White Paper
October 2021

New semiconductor technologies are driving higher efficiency in power conversion

Dr Anup Bhalla, VP Engineering at UnitedSiC

ABSTRACT

Power conversion is a common element in almost every electronic device, implemented in a variety of topologies. New and emerging applications bring their own unique requirements, putting pressure on engineers to develop AC-DC and DC-DC converters that offer the optimum balance of performance and efficiency. However, this isn't always a simple task.

Choosing the right topology is only the beginning of the challenge - it is also necessary to select power components carefully and as new semiconductor technologies come to market, engineers have the opportunity to discover and evaluate new solutions to old problems.

This white paper provides the context behind the development of new semiconductor technologies with examples given of innovative parts that are placed to provide the right mix of features for current and emerging power conversion applications.

Dr. Anup Bhalla has a Bachelor's degree from Indian Institute of Technology, Delhi and a Ph.D. from Rensselaer Polytechnic Institute. He has worked at UnitedSiC for 9 years and has more than 25 years of experience in the Electronics Industry.

WHITE PAPER

Modern society is underpinned by electronics and electrical machines – it's hard to imagine life without the myriad of devices that keep us productive, comfortable, informed and entertained, both at home and in business. At the broadest level, this equipment needs electrical power to operate, whether variable frequency and amplitude three-phase AC for a 500kW industrial motor or 0.6V DC for a digital processor.

All the way from the latent energy in fossil fuels or renewables down to the generation of a CPU core voltage, stages of power conversion are required with the minimum of losses to the environment. However, with global energy consumption ever increasing, about 180,000 TWh in 2019[1], less than perfect conversion efficiency adds to heat generation, global warming and dollar cost to energy providers and consumers alike.

International efforts are being made to reduce energy consumption where possible, but levels inexorably increase as economies round the world modernize. At the same time, governments are setting targets for energy savings. In the European Union, for example, an improvement in efficiency netting a 32.5% reduction in energy draw from primary sources, compared with 2007 projections, is required by member states collectively by 2030. This is all against the background of explosive growth in demand for electronic equipment driven by markets such as IoT, electric vehicles, 5G rollout and data centers. The final stages of power conversion in these applications are, of course, the most numerous and have a massive market value. DC-DC converters for example, were worth $8.5B in 2019 and are set to rise to $22.4B by 2025, a CAGR of 17.5%[2], with telecomms applications leading the increase. It's clear that the only way to achieve the target energy savings with growing markets is to make the power conversion process ever more efficient.

Close to the end load, efficiency concerns relate to local temperature rise as well as the financial and environmental cost of wasted energy; when running hot, equipment reliability and lifetime falls and users are often forced to provide active cooling. This however, consumes yet more energy in itself, while just moving excess heat to a different place. Reducing losses is therefore an imperative in any power conversion design.

EMERGING APPLICATIONS

DC-DC conversion has always been an integral element of switched-mode power supplies, whether directly or as an intermediate stage, but over the years, power and voltage levels have significantly changed. Early equipment power supplies would convert rectified mains AC to perhaps 12VDC for analog and general use and a relatively loosely regulated 5V for TTL logic. Now, most power is consumed by digital circuitry power rails which need to be more accurate and are often sub-1V. For the same power, current levels multiply up when using low voltages, introducing higher interconnection losses. Also, fixed voltage drops such as in conventional rectifier diodes become more of a proportion of the end voltage, introducing still further losses. With server farms said to be around 1% of global energy demand[3], the efficiency of conversion from the primary energy source to the end-load voltages is clearly important in this application. Addressing the issue, schemes using an 'intermediate bus' are used to distribute power at higher DC voltages and proportionally lower current with 'point of load' DC-DC converters providing the final voltage. Cascaded intermediate buses have been used to minimize losses throughout an installation but a current trend is to generate 48V from the primary AC source, couple in battery backup at this point, then convert directly down from 48V to sub-1V at the loads, **Figure 1**. This can obviate the need for a second intermediate bus but the final, large, down-conversion ratio poses its own efficiency problems, demanding high performance semiconductor switches.

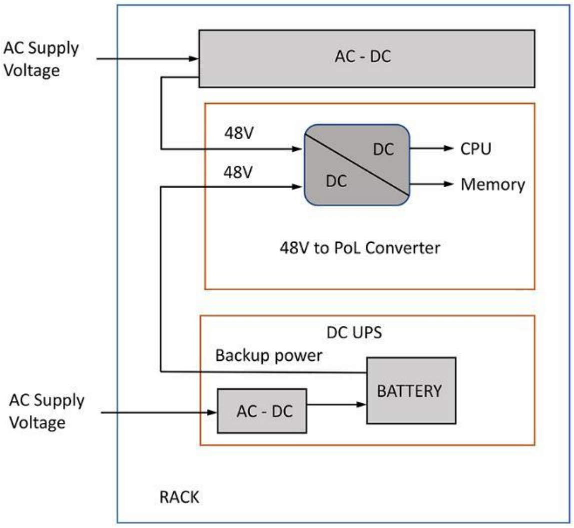
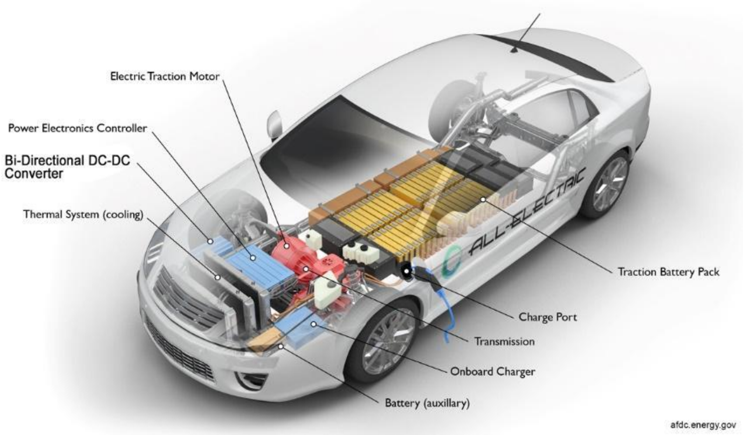


Figure 1. Typical modern data center power arrangement

Practical electric vehicles have gone from science fiction to mainstream within just a few years and have spawned a whole new application area for power conversion, set to become a significant market value (**Figure 2**). An obvious function is the high-power traction inverter, converting high voltage battery DC to three-phase motor drive, but there are many other stages as well: For legacy equipment EVs still use a 12V battery which needs to be charged through a DC-DC converter off the traction battery. The converter is increasingly designed for bidirectional energy flow so that excess charge can be utilized for traction in emergency conditions. There will also be an on-board charger (OBC) - an AC-DC converter which may also be bidirectional to return energy to the grid for utility load levelling. The control, safety and infotainment electronics in the vehicle is naturally mostly digital with a multitude of dedicated DC-DC converters providing local power rails and at the other end of the spectrum, fast roadside or home chargers provide traction battery voltage at power levels in the hundreds of kilowatts. In the vehicle, every watt lost in power conversion translates to shorter range and in chargers translates to higher running costs and longer payback. So, efficiency is again key with an emphasis on the need for high voltage semiconductor switches with lowest loss.



afdc.energy.gov

Figure 2. Power conversion in a typical EV

In wider society, the proliferation of mobile devices with their chargers generates an increasing need for efficient power conversion and in industry, the Industrial Internet of Things (IIoT) or ‘Industry 4.0’ is a driver for the market for large numbers of lower power sensors and actuators. These need internal DC-DC converters as they operate from batteries, energy harvesting or perhaps Power over Ethernet (PoE), rather than the traditional centralized equipment arrangement with one large power supply.

CONVERSION TOPOLOGIES

Where DC-DC conversion is implemented to generate final load voltages, there are a number of topologies available, depending on the power level and whether isolation is required for safety or functional reasons. Apart from non-isolated, inefficient linear regulators, switched-mode regulators are ubiquitous for high efficiency, with a topology derived from two basic configurations: ‘buck’ or ‘boost’ (**Figure 3**). Buck converters pass energy directly to the output in pulses with an energy storage inductor providing continuing current to the output during the main switch off-time. Boost converters store all the output energy requirements in an inductor during the main switch on-time and pass it to the output during the switch off-time with a capacitor smoothing the output to DC in both cases. In isolated converters, the principles are the same with the equivalent transformer-coupled topologies, ‘forward’ and ‘flyback’ converters respectively.

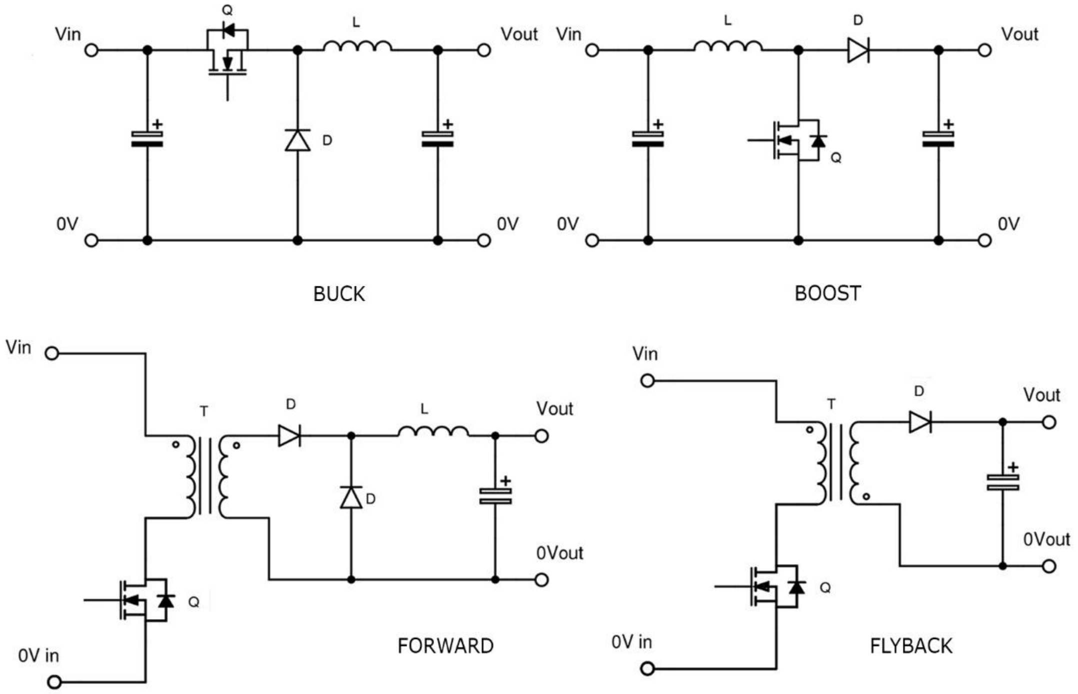


Figure 3. Buck, boost, forward and flyback topologies

Buck-derived converters are by far the most popular in both isolated and non-isolated applications and certainly for power levels above a few tens of watts. This is because the size of magnetic components in boost derived converters tends to scale directly with power, whereas in buck converters, this is less the case, with practicalities of wire sizing and isolation distances being more relevant to overall magnetics size. Non-isolated buck converters scale to high power with low losses with the addition of features such as synchronous rectification, where the diodes in Figure 3 are replaced by a MOSFET: multi-phase versions spread the stress on semiconductors by having two or more power stages driven out of phase and latest generation wide band-gap (WBG) semiconductors provide low conduction and switching losses. For isolated converters, there is a wider choice of buck-derived topologies ranging from single switch types through to half- and full-bridges, again coupled with synchronous rectification and utilizing multiphase arrangements at higher power levels.

With all topologies mentioned, power can be dissipated during switch transitions when voltage and current can be simultaneously high. To counter this and increase efficiency, ‘resonant’ or ‘soft-switched’ designs have been developed which delay the rise of current until voltage has dropped to zero on switch turn-on (zero voltage switching or ZVS). Zero current switching (ZCS) can similarly be arranged during switch-off. Achieving correct timing for ZVS or ZCS is difficult under all conditions of input, loading and changing device characteristics with time and temperature, so control techniques can be complex, but there are now dedicated control ICs for the function. At high power, the resonant Phase Shifted Full Bridge (PSFB) has become popular with its easy 50% duty cycle switch drive and regulation achieved by varying the phase of pairs of gate drives in the bridge arrangement.

For intermediate powers, the LLC series resonant converter (**Figure 4**) is now a standard for high efficiency, again with easy 50% duty cycle gate drive to a half or full bridge, with regulation achieved by varying switch frequency over a relatively narrow range.

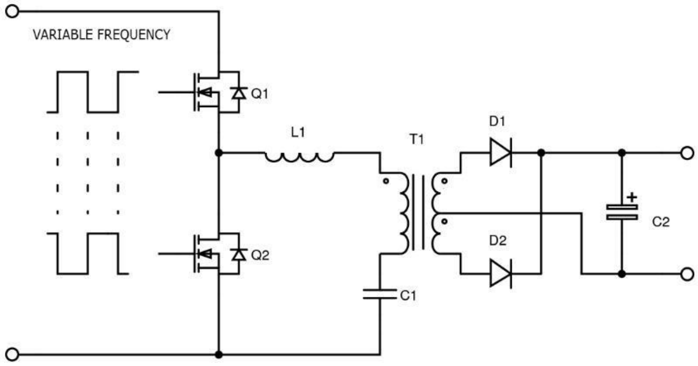


Figure 4. The LLC resonant DC-DC converter

Adoption of the complex resonant designs such as PSFB and LLC types has also been facilitated by introduction of digital control techniques which give the flexibility to adapt the circuit dynamics to changing conditions, for high efficiency across the operating range.

THE LLC CONVERTER

It's informative to examine the LLC converter a little further to see how the topology results in low power dissipation in the semiconductor switches. In the outline circuit of Figure 4, the two switch gates are driven in antiphase at 50% duty cycle providing a simple square waveform to the resonant circuit or 'tank' formed by L1, C1 and the primary inductance of transformer T1. Simplistically, the tank and load reflected through the transformer form a voltage divider such that at resonance, the tank is resistive and a minimum value so that there is no attenuation. At higher or lower frequencies, away from resonance, impedance of the tank is either capacitive or inductive and attenuation varies, but peaks at the main resonant frequency, which is itself load-dependent. This allows control of the output voltage by varying drive frequency, with the additional effect that the tank circuit filters the square wave drive to produce essentially a sinusoidal current in the transformer primary and secondary. No output filter inductor is therefore necessary. In practice, there are two resonances formed by L1/C1 and L1 with the magnetizing inductance of the transformer, with C1, so the variation of gain through the power circuit is complex (**Figure 5**). Practical circuits operate around the L1/C1 resonance, Fr1 in Figure 5.

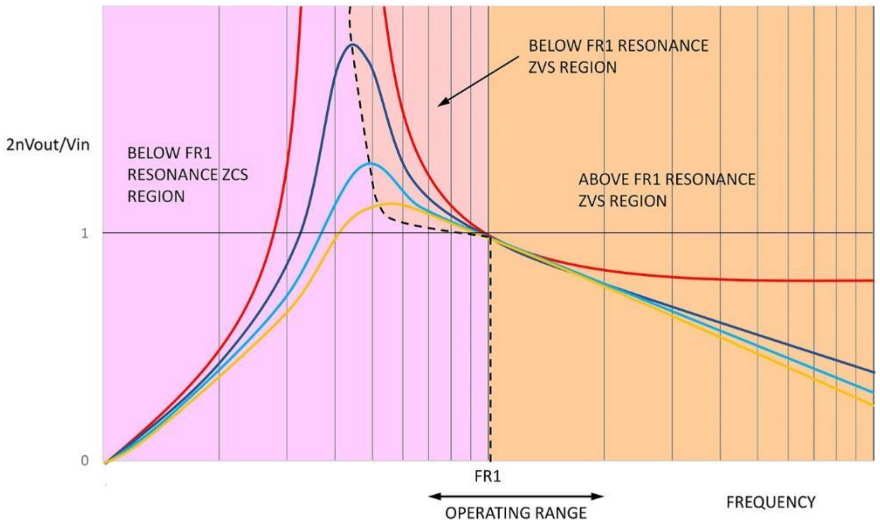


Figure 5. Variation of power stage gain in an LLC converter with frequency at differing load levels

Zero voltage switching can be achieved in both primary switches. Again simplistically, with an inductive load, current lags voltage so if the LLC converter is operated above its main resonance where the tank looks inductive, current will only rise after voltage giving minimum overlap and dissipation. Energy stored in the magnetizing inductance causes reverse current flow in the switch Q2 during dead time after Q1 has turned off and before Q1 has turned on, discharging the capacitance at the common switch connection point, a necessary condition for ZVS, with an equivalent mechanism for ZVS occurring for Q1 turning on and Q2 turning off. Zero current switching in the output diodes naturally occurs. ZVS can be lost however resulting in lossy 'hard switching' with over-loads or short circuit, when the circuit is forced to operate at low frequency in the capacitive region, where current is leading voltage. It can also be lost at light loads, when the energy stored in the inductance is insufficient to discharge the switching node capacitance. Semiconductor switches with minimum output capacitance and corresponding E_{OSS} are therefore preferred for lowest loss switching under all normal conditions and fast body diodes with low recovery charge Q_{RR} are required if ZVS is lost under abnormal conditions.

SEMICONDUCTOR SWITCHES AND THEIR FIGURES OF MERIT (FoM)

There is a choice of semiconductor switch types that can be used for LLC converters and similar topologies. Silicon MOSFETs have been the standard solution but there are some limitations to their use and pitfalls to avoid. Output capacitance C_{OSS} and stored energy E_{OSS} in MOSFETs are very non-linear quantities and can be significant values, requiring longer than ideal dead-times to discharge. Ensuring that the energy is discharged before switching is important for ZVS but there is still power dissipated in the action of charging the capacitance $P = f \times 0.5 \times C_{OSS} \times V^2$, with higher voltages being more problematic due to the V^2 term. Clearly E_{OSS} must be as low as possible but it is also a trade-off against on-resistance, all other things being equal. A larger die can have low $R_{DS(ON)}$ with many parallel cells giving low conduction losses but C_{OSS} and consequent E_{OSS} will be naturally higher. The FOM $R_{DS}*E_{OSS}$ is therefore important when comparing devices. Given similar RDS*EOSS values, another differentiating FOM is RDS-A, on-resistance per unit die area. Small values imply low device capacitances and higher yield from wafers for a given target on-resistance and consequent lower unit cost.

When comparing devices, the characteristics of the body diode or diode effect is important. In resonant converters, the inherent diode in a MOSFET conducts naturally during soft switching but is relatively poor performance with high forward voltage drop and slow charge recovery QRR, which, at high frequency with short deadtimes may be incomplete in the switching cycle, causing losses. Wide band gap devices such as Gallium Nitride (GaN) HEMT cells do not have a diode but conduct from source to drain in the 'third quadrant' through the main channel rather than through the parasitic diode found in MOSFETs. Although there is no charge recovery in HEMT cells in third quadrant conduction, the forward voltage drop is also quite high, equal to the gate turn-on threshold voltage plus any negative off drive voltage applied. MOSFETs in WBG Silicon Carbide (SiC) technology have a parasitic diode which is fast like a Schottky diode, but again, forward voltage is high, around 3V. Although third quadrant conduction time is short, losses can still be significant in the diode or diode effect when highest efficiency is needed. As a measure of the combination of channel conduction and diode loss, RDS*QRR is a useful FOM. SiC MOSFETs and GaN HEMT cells also have very sensitive gate drive requirements for optimum efficiency.

A device which includes the best of all characteristics is the SiC FET (**Figure 6**), a combination of a low voltage Si-MOSFET and a SiC JFET in a cascode configuration which, like-for-like, has lower RDSA, RDS*EOSS and RDS*QRR FOMs than Si-superjunction MOSFETs, SiC MOSFETs and GaN HEMT cells.

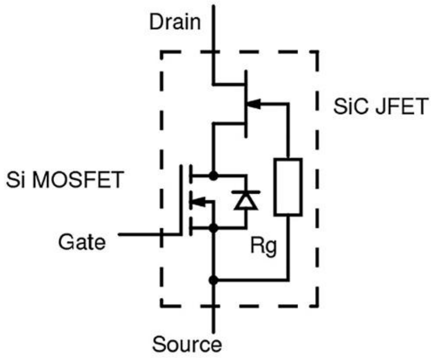


Figure 6. The SiC FET – a cascode of Si MOSFET and SiC JFET

SiC FETs have the advantages of SiC; ultra-fast switching, high thermal conductivity and high temperature operation but with the easy gate drive of a low voltage Si-MOSFET. Device capacitances and stored charge are all low and there is a body diode effect which is fast and with a low forward voltage drop of around 1.5V at 25°C. Unlike GaN devices, there is an inherent avalanche capability and current self-limits under short circuit conditions.

CONCLUSION

Efficiency is a driver for all modern power converter designs for energy and cost savings and for the reduced size that can be achieved with less power dissipation. Modern circuit topologies using resonant switching are routinely achieving efficiencies in the high nineties with remaining losses concentrated in residual conduction and switching effects. To push towards lower losses still, wide band-gap semiconductor switches such as SiC FETs are now available with on-resistances measures in milliohms and switching characteristics that approach the ideal. Coupled with easy circuit implementation, and a full portfolio of SiC FETs[4] device options, UnitedSiC delivers a high-performance, robust solution to low-loss power switching.

References:
[1] https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html
[2] https://www.prnewswire.com/news-releases/the-dc-dc-converters-market-is-expected-to-grow-from-usd-8-5-billion-in-2019-to-usd-22-4-billion-by-2025--at-a-cagr-of-17-5-300956732.html
[3] https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use/
[4] https://unitedsic.com/group/sic-fets/