The Sine Amplitude Converter™ Topology Provides Superior Efficiency and Power Density in Intermediate Bus Architecture Applications

Maurizio Salato, Applications Engineering, Vicor Corporation

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Introduction

The Sine Amplitude Converter™ (SAC™) topology is the dynamic, high-performance engine at the heart of Vicor's new VI BRICK™ Bus Converter products. A core Vicor technology, the SAC topology was first introduced with the V•I Chip BCM™ bus converter and has a proven track record of providing unparalleled benefits to OEM power designers seeking to maximize system performance and gain competitive advantages. This white paper will discuss the operation of the SAC topology and present a market-specific example of the effectiveness and benefits of the Vicor's Sine Amplitude Converter in Intermediate Bus Architecture applications. The paper examines the performance of the VI BRICK IBC in terms of efficiency, power density and transient response and other important factors.

We will use computer systems to provide context for explaining the unique benefits that the SAC-based IBC provides. Computing systems represent a very large market for high performance power supplies and demonstrate the universal challenges as all systems make the transition to providing multiple low-voltage, high-current power rails.

A Brief History of Computer Power Distribution

To develop an understanding of current power distribution technology it is useful to step back and review the changes that have occurred as computer systems have grown in power and complexity. Computer power distribution technology in the modern era has been driven by the need to provide clean DC supply rails to the variety of devices in a system including microprocessors, memory subsystems, mass storage, network devices and the analog and digital interfaces that complete the system. Early systems generated all of the required levels from a central power supply and distributed it to all of the system racks, backplanes, and PCBs through buses designed to minimize the voltage drop and electrical noise induced in the rails from the switching loads. This worked well, provided that the supply buses (and especially the return paths) were sized correctly and decoupling was applied properly to handle the spectrum of noise generated by the system components.

As system speeds increased, chip designers working with leading edge processes were forced to drop the power supply voltage to accommodate the smaller transistor geometries. 5 volt rails dropped to 3.3 volts then to 1.8 volts and even lower voltages required by high-end microprocessors in today's systems. As a consequence of the lowered supply voltages, noise margins for the digital logic signals also shrank.

Supply currents increased dramatically due to the ability to place massive numbers of transistors on modern chips. These factors combined to increase the demands on power supplies for better regulation and lower noise while providing high currents at low voltage. While the leading edge devices were driving the march toward low voltage, legacy and electromechanical devices maintained the need for the older 12 volt and 5 volt levels. Centralized Power Distribution was severely challenged by both trends. At the same time, engineers were shrinking the switch-mode power supply and integrating it into a new compact modular DC-DC converter "brick" form factor. The DC-DC converter brick enabled a revolution in the distribution of DC power. In all but the smallest systems, centralized power gave way to designs where central power supplies (or possibly a pair or more of supplies for redundancy) generated a relatively high voltage (usually 48 Vdc) bus for distribution across the system and the required supply voltages were locally derived with DC-DC converters on the backplane or PCB where the load was located. This greatly reduced the current levels and I^2R losses in the distribution bus but necessitated the use of multiple DC-DC converter modules in large-scale systems. This Distributed Bus Architecture overcame many of the problems of the Centralized Power Architecture but eventually presented a new set of design challenges. However, DC-DC converters added up in cost and took up precious real estate at the Point of Load.

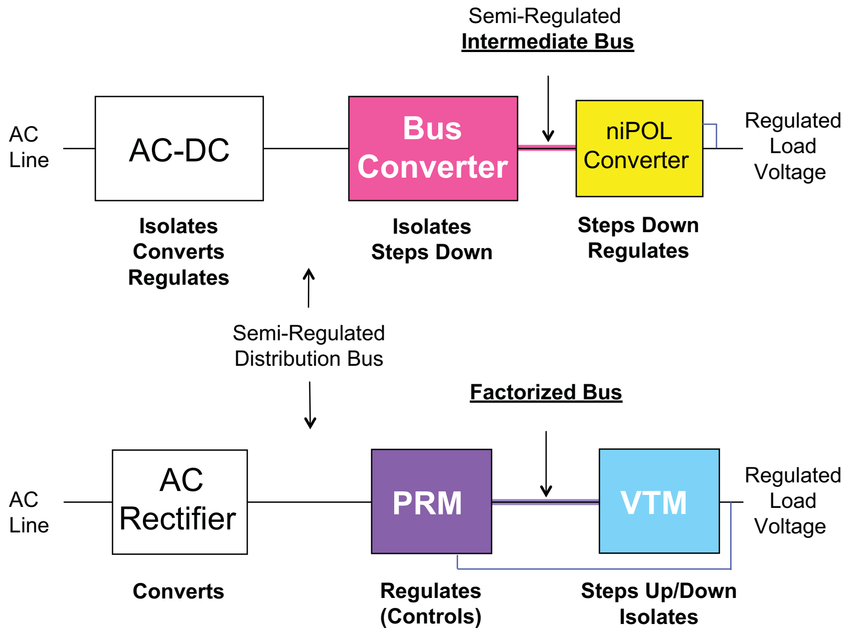
A solution to the challenges was the Intermediate Bus Architecture (IBA), where the distribution bus (~48 V) was stepped down to an intermediate bus level (of 5 – 15 Vdc) at the PCB and subsequently stepped down to the required device levels at the point of load by Point of Load regulators. IBA designs standardized on an implementation where the bus converter (which reduces the voltage from the distribution level to the intermediate level) provides both DC isolation and fixed ratio voltage transformation through a transformer, but no regulation. The Intermediate Bus voltage is fed to POL regulators which are simple buck regulators with no isolation (niPOLs) that take the semi-regulated intermediate bus as input and provide a lower, regulated output voltage. IBA has been widely adopted in a variety of applications, including computing and telecommunications and numerous power component companies are producing parts that conform to this general description of IBC and niPOL modules.

Vicor developed a different approach to address the shortcomings of the Distributed Bus Architecture. Factorized Power Architecture™ (FPA™), Vicor's approach to advanced power distribution, partitioned the functions of isolation, regulation and voltage transformation such that the distribution bus is first regulated by the PRM block and the regulated output of the PRM is then transformed by a fixed ratio in the VTM (using an implementation of the Sine Amplitude Converter) and the load is isolated through its integrated transformer.

The Factorized Power Architecture provides tremendous benefits over IBA in system performance, flexibility, and cost, and has been adopted by many customers developing systems for different markets. Now with an IBC available from Vicor, in the

Figure 1

IBA and FPA block diagrams



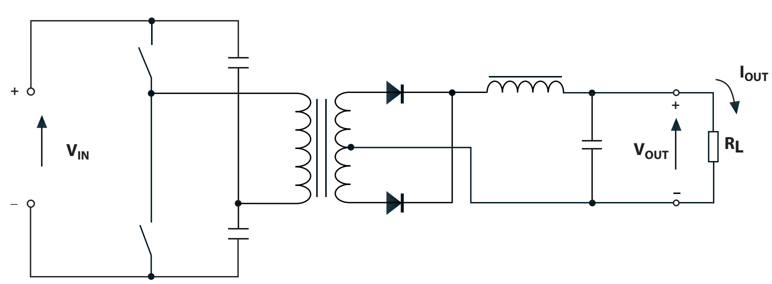
conventional IBA brick footprint, IBA systems can take advantage of Sine Amplitude Converter technology with its superior performance including higher efficiency and power density. The next section will focus on the unique qualities of the SAC which enable the superior performance of the VI BRICK IBC products.

Sine Amplitude Converter Operation

In order to appreciate the operation of the Sine Amplitude Converter, it will be useful to start with the earliest DC-DC converter circuits (Figure 2) which used a "hard switched" waveform to drive the power inductor or transformer with an approximate square wave. The good news is it works. By developing a square wave input on the primary, a voltage is induced in the secondary which, when rectified, results in a DC voltage at the output. The bad news is the switch elements (most commonly MOSFETs) are dissipating power during the switching events and the square wave contains high energy at the harmonics of the switching frequency which must be filtered or it will conduct or radiate throughout the system.

Figure 2

Hard switched converter

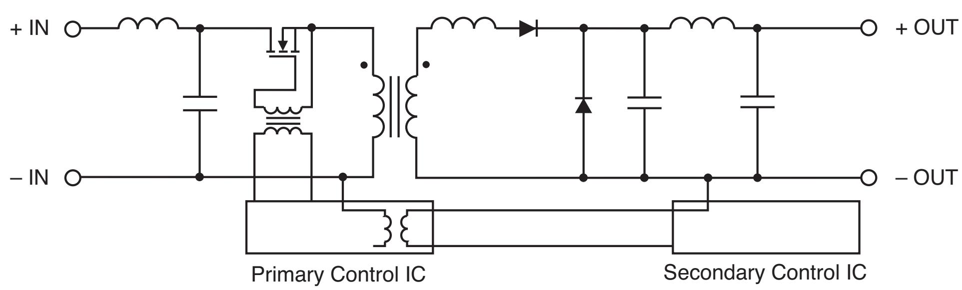


In a “hard switched” converter the output power is proportional to the converter duty cycle, which can be varied, to provide more or less power from the secondary, giving rise to the common name given to this category of circuits, Pulse Width Modulated or PWM converters. The switching frequency is practically limited to 400 kHz by the high levels of power dissipated by the switching devices. Despite its shortcomings the PWM converter was superior to linear regulators in applications where the input/output voltage ratio was large; and the PWM converter started the movement to the widespread use of DC-DC converters.

To solve the efficiency and noise problems of the PWM converter, power supply companies improved on the design by devising converters built around a resonant tank circuit on the primary that could be switched on the zero voltage and zero current crossings (Figure 3). These are referred to as ZCS/ZVS resonant converters and provided great improvements over the “hard switching” converters. By including a capacitor in the primary circuit, a quasi-resonant circuit is formed. By switching at the zero crossing of the resonant waveform the harmonic frequencies were greatly reduced and the efficiency was improved since the switches dissipated much less power. Hybrid bricks using the ZCS/ZVS (Zero Current Switching/Zero Voltage Switching) resonant technique were able to achieve power densities of 100 W/in^3. Since the energy to be transferred from the primary to the secondary is stored in the inductance of the primary and is proportional to LI^2 (where L represents the primary inductance and I represents the primary current,) it is constant for a given circuit configuration. This represents the “energy packet” size for the circuit. To increase the rate at which energy is transferred, the switching rate must be increased, thereby increasing the number of packets transferred in a time period. It follows that the output power is directly dependent on the switching frequency. Switching frequencies in ZCS/ZVS resonant converters are limited by the trade-off between stored energy per cycle and the necessary conditions to achieve ZVS or ZCS.

Figure 3

ZCS/ZVS converter



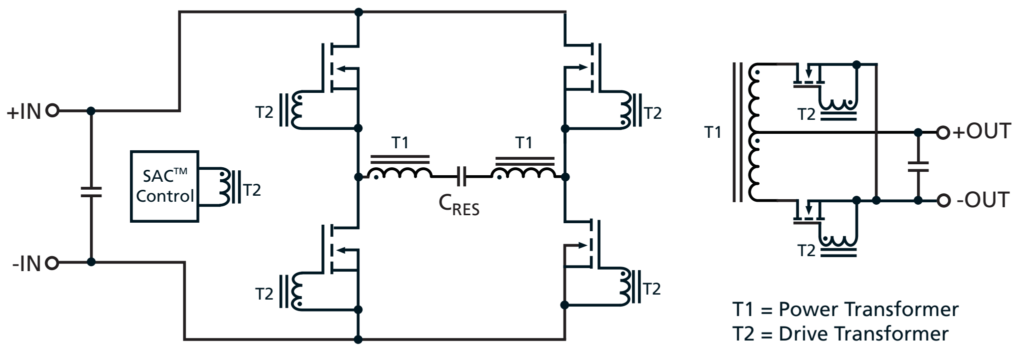


Figure 4

SAC converter

The Sine Amplitude Converter Topology (Figure 4) bears some similarity in topology to the ZCS/ZVS resonant converter at first glance, but its operation is entirely different. The SAC is a transformer-based series resonant topology. Unlike quasi-resonant ZCS/ZVS converters, the Sine Amplitude Converter operates at a fixed frequency equal to the resonant frequency of the primary side tank circuit. The switching FETs in the primary are locked to the natural resonant frequency of the primary and are switching at zero crossing points, eliminating power dissipation in the switches (boosting efficiency) and greatly reducing the generation of high order noise harmonics (requiring less filtering of the output voltage). The current in the primary resonant tank is a pure sinusoid rather than a square wave or a partially sinusoidal waveform as seen in prior generations of converters. This also contributes to greatly reduce harmonic content and provide a much cleaner output noise spectrum.

The leakage inductance of the primary is minimized in a Sine Amplitude Converter since it is not the critical energy storage element (in contrast to the ZCS/ZVS resonant converter). The SAC can therefore operate at a much higher frequency allowing for a much smaller transformer, and increasing both power density and efficiency. The Vicor IBC and VTM operate at a frequency of several MHz. In contrast to traditional ZCS/ZVS converters, this frequency is fixed regardless of load. In response to an increased load on the secondary, the Sine Amplitude Converter reacts by increasing the amplitude of the sinusoidal current on the primary resonant tank. This, in turn, increases the amount of energy coupled into the secondary, countering the increased load (Figure 5). When the load is reduced, the amplitude of the sinusoid decreases, approaching zero under "no load" conditions.

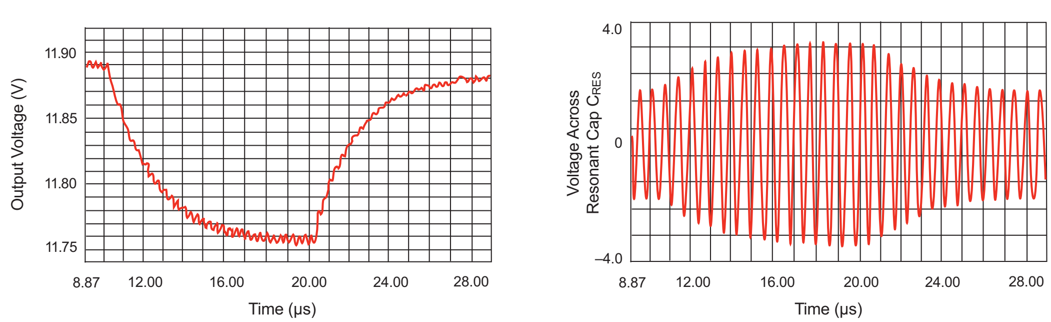


Figure 5

Amplitude of tank current vs. load

VI BRICK™ Intermediate Bus Converter Features and Benefits

Vicor IBCs, powered by the patented Sine Amplitude Converter™ topology offer the OEM designer an Intermediate Bus Converter with a number of unique benefits. We'll use as an example Vicor's IB050Q096T70N1-00 bus converter which provides a 5:1 voltage reduction from a nominal 48 V input (36 – 60V range). With efficiency rated at 98%, the VI BRICK bus converter has almost half of the loss of competitive bus converters. Less power dissipated inside the converter per Watt delivered allows for higher rated output current in a given package. The output current is rated at 70 A at 25°C and 100 LFM (0.5 m/s) of airflow. The module maintains this output level at 55°C ambient and 200 LFM (1 m/s). A competitive quarter brick is rated at 54 A at 25°C and 100 LFM (0.5 m/s) and drops off to 49 A at 55°C and 200 LFM (1 m/s) of airflow. The increased output current enabled by the high efficiency of the Vicor module, coupled with the reduction in volume achieved through the use of smaller magnetics, results in power densities for the VI BRICK Bus Converter on the order of 550 W/in^3, which is considerably higher than competitive offerings.

As discussed in the preceding section, the unique operation of the SAC circuit enables a higher switching frequency. High operating frequency confers obvious advantages to the transfer of power to the load. Power is transferred to the output more often during operation at high switching frequency, and this results in a faster response to changes in load current. The VI BRICK Bus Converter switches at 8x the rate of typical competitive bus converters and responds to load changes within a few switching cycles (<10 µs).

The output impedance of the Vicor IBC is extremely low, reflecting the low output impedance of the resonating tank circuit on the primary side of the transformer, which ideally presents zero impedance at its resonant frequency. The actual output impedance of Vicor's IB050Q096T70N1-00 is specified at 3.8 mΩ. This impedance is essentially flat up to approximately 2/3 of the resonant frequency (1 MHz). This is approximately one half the output impedance of a conventional IBC.

The sinusoidal nature of the current in the primary leads to advantages in the electrical noise profile of the SAC. The output noise spectrum is very narrow with major components at the switching frequency and 2x the switching frequency (due to the full wave rectification of the output). Higher order components are very low. Output filtering is easily achieved with small high-frequency ceramic type capacitance.

Conclusion

The Vicor VI BRICK Intermediate Bus Converter is based on the same high-performance patented technology that powers Vicor's V•I Chip VTM and BCM modules. This new generation of power converters exceeds the performance of conventional converters in many dimensions—conversion efficiency, power density, transient response, switching noise, etc... In the important factor of conversion efficiency, the power loss per unit of delivered power is halved in the VI BRICK Bus Converter. Power density is 50% greater, reflecting this increased efficiency and the reduced component size enabled by the high operating frequency.

The following chart details the differences between the VI BRICK Bus Converter and a competitive quarter brick 5:1 bus converter. Any one of these differences is compelling. The sum of these differences represents a generational shift, providing Intermediate Bus Architecture users with major boosts in performance within the same physical footprint.

Figure 6

Horizontal Bar Chart of Vicor IBC vs. Conventional IBC