WHITE PAPER

Preventing transformer saturation in static transfer switches

A Real Time Flux Control™ Method

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Introduction:
Static Transfer Switches (STS) are essential components in data center power system configurations. Mainly relying on transformers primary side switching, these devices are the bridge between the power sources and the power distribution units. This architecture offers many advantages to the customer in terms of smaller footprint and lower costs; however, if not properly switched high transient inrush in downstream transformers will occur.

The inrush currents produced degrade the power quality of the preferred source, overload upstream UPS's and trip protective circuit breakers. The inrush currents can also create intolerable forces in the windings, which in turn reduce the lifecycle of power transformers as these currents can reach the short circuit rated value and can last many cycles before they dissipate.

This paper will explain the saturation phenomena in detail, derive appropriate equations to understand this behavior and present a state of the art method used by the SuperSwitch®4, static transfer switch, to successfully eliminate and limit the inrush should a transfer be needed.

What are we solving?
The typical data center system design incorporates two separate Uninterruptible Power Supplies A and B feeding the preferred and alternate sources of the SuperSwitch®4, this is shown in figure 1. These devices are the bridge between the power sources (UPSs) and the power distribution units (PDUs) where a transformer is needed to typically switch the 480V side (primary) to the 208V side (secondary). The primary side switching (480V) is the most common and cost effective architecture to the customer in terms of smaller footprint and lower costs because only one transformer is needed. The alternative architecture would be to switch the secondary which would require each source to have its own fully rated transformer and increase the rating of the SuperSwitch®4.

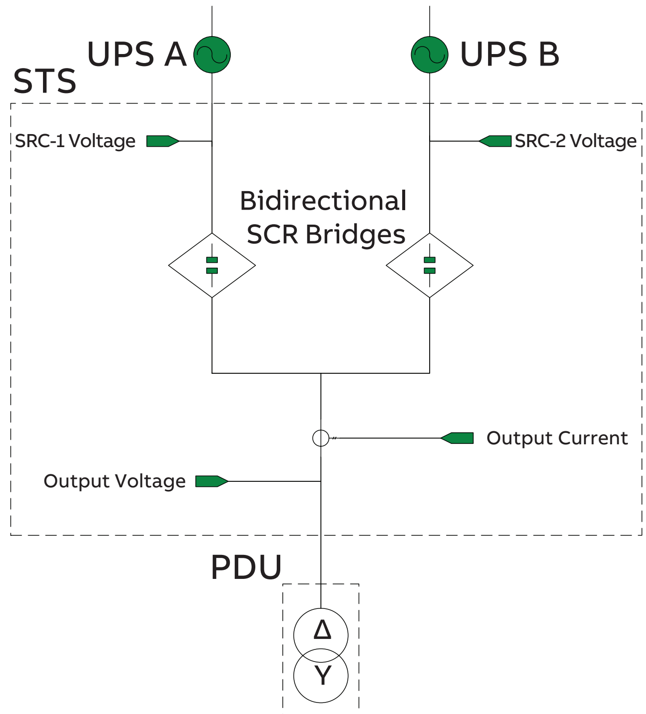

Figure 1: Primary Switching Architecture

Typically UPS A and B are fed from the same utility grid and thus their inverters will synchronize to their inputs and accordingly will be in phase. However, during battery operation, each UPS runs on its own internal clock and the sources will drift apart in phase. The problem is more obvious if each UPS has its own dedicated emergency generator. When a 480V SuperSwitch®4 needs to conduct an emergency transfer during an out of phase condition large inrush currents drawn from downstream PDU transformers can occur if the method of switching is improper. Depending on the transformer used, the inrush produced is capable of reaching 11x the rated current during an emergency transfer, the SuperSwitch®4 and its components are designed to handle this extreme overload situation but there are some significant problems triggered elsewhere threatening the data center reliability and availability:

- Breakers will likely trip depending on their sensitivity and the inrush magnitude.
- Upstream UPSs should enter some “current limit mode” and might transfer to Bypass.
- Stress caused to all upstream infrastructure.

Some solutions:
Few solutions exist to this problem; one would be to have a topology where each source is connected to its own PDU. This approach would not suffer from inrush as the downstream transformer is completely eliminated; however, more space is required and the additional magnetics is costly. Some UPS manufacturers have worked on solutions to force UPSs to be synchronized, however this adds complexity and single points of failure which would threaten the reliability and availability of the data center.

The best solution:
A real time switching method
With state of the art digital signal processors and a newly developed algorithm[1] that will be introduced in this paper, an innovative approach was created: Real Time Flux Control™ for dynamic inrush restraint (DIR), this approach makes it possible to switch the primary side of the transformer while exceeding the CBEMA/ITIC standards regardless of the phase difference of the two sources or the failure type. The method computes the flux trapped in the transformer in real time and continuously determines which SCRs to fire independently should a power quality event occur.

The next sections will introduce some transformer principles and derive appropriate equations to solve the problem discussed, results will be examined and peak inrush investigated so as to evaluate the method.

Transformer saturation and the inrush equation:
To understand the transformer saturation and how it produces inrush currents a simplified equivalent circuit for an unloaded transformer is shown in figure 2.

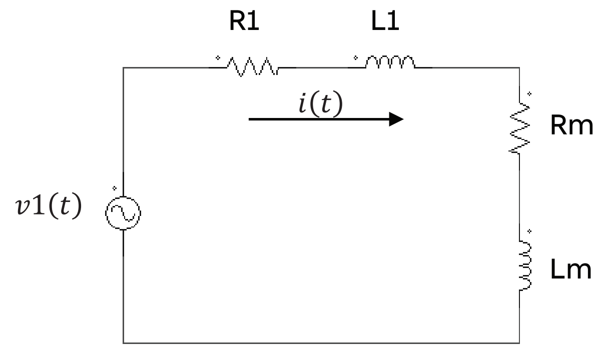

Figure 2: Equivalent Circuit of an unloaded transformer.

Where:

V1 is the supply voltage.
Lm is the core magnetizing inductance.
Rm is the core loss resistance.
L1 is primary winding inductance.
R1 is primary winding resistance.
Assuming the transformer supply voltage has a sinusoidal waveform:

$$v1(t) = Vm * \sin(2 * \pi * f * t + \alpha) \qquad (1)$$

Where:

Vm is the voltage Amplitude.
f is the frequency in Hz.
α is the energizing angle, this parameter as it will be shown later, is of great importance.

Writing KVL[2] for the circuit shown above:

$$L * \frac{di(t)}{dt} + \mathrm{R} * i(t) = Vm * \sin(w * t + \alpha) \qquad \mathbf{(2)}$$

Where:

$i(t)$ is the instantaneous no-load current, L = L1 + Lm and R = R1 + Rm.

[1] Patent Pending
[2] KVL: Kirchhoff's Voltage Law

Alternatively:

$$L_m * i(t) = N_1 * \emptyset(t) \qquad (3)$$

Where:

N_1 is the number of primary turns.
$\emptyset(t)$ is the instantaneous magnetic flux.

Substituting (3) in (2) produces a first order differential equation:

$$N_1 * \frac{d\emptyset(t)}{dt} + N_1 * \frac{R}{L} * \emptyset(t) = Vm * \sin(w * t + \alpha) \qquad (4)$$

The solution to equation (4) takes on the following form:

$$\emptyset(t) = -\emptyset_m * \cos(w * t + \alpha) + C * e^{-\frac{R}{L} * t} \qquad (5)$$

Where:

$\emptyset_m$ Is the flux amplitude and can be obtained from the applied voltage.
C is a constant that is derived from the initial power up.

When the transformer core is magnetized in a specific direction, it will not drop back to zero magnetization when the initial field is removed. It can be driven back to zero by a field of opposite direction. This causes the magnetizing curve of the transformer (or any ferromagnetic material) to trace out a loop called the hysteresis loop or the B-H curve, as shown in figure 3.

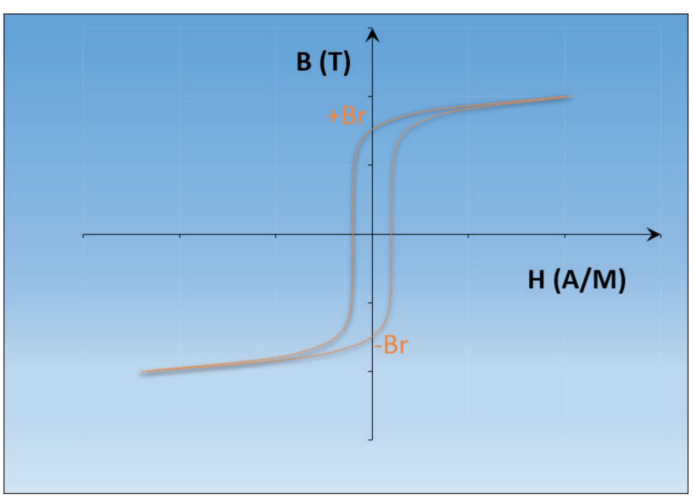

Figure 3: B-H curve of a power transformer

The amount of flux trapped in the core material of any transformer is called the original flux density and can take either a positive or a negative value (Br) as shown in figure 3. At first power up the transformer will still hold this amount of flux noted $\emptyset_r$.

In this case:

$$\emptyset(0) = \pm\emptyset_r \qquad (6)$$

Using equations (5) and (6) and solving for the constant C:

$$C = \emptyset_m * \cos(\alpha) \pm \emptyset_r \qquad (7)$$

Replacing C in equation (5) yields:

$$\emptyset(t) = -\emptyset_m * \cos(w * t + \alpha) + (\emptyset_m * \cos(\alpha) \pm \emptyset_r) * e^{-\frac{R}{L} * t} \qquad (8)$$

Knowing the instantaneous flux the current can easily be calculated by:

$$i(t) = \frac{N_1}{L} * \emptyset(t) \qquad (9)$$

From equations 8 and 9, it is clear that the transformer saturation depends on the firing angle α and the residual flux $\emptyset_r$ trapped in the core. Because power transformers are operated at a peak flux $\emptyset_m$ close to the knee of the transformer's B-H curve, only a modest flux increase beyond saturation, or a symmetry shift of the flux will result in very high magnitude current "pulses," because at that instant the slope and therefore the inductance is very small, in figure 3 the slope at any point is proportional to the winding inductance L.

Transformer switching theory:
Equation 8 can further be split into a DC component and an AC component:

$$\emptyset(t) = \emptyset_{AC}(t) + \emptyset_{DC}(t) \qquad (10)$$

Where:

$$\emptyset_{AC}(t) = -\emptyset_m * \cos(w * t + \alpha) \qquad (11)$$

$$\emptyset_{DC}(t) = (\emptyset_m * \cos(\alpha) \ \pm \emptyset_r\ ) * e^{-\frac{R}{L}*t} \qquad (12)$$

As explained in the previous sections, in order to avoid any inrush currents the transformer core needs to be kept away from saturation, which implies that the DC component represented by equation 12 has to be mitigated. The residual flux $\emptyset_r$ is uncontrollable and is mainly dependent on the transformer geometry and the instant of de-energization. On the other hand the firing angle can easily be controlled since the power supply V1 is usually connected to the transformer through some power semiconductors SCRs, IGBTs, etc. In that context α will be of highest importance in the inrush restraint algorithm. It should be observed that the DC component of the flux has an exponential term which is responsible for the decaying nature of the inrush current.

Figure 4 shows instances of optimal transformer energizing or re-energizing. At these two instants, the prospective flux and the residual flux are equal, eliminating the DC component of the flux $\emptyset_{DC}$ thus preventing the transformer saturation and inrush currents.

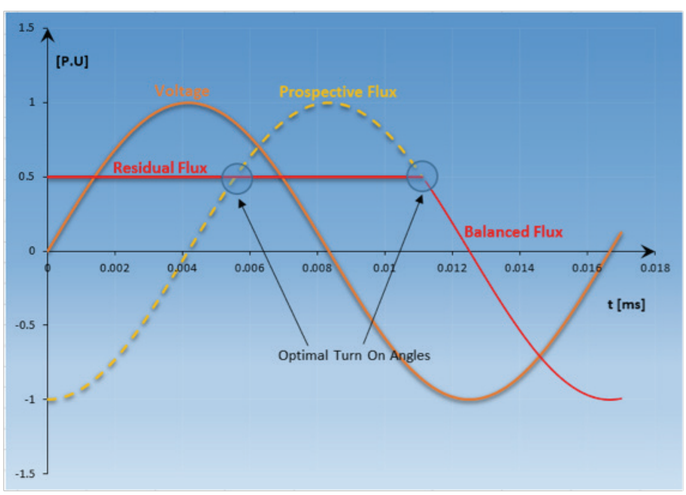

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Figure 4: Optimal firing angles

The static transfer switch architecture:
As stated in the introduction of this document, Static Transfer Switches (STS) are devices that bridge the power sources and the power distribution units (PDUs) by using SCRs as switching devices as described by figure 1. The theory of transformer saturation was covered in the previous sections. From this point and forward the SuperSwitch®4 performance and how it handles transfers will be the focus. To avoid saturating the transformer, a controlled switching method needs to be implemented to eliminate the DC flux component described by equation 12 in the previous paragraphs. To maintain acceptable power quality the SuperSwitch®4 needs to transfer the load from being fed by a preferred source to an alternate.

The missions that the SuperSwitch®4 needs to accomplish when performing a transfer are summarized by the following points:

1. Suitable primary switching method for three phase power systems
2. Compatible with all types of transformers
3. Meets for exceeds the CBEMA or ITIC standards
4. Inrush in all three phases

To overcome all the shortcomings and achieve the targets discussed herein, the Real Time Flux Control™ method was developed as the ultimate flexible solution. Taking advantage of proprietary state of the art printed circuit board (PCB) developed, powerful digital signal processors (TMS320C6746) were used for the necessary computation and power detections algorithms. The PCB used communicates via high speed fiber links with gate drive boards controlling all the SCRs at each source, the embedded controls is in charge of finding the optimal firing angles limiting the inrush in case a transfer is needed.

Real Time Flux Control™ method:
Taking advantage of the internal architecture of the SuperSwitch®4 and cutting edge technology available, a method was invented to dynamically reduce the transformer inrush. This method controls the amount of flux induced in the core should a transfer be needed, accordingly given the name Real Time Flux Control™ for dynamic inrush restrain. Because the goals discussed in the previous section must to be met and the transformers used in these applications are delta to wye, the algorithm will have two optimal firing angles.

The DSP receives the voltage samples via high speed communication links and computes the normalized flux in real time. Should a transfer decision be made the processor will have to fire the SCRs at the optimal closing times given by:

$$\begin{cases} \lambda 1 = \int v1(t).dt \\ \lambda 2 = \int v2(t).dt \end{cases} \Leftrightarrow \quad |\lambda 1 - \lambda 2| \leq \epsilon \qquad (13)$$

Where:

$\lambda 1$ is the normalized three phase fluxes of source 1
$\lambda 2$ is the normalized three phase fluxes of source 2
ϵ is the error allowed and should be kept as small as possible

The fact that the fluxes are normalized makes the SuperSwitch®4 compatible with any transformer type and size, no changes are needed should the customer need a new Power Distribution Unit with a different transformer. If an emergency transfer is needed the SuperSwitch®4 would first issue an un-gate command to disconnect the load from the failing source. This is shown by step 1 in figure 5 where all the SCRs are turned off[3]. Once the SCRs have completely commutated off, the algorithm then starts monitoring the very first phase that satisfies equation 13. Once that phase is found it has to be fired as fast as possible; this is represented by step 2. The algorithm was designed such that it does not miss an optimal time to fire, thus enabling to transfer the load within a cycle and thus exceeding the CEBMA and ITIC standards.

Finally, the system monitors the other two remaining phases, once equation 12 is satisfied all phases are fired completing the transfer from the preferred to the alternate source, step 3. The total time required to finish all these steps cannot violate the CBEMA or ITIC standards as stated before. The next section will demonstrate this performance further.

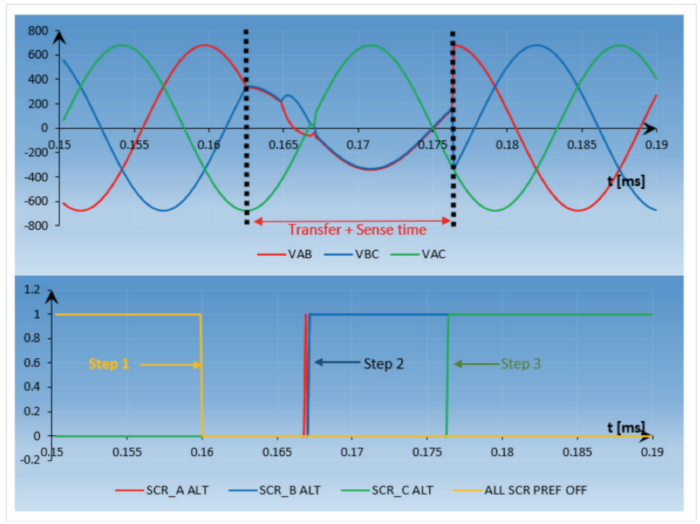

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Figure 5: Steps required to transfer the load.

The algorithm can fire all the phases at the same time as well if the fluxes of the alternate source are deemed satisfactory to equation 13. This is possible only under certain cases if the phase difference between the two sources allows for such a condition to happen. If this is done, then the transfer is accomplished very quickly and called a super transfer. This makes the combined sense and transfer time less than 8 milliseconds as shown in figure 6.

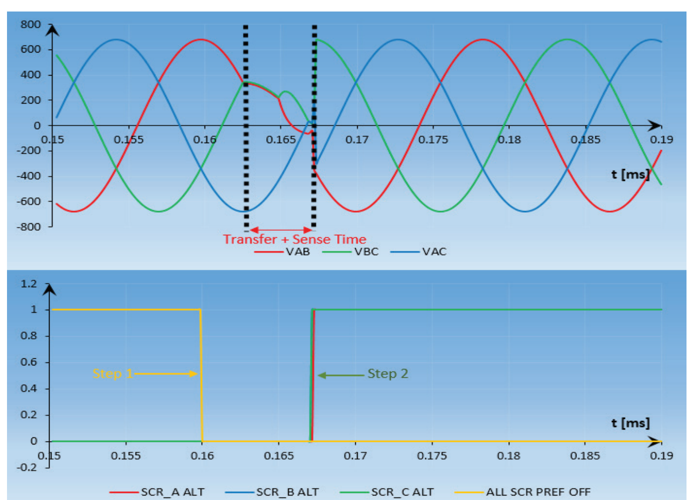

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Figure 6: Steps required to do a super transfer

[3] For an SCR to completely shut off the gating signal needs to be removed and the current flowing should get to the next zero crossing

How well does the novel method work:
Currents and voltages were measured at the different probing points shown in figure 1. Figures 7–12 show the performance of a 480V, 600 amp SuperSwitch®4 feeding a 225kVA PDU transformer. No inrush was observed, in addition the combined sense and transfer time is given below each waveform and is measured to be less than a cycle even under severe test corners, like a complete loss of source or loss of one phase.

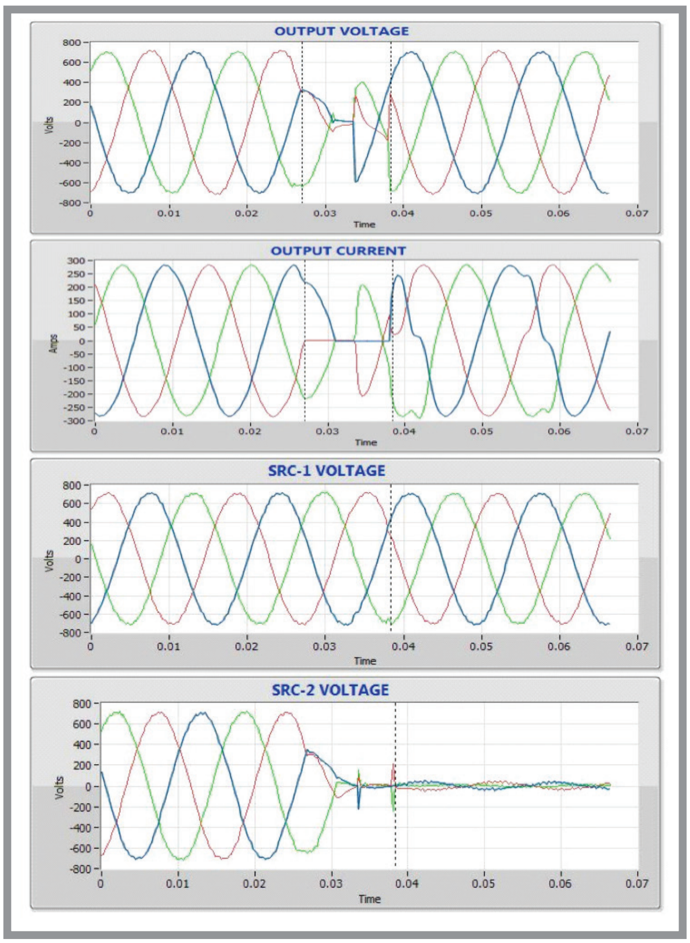

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Figure 7: Phase: 120 degree, outage time: 11.50 ms
Condition: Loss of source 2

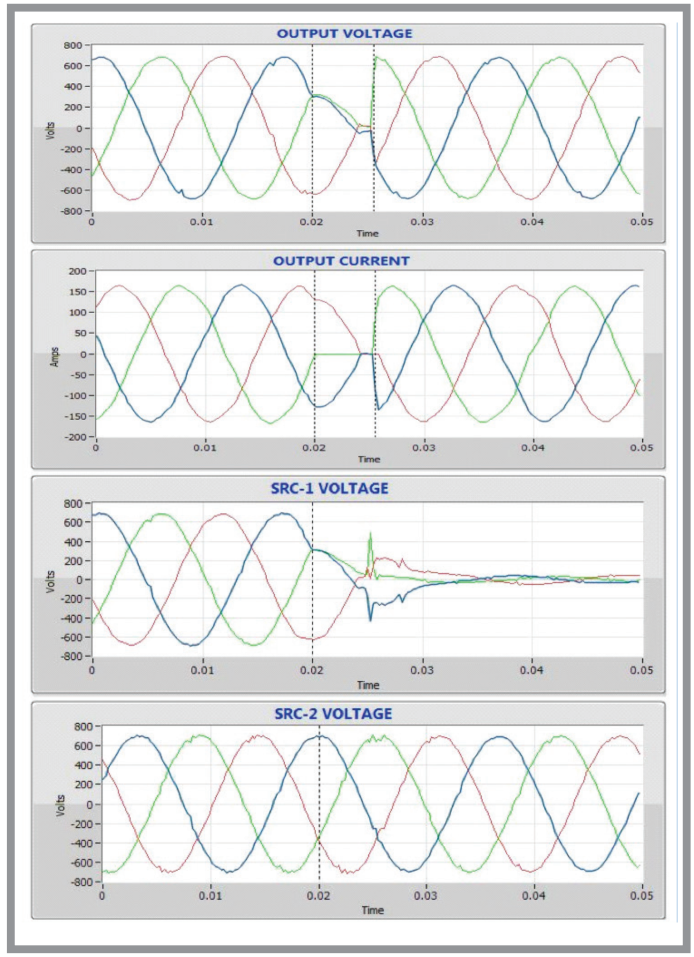

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Figure 8: Phase: 60 degree, outage time: 5.50 ms
Condition: Loss of source 1

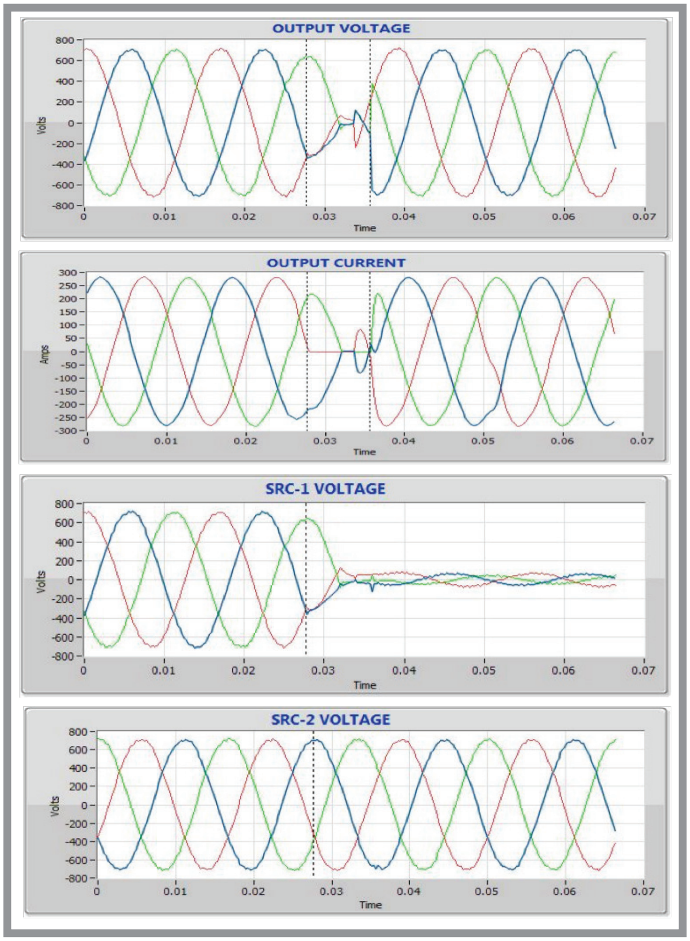

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Figure 9: Phase: -120 degree, outage time: 8.00 ms
Condition: Loss of source 1

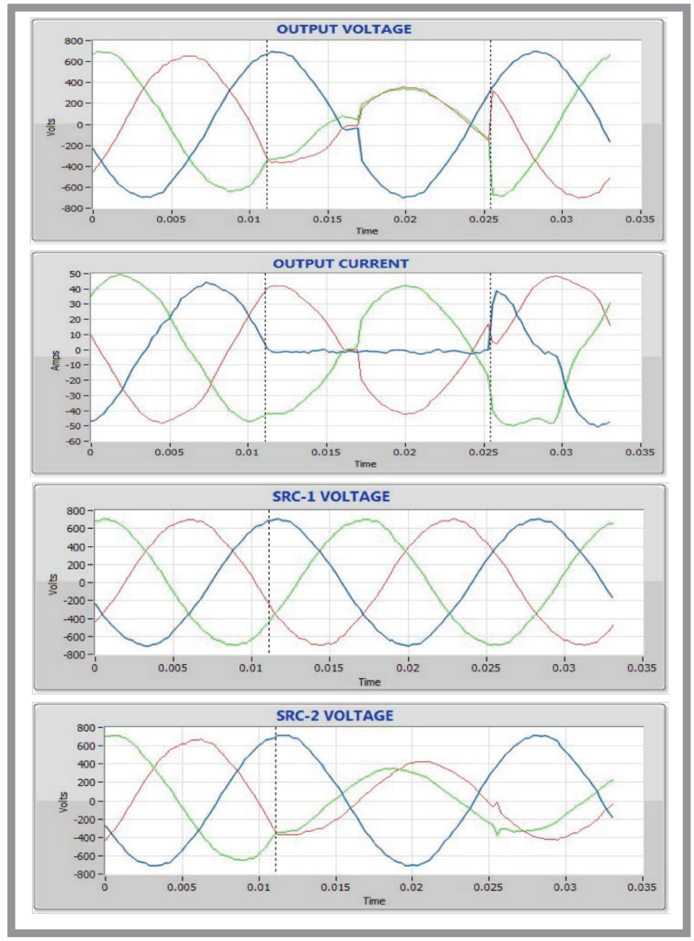

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Figure 10: Phase: 0 degree, outage time: 14.50 ms
Condition: One phase loss of source 2

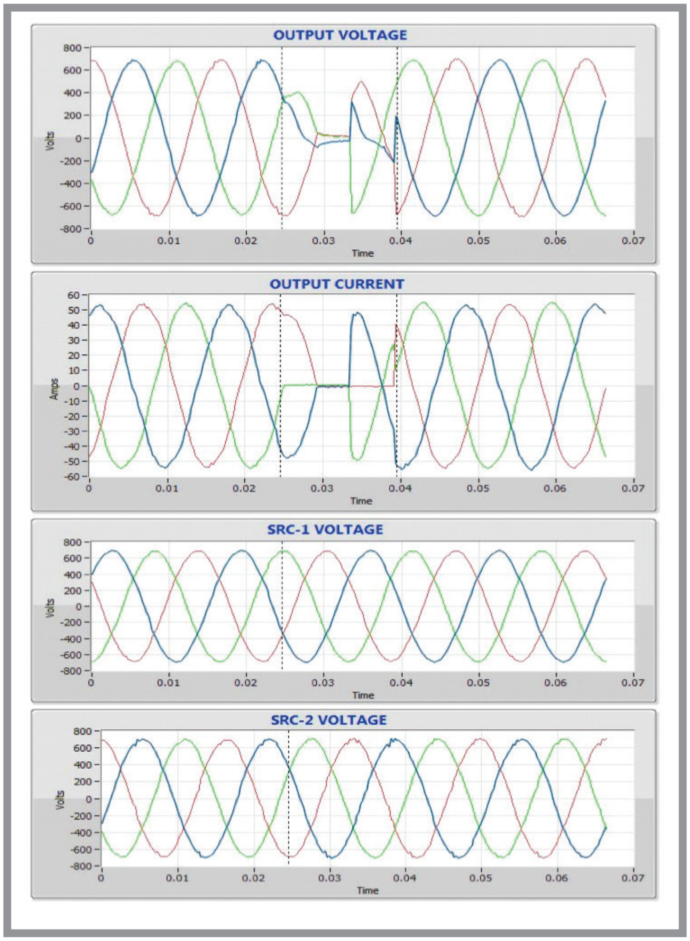

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Figure 11: Phase: -60 degree, outage Time: 14.50 ms
Condition: Manual transfer

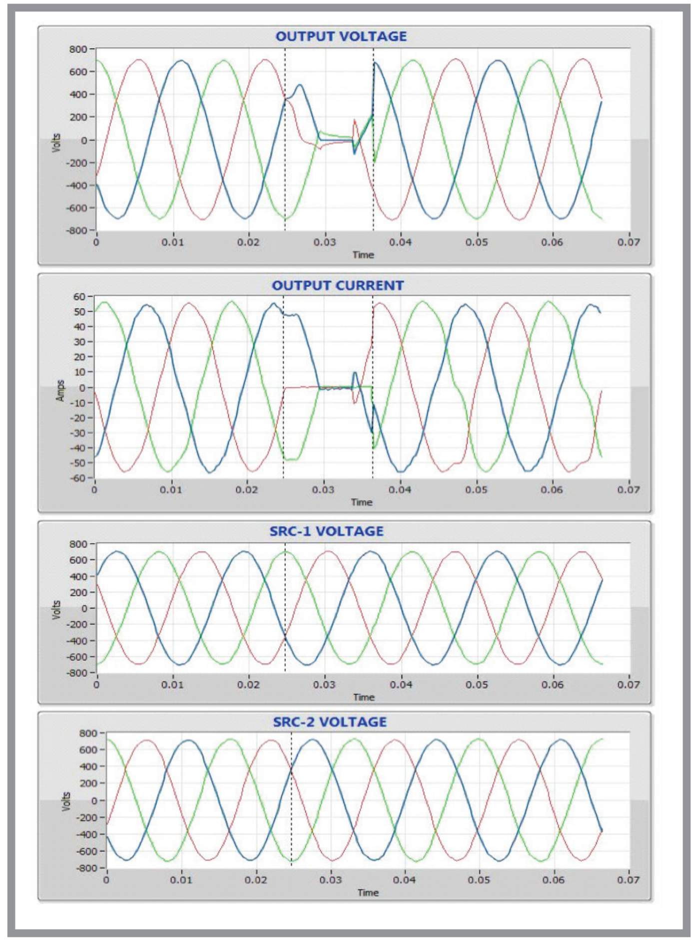

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Figure 12: Phase: 180 degree, outage time: 11.50 ms
Condition: Manual transfer

The waveforms shown in figure 7–12 clearly prove that the SuperSwitch®4 is capable of successfully transferring the load under multiple fault condition in less than a cycle. Note that in figure 8 a super transfer was possible and all the alternate source SCRs were fired at the same time making a complete transfer possible in less than 8 milliseconds. The lowest RMS drops observed during all the transfers taken for phases A, B and C were computed by:

$$\%\,RMS\ drop = \frac{Rated\ RMS\ Voltage\ Bus - Lowest\ RMS\ drop\ measured}{Rated\ RMS\ Voltage\ Bus} * 100 \quad (14)$$

For the case of a 480V RMS load we get:

$$\%\,RMS\ drop = (1 - \frac{Lowest\ RMS\ drop\ measured}{480}) * 100 \quad (15)$$

These values were then plotted against the outage time, figure 14 shows that all the data points obtained are located well inside the acceptable power zone and thus exceeding the CBEMA and the ITIC requirements.

The Real Time Flux Control™ for dynamic inrush restraint also does a phenomenal job limiting the inrush peak value in transformers to below 1.2x. This value is calculated as shown in figure 13 where the peak transformer current rating is always a constant depending on the KVA of the system.

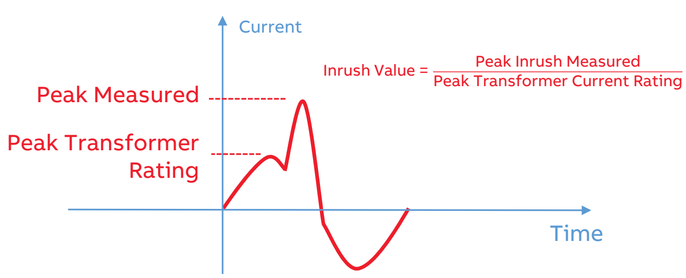

Figure 13: Graphical representation of inrush value

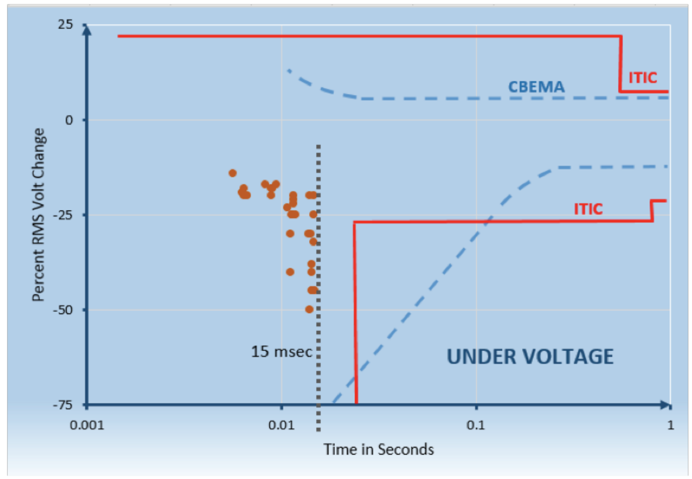

Figure 14: 60Hz data for critical loads meeting CBEMA/ITIC curves.

How is the SuperSwitch®4 set to handle transfers?
As explained before, the SuperSwitch®4 constantly monitors the power quality of both sources taking into account the customer specified thresholds. In addition three transfer modes are available to customers to choose from: A9, DIR always and DIR Limited.

1. **A9:** is a proprietary algorithm that is used only when the phase difference between the sources is less than a user defined phase angle, the range of this setting is adjustable up to a maximum of 30 degrees. This method is not recommended for larger phase differences and customers are recommended to make this window as small as their application permits. To explain this method further and limiting the study to only one phase instead of three for the sake of simplicity, the layout of the SCRs and sources is shown in figure 15. If A9 was the chosen transfer mode and the two sources were synchronized then the first step is to un-gate both Source 1 positive and negative SCRs. The algorithm then detects which SCR is safe to fire on source 2 as an alternate depending on the phase difference of the two UPSs, if the sinusoidal voltage happens to be positive then the negative SCR will be fired because it is not conducting and no chances of cross connect exist. In a third and final step the SuperSwitch®4 would then wait until the next zero crossing to fire the positive SCR completing a seamless transfer. These steps are clearly depicted in figure 16.

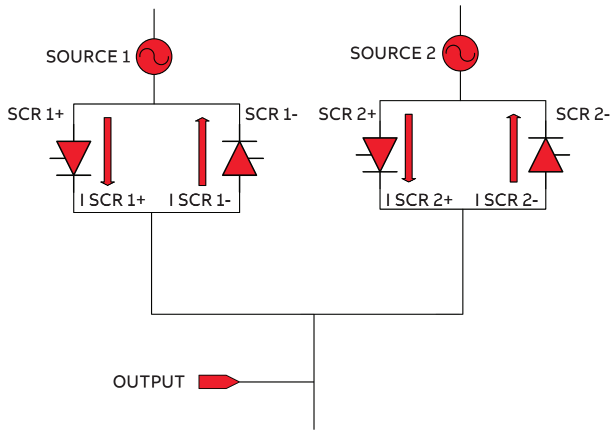

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Figure 15: Static Transfer Switch and A9 algorithm

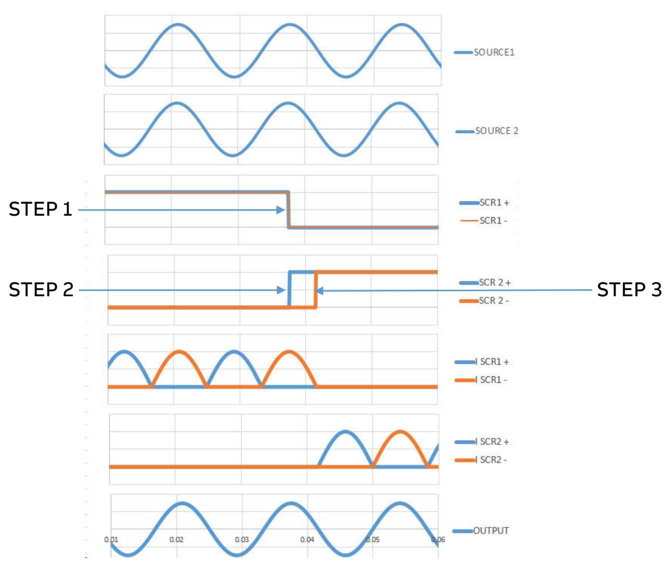

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Figure 16: A seamless A9 transfer, synchronized sources

2. **DIR always:** implies that the SuperSwitch®4 will always transfer using the approach described before and should result in no inrush no matter how far the two sources are drifted apart.

3. **DIR limited:** is the setting recommended for the SuperSwitch® 4 to determine which of the previous two methods to pick from depending on the phase difference.

Most customers use the recommended setting of **DIR limited** because the SuperSwitch®4 will auto select when, and if, the DIR function is needed depending on the phase difference as illustrated by figure 17.

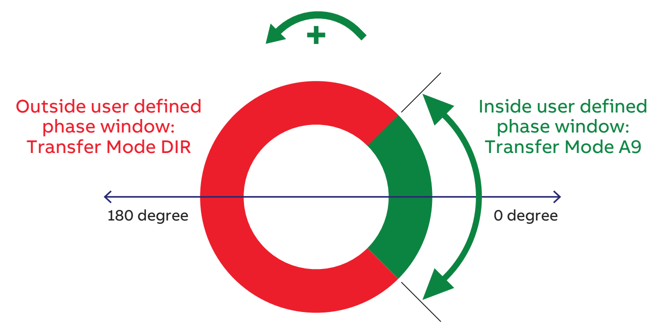

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Figure 17: DIR limited vs phase angle

Conclusion:
The data that was collected and presented in this literature proves that the Real Time Flux Control™ method for dynamic inrush restraint prevents the transformer from saturation while the SuperSwitch®4 transfers the critical load from a failing to an alternate source.

The following are some key points that this method achieves:

- Makes secondary switching (one PDU transformer) reliable.
- Eliminates the need for complex inverter control schemes.
- Maintains true independence between UPS systems (higher reliability).
- Keeps inrush value lower than 1.2x.
- Exceeds the ITIC and CBEMA curves standards for critical loads.
- Smoothly transfers the load without creating unnecessary voltage discontinuity and disturbances to the load.

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