TECHNICAL NOTE: USING AN OPTIMIZED TRANSFER APPROACH WITH STATIC TRANSFER SWITCHES TO PREVENT TRANSFORMER SATURATION CURRENT AND ENHANCE DATA CENTER AVAILABILITY

Introduction

Many data center power system configurations employ static transfer switches that rely on primary-side switching. This is where the static switch is implemented between the data center power source and the data center power distribution unit. While this approach offers advantages in terms of smaller footprint, lower initial costs and lower installation costs, it also has the potential to cause downstream transformer saturation during source switching operations. If that happens, it creates a transformer inrush current which can overload primary power sources and trip upstream protective circuit breakers.

There are several static transfer switches available on the market today that incorporate improved switching methods to eliminate transformer saturation current during transfer operations. The two methods compared in this paper are the commonly used "phase delay" method, and the "optimized transfer" method. A closer look at the two approaches highlights the significant performance difference between the two and shows why the optimized transfer method patented by Vertiv™ offers the best solution for eliminating transformer saturation current.

Transformer Saturation Defined

A few basic equations help explain the concept of transformer saturation. Those with an engineering background may recall that Maxwell's equations show that electric and magnetic fields are inter-related; an electric field creates a changing magnetic field and a changing magnetic field creates an electric field. The equivalent simplified equations are below.

Equation 1

$\int E$ (electric field)dt $\rightarrow ø$ (magnetic field)

integral (area under curve) of voltage = flux

Equation 2

d/dt ø (magnetic field) → -E (electric field)

derivative (rate of change) of flux = - voltage

With these equations and the relationship between electric and magnetic fields as a foundation, the following concepts can be presented:

- A transformer's magnetic field flux density is directly proportional to the integral of the AC voltage (volt-seconds area) applied to the transformer primary winding (Equation 1). As the AC voltage alternates positive and negative, so does the polarity and magnitude of the magnetic flux created in the core.
- The rate of change of the magnetic flux in the transformer core generates a voltage in the primary winding that is opposite in polarity to the applied voltage; this is called counter-electromotive force (counter EMF) (Equation 2). This opposing voltage limits the current in the primary winding of the transformer, which would otherwise be determined by the relatively small resistance of the winding wire.
- Depending on the transformer material and mechanical design, there is a limit on how much magnetic flux can exist in a transformer's core. This means that the total volt-seconds applied to a transformer's primary winding must be maintained within a limited range and at a net balanced value around zero. Otherwise, excess flux is created in either the positive or negative direction and the transformer core becomes "saturated" in the sense that no additional flux can be generated in that direction.

When a transformer core becomes saturated, the normal rate of change in the magnetic flux is greatly reduced. This, in turn, reduces the generated counter EMF, which normally limits the primary winding current. In essence, when a transformer becomes saturated, the primary winding's effective impedance becomes very small and the applied voltage – un-opposed by the counter EMF – creates very high currents. This is known as an inrush current.

Phased Delay Method

The phased delay method provides a simple, yet flawed, means for eliminating transformer saturation. The basic idea behind the method is that the best way to prevent transformer saturation when a primary source failure is detected is to delay for a period of time before turning on the alternate source. The length of the delay is determined by the source phase difference, and the transfer is completed by all three phases of the alternate source being turned on at the same time.

For a better understanding of this approach, it is first important to remember that during source transfers it is critical to maintain the total volt-seconds applied to the transformer primary within proper bounds and balanced around zero. Let's assume that two static switch sources are 180° out of phase and that a primary source failure is detected just after a full positive half cycle of voltage has occurred. If the alternate source is turned on immediately, then the static switch output will see another positive half cycle of voltage; two positive half cycles in succession— or twice the normal value. This would create a large imbalance in the volt-seconds applied to the transformer over that one-cycle period, which would in turn create severe flux saturation.

If instead, the static switch waited one half cycle of time (8.33 milliseconds) before turning on the alternate source, the positive half cycle (from the primary source) would be followed by a negative half cycle from the alternate source. The total volt-seconds applied to the transformer over the one-cycle period would be balanced around zero and kept within normal bounds; proper transformer flux is maintained and saturation does not occur.

The brief moment where the output was zero volts while the static switch waited for the one half cycle would not have any effect on the net flux. This is because when voltage is removed from a transformer, flux level in the core decays very slowly (over minutes). So in the above example, during the half cycle while the static switch output is zero, the flux change is trivial. As far as the transformer core is concerned, the positive half cycle of voltage is immediately followed by a negative half cycle just as if the voltage interruption never occurred.

The amount of time the static switch delays is determined by measuring the phase difference between the sources. For example, if the source phase difference is 180° , the transfer is delayed one half cycle; if the phase difference is 90° , the transfer is delayed ¼ cycle, etc. Note that the point in the cycle where the primary source failure occurs is not of particular concern; the correct transfer delay is still determined by the phase difference between sources.

Figure 1 illustrates an example where the source is 90° out of phase and the source failure is occurring at a random point indicated by the vertical red line. For clarity, only one of the three phases is shown. The transfer to the alternate source is indicated by the vertical blue line, which is one quarter cycle (90°) delayed from the failure detection point. The volt-seconds from the failing source voltage (red shaded area) added to the volt-seconds of the alternate source voltage (blue shaded area) equal one full half cycle of area; the correct volt-seconds and normal resultant total flux which would be created by an un-interrupted full half cycle of voltage.

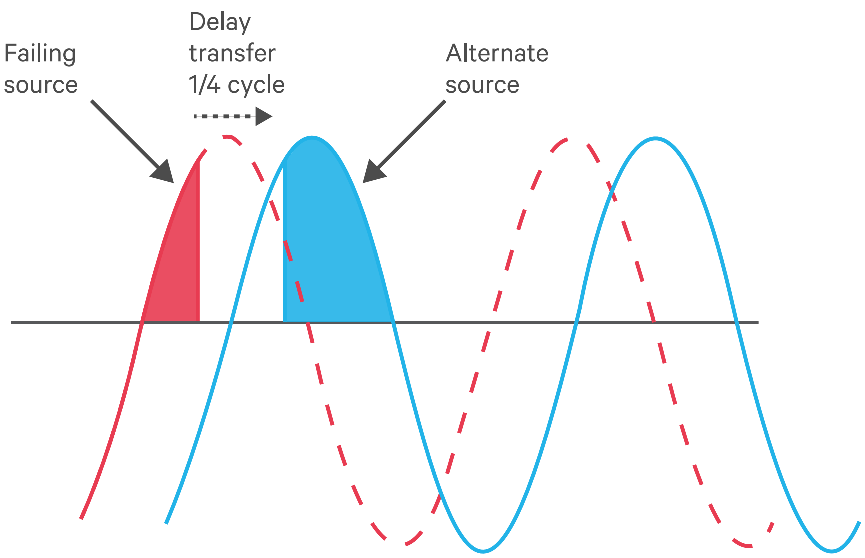

Figure 1

The flaw in this approach lies in the fact that it only works effectively for three-phase voltage systems under certain conditions. Specifically, if all three phases of the primary source fail simultaneously, such as with a three-phase breaker opening, and the breaker opens in a manner that causes all three voltages to collapse quickly to near zero volts. If this occurs, then the optimal time to turn on all three phases of the alternate source is identical and the method works perfectly.

However, in other common source failure modes, such as a single phase loss or a phase-to-phase short event, the three phases do not fail simultaneously. In these cases, the optimal transfer time for each phase would be different and one common transfer time simply determined by the phase difference between sources would not balance the volt-seconds on all three phases. The probability that significant transformer saturation would occur on some of the phases is very high.

In addition, the phase delay method might not even work during all three-phase source failures. There are some three-phase source failures where all voltages do not collapse to zero volts immediately, such as a drooping source voltage due to heavy overload or excessive contact arcing when a breaker opens. In these cases, simply using the phase difference as the transfer time delay will create an error because it assumes that the volt-seconds accumulation stops at the time of the failure detection (as in Figure 1), and resumes only when the alternate source is turned on. This assumption can create a total volt-seconds which is unpredictable. (Figure 2)

In Figure 2, the source failure waveform is shown by the slowly decaying solid red line, while the point of source failure detection is indicated by the dashed vertical red line. As in the Figure 1 example, the transfer is delayed starting from the point of failure detection and ending at the point indicated by the vertical blue line. Although the light red and blue shaded areas add up to a full half cycle area, the actual volt-seconds applied to the transformer also includes the extra dark red area. This makes the total area (and resulting flux) much larger than a normal half cycle area, causing at least a partial saturation of the core.

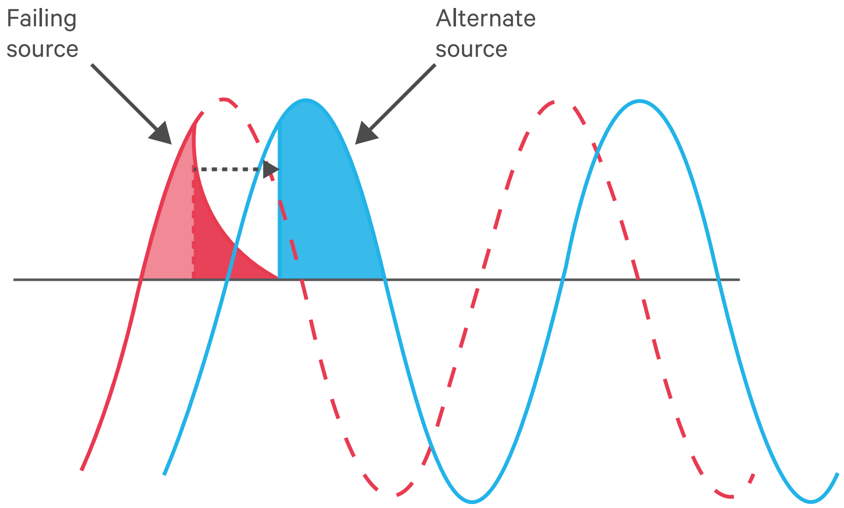

Figure 2

Optimized Transfer Method

The optimized transfer algorithm method, which is patented by Vertiv™ and used in its Liebert® STS2 static transfer switches, eliminates the issues associated with the phase delay method; thus giving it a distinct advantage over other methods. This method continuously tracks and integrates each phase of the voltage applied to the transformer primary windings. This means that the control algorithm knows the state of flux for each phase at all times prior to – and during – a transfer operation. The algorithm individually determines the proper time to turn on each phase of the alternate source so the resulting flux is maintained within tolerance levels and is balanced around zero for all three phases. This is accomplished independently of how quickly each phase voltage collapses, as well as which of the phases or how many fail.

Through the use of some typical source failure events, one can see how the optimized transfer method of eliminating transformer saturation compares to the phase delay method.

Figure 3 illustrates the typical currents created by not eliminating transformer saturation. The figure illustrates a primary source failure by tripping a three-phase breaker when the sources are 90° out of phase. The alternate source is switched on as soon as possible after detecting the primary source failure, creating severe levels of transformer inrush current. (Note that the alternate source cannot be turned on immediately; a "break-before-make" delay is necessary to avoid cross conduction between sources.)

Figure 3

Illustrating a transfer under the same conditions as in Figure 3, Figure 4 shows how the optimized transfer method completely eliminates the transformer inrush current.

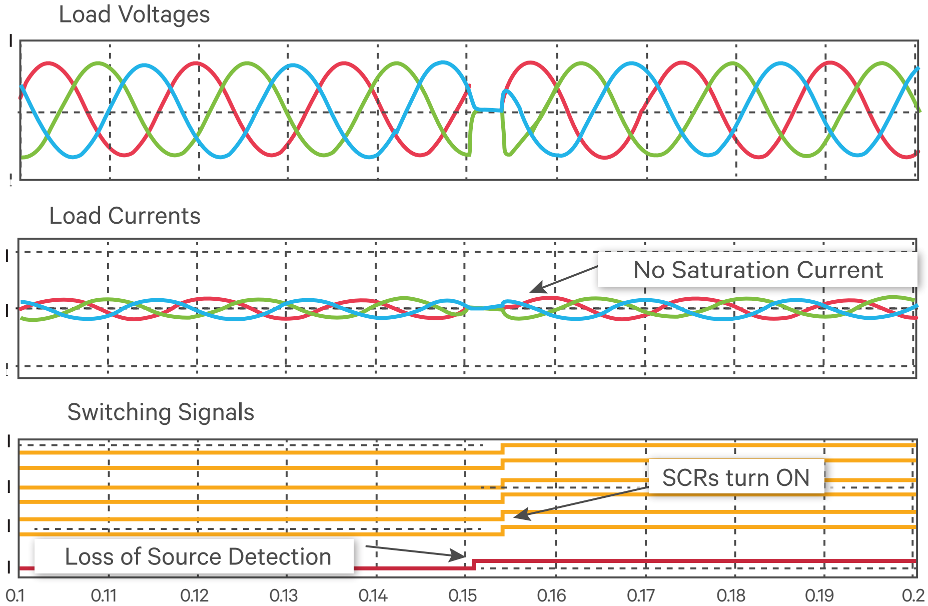

Figure 4

Figure 5 shows how the phased delay approach works for a three-phase open breaker failure.

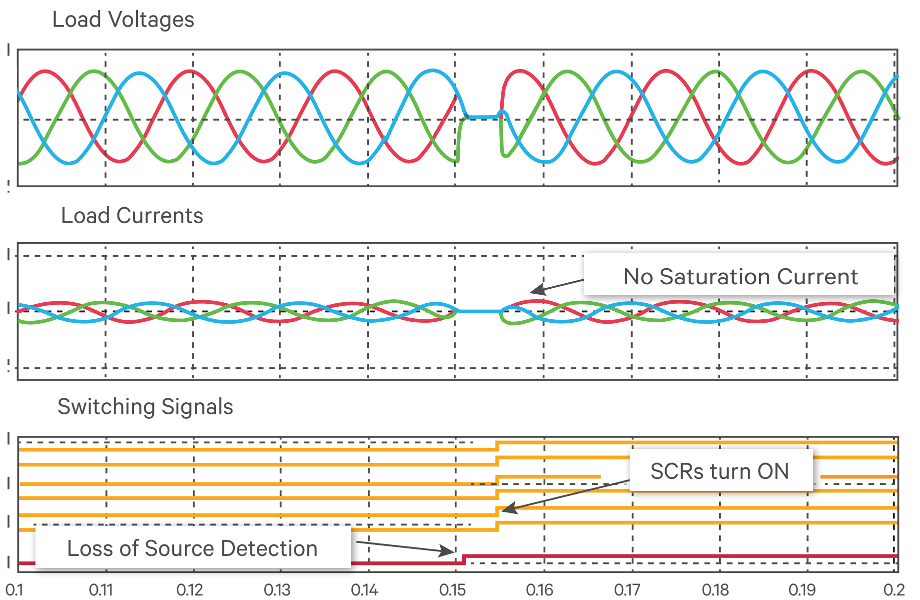

Figure 5

Figure 6 illustrates how the optimized transfer method works for a single phase line to ground short event with sources 90° out of phase (preferred leads alternate).

The illustration shows that the saturation currents are completely eliminated just as with three-phase the breaker open example. Also, the alternate source phases are not all turned on at the same time, keeping the flux balanced on all three phases.

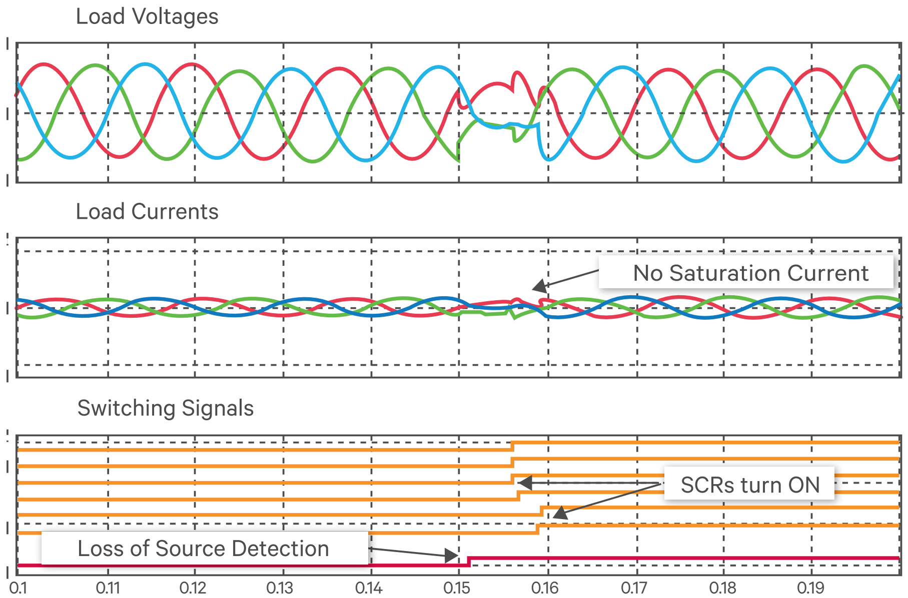

Figure 6

Figure 7 illustrates how utilizing the phased delay method under the same condition results in all phases being turned on at the same time.

This does not balance the flux and significant saturation currents result.

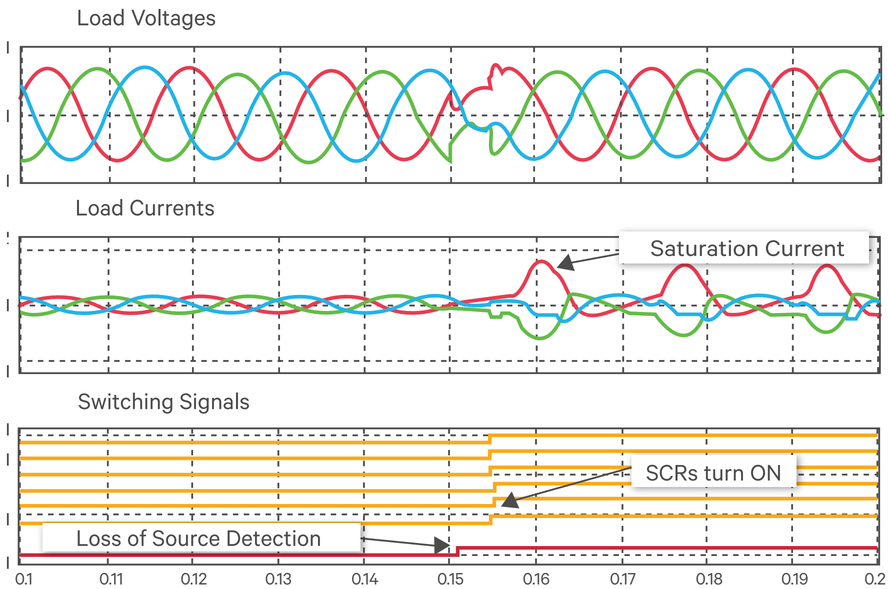

Figure 7

Optimized Transfer Voltage Pulsing

Depending on the phase angle difference between sources and the point in the voltage waveform where a preferred source failure occurs, there may be transfer conditions which result in a relatively long period of time before the flux balance point is reached and the alternate source is turned on (i.e., a long transfer time). Although transformer saturation is still avoided in these cases, the load voltage interruption may be less than desirable in certain applications.

Figure 8 illustrates an example of a long transfer time. In this case, the alternate source leads the preferred source by approximately 115°. It shows the preferred source (red line) failing and a transfer to the alternate source. To balance the flux and avoid transformer saturation, the alternate source must be turned on at the point indicated by the "balance flux" arrow. The areas under the two voltage curves – shown by the red and blue shaded areas – must equal a full half cycle of area to maintain flux balance. This results in no voltage at the static transfer switch output for nearly three-quarters of a cycle.

This is where the "voltage pulsing" function of the optimized transfer method provides an advantage. While waiting for the flux balance point to occur, if it is determined that the alternate source voltage can be applied briefly (turned on then back off) without creating excess flux, and then subsequently turned on again at a point which will re-balance the flux (successfully avoiding transformer saturation), then the static switch creates a voltage pulse.

This action has two benefits. Not only does it apply voltage to the load that would not have been applied otherwise, it also can cause the eventual flux balance point to occur earlier during the next half cycle so that the overall transfer time is shortened. Consequently, the average root mean square (RMS) voltage seen by the load during transfers is significantly increased.

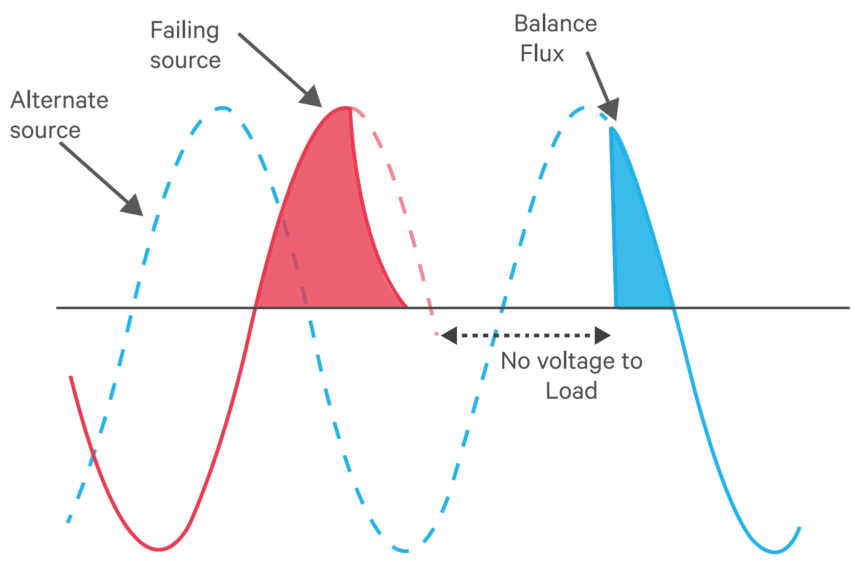

Figure 8

Figure 9 shows the same transfer conditions as Figure 8, but with voltage pulsing applied. In this case, turning on the alternate source at the point indicated by the pulse arrow creates a negative flux (since the voltage is negative) as opposed to the positive flux which was created by the failing source. This pulse area does not result in a total area (blue area subtracted from red) that adds up to a full half cycle. However, if the voltage is turned off at the point indicated by the turn off arrow, and then back on at the point indicated by the balance flux arrow, the sum of all three areas does sum properly - the red area, minus the first blue area, plus the second blue area sum to one full positive half cycle area. The time of voltage loss is significantly decreased as compared to Figure 8 where voltage pulsing is not used.

The voltage pulse results in a temporary reduction of net flux (the red area minus the first blue area) so it does not risk saturating the transformer. This is a requirement of the voltage pulsing action – the net flux created by the voltage pulse must not result in a flux which saturates the transformer. Furthermore, the resulting net flux value must be such that it can be subsequently "corrected" (i.e., made to sum to a full one half cycle area) on the next half cycle of alternate source voltage.

This voltage pulsing operation, an exclusive feature of The Liebert® STS2, represents a significant advantage over other available products by maintaining voltage to the load during emergency transfer events.

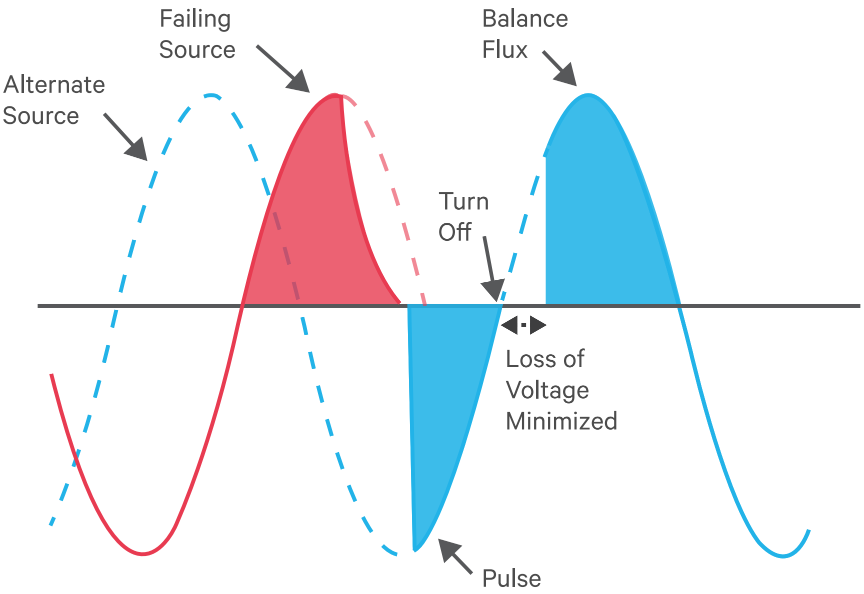

Figure 9

Conclusion

The phase delay method of preventing transformer flux saturation simply delays the transfer to the alternate source based on a time delay derived from the phase difference between the two static switch sources. While this method works well for sudden three-phase voltage failures, it does not work well for other common source failure cases, such as single phase losses.

The optimized transfer method patented by Vertiv™ is a more effective means for eliminating transformer saturation. This method continuously calculates the transformer flux for each phase independently and turns on each phase of the alternate source at the right time to prevent saturation on all phases, no matter how the source failure occurred. In addition, the optimized transfer determines when a voltage pulse may be applied to the static transfer switch output, which will maintain a higher average voltage to the load during otherwise long transfer times while still preventing transformer saturation.

Read more about optimized control in the Vertiv white paper: "Using Static Transfer Switches to Enhance Data Center Availability and Maintainability" on VertivCo.com.

VertivCo.com | **Vertiv Headquarters,** 1050 Dearborn Drive, Columbus, OH, 43085, USA

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