Team Name: Silicon Contact Tyndall	**Registration Code:** 545-l6t7ZP-60068

Technical Approach: Interleaved, Folding, Interpolating dual-path Adiabatic Autotransformer based power converter

Overview

Our approach centres around two identical autotransformers driven adiabatically 90° out of phase with each other. Both transformers contribute to the power conversion, ensuring that at any one time at least one of the transformers provides a continuous power path from the input supply to the output.

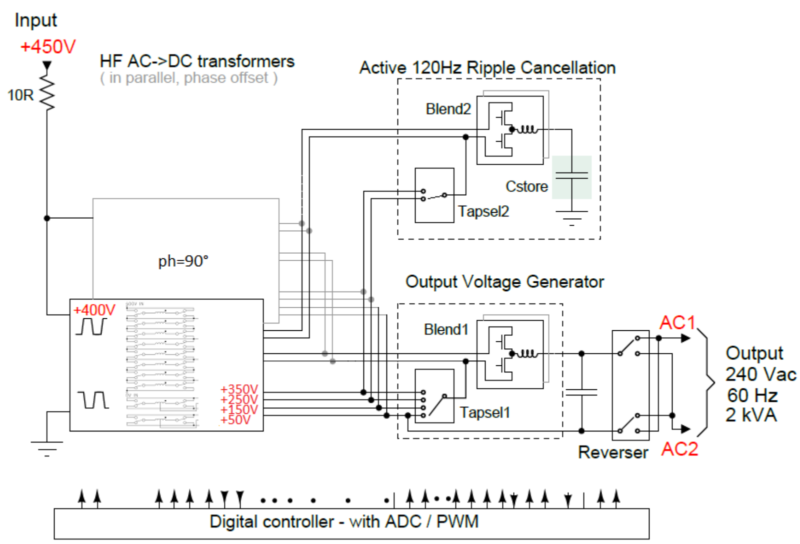

Figure 1: Overall architecture. Voltages shown for 2kW loading; these are the nominal voltages used throughout the document.

Each autotransformer is composed of a series of windings (each having an inductance of 8.2µH) that are connected in series through transistors in H-bridge arrangements (see figure 2), effectively making the transistors an integral part of the transformer. Excitation voltages are applied by switching the polarity of each winding, rather than the transformer as a whole, allowing the output taps to be DC. The polarity switching is performed adiabatically—the H-bridges are turned off, the voltages across each winding are allowed to reverse naturally due to the demagnetisation of the core and the H-bridges are turned on in the opposite polarity at the moment when there is no voltage across the driving transistors, so there are no switching losses; this is in complete contrast to conventional hard switching, in which switching losses dominate. The inter-winding capacitance works as a charge pump when there is unbalanced load on the windings, helping to keep the tap voltages stable.

A toroidal isolating transformer (1.2µH) is used to drive the H-bridge transistor gates, with one secondary winding per transistor (see figure 3). This allows the gate charge to be recovered, eliminating this source of power loss, too. This makes the size of the gate capacitance irrelevant for efficiency, so several transistors are used in parallel to reduce conduction losses. Low voltage MOSFETs are used as each winding is switched by far lower voltages than the input voltage, bringing advantages of size reduction, lower on resistance and lower cost.

The toroidal transformers, and hence the autotransformers, are switched at frequencies between 320kHz and 600kHz. This is controlled by an FPGA, as are all other timings in the circuit.

Each transformer has a main multiple-tapped winding and two isolated centre-tapped auxiliary winding, which provide floating supplies for fine adjustment of the output voltage and for charging and discharging a capacitor bank for ripple elimination. Output shaping consists of a coarse/fine approach, with one of the main taps being selected, using a tree structure of MOSFETs (which allows lower voltage components to be used), to give a coarse voltage (nominally 100V steps) and the floating supply being pulse width modulated and added to or subtracted from this coarse voltage by a blender circuit. The fine adjustment winding is centre-tapped, providing floating supplies of nominally 25V and 50V. This circuit topology enables the pulse width modulation to be performed at far lower voltages than would normally be used, again allowing the use of lower voltage MOSFETs.

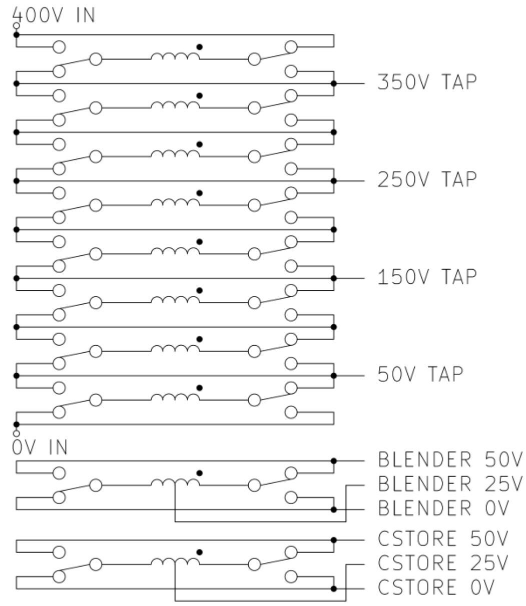

Figure 2: Autotransformer configuration; each switch represents a half H-bridge

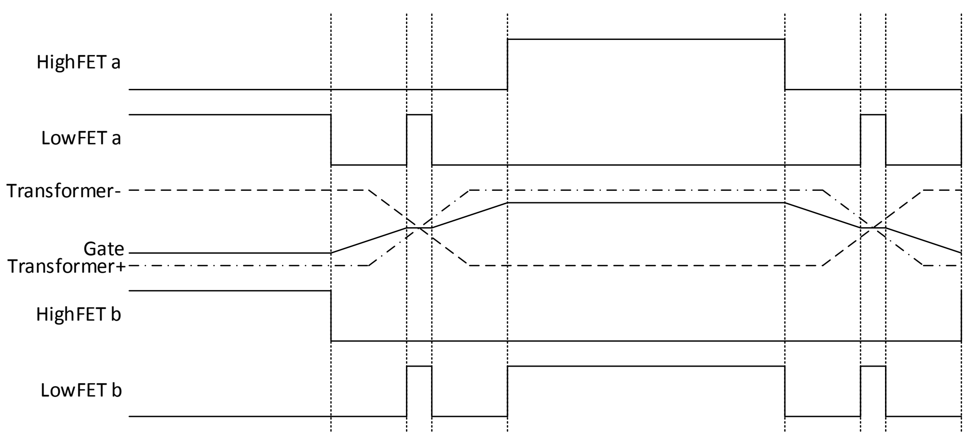

Figure 3: Timing of H-bridge driving toroidal transformer primary winding, resulting signal on the secondary windings that drives the gates of the autotransformer H-bridges and the autotransformer winding voltage reversing while floating

A final H-bridge reverses the output to give the negative half of the sinusoid.

The dimensions of our enclosure are 3.9 in x 1.5 in x 1.2 in, giving a volume of 6.9 in^3, resulting in a power density of 290 W/in^3 at 2kVA with a resistive load. Due to project timescales and budget constraints silicon MOSFETs were used throughout; simulation shows that use of GaN transistors may double the power density.

120Hz Ripple Reduction

The ripple compensation winding of each autotransformer is used in conjunction with the two highest taps as a supply for charging and discharging a bank of ceramic capacitors (150µF total), to maintain a constant overall load to eliminate input ripple. The charging and discharging is performed actively, using pulse width modulation, allowing far better ripple reduction than a passive approach. This gives an energy reservoir of up to $\frac{1}{2}C(400\text{V}^2 - 200\text{V}^2) = 9\text{J}$, which is equivalent to a 1875µF capacitor attached to the input with 3% ripple voltage present. This approach allows a much smaller capacitance to be used, giving a size and cost reduction, and ripple elimination rather than just reduction.

Miniaturisation of Components

The autotransformers are manufactured to a high quality to reduce leakage inductance to ultra-low levels—each winding is made using multiples of three fine wires twisted together to minimise inductive losses and a ferrite core is used with air gaps. MOSFETs are integral to the construction of the transformers' main windings, serially linking together individual turns. The polarity of each smaller winding is switched, rather than the chain as a whole, which maintains a constant voltage between neighbouring turns, eliminating capacitive losses. Hence the transformer operates in dual mode—autotransformer mode and switched capacitor mode.

The topology allows much lower voltage rated components to be used in most places, giving gains in terms of component size and on resistance (allowing denser packing of components due to lower heat dissipation).

Adiabatic switching of transformer windings eliminates switching losses as the transistors are turned on and off when there is zero voltage across them. Adiabatic switching of MOSFET gates eliminates power losses associated with charging the gate capacitances, as this energy is efficiently recovered by the transformer.

Conduction losses in the MOSFETs are reduced by using multiple transistors in parallel. The number of components in parallel in each situation is chosen to balance the gain in component packing density with the increased circuit size.

Moving the energy storage for ripple reduction from the input to a lower voltage tap of the transformer and actively charging and discharging allows far more effective use of capacitance, reducing the size of the capacitor bank through both reduced overall capacitance and reduced capacitor voltage rating.

Thermal Management

Due to the very high efficiency achieved, the heat dissipated is in the region of 10W at 2kVA, so thermal management is straightforward. The device is fully enclosed in a copper housing with apertures only for cables, the toggle switch and the LED. This spreads any local hot spots on the surface while affording excellent EMC shielding.

Electromagnetic Compliance

The enclosure consists of folded sheet copper, soldered at the seams, with apertures only where required for cables, the toggle switch and LED. This gives excellent shielding against radiated emissions.

High frequency PWM is used to shape the output voltage, giving accurate results, so a small LC filter (*e.g.* 2.5µH and 10µF) is all that is required on the ac output to reduce conducted emissions to acceptable levels.

References

The principal investigator has previously demonstrated adiabatic principles generating square waves at multi-GHz frequencies for high speed processor clock generation:

‘Rotary traveling-wave oscillator arrays: a new clock technology’, IEEE Journal of Solid-State Circuits, Volume: 36 , Issue: 11

Many other papers on adiabatic principles are available from here:

http://web.eecs.umich.edu/~marios/pubs.html

Appendix: Biographies

John Wood

John Wood of Silicon Contact Ltd has over 30 granted patents in fields of Control Systems, Infrared Welding and Digital Signalling Transmission amongst others and is best known for his invention of the RTWO (Rotary Travelling Wave Oscillator). He has presented at two different IEEE International Solid State Circuits conference and was invited by the IEEE to author a paper on the RTWO technology for the Journal of Solid State Circuits in 2001 which has been cited over 200 times. John has been guest editor of IMAPS conference committee and has been on the IEEE transaction on microwaves devices peer review committee. His experience is particularly relevant for this product because he has a background in high-speed CMOS circuitry and electromagnetics and inductance phenomena. John has also previously licenced digital-audio signalling systems.

On the management side, John founded and managed the company MultiGig Ltd to exploit his RTWO technology acting as CEO from 2000 to 2004 with 10 employees and moving from the start-up in the UK to Silicon Valley, USA. MultiGiG was eventually purchased by Analogue Devices Inc and the patented RTWO technology exists today in many mobile phones, internet routers and retiming circuits and is widely licenced in the semiconductor industry. John is an expert designer of power control electronic systems, multi gigahertz oscillators, phase-locked loops and programmer of embedded systems.

For the past five years, John has focussed on power electronics. In this time, he has filed multiple patent applications for new power device structures as well as a novel and innovative method of driving high power solid state switches. Other inventions include conversion systems including ultra-low loss rectifiers. These inventions have already drawn a great deal of interest for their potential in green energy and smart grid applications and are currently being developed for deployment to the market.

Ed Shelton

Ed Shelton studied engineering at Cambridge University and graduated with a masters degree in 1997. Since that time he has worked in the engineering consulting industry developing high tech products for a number of industrial and medical clients. More recently he has been involved in a Cambridge startup business that attracted $20m in investment, and which has recently been acquired by a multinational company.