Pre-Switch, Inc.

# The Operation of Auxiliary Resonant Commutated Pole (ARCP) and Its benefits for Electric Motor Drives

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## Abstract

This paper details the workings of the Auxiliary Resonant Commutated Pole (ARCP) forced resonant soft-switching architecture, which is now commercially valuable because of the advent of Pre-Switch's AI-based control technology, Pre-Flex™. This article also briefly discusses how Pre-Switch technology can be used to improve electrical motor efficiency and solve significant motor design challenges such as dV/dt ($^{dU}/_{dt}$), overshoot, and common mode noise. Pre-Switch estimates that before any other system parameters are optimized to take advantage of Pre-Switch's new possibilities, simply doubling the switching frequency ($F_{sw}$) will have a dramatic impact on the quality of the sine waves to the motor resulting in more torque and higher system efficiency from the battery terminals to the driveshaft. These benefits improve system efficiency, reliability, and available torque from low RPM, low torque, through to high RPM at full power output in EV and industrial motors.

*Note: The application of Pre-Switch technology to the benefit of other DC/AC and AC/DC applications such as solar, wind, and industrial markets is outside of the scope of this paper.*

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## Introduction

Pre-Switch significantly reduces switching losses by leveraging the ARCP topology in combination with Pre-Flex™, an intelligent soft-switching control technology. Pre-Flex has been shown to enable an ~80% reduction in IGBT switching losses and a ~95% reduction in switching losses in SiC and GaN MOSFETs. The effective elimination of switching losses opens a new frontier for system-level improvements in cost, efficiency, power density, motor efficiencies, and motor reliability. Pre-Flex also reduces EMI, inverter dV/dt ($^{dU}/_{dt}$), and common mode currents in motor bearings.

It is tempting to focus on the immediately evident inverter-level benefits such as increased efficiency, which cuts cooling cost requirements and can extend EV range modestly, or to increase the power throughput of the same output transistors in the inverter, which effectively lowers the switching costs and increases power density.

Alternatively, for the first time, engineers can now use switching-loss savings to increase motor inverter switching frequencies (~5X for IGBTs and ~20X faster for SiC and GaN) for the same inverter efficiency. In short, inverter output can improve efficiency in electric motors. The new motor efficiencies result from the increased inverter switching frequencies, which reduce the output ripple in the sine waves of current being fed to the motor. The reduction in output ripple lowers electric motor iron losses, the dominant cause of loss at low torque. The decrease in output ripple and resultant improvement in motor efficiency reduces heat generated in the motor. In-house and customer tests show that system-level gains are highest when the loss budget is used to switch faster to improve motor efficiencies.

## ZVS Background

In the late 1980s, engineers at General Electric invented the ARCP architecture to reduce switching losses significantly by zero-voltage switching (ZVS) and/or zero-current switching (ZCS). By the 1990s, the ARCP architecture was being extensively researched and was expected to find its way into all hard-switching applications. There was an expectation that a control loop with inputs including current, volts, and temperatures would be adequate control parameters to perform ZVS accurately and consistently. Unfortunately, these systems would 'react' to external events, resulting in hard-switching. Even if the timing calculations were correct, delay was inevitable. For these reasons and others, the ARCP ZVS system could not be kept stable across load, temperature, and manufacturing variances. The ARCP, without commercial success, was all but abandoned for DC/AC and AC/DC power converter applications by the late 1990s.

The fundamental obstacle was how to control the topology with varying input, output, temperature, and device behavior conditions. The Pre-Switch team reexamined the challenges presented by ZVS/ZCS through the lens of artificial intelligence (AI), with inspiration from the field of robotics. This new approach made it clear that ZVS is a classic intelligence application for two main reasons. First, the system has limited access to parameters, in a noisy environment, and therefore must operate with degrees of uncertainty. Second, as reactive behavior can never be 'on time,' the system must 'pre-act.' Signals must 'launch' without a well-defined stimulus to indicate when to act. Making ZVS a reality, therefore, requires a system that is statistical in adaptation and predictive in nature; an ideal application for AI.

A hysteretic type of error calculation was developed offline and scores a transition and adjusts for the next cycle. The algorithm accepts that it cannot know parameters such as $T_{jv}$ (virtual junction temperature) directly. As it turns out, as long as the control loop is fast and tight enough, there is no need to know $T_{jv}$. The Pre-Flex algorithm, therefore 'pre-acts' by driving the gates of the power switches, for example, based on a prediction of relative signals, on a cycle-by-cycle basis.

Pre-Flex accurately controls the timing of small, relatively low-cost auxiliary resonant switches, which are combined with inductors, and capacitors to ensure that ZVS or ZCS soft-switching continues independent of changes in bus Voltage or load currents. Pre-Flex also introduces Pre-Switch Blink™, a set of advanced safety features that monitor device performance and continuously communicate these data through an integrated serial port. Pre-Flex learns, remembers, and adjusts in-system on a cycle-by-cycle basis, ensuring clean and accurate soft-switching despite changing parameters such as input voltage, load, device tolerances, device degradation, and system and device temperatures. The result is the birth of true soft-switching for DC/AC applications as well as substantial improvements in AC/DC soft-switching. It was not until the introduction of Pre-Flex technology (along with other advancements over the past decades) that forced-resonance soft-switching became commercially viable.

## Benefits to electric motors

Pre-Flex technology dramatically reduces switching losses in IGBT and SiC MOSFETs. In electric motors and generators, this reduction of switching losses enables two new degrees of design freedom for EVs:

1. When $F_{sw}$ is kept unchanged, Pre-Flex technology adds efficiency gains within the inverter; the results will be more torque to the motor for the same battery power, an increased battery range, and reduced cooling needs and associated weight savings.
2. When Pre-Flex technology is used to increase the $F_{sw}$ to the point of the same inverter efficiency, current ripple is reduced, which decreases associated motor conductor and magnetic losses. The increased ratio between $F_{sw}$ and the electrical fundamental frequency thereby decreases the total harmonic distortion (THD) of the motor's phase current waveforms. The result is superior 'battery to driveshaft' system efficiency, increased battery range, and motor torque for the same input power - all with a cooler, more reliable motor.

Pre-Switch technology enables each of these options or any combination thereof. Further, Pre-Switch enables the advantages of a low dV/dt ($^{dU}/_{dt}$) in the motor despite an increase in the switching frequency. This benefits motor insulation, motor bearing reliability, and it reduces EMI. Preliminary designs suggest that Pre-Flex technology can extend EV range by 5-12% and significantly improve the efficiency of industrial motors.

The ability to balance between switching losses in the inverter and motor losses, as well as the elimination of a set of stubborn historical design constraints will unleash a new wave of advancement and innovation in motor design.

## Auxiliary Resonant Commutated Pole (ARCP)

The following is a simple explanation of the forced resonant soft-switching circuit topology known as ARCP utilizing MOSFETs. (external anti-parallel diodes shown for clarity)

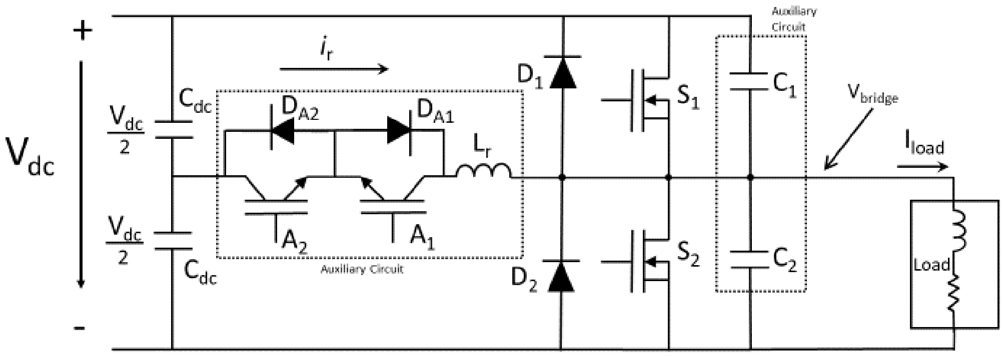

*Figure 1: ARCP half single-phase schematic*

## Description of the ARCP circuit

An ARCP circuit is used for each phase leg in power converter designs as shown in Figure 1. The circuit consists of resonant devices $C_1$ and $C_2$ (the sum of which is $C_r$), $L_r$ and active switches $A_1$, $A_2$, and rectifiers $D_{A1}$ and $D_{A2}$ shown above. It is important to point out that the additional resonant devices are small and low cost when compared to the main switches $S_1$ and $S_2$. With Pre-Flex's control, the ARCP circuit enables new efficiencies and higher switching frequencies for enhanced power conversion performance and cost reduction.

As shown in Figure 1, Pre-Switch uses low-cost IGBTs for resonant switches on both IGBT and SiC/GaN MOSFET-based systems. The resonant switches are generally selected to conduct ~1.5x the peak load current, but the switches only need to carry this current for a minimal duty cycle (1-5%) and hence only need to be pulse rated. The size of the capacitors for $C_1$ and $C_2$ are typically between 10-200X larger than the Miller capacitance of the main switches, so they are a low-cost component addition. The resonant inductor $L_r$ is also surprisingly small and inexpensive. $L_r$ varies with parameters such as voltage, $F_{sw}$ and resonant current, among others. Pre-Switch uses advanced modeling techniques to determine the resonant component types and values to achieve the desired system goals.

## Theory of operation

The following section refers to the ARCP circuit in a single-phase leg of a power converter using SiC MOSFETs. (External anti-parallel diodes shown for clarity.) The circuit dramatically reduces switching losses during transitions for the following cases:

1. Commutation from low to high switch where current flows from ground to output, requiring ARCP current injection to force the transition (Figure 7), and;
2. Commutation from high to low switch where current flows from $V_{bus}$ to output, requiring only a correct dead time as the bridge is self-commutating (Figure 10).

## State 1: Initial condition - Low side switch conducting

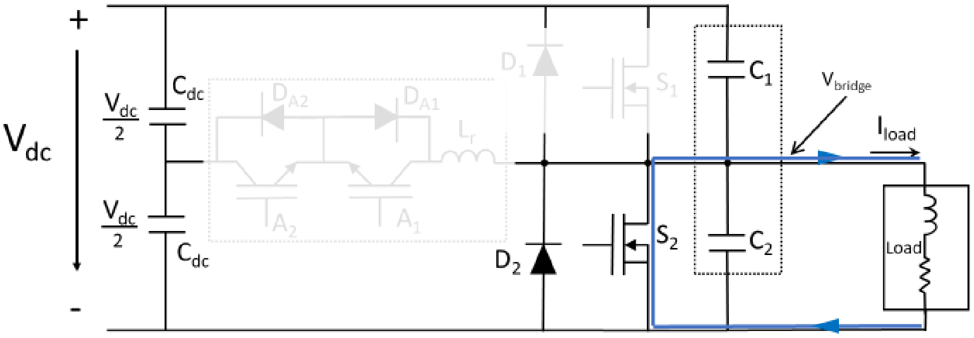

*Figure 2: State 1, initial state with D2 forward biased*

State 1 shown in Figure 2 shows $S_2$ as conducting. No power is coming from the supply. This is a typical situation when the load is inductive and current is flowing into it. Switch $S_2$ is on, but current flows in the reverse direction (and possibly also through $D_2$ depending on $V_{S2}$). The Voltage across $C_1$ equals $V_{dc}$.

## State 2: ARCP pre-charge

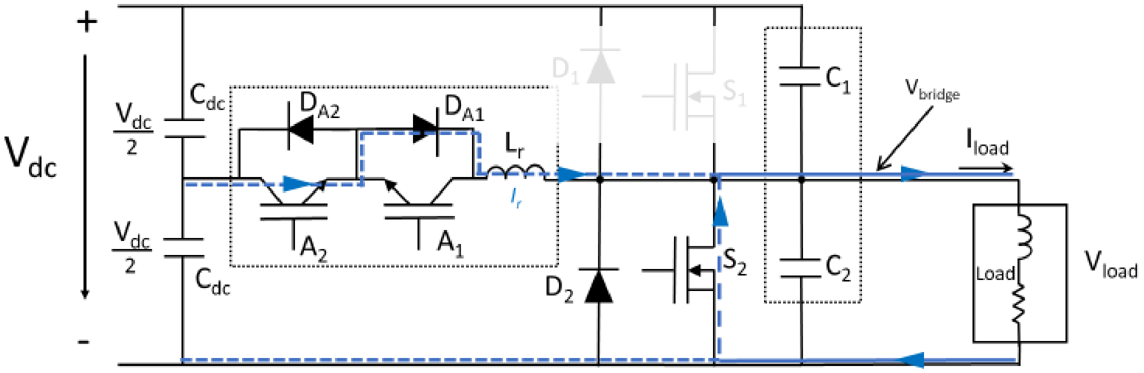

*Figure 3: State 2, Charge resonant inductor with $I_{load}$*

With a control signal to change $V_{bridge}$ from low to high; $A_2$ is turned on, applying a Voltage $V_{dc}/2$ across $L_r$. Current flows through $A_2$, $D_{A1}$, and $L_r$ shown above in Figure 3. The current through $L_r$, ($I_r$) increases according to the equation at right, where *t* is the charge time. During this period, as the current in $L_r$ increases, the current in $S_2$ falls. The total of $I_{S2} + I_r$ is the load current $I_{load}$. $S_2$ turn off timing is optimized to limit current through $D_2$. When $I_r$ equals $I_{load}$ (referred to as the 'pre-charge current'), and with $S_2$ now off; $V_{bridge}$ starts to rise.

$$Ir = \frac{\frac{Vdc}{2} * t}{Lr}$$

## State 3: Resonant commutation

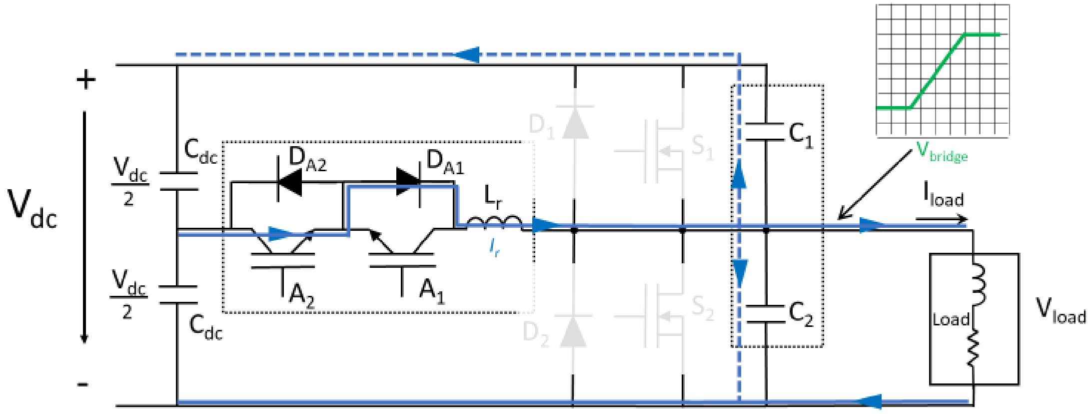

*Figure 4: State 3, resonant commutation of bridge Voltage*

In Figure 4 the current in $L_r$ ($I_r$) continues to increase. This increased current over the load current (or 'pre-charge current') is herein referred to as the 'commutation current.' With $S_2$ off, the current in excess of $I_{load}$ charges $C_1$+$C_2$, causing $V_{bridge}$ to rise from 0V. The ARCP current ($I_r$) continues to rise until the $V_{bridge}$ equals $V_{dc}/2$. At this point, the current in $L_r$ begins to fall because the Voltage across $L_r$ has now reversed. During this period both the $V_{bridge}$ and the ARCP additional current (($I_r$ - $I_{load}$) or 'commutation current') is sinusoidal with period:

$T = \pi\sqrt{\mathrm{Lr}C}$ *Where $C = C_1 + C_2$ in this example*

The current in $L_r$ continues to drive $V_{bridge}$ towards the positive rail of $V_{dc}$. When the Voltage across $S_1$ approaches zero, it ($S_1$) is turned on to begin sourcing load current. The timing of the turn-on of $S_1$ is critical and is done to minimize the turn-on (switching) loss. This timing varies due to parameter volatility, such as input Voltage (which affects the $I_r$ ramp time), temperature (which varies the speed of the $S_1$ turn on as well as other parameters), diode reverse recovery (if $D_2$ conduction occurred - more important when IGBTs are the primary switches) and load changes (which determines the peak of the $I_r$ current required to commutate). The inability to accurately control this timing prevented the commercial use of ARCP before the introduction of Pre-Switch technology.

## State 4: ARCP discharge

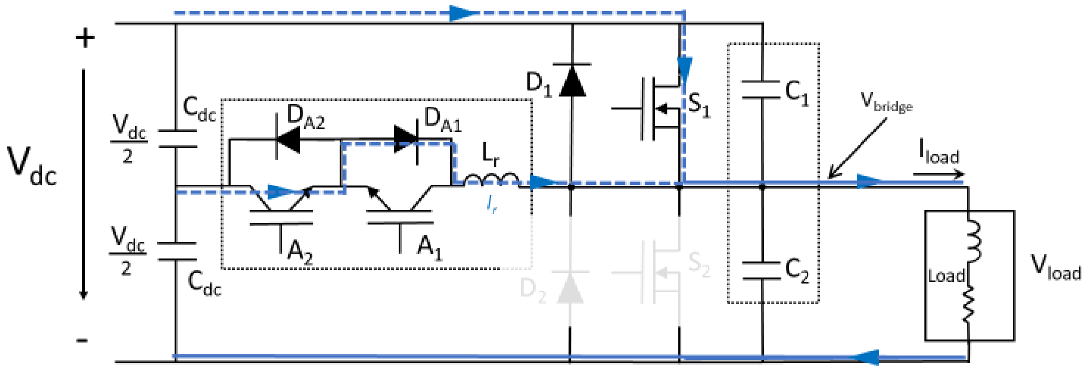

*Figure 5: State 4, Resonant Energy recovery*

Once the ‘commutation current’ has discharged, current in $L_r$ continues to fall as the ‘pre-charge current’ in State 2 is discharged to the load (shown above in Figure 5). Once the current in $L_r$ is zero, $A_2$ is turned off. The timing for this event is not extremely critical because $D_{A1}$ prevents the current in $L_r$ from reversing.

## State 5: Transition complete

In Figure 6 the switching transition is complete with practically no switching loss. S1 is conducting the full load current, and the ARCP circuit has no current. The soft-switching created by the ARCP combined with Pre-Switch technology has minimized switching loss and at the same time reduced dV/dt (dU/dt).

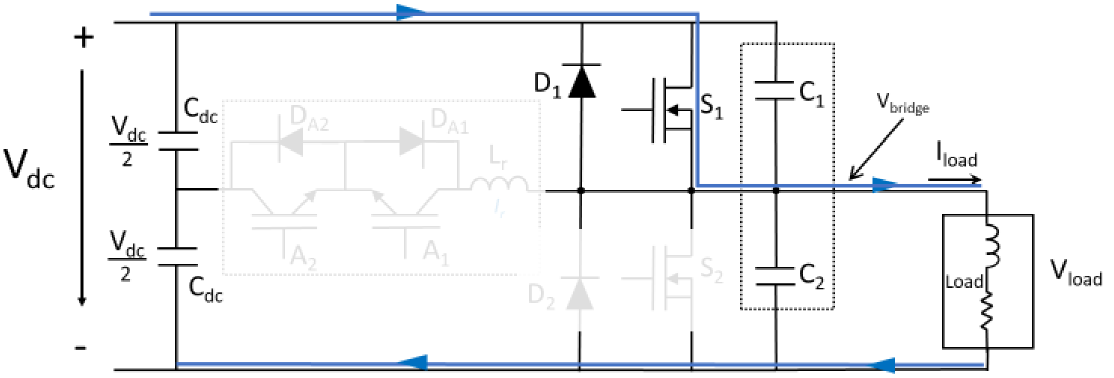

*Figure 6: State 5, Transition complete*

## Forced-resonant transition waveforms

Figure 7 illustrates the corresponding current and Voltages for the resonant switching described above. The exact timing is dependent on detailed circuit conditions, input Voltage, device variation and temperature, and load.

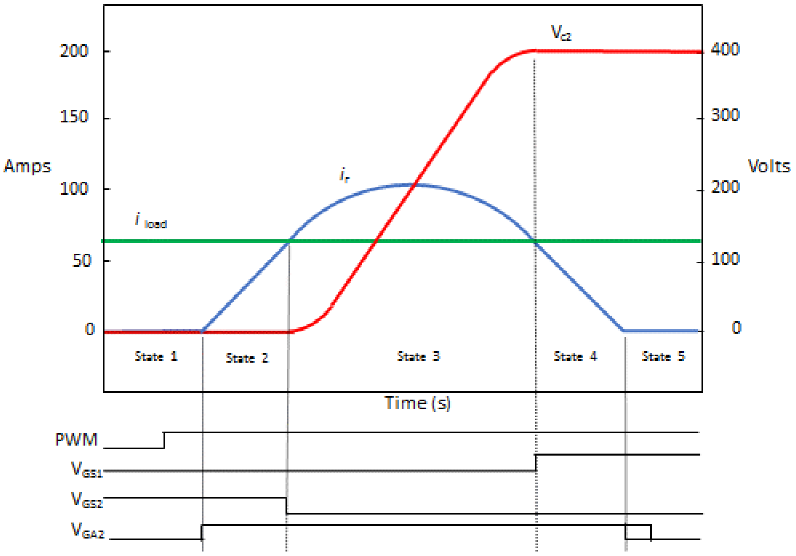

*Figure 7: ARCP forced commutation waveforms*

## State 6: High to low commutation from conducting transistor ($S_1$)

In this state (Figure 8) the reverse $V_{bridge}$ commutation occurs. $S_1$ is assumed to be forward conducting the full load current as shown above in state five. Initially, $S_1$ is turned off, causing the Voltage $V_{c1}$ to rise (and $V_{c2}$ to fall) according to the equation below.

$$Vc1 = \frac{\frac{Iload}{2} * t}{c1}$$

When $S_1$ is turned off; the load current is shared between $C_1$ and $C_2$ which slows down the dV/dt ($^{dU}/_{dt}$), allowing $S_1$ to turn off entirely before the Voltage across it has risen significantly. The Voltage rate of change dV/dt ($^{dU}/_{dt}$) is now controlled primarily by the resonant capacitance ($C_1$+$C_2$) rather than the turn off speed of $S_1$. The load current drives $V_{bridge}$ towards 0V. $S_2$ is turned on with timing to minimize hard-switching (either due to non-zero $V_{C2}$ or by diode $D_2$ conducting excessively).

The fact that the value of $C_1$ and $C_2$ can be selected to limit the dV/dt ($^{dU}/_{dt}$) has profound benefits for electrical motors, particularly in applications using SiC and GaN MOSFETs. Further, as battery voltages in EVs are increased towards 800$V_{dc}$ to minimize conductor and motor costs and weight, dV/dt ($^{dU}/_{dt}$) will become a more prominent issue.

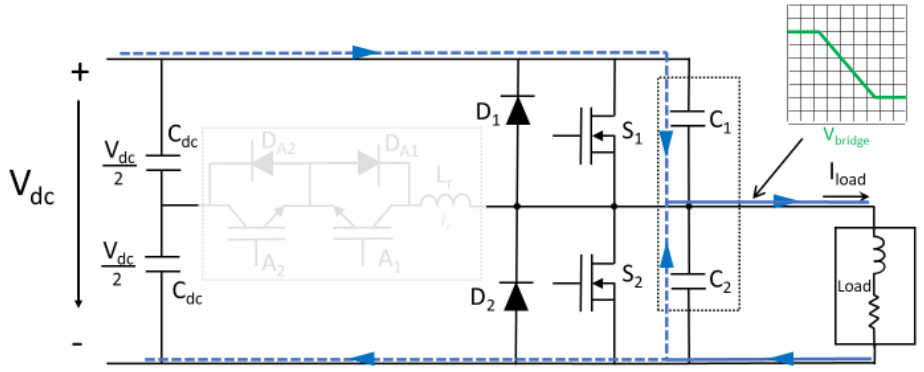

*Figure 8: State 6, High to low commutation from conducting transistor*

## State 7: Steady-state low side bridge conduction

The load current flows through $S_2$ (and $D_2$ depending on $V_{S2}$). As can be observed, Figure 9 is the same as State 1.

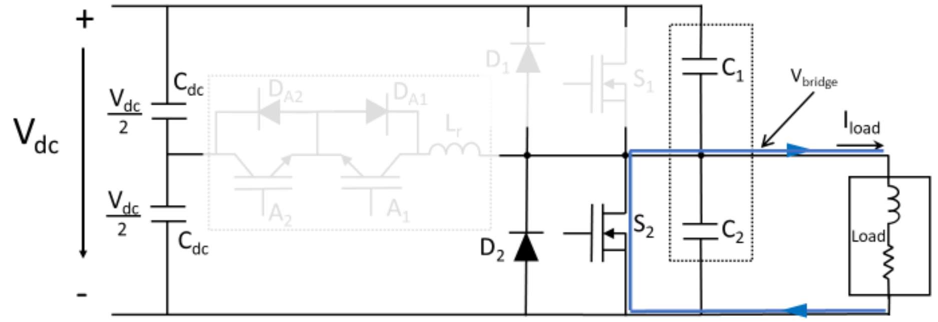

*Figure 9: State 7, same as State 1: Freewheel*

## Self-commutation transition waveforms

Figure 10 illustrates the linear Voltage ramp down due to the effectively constant load current (during the transition period).

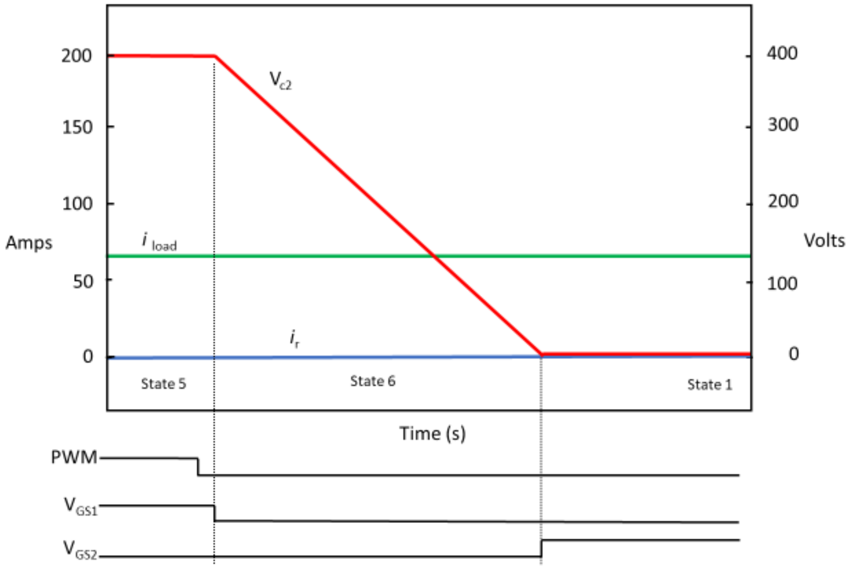

*Figure 10: Load current commutated waveforms*

## ARCP in a 3-phase Motor Drive

One use for the newly available power dissipation budget is to increase the current through the same sized transistors for a motor drive. Given that most drive inverter designs spend more than half of their loss budget on switching losses, the current through a Pre-Switched inverter could approach twice that of hard-switched levels. This dynamic implies the potential to use only half the number of transistors or modules, as the most significant savings are observed at maximum current, resulting in a simpler, lighter, and more efficient inverter.

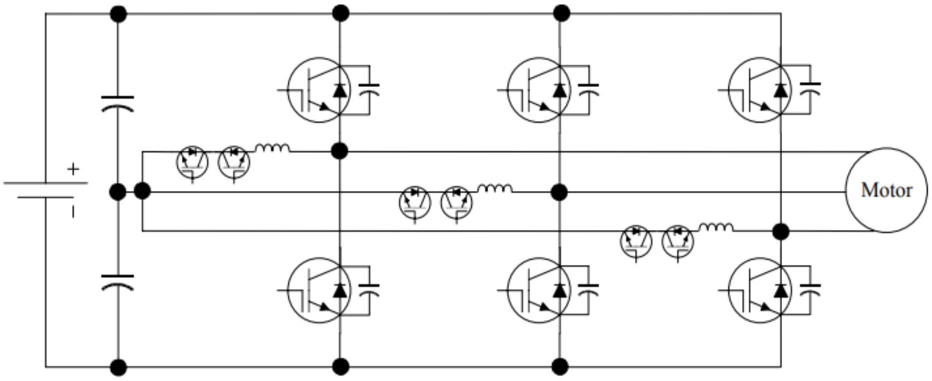

*Figure 11: 3-phase inverter with ARCP block diagram*

With no change to the configuration or transistor/module current, the vastly lower switching losses will result in cooler die, which in turn mean lower $R_{ds}$ and therefore lower inverter conduction losses, resulting in yet further heat reduction, etc. Again, this remains the case even if $F_{sw}$ increases, as the remaining switching losses are in the ARCP devices, not the power devices.

## Conclusion

Pre-Switching technology offers a quantum leap in switching-loss elimination. The results include increased torque, reduced motor temperatures, and increased system efficiency. Pre-Switch technology also provides a low-risk design path and is not dependent on exotic materials. The gains can be used in the inverter, in the motor, or apportioned between the two for the ideal combination of desired system gains. While these gains can improve designs in many industries, they are particularly useful for increasing battery range for consumer EVs.

## References:

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