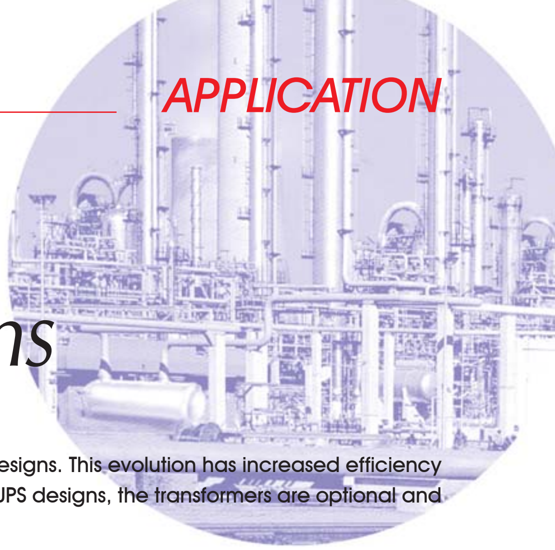

The role of isolation transformers in UPS systems

by Neil Rasmussen, Schneider Electric

Most modern UPS systems do not include the internal transformers that were present in earlier designs. This evolution has increased efficiency while decreasing the weight, size, and raw materials of UPS systems. In the new transformerless UPS designs, the transformers are optional and can be placed in the best location to achieve a required purpose.

Every data centre power system includes transformers. Isolation transformers have historically had a number of different roles in the power architecture of data centres:

- Voltage step down from medium-voltage mains supply to the utilisation voltage.
- Within a UPS, to act as an integral part of the power conversion circuits.
- To create a local ground-bonded neutral.
- To reduce harmonic currents within power distribution units of a UPS.
- To provide taps to accommodate abnormally high or low mains voltages.
- To eliminate ground loops with multiple generators or mains sources.
- For stepdown from the data centre distribution voltage of 480 V or 600 V.
- To provide additional utilisation voltages.

UPS systems have historically had one or more permanently installed internal isolation transformer to provide one or more of the above functions. Newer UPS systems do not require power transformers as part of their circuits, improving efficiency and reducing weight, size, and cost. Instead, transformers are added to a transformerless UPS as needed to achieve a desired function. In almost all cases where a transformer is needed, the transformerless UPS design is superior because it allows the transformer to be installed in a more optimal part of the power path.

The role of transformers in UPS systems

Internal transformers were used in early UPS systems because they were required for the power inverter. The first UPS products were developed over 40 years ago and used a ground-referenced battery system. The grounded electronics and battery configuration required these systems to have two transformers for isolation from the mains – one on the input rectifier, and one in the output inverter. Later improvements in these designs, where the battery bus was moved to the neutral wire or electrically floated, eliminated one of the transformers, typically the rectifier transformer. Taking advantage of high-voltage, high-speed power semiconductors that did not exist many years ago, most recent UPS designs use newer designs that eliminate both the input and output transformer.

In some data centre power system designs, no transformers are needed in conjunction with the UPS, but there are many situations where transformers must, or are advised to be, installed in combination with the UPS. It is not possible to consider the use of transformers in a UPS system without understanding the important differences between the different options. The configuration of a UPS system falls into three basic categories, called single mains, dual mains, and single mains without bypass. They are schematically illustrated in Fig. 1.

Single mains configuration: One mains connection supplies both the bypass and UPS module. This is the most common arrangement, and is the only arrangement supported in many small UPS systems. The main benefits of this system are the simplicity and low cost of installation and the fact that many complexities relating to circulating currents and grounding are eliminated. The downside of this system is that the actual mains supply system cannot be taken down for maintenance without disrupting power to the critical load.

Dual mains configuration: The bypass is fed from a second mains that is different from the mains feeding the UPS rectifier input. The difference in the mains can range from minor (e.g. they are fed from different breakers on the same panel) to major (e.g. they come from completely independent sources with different ground systems and even different voltages). There are a variety of data centre redundancy architectures that specify this type of configuration. Another reason for the dual mains configuration is to allow either of the two mains to be taken down for maintenance while providing power to the critical load. The dual mains configuration is required in some data centre architectures, and is chosen by preference in many larger data centres in

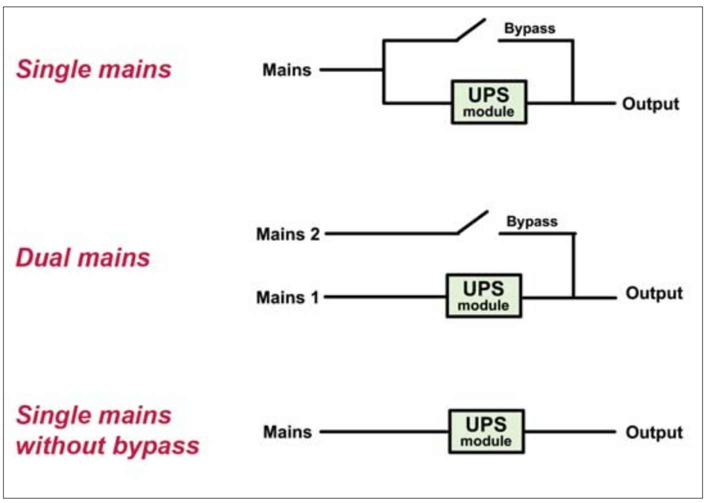

Fig. 1: Three basic configurations of mains and bypass for a UPS system.

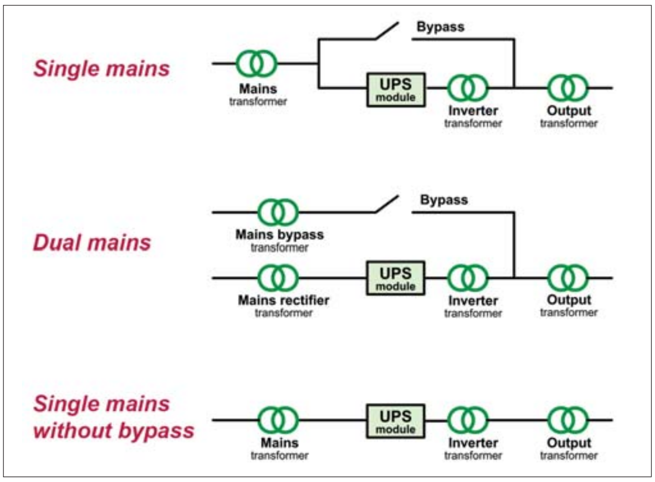

Fig. 2: Possible location of isolation transformers in the three basic UPS system configurations.

order to allow for concurrent maintenance and/or to improve the overall system reliability by preventing the wiring and breaker upstream of the UPS from being a single failure point for the power system.

Single mains without bypass: This is mainly used in environments where the mains power quality is considered to be extremely poor, to the point where it has been determined that it is not desired to ever power the critical load from the mains via a bypass. This can occur in industrial situations, shipboard, or on small islands, where the mains frequency (50 or 60 Hz) is not the same as the IT load frequency, or in stressed electrical grids in developing nations. The three configurations described above can include one or more transformers in the power path. Fig.2 shows the possible locations of transformers in the three UPS configurations.

In each of these three UPS system configurations any combination of transformers may be present. For the single mains configuration, there are eight possible transformer arrangements; for dual mains there are 16 arrangements, and for single mains without bypass there are eight arrangements, for a total of 32 possible arrangements. Furthermore, the mains transformers and output transformers can be located either locally or remotely from the UPS, which affects the grounding system. This adds an additional 60 variations, for a total of 92 ways transformers can be installed with a single UPS. Virtually all of the 92 transformer installation variations have been used in real installations. However, not all transformer arrangements are logical, and there are a few that offer a superior combination of performance, economy, and efficiency. To understand when the use of a transformer is required or why various transformer locations exist for the three UPS configurations, we first must consider the effect of transformers on the neutral and ground wiring.

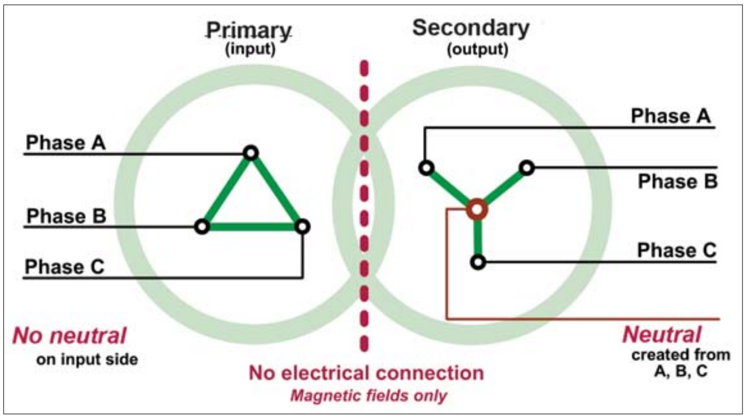

Fig. 3: Wiring diagram showing input and output connections to a power isolation ("deltawye") transformer.

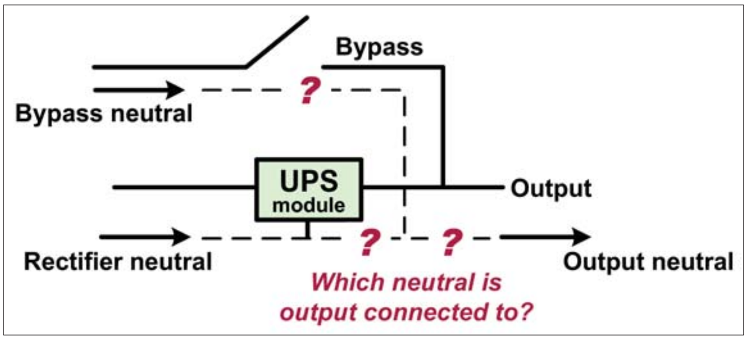

Fig. 4: How to create a single output neutral, with two input source neutrals.

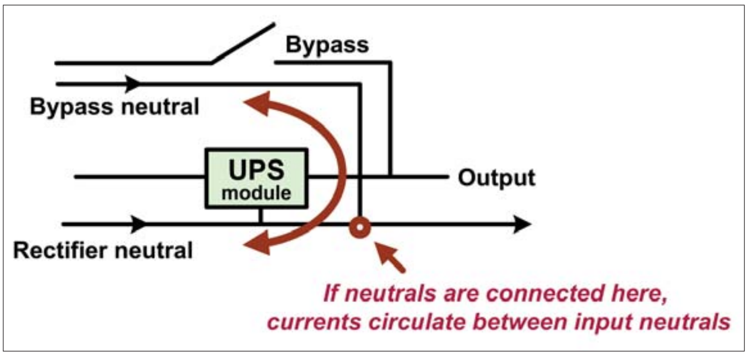

Fig. 5: Circulating current created by connecting two separate input neutral wires to create a single output neutral.

Characteristics of transformers

There are different types of transformers, but here a transformer refers to a "deltawye" configuration, which is the type used in almost all UPS applications. Deltawye transformers have a number of characteristics, both good and bad, that impact their use in UPS systems:

Good characteristics

- Voltage change (for example, 480 V to 208 V).
- Impedance that limits fault current or acts as a noise filter.
- Blocking the 3rd, 9th, 15th, and other multiples-of-three harmonic currents.
- Isolation of the output neutral from the source.

Bad characteristics

- Weight, cost, consumption of natural materials, and taking up space
- Electrical losses and contribution to data centre inefficiency

Because the last two penalties are severe, transformers should only be used when the beneficial characteristics are useful to the mission of the data centre.

Voltage change: This is necessary in applications where the mains voltage is not the same as the voltage used by the IT equipment. This is a common condition in North America where the mains voltage is 480 or 600 V in larger data centres. In most of the world, the 400/230 V three phase mains voltage is the same voltage used by the IT load equipment, so this function is not required.

Impedance: This is generally secondary and unimportant in the modern data centre.

Blocking harmonics: This was historically a useful function to prevent the harmonic currents created by the UPS from affecting the mains, and to prevent IT-load harmonic currents from affecting the mains via the UPS bypass. Both the modern UPS and modern IT loads are "power factor corrected", which means their harmonic current generation has been dramatically reduced to the point where no additional filtering is necessary. Therefore, the use of transformers to reduce harmonic currents is no longer a necessary function in the modern data centre.

The first three beneficial characteristics therefore have limited or obsolete value, which leaves the fourth characteristic.

Isolation of neutral from the source: It is this characteristic that causes transformers to be useful, necessary, or even legally mandated under certain conditions. Because isolation of the neutral is the key to determining the role of transformers, we must understand this function.

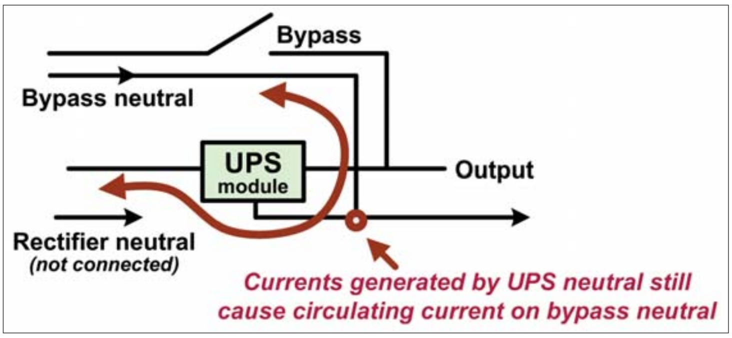

Fig. 6: Circulating current can still exist even if the rectifier input neutral is not connected.

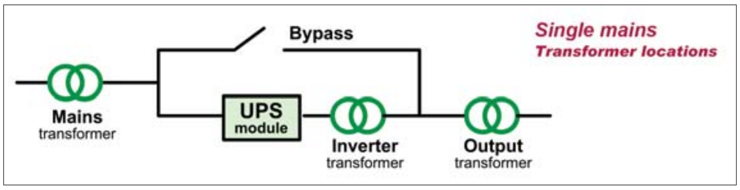

Fig. 7: Possible transformer locations in the "single mains" UPS configuration.

Transformer isolation

The actual wiring diagram of a transformer, is shown in Fig. 3 and is important to understand for the remainder of this paper.

The three power phases are applied to the transformer windings (green lines) that are connected in the "delta" configuration. The secondary, or output, is connected in the "wye" (Y-shaped) configuration and consists of three power phases and a centre point, or neutral. There is no electrical connection between the input and output. What is important to note is that there is no neutral connection on the input. The transformer "makes" a new neutral on the output – a neutral that has no electrical connection to any neutral on the input. In fact, the whole output circuit is at an indeterminate voltage with respect to the input or ground, which is referred to as "floating".

Since IT load equipment is grounded, it is never appropriate to supply floating power at an indeterminate voltage because this could cause insulation failure and other hazards. Therefore, the neutral on the output of the transformer is connected to ground in virtually all data centre applications. When an isolation transformer has a grounded neutral, its output circuit is often referred to as a "separately derived source". Grounding the output neutral can be achieved by directly connecting the neutral to the nearest grounded metal (equipment enclosures, ground rods, or ground wire known to be grounded), or it can be connected to an existing neutral wire known to be grounded. All of these techniques are used in data centres. Considering the above isolation properties of a transformer, we can now describe the key beneficial – and sometimes necessary – functions resulting from isolation:

- Changing different mains grounding systems to the system required by data centre IT equipment.
- Creating a new neutral connection when the mains neutral has serious power quality problems or the neutral is subject to disconnection when upstream 4-pole circuit breakers are used (as required in some countries).
- Combining two sources without the need to connect their neutral wires together.
- Preventing circulating currents that could cause residual current detectors (RCD) or other safety systems to activate unnecessarily.

Changing a mains grounding system in a data centre to the grounding system required by IT equipment is clearly an essential function. IT equipment in a data centre is always operated from a TN-S grounding system. In some cases, the mains provides a TN-S system so no change is required. Generally, IT grounding systems require conversion to TN-S by use of a transformer before they can be utilised by IT equipment. This grounding conversion can occur before the UPS or after the UPS. The second function, of creating a new neutral when the mains neutral has serious power quality problem, is used when the provided mains neutral is shared with other customers, is generated a distance from the data centre, or is deemed unreliable to the point where it might either be interrupted or become disconnected from earth.

The third function, combining sources without the need to connect the neutrals, is a function that is unique to emergency power systems that have backup sources, such as commonly used in a data centre. A data centre may be fed from a combination of multiple mains services and generators that are combined with switches to assure power continuity to the critical load. The bypass path within a UPS is itself an alternate power path from the UPS module that is essentially "combined" at the output of the UPS. Whenever two sources are combined through a switching arrangement, a situation may arise where there are two input neutral connections and a single output neutral connection. This leads to the problem of how to connect a single output neutral given two input neutrals as shown in Fig. 4.

Since switching between neutrals supplying an IT load creates a momentary open-neutral condition which can be hazardous or destructive, the neutral to the critical load should never be switched. This means if two alternate sources are combined in the UPS, they must have their neutral wires permanently connected to each other. However, connecting the input neutrals together to the output neutral can create circulating currents between the input neutrals as shown in Fig. 5.

While these circulating currents are a minor nuisance when the bypass and rectifier come from the same source, this can be a hazard if the two input neutrals come from different sources. The connection of two independently derived neutral sources together is universally not permitted by law. The insertion of a transformer in series with one of the two sources solves this problem. Whenever a dual mains UPS is supplied by separately derived neutral sources, a transformer is required.

The fourth function, preventing circulating currents that could cause RCDs or other safety systems to activate unnecessarily, is also related to the situation where sources are combined such as in a dual mains configuration. Circulating currents can occur even when a UPS is supplied from two inputs that are derived from the same neutral. Therefore, in any system where both a rectifier and bypass neutral connection are provided to the UPS, any RCD protection on the supply circuits will activate unnecessarily. An isolation transformer located in either the rectifier supply, the UPS module output, or the bypass is needed to prevent RCD activation.

At first it seems that if the rectifier input neutral connection could be omitted, the circulating current problem should be solved. In fact, all UPS systems designed for dual mains are designed to operate without a rectifier neutral connection; the UPS input rectifiers draw power between the input phases and do not require a neutral connection to function. As long as the rectifier source is known to be grounded, the rectifier neutral need not be provided. Since there is no longer any rectifier neutral connection, it seems that circulating current should not be possible. Unfortunately, although this it is widely believed that the absence of a neutral connection on the rectifier eliminates circulating currents, it is not true.

Fig. 6 shows the dual mains UPS system configuration with the rectifier supply

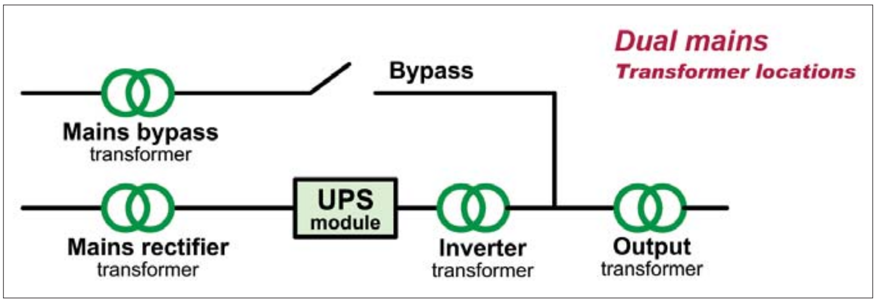

Fig. 8: Possible transformer locations for the dual mains configuration.

neutral not connected. The red line shows the flow of circulating current which still exists but flows through the UPS module instead of the rectifier neutral. Any UPS inverter module that has an output neutral will inject current onto the output neutral bus in excess of any neutral current required by the load. This "excess" neutral current is a side-effect of inverter operation and is caused by reactive loads, non-linear loads, and imbalances in the load currents. RCD protection (mandated in some conditions in some countries), then these protective devices will sense this neutral current as an unexpected current and misinterpret it as a ground fault, possibly shutting down the system. This leads to a very important principle of data centre power system design: In dual mains systems with RCD protection, there must always be a transformer present somewhere in one of the mains paths. Removing the rectifier neutral connection is not sufficient to prevent circulating currents.

We will now consider each of the three basic UPS configurations and show the preferred transformer arrangements based on the situation.

Transformer arrangements in practical UPS systems

Transformer options for the "single mains" configuration.

The single mains system is the most common UPS configuration, used in over 50% of all UPS installations. In smaller systems (below 100 kW), it is even more dominant, making up approximately 90% of all installations. The advantage of this system is that it is relatively simple to design and install, yet it provides a bypass that gives a variety of redundancy and maintenance benefits. Small UPS systems below 10 kW typically only have a single input and must be used in the single mains configuration. UPS systems over 10 kW usually provide for dual mains input but are converted to single mains by simply connecting the two mains inputs together. The majority of UPS systems shipped with dual mains input connections actually end up configured for single mains input.

In the single mains configuration, transformers can be located in three positions as shown in Fig. 7. Any combination of these transformers, including none or all three, might exist in a UPS installation.

The following observations can be made from a study of the functions of the transformers in the single mains UPS configuration:

- There is no advantage to using a transformer based UPS in the single mains configuration.
- An option for large data centres is to add an input transformer to the "single mains with remote output transformer" arrangement, to allow for use with very poor mains grounding systems or a mains supply with an incompatible grounding system, but this would be an uncommon situation.

Transformer options for the "dual mains" configuration

The dual mains configuration is used in many, but not all, larger installations. Fig. 8 shows four options for transformer location in a dual mains system.

There are two core reasons that the dual mains system is used. The dual mains approach must be used when the system architecture prescribes that the rectifier and the bypass supplies come from different sources. In most systems with alternate supplies, such as diesel generators or secondary utility mains supplies, an automated transfer switch is provided upstream of the UPS because there are other loads in addition to the UPS – such as cooling plants – that must be backed up. The second reason the dual mains design is used is to allow for concurrent maintenance of the distribution wiring and breakers feeding the UPS.

The diagram in Fig. 8 accurately represents the flow of power but does not completely describe the grounding system, because the physical location of the transformers must also be considered. The inverter transformer, if present, is always integral to the UPS, but the rectifier, bypass, and output transformers can be either located at the UPS or remotely located.

In many cases there is no advantage to using a transformer-based UPS in a dual mains configuration.

The following observations can be made from a study of the functions of the transformers in the dual mains UPS configuration:

- If voltages must be changed, transformers must be installed.
- If the mains and/or UPS ground system are not TN-S, then transformers must be installed.
- The inverter transformer provides the function of breaking the neutral connection between the rectifier and bypass inputs, but this function is also provided by either a rectifier or bypass transformer.

The most important characteristic of the dual mains design is that there are many options and the interactions between the options and other equipment such as RCD and circuit breakers is quite complex. The successful installation of a dual mains system requires not only a careful trade off analysis and design, but also requires care during installation. These factors are further compounded in designs of paralleled systems or complex redundancy configurations.

Transformer options for "single mains without bypass"

The single mains without bypass configuration is commonly used when the quality of the input mains power or the mains grounding system is poor, degraded, or shared with industrial loads.

When the mains power is of very poor quality or the grounding system is unstable, it can be undesirable to ever expose the IT load to the mains via a bypass, so no bypass is provided in this system. The inverter transformer, if present, is always integral to the UPS, but the mains and output transformers can be either located at the UPS or remotely located.

The use of this configuration, single mains without bypass, is common in countries with very poor power. However, in most cases where it is used, the single mains configuration with a bypass would be a better choice brcause without bypass configuration the load fault current is always limited to the UPS inverter output current, which is typically much lower than the mains available short-circuit current. This can cause difficulty clearing breakers downstream of the UPS, and can result in a total load drop when a downstream fault does not clear, or even if it does not clear quickly.

Contact Jacqui Gradwell,
Schneider Electric, Tel 011 254-6400,
jacqui.gradwell@schneider-electric.com ❖