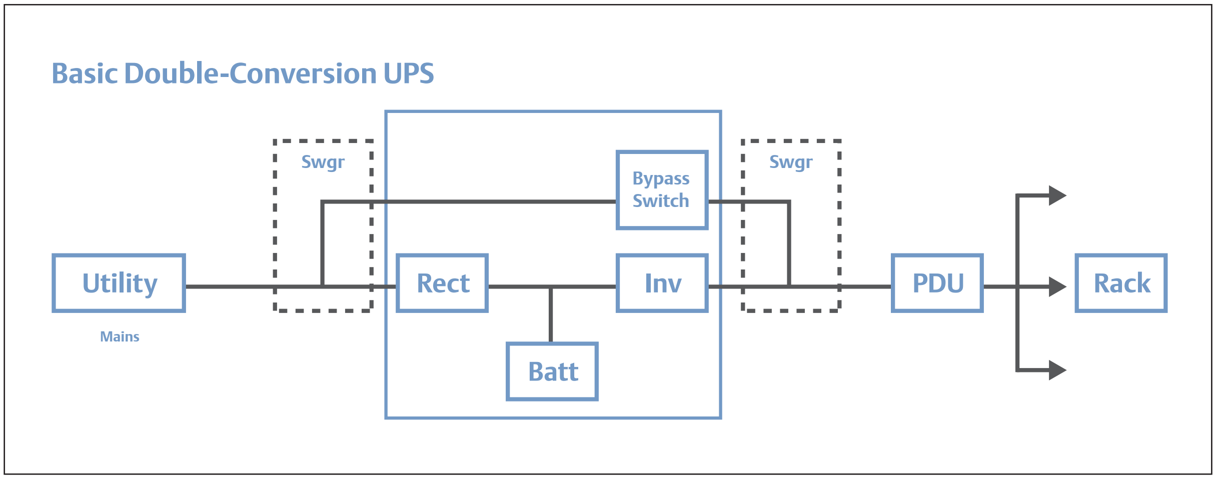

Figure 1. Basic double conversion UPS functional diagram.

Transformer-Based UPS

Figure 2 shows a simplified block diagram of a state-of-the-art transformer-based UPS. Large systems are typically manufactured based on serviceable subassemblies and are available in discrete units rated up to 1100 kVA.

The key components of this design include:

- A passive filter (inductors and capacitors) on the rectifier input to reduce input current distortion and improve the power factor.
- A six-pulse (or optional twelve-pulse), SCR-based rectifier on the input. Optionally, an additional transformer (Xfmr) provides AC-DC isolation for the DC bus and the battery.
- A DC energy storage system (typically a battery) connected directly to the DC bus between the rectifier and the inverter to provide AC output power ride-thru capability during a loss of AC input power. This example uses 540 VDC.
- An IGBT-based PWM inverter on the output.
- An isolation transformer (Xfmr) on the inverter output to derive the appropriate output voltage. This also provides a convenient and solid point for referencing the AC output neutral to ground. This neutral ground connection provides excellent common mode noise rejection.
- A passive filter on the inverter output to provide a very low distortion AC voltage supply.
- An automatic bypass switch (static switch) using power semiconductors (SCRs) provides instantaneous switchover to an alternate source if a UPS output disturbance occurs.

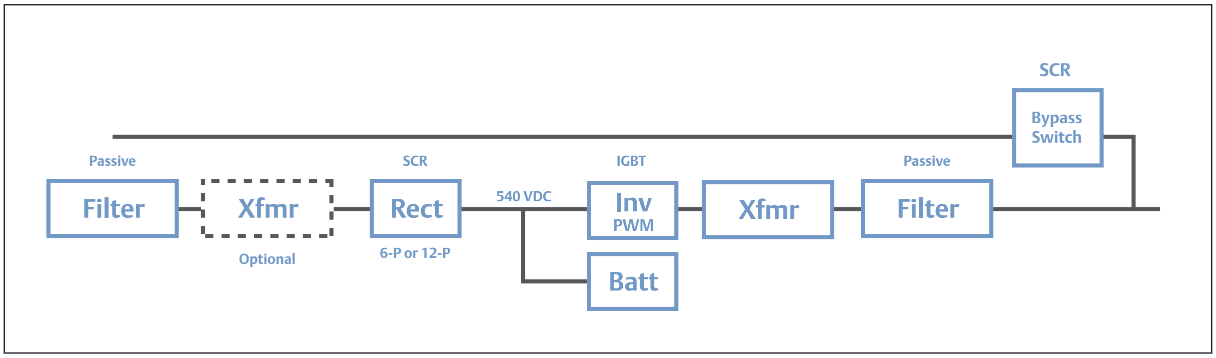

Figure 2. Transformer-based UPS block diagram.

Rectifier Section Detail

Transformer-based UPS rectifiers are technically elegant, well-proven and robust. They use passive input filtering techniques to produce relatively low levels of input current distortion and a relatively high input power factor. Lower power rated (less than 500 kW), transformer-based models typically incorporate a six-pulse SCR (Figures 3 and 4). Higher power rated units (500 kW and higher) normally use a 12-pulse design as standard (Figure 5).

Input isolation transformers are optional with six-pulse rectifiers (Figures 3-4) and required with 12-pulse rectifiers (Figure 5). In combination with the inverter output isolation, a rectifier input isolation transformer will isolate the UPS AC input source and AC output critical load from DC bus ground faults. This feature is perhaps best used with remote battery plants (in particular, those with open racks) or high resistance AC grounding systems.

The SCRs are naturally commutated with the line voltage and present a very efficient and robust application. SCR phase-control inherently provides a power walk-in (soft-start) function at turn-on without additional power control components. The output DC voltage is regulated for both inverter input and for battery charging over a wide input source voltage range.

A natural operating characteristic of a six-pulse rectifier is the generation of harmonic currents on the input source. A six-pulse rectifier will generate a total harmonic current distortion (THD) of greater than 30 percent. Therefore, in most applications, a passive (capacitance plus inductance) input filter is included to bring this current distortion under 10 percent while improving the input power factor.

A twelve-pulse rectifier with filtering will reduce the current distortion to less than 5 percent and further improve input power factor, though the additional magnetics do come with an efficiency cost.

At light UPS loads, a passive-input filter can force the UPS input current to a leading power factor (capacitive load appearance) and must be considered with engine-generator controls. Most UPS manufacturers offer options to eliminate leading power factor conditions at light loads.

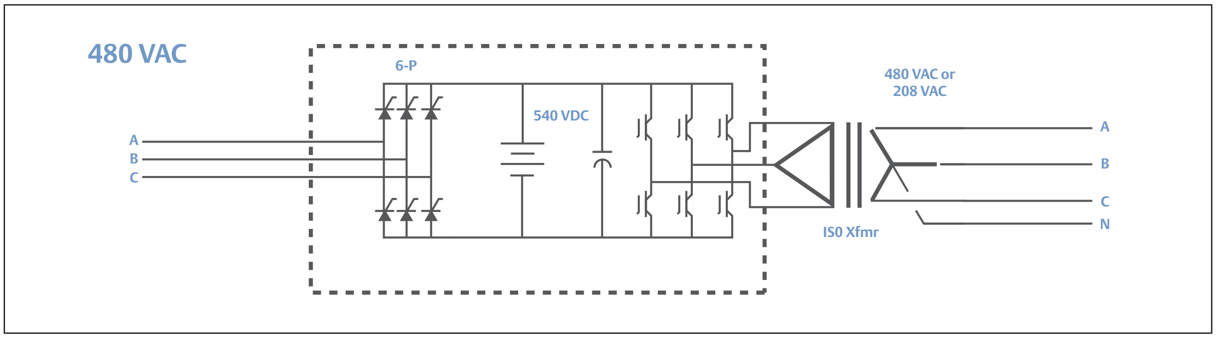

Figure 3. UPS with Six-Pulse (6-P) SCR-based rectifier and output isolation.

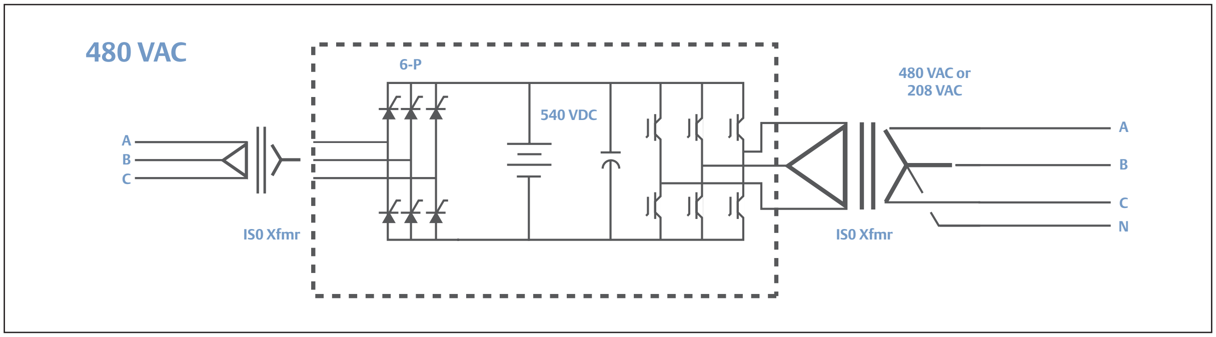

Figure 4. UPS with Six-Pulse SCR-based rectifer and input/output isolation.

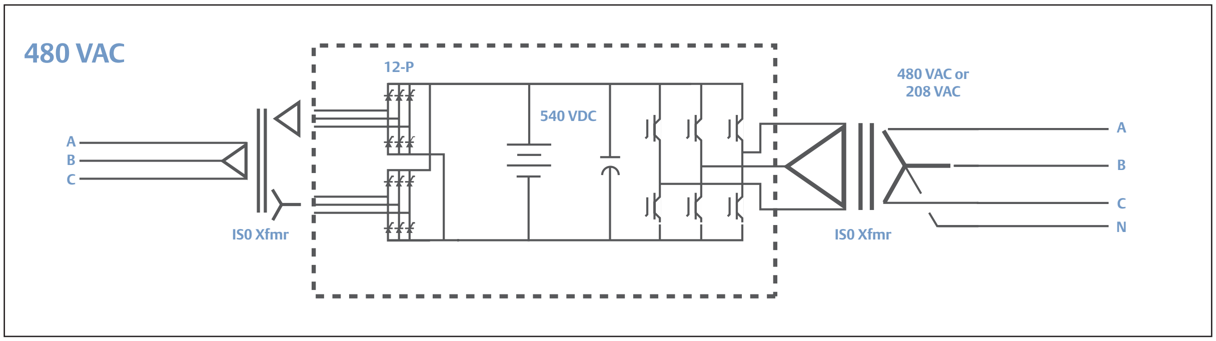

Figure 5. UPS with Twelve-Pulse (12-P) SCR-based rectifier and input/output isolation.

DC Bus – Energy Storage Detail

The DC energy storage system (Batt – Figure 2) in the transformer-based design is connected directly to the DC bus connecting the rectifier output to the inverter input (Figures 3, 4 and 5), which contributes to reliability. This circuit formation provides excellent performance during loss of utility power as the charged battery is intrinsically and immediately available. However, since the battery is connected to the output of the rectifier and the input to the inverter, it will be subjected to AC ripple currents and voltages. Although these ripple currents are mitigated via a DC filter capacitor assembly, they still exist to a small degree and may have some effect on the battery, especially at higher ambient temperatures. Proper design minimizes ripple effects on the battery.

Inverter Section Detail

Transformer-based UPS inverters are relatively simple, well-proven and robust. These units employ an IGBT-PWM inverter (Figures 3, 4 and 5) that operates at a lower DC bus/battery voltage (540 VDC illustrated as an example). They use passive output filtering techniques to produce relatively low levels of output voltage distortion over a reasonable range of connected load characteristics. A passive output filter works with the transformer impedance to provide a low harmonic sine-wave voltage (< 5 percent THD) for all load operating conditions. The inverter three-phase AC output power flows through a three-phase delta-wye isolation transformer that provides flexibility in UPS input/output voltage combinations. The UPS output 4-wire voltage and neutral configuration is established by the transformer secondary wye winding. This ensures magnetic (galvanic) isolation of the DC battery system from the UPS AC output. When a transformer is used with the rectifier, the AC input will also be galvanically isolated from the DC bus.

With an output transformer, the AC output voltage of the UPS does not need to equal the rectifier input voltage, but must equal the bypass voltage. The bypass voltage source and the rectifier voltage source can be separate sources.

Transformer-free UPS Design with PWM Rectifier

Transformer-free UPS topologies replace simple passive magnetic-voltage transformation functions with solid-state power electronics circuitry. Figure 6 shows a simplified block diagram of a transformer-free UPS design. There are a number of key differences between this circuit and the unit depicted in Figure 2.

By replacing passive power components (transformers, capacitors, inductors) with power circuit assemblies utilizing PWM power conversion techniques, transformer-free UPS rectifiers are physically smaller and produce low input current harmonics with near unity input power factor.

Typically, the UPS battery in transformer-free applications is connected to the internal DC bus (about 800 VDC in this example) through an integrated bi-directional DC/DC converter. This puts an additional power conversion element in series with the battery.

Using similar PWM power conversion techniques, transformer-free UPS inverters are physically smaller as well, and produce low output voltage harmonics over a wider range of connected load characteristics.

The bypass function (static bypass switch) is similar to the transformer-based design. However, without external transformers added, the bypass AC input must be the same voltage as the inverter AC output.

Transformer-free UPSs are typically designed and styled for both computer room in-row lineups or equipment room installations. Complete transformer-free UPS units are typically an assembly of standard frames plus functional control and power modules.

A transformer-free UPS is lighter and smaller than the power-equivalent transformer-based design with both physical volume and footprint being less. However, other external transformers may be required for AC-DC isolation purposes, safety reasons, AC voltage changes, or to provide power distribution flexibility. With the addition of external transformers, the overall facility weight and footprint totals may be higher than with a transformer-based UPS design with implications for end-to-end system efficiency. If transformers need to be added to a transformer-free unit to make it compatible with a facility, a transformer-based unit may be a better solution.

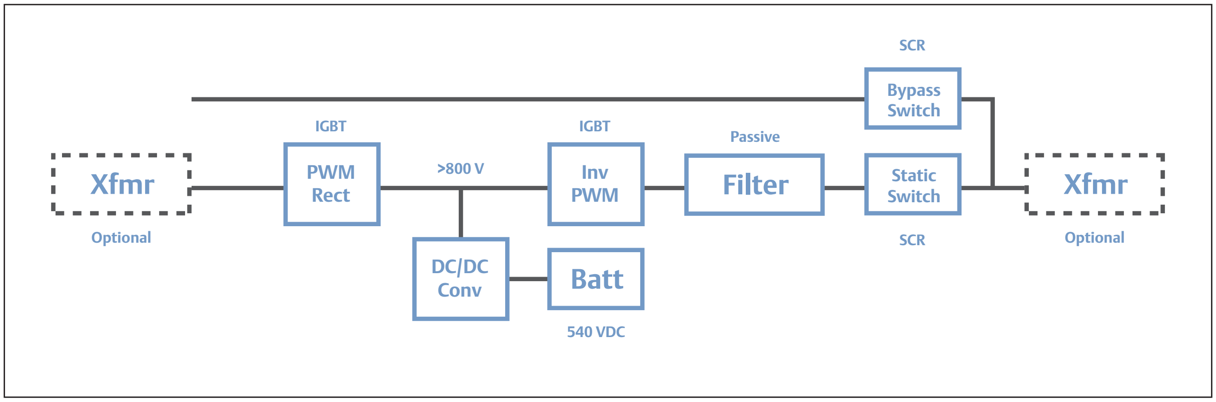

Figure 6. Transformer-free UPS block diagram.

Rectifier Section Detail

In the typical transformer-free UPS, the SCR rectifier is replaced with a PWM IGBT three-phase, power-factor and current-waveform-corrected rectifier. The operation and control algorithms expand the basic functions of rectification and DC regulation to include control of the input current waveform, power factor correction and power walk-in functions.

In addition to its primary function of rectification of AC power into DC power, the rectifier now has the ability to regulate the input current to near unity power factor and input current distortion below 3 to 5 percent over the full load range. Therefore, the larger passive input filter employed in the transformer-based design is not required. Since the power factor is not changing with load, input kVA is approximately equal to input kW under all conditions, allowing a lower input circuit breaker rating and closer engine-generator size matching.

DC Bus – Energy Storage Detail

The transformer-free design applies the battery differently than the transformer-based design described in the previous section. The battery is not connected directly to the DC bus, but maintains its charge from supplemental battery charging (DC/DC Converter) (Figure 7). This also isolates the battery from incremental aging effects of the rectifier/inverter DC harmonic currents.

During utility outages, the battery must be discharged through the DC/DC converter assembly, which acts as a boost regulator during battery discharge. This boost regulator will result in reduced DC/AC conversion efficiencies at some load levels, but the efficiency curve is generally flatter than is the case with transformer-based units. The additional components of the DC/DC boost converter and DC/DC battery charger incrementally reduce the overall UPS unit MTBF.

Note that there is no AC input or AC output galvanic isolation in this configuration. If it is preferred to eliminate the risk of DC faults from propagating to the input feeder and/or output critical bus, an isolation transformer would need to be added externally on the rectifier input and/or the inverter output. Isolation transformers are also recommended for use with batteries, and in particular open-rack batteries, installed remotely from the UPS unit.

Inverter Section Detail

The three-phase PWM inverter output is passively filtered and presented to the UPS output terminals without flowing through an output transformer. This provides a three-wire output (Figure 7). A fourth inverter switching leg is required to balance the DC bus voltage around zero volts or support a four-wire output (three phases plus neutral) if needed (Figure 8). If a neutral (i.e., a four-wire wye output) is required on the inverter output, it will require a full-capacity neutral run through from the rectifier or bypass AC input source through to the inverter output and connected load.

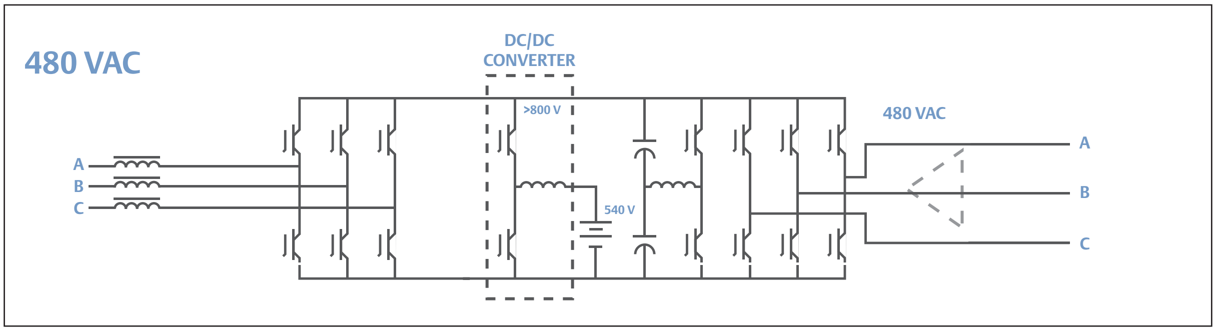

Figure 7. Three-wire transformer-free UPS.

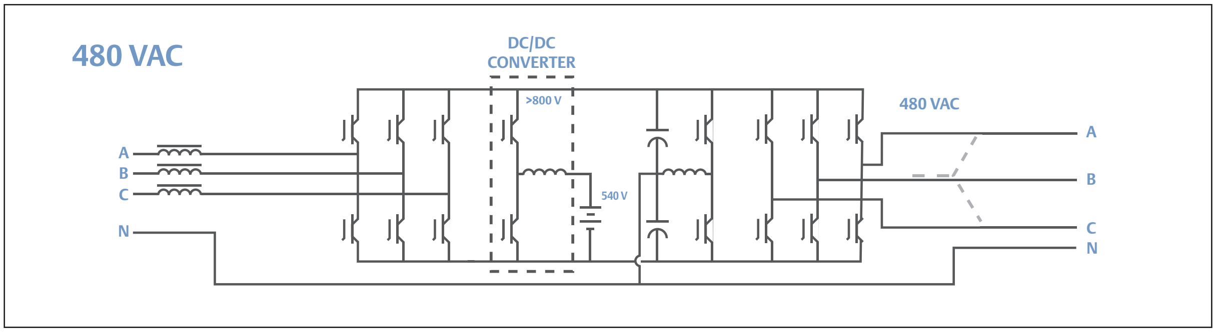

Figure 8. Four-wire transformer-free UPS.

It should be noted that in this transformer-free implementation, the normal output is 3-wire and requires the input, output and bypass AC voltages to be the same voltage. It is also recommended (but not required, providing specific application guidelines are followed) that the input and bypass circuits come from the same AC source.

With a 3-wire inverter output, a step-down to a different distribution-level voltage (e.g.; to 208/120 Volts output from 480 VAC input) would be provided downstream within a Power Distribution Unit (PDU). The PDU requires an isolation transformer that would also provide for PDU output neutral formation and a local grounding point.

Technical Features and Performance Differences

While accomplishing similar high availability performance goals, transformer-based and transformer-free UPS units use somewhat different approaches to meeting specific output performance requirements.

In UPS system applications, transformers provide passive fault isolation, arc flash mitigation, electrical noise reduction, voltage changes, a solid neutral reference and some degree of fault current limiting. Transformer-free UPS units utilize all active power conversion techniques to accomplish similar performance. Transformer-based units integrate passive magnetics with fewer active power conversion components resulting in a relatively simpler, more robust UPS unit.

In choosing between transformer-based and transformer-free UPS solutions, a system designer should determine where transformers are best utilized and whether they should be internal and/or external to the UPS in view of physical and electrical distribution requirements and tradeoffs. This section reviews the techniques and tradeoffs utilized in the various rectifier, DC energy storage, inverter and static bypass functions of these two UPS designs for various UPS system performance functions.

Site Planning and Adaptability

Many users find that transformer-free UPS equipment provides greater flexibility in accommodating uncertain future requirements. Transformer-free designs are usually smaller in size than an equally power-rated transformer-based design, providing opportunities to locate the UPS physically closer to the point of power usage or on a more lightly rated (pounds/sq. ft.) raised floor.

Applying a transformer-free UPS to a critical power distribution system does not mean that all transformers in the power path can be eliminated, but does allow the system designer to place transformers only where they are needed.

Isolation transformers, which are integrated into transformer-based UPS, still are needed to perform certain necessary functions within the critical power distribution system, such as:

- Establish a separately derived, 4-wire (three phase-plus-neutral) source from a 3-wire input.
- Provide local points for neutral-to-ground bonds.
- Establish local grounding points for safety as well as common mode noise reduction.
- Permit rectifier and bypass input sources to be separate.
- Allows the input distribution voltage to be different than the critical load input voltage.
- Provide additional source impedance for fault-current and arc-flash reduction.
- Easier implementation and improved performance of high-resistance grounding schemes.
- Handle unbalanced wye-connected loads when applied to 3-wire distribution.
- Improve the performance of overcurrent protective devices (fuses and circuit breakers) by reducing fault-current path resistance.

Once it is determined where transformers may be needed in the system, transformer-free UPSs may permit more optimal placement in the power distribution path. However, it must be remembered that transformer-based UPSs have some of these functions internally integrated as part of the system design, a potential reliability benefit.

Reliability and Availability

Transformer-based UPSs have an inherently higher reliability due to a much lower parts count, robust redundant configurations, and simplified maintenance. They also benefit from technology innovations and an installed base of thousands of machine-years of experience and refinement.

The newer design of the transformer-free UPS achieves its high-availability performance through advanced power conversion technologies, redundancy, modularity, active fault management and lessons-learned from transformer-based designs. All major UPS manufacturers produce both topologies for mission critical applications to accommodate UPS system designer preferences.

Transformer-based UPS units utilize a combination of passive and active fault management systems, while transformer-free systems use a control-intensive active-only design. The control strategies and expanded power conversion processes within the PWM rectifier, DC/DC converter and inverter of the transformer-free UPS compare somewhat less favorably in predicted Unit Mean-Time-Between-Failure (MTBFu). The fact that transformer-based UPS power units are available in discrete units up to 1100 kW whereas the largest transformer-free UPS modules are less than 300 kW, illustrates the potential limit on availability of the highly paralleled components within a transformer-free UPS when more than one module is required to meet capacity. However, in analysis of the Mission Mean Time Between Failure (MTBFm), (i.e., sustaining the critical load) and availability of the mission-critical power, both product executions will be similar.

Robustness

In general terms, robustness is an expression of a qualitative level of abuse that a UPS system can handle beyond its 0-to-100 percent ratings while still meeting its availability requirements. Both transformer-free and transformer-based UPS can provide excellent and similar dynamic overload capabilities for phase-to-neutral or three-phase dynamic load events. These units provide automatic handling of temporary overloads and faults on the downstream distribution network and can provide on-the-fly paralleling with the AC bypass in support of overload and load fault management. Transformer-based UPSs add the benefit of some degree of passive fault handling through internal transformers and filters.

Most transformer-based designs use circuit breakers at key disconnect points (Input, Output, Bypass and Battery). These circuit breakers provide over-current protection and allow for greater fault clearing capabilities.

Some transformer-free designs may use a contactor and fuse combination which can present problems during certain overload or fault conditions. Specifically, an inverter IGBT can fail short which may cause the contactor to weld and introduce a DC current onto the critical bus. In addition, most contactors will be unable to open during DC fault conditions or high AC fault current situations which could be easily handled by a properly sized circuit breaker. Also, in a transformer-based UPS, the DC fault current cannot pass through an isolation transformer. As a result, the input feeder or the critical bus cannot experience any DC fault conditions, or cascading DC faults.

DC Energy Storage System Isolation

Internal or external transformers can enhance the reliability of the DC link in several ways. Transformers add a degree of impedance to the power circuit, serving to incrementally reduce the magnitude of fault currents. An output transformer associated with the inverter will further serve to isolate the AC output from DC faults. Similarly, an input transformer prevents a DC ground fault from causing an AC ground fault on the input source. High impedance DC faults, typical with open batteries, can only be detected when both isolation transformers are used. If both AC input and AC output transformers are included in the power system, the AC input and AC output will be unaffected by DC faults to ground, DC ground fault sensors will operate better, and battery maintenance/service procedures will be significantly safer. DC isolation may be preferred when open-rack batteries (e.g.; flooded cells) are used, and particularly when they are located in remote battery rooms.

Engine-Generator Interface

The input filter on the transformer-based design is large enough in kVAR to cause the input power factor to become leading (capacitive) when the UPS is lightly loaded (less than 40 percent). This can cause engine-generator (Genset) control issues if not taken into account during the engine-generator/UPS integration design. The added kVAR of the filter also requires that the engine-generator be oversized when compared to the UPS power rating. For this reason, most UPS manufacturers offer an option to automatically eliminate the leading power factor under light loads.

The transformer-free design, with its near unity power factor and very low input current distortion over the full output load range, circumvents these characteristics and allows a more closely matched engine-generator to be used. The engine-generator may still need to be oversized to some degree to handle the full critical load plus battery recharging.

As a side note regarding system design, be sure to confirm that the engine-generator, as well as any other power distribution components, can handle the critical load power factor and AC current distortion separately from the UPS. From time to time, the UPS will be on bypass, with the critical load powered directly from the utility input source, engine-generator or other alternate AC source.

UPS Output Considerations

The output transformer in the transformer-based UPS design provides flexibility in output voltage, phasing and grounding. The delta-wye transformer can be configured as a 3-wire delta (three phases plus ground) or 4-wire wye (three phases plus neutral plus ground), 600, 480, 400 or 208 Volt system output. The wye provides for adherence to the National Electric Code separately derived neutral definition. It also permits the neutral to be grounded and a local distribution reference established. Grounding points for separate rectifier AC input and bypass AC input sources will not need to be closely coupled, as would be required for transformer-free designs.

Transformer-free UPS design is typically executed as a three-wire in-and-out-only system with the output voltage the same as the input voltage (Figures 6 and 7). Neutral establishment (i.e., 4-wire wye output) for distribution occurs farther downstream in an isolation transformer, whether stand-alone or within a Power Distribution Unit (PDU).

If an output neutral is required in a transformer-free UPS, a fourth leg is added to the inverter (Figure 8). The created neutral does not have magnetic isolation and will be referenced to the input (rectifier or bypass) through multiple impedances. This lack of isolation can create challenges where managing the neutral voltage on a line-to neutral load is required. Physically, a full-capacity, low-impedance (for proper over-current protection performance) neutral conductor cable needs to be run from the AC input source to the downstream load, an additional cost consideration. On the other hand, this may reduce the need for transformers downstream, potentially reducing the overall system cost.

High Resistance Grounding

High resistance ground (HRG) schemes are implemented by some designers to provide nuisance-trip protection for circuit breakers from low-level ground faults. HRG systems also permit locating and servicing low-level ground faults easier and safer. HRG systems are straight-forward to install on transformer-based UPS systems. Transformer-free designs will need additional components added to the system to provide the needed electrical ground separation points.

Fault Current Availability

A key requirement for all UPS products is an ability to manage internal fault currents while preventing disturbances to critical load operations. System designers are required to provide fault current magnitude calculations as part of their overall fault management design. Transformer-based units handle this fault management requirement through the combination of internal magnetic impedance (current limiting effects) and active fault control techniques.

The transformer-free UPS has, in general, the ability to pass more fault-current through its structure and into its faulted circuits since the limiting impedance may only be a function of the rectifier and inverter power semiconductors. Transformer-free units must depend on fast-acting, complex active means to achieve a level of fault management similar to that of transformer-based designs.

It should be noted that the static bypass path in either topology represents an even more direct path for fault currents to pass from the bypass input source to the output load, or to backfeed the inverter. An inverter output transformer reduces internal fault current magnitude to some degree, depending on how the output transformer is connected within the UPS system.

Arc Flash Energy

Arc Flash is a consequence of a low impedance arcing short circuit fed by one or more paths of source energy. There are many factors that must be considered when estimating arc flash energy, including: source voltage levels, potential fault current magnitudes, source impedances, number of contributing paths and circuit breaker trip (time plus magnitude) characteristics.

UPS design and physical location within the infrastructure critical power path will also influence the available energy that may be realizable at the fault location. In general, the impedance of the included transformer(s) within the transformer-based UPS will lower the available fault energy within the downstream distribution system. With a transformer-free UPS, a system designer may find that an external transformer(s) must be added downstream of the UPS to assist in limiting fault currents, and therefore arc flash energy levels. This may mean the difference between requiring Level 1 PPE (Personal Protective Equipment - a flame resistant cotton coat) and Level 4 PPE (an insulated, Arc flash protective suit, gloves and helmet) during maintenance procedures.

Isolation

Aside from fault current handling and arc flash mitigation, electrical distribution systems must include provisions for sectionalizing feeder and branch circuits for the following:

- Ground and neutral conductor management.
- Limiting fault and neutral current loop lengths (reduces current impedance).
- Providing safety ground paths.
- Limiting common mode electrical noise.

Other functions may include voltage-transformation, delta-wye transformation, neutral formation, AC-to-DC-to-AC circuit isolation, and reducing risk during maintenance procedures. Line-frequency transformers are the typical method to provide these many functions. The internal transformer(s) within transformer-based UPS units provide comprehensive, integrated magnetic solutions for essentially all of these functions. They are designed-in and tested as a complete package. If other local neutral/grounding points are needed, they can be added using additional, external transformers.

The more compact, transformer-free design, while providing size and weight benefits, does not provide the aforementioned electrical distribution and isolation functions internally. The benefit for the system designer is the ability to place transformers only where they are determined to be needed and not duplicated, potentially saving costs, space and weight. These benefits must be balanced against the fact that the UPS units and third-party isolation transformers cannot be designed and tested as a system in the factory, creating the possibility that something in the system design is overlooked, such as dual AC input source isolation requirements or arc flash mitigation needs.

Maintainability

Maintainability is a reflection of the convenience, safety, speed, accuracy and risk of performing maintenance and service on the UPS system components. The transformer-based design has a long history of ease of maintainability and safety for service personnel. The magnetic isolation and impedance provided by the integrated transformer(s) is an asset when planning maintenance actions. Most transformer-free UPS systems utilize modular techniques so that they may be reliably serviced in sections while maintaining critical load operations with minimal risk.

Total Cost of Ownership

When considering the total cost of ownership for a UPS system, it is important to include both the initial upfront or capital expenses (CAPEX) as well as the ongoing or operating expenses to power, maintain and service various options (OPEX).

- **Initial Costs (CAPEX):** Due to the absence of transformers, most transformer-free UPS modules will be less expensive than the transformer-based models. They will also have a smaller footprint, reducing the need for additional space in the data center. The cost/benefit of these systems can be deceptive if an engineer determines that an input and/or output isolation transformer(s) is required. The addition of transformer requirements outside the UPS results in higher overall purchase costs, increased total footprint, and increased labor to install and wire the additional equipment. Plus, the external transformer may not be as well-coordinated as it would be with a transformer-based UPS design.

- **Operating Costs (OPEX):** Both the transformer-free and transformer-based UPS modules can achieve similar efficiency and full-load performance factors, with transformer-free having the edge. Both designs typically feature efficiency optimization options, including enabling the critical load to normally operate in the UPS bypass mode (“eco-mode”), transferring back to the UPS inverter within a few milliseconds when the input source has an out-of-limits disturbance.

- Technological evolution is constantly impacting the relative efficiency of transformer-based and transformer-free solutions. After years of optimizing performance, transformer-based UPS systems have achieved a relatively flat efficiency curve from 30 percent to 80 percent loading where typical Tier 3 and Tier 4 data centers operate. The latest transformer-free designs also have very flat curves down to as low as 20 percent of capacity, and have efficiencies in the 96 percent range in double conversion mode. A study of the whole system design is necessary to determine the relative efficiencies as the addition of transformers, and the efficiency of those transformers, will have an impact.

Conclusion

Transformer-based UPS AC output availability has steadily improved over the decades as component, design, control and manufacturing techniques have been refined and proven. Performance has also significantly improved while component count has decreased. These designs, intended primarily for equipment room installation, have consisted largely of an assembly of replaceable/repairable subassemblies. As the key power source for higher-power mission-critical applications (more than 200 kW), their field observed availability numbers have climbed to remarkable levels.

At the same time, transformer-free UPS topologies have emerged to meet the demand for more efficient, flexible, smaller footprint, lighter weight UPS systems. The price of these performance feature improvements has been the replacement of a few robust but physically large and heavy passive components (e.g., transformers, inductors, capacitors) with functional power electronic equivalents implemented using many more components packaged in field-replaceable, modular subassemblies. It is reasonable to expect that, while achieving system output availability values that approach those achieved by transformer-based designs, the transformer-free units will have service call rates somewhat higher than their transformer-based counterparts.

Transformers, whether internal or external to the UPS, are necessary to establish circuit isolation and local neutral and grounding points, as well as to provide voltage transformation points. This facilitates, for example, the implementation of very high power density installations based on 600 Volt distribution sources, subsequently stepped down to 208/120 Volts for IT load applications systems. When utilized in conjunction with the UPS internal DC link, DC-to-AC output and AC-to-DC input isolation can be provided, reducing or eliminating the risk of DC faults propagating upstream or downstream of the UPS. Because of data center designer requests, most leading UPS suppliers continue to offer both topologies as part of transformer requirement solutions.

A summary of top-level performance attributes for the two designs is provided in Figure 9.

Feature	Xfmr-based	Xfmr-free
Size & Weight (smaller / lighter preferred)	+	+++
Location Flexibility (smaller / lighter footprint)	+	+++
Input AC waveform management	+	+++
Genset compatibility	+	+++
Initial system costs (end-to-end)	++	+++
Adaptability / Scalability / Modularity	++	+++
UPS system efficiency	++	+++
UPS eco-mode efficiency	++	+++
Dynamic output performance (including eco-mode)	+++	+++
Availability, system	+++	+++
Delta (3-wire) distribution	+++	+++
Robustness / Fault management	+++	++
Wye (4-wire + Neutral) distribution	+++	+
HRG implementation	+++	+
Component count	+++	+
Input / DC / Output Isolation	+++	+
Input / Output configuration flexibility	+++	+
Reliability, per unit	+++	+
Best = +++ Better = ++ Good = +		

Figure 9. Summary comparison of transformer-based and transformer free UPS design performance features.

Emerson Network Power
Liebert Corporation World Headquarters
1050 Dearborn Drive
P.O. Box 29186
Columbus, Ohio 43229
United States Of America
800 877 9222 Phone (U.S. & Canada Only)
614 888 0246 Phone (Outside U.S.)
614 841 6022 Fax

liebert.com

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