# Resonant Motor Drive Topology with Standard Modules for Electric Vehicles

Weight and volume reduction of the system have the highest priority in electric vehicles, which leads to high motor frequencies. To gain the advantage of high speed drives without the disadvantage of high power losses, resonant switching topologies are required, without becoming too complex and whilst still satisfying the required reliability. The automotive miracle of increased reliability at reduced cost has to become true again to make this vision real. A new standard component which supports an innovative switching topology might be an important step forward. **Michael Frisch, Vincotech, Munich, Germany**

**The demand for electrical drive solutions** for transportation applications has increased heavily. This is driven by the so-called mega trends such as mobility, energy efficiency, and reduction of $CO_2$ emissions.

Besides, the electrical drive technology offers additional functions and features for those applications. In the current situation the availability of technical solutions is the bottleneck for a realisation of the new applications which pop up in excessive numbers. The Swiss company BRUSA is one of the commercial know-how sources for the required drive system. It decided to develop a standard inverter with the purpose of covering multiple high-end applications with small volume, and having a proven and tested concept as a starting point for a development of high volume applications as hybrid car or electrical car.

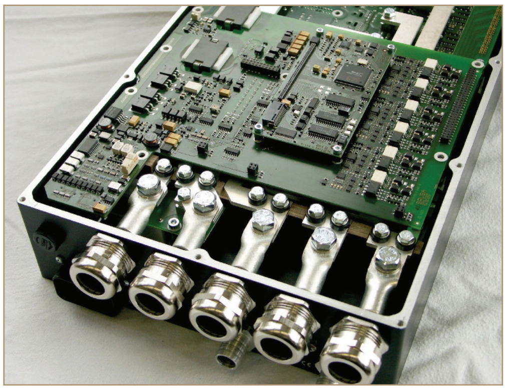


Figure 1: 3~ inverter DMC144

## Specification for a standard motor drive inverter

BRUSA developed a 3~ inverter which had to cover the requirements of the project, but also to provide the flexibility of possible usage in other applications (Figure 1).

The requirements for this motor drive system comprised two types of 3~ inverter with 100 to 500VDC and 200 to 1000VDC voltage, scalable output power in 40kW steps (e.g. 40kW, 80kW), compact outline, liquid cooled, IP65 protection grade, and efficiency >97%.

To achieve small size and weight goal the maximum motor speed will be high. When using a sinusoidal motor current the PWM frequency has to be relative high. The alternative of a rectangular pulsed phase current will cause a DC-current ripple and also a mechanical torque ripple (Figure 2). This ripple will cause several unwanted effects such as additional losses in the battery, audible noise, and vibration which might cause unpredictable problems in the whole electromechanical setup as a broken electrical interconnection or increased thermal contact.

A sinusoidal phase current will generate continuous torque without high frequency vibrations (Figure 4). On the other hand, an inverter with sinusoidal output current requires higher PWM frequencies. In order to avoid increased power dissipation in the inverter electronics, a solution for low switching losses in the inverter is needed.

## Inverter electronics at component level

Highest quality and reliability levels are a must in automotive applications. All subsystems have to be qualified and optimised to achieve the reliability and cost targets. All this has to be done with the available resources in reduced time to meet the time to market specifications. To increase the reliability and reduce cost in a high volume series production, it is important to minimise the complexity of the system. Repeating structures can be realised with identical functional blocks. This reduces development as well as qualification efforts and time. The repeating power electronics structure for drives and

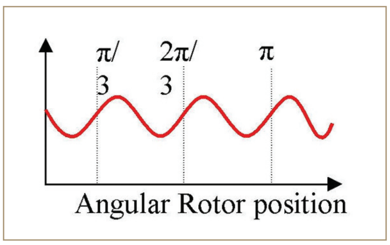



Figure 2: Torque ripple with rectangular pulsed phase current

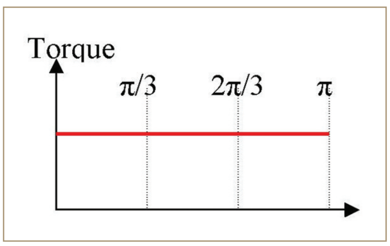



Figure 3: Torque signal at sinusoidal phase current

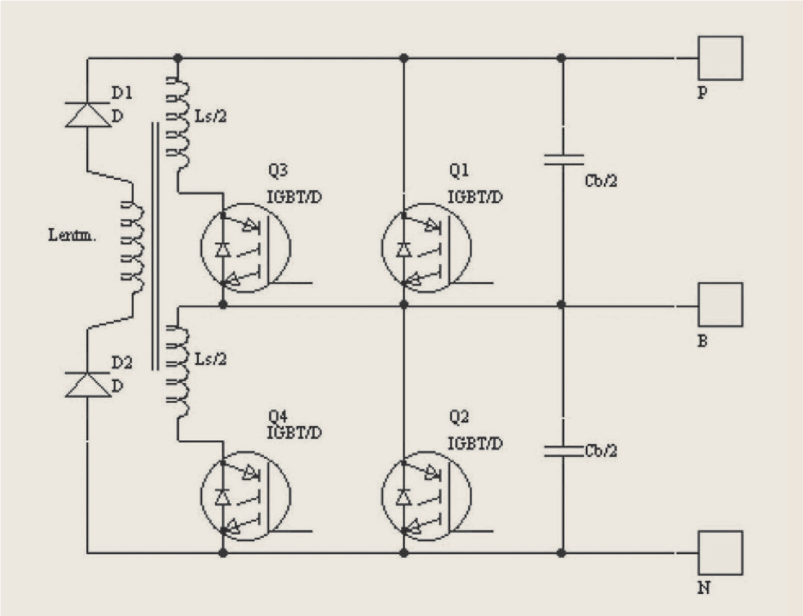



**Figure 4: SoftSwing – topology**

bi-directional DC/DC converters is the half-bridge circuit. A module which incorporates this function is a conclusive subsystem for motor drive applications.

The combination of a high and low switch in one module makes it easy to minimise the inductive loop in the DC-link by retaining the flexibility to distribute the circuits in the available space. This increases the freedom for the system design and reduces the complexity, which is especially important in the limited space in hybrid car applications.

Power modules with half-bridge topology are available as standard products, e.g. flowPHASE 0 (1200V/150A and 600V/200A).

The requirement of compact high performance motors without torque ripple leads to solutions with high motor speed and high PWM frequencies. Switching frequencies >20kHz will cause unacceptable switching losses in standard hard switched inverter topologies with the usual three-phase inverter bridges. Special soft switching concepts are required to reduce the maximum power dissipation in the semiconductors. The resonant SoftSwing topology was selected to answer this challenge. Hard switching inverters provide a considerably lower PWM-frequency than Soft Swing inverters would do.

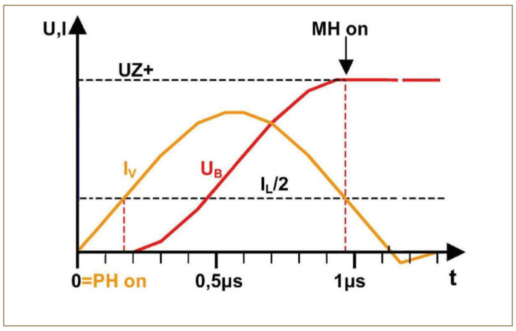
However, the standard half-bridges are obsolete now. The modules do not support such an approach sufficiently. The new task is to develop a universal power module for motor drives and DC/DC converters in hybrid and fuel cell vehicles with electrical output power: 30 to 100kW, DC-voltage 150 to 450V and 600 to 900V. The module has to support the special requirements of the SoftSwing topology at an ultra-high motor speed of 100,000rpm (ca. 1700Hz) and a PWM frequency of 24 to 48kHz.

The bridge point is formed by the two main IGBTs and is connected to an auxiliary circuitry, consisting of small bridge capacitors and an auxiliary half-bridge with small IGBTs and coupled inductors on their drains (Figure 4). In the case of active switch-on (Figure 5), the external gate stimulus turns on only the auxiliary IGBTs (PH on), which conduct first. Subsequently, the current ramps up flowing into the inductor. Due to the coupling, the same current ramps up in the other inductor through the free-wheeling diode of the passive auxiliary switch. Once the sum of these auxiliary currents reaches the load current level, no load current flows through the main free-wheeling diode, which is then about to set the bridge point free.

The bridge capacitors and the inductors form an LC-oscillator and the bridge voltage starts to swing around its neutral point, which, in this case, is the virtual centre tap of the DC-link. If the damping is sufficiently low, the bridge voltage nearly reaches the other rail potential where it is trapped by the zero current, zero voltage turn-on of the corresponding main IGBT (MH on). From this point on, the auxiliary inductors release their stored energy as their currents start to ramp down. With the load current continuously flowing, the main IGBT current must ramp up to compensate for the disappearing auxiliary current. Once the load current is completely commuted, the inductors need to be demagnetised, for which the auxiliary IGBT has to be turned off. One solution to perform demagnetisation is by using a well-coupled demagnetising winding. Once the auxiliary inductors are completely demagnetised, the half-bridge is ready for another active commutation.

Advantages of this topology are zero current - zero voltage switching. The reverse recovery charge is not absorbed when the load current commutes from the free-wheeling diodes into the IGBT. The bridge capacitors protect the IGBTs from high voltage as the tail current occurs during turn-off. Due to the absence of significant switching losses, the IGBTs can be utilised up to their rated DC-capability. Ageing related to periodical thermal expansion of the chip, caused by adiabatic switching loss absorption, is completely avoided. The circuit is extremely rugged and tolerant in overload conditions. At 24kHz, the power dissipation is only half that of conventional hard switched topologies. Due to the absence of reverse recovery spikes, the circuit generates extremely low disturbance emissions. In particular, DC-link filtering against conducted emissions becomes

**Figure 5: Switch on signals**



unnecessary. High PWM-frequencies are allowed, leading to sinusoidal motor currents of up to 2kHz or more. This allows innovative, high power density motor concepts. Low du/dt reduces the dielectric stress of the motor insulation and thus, enhances the reliability during the expected lifetime of the vehicle.

On the other hand, the commuting time affects the PWM of course. Generally, the turn-on delay, which depends on the current, has to be considered at the control part. In addition, the demagnetising time limits the minimum turn-on time to approximately 3% of the PWM cycle time. Standard gate drivers cannot perform well, in particular if they operate with a fixed dead time. Any dead time will increase the turn-on delay and is therefore counterproductive.

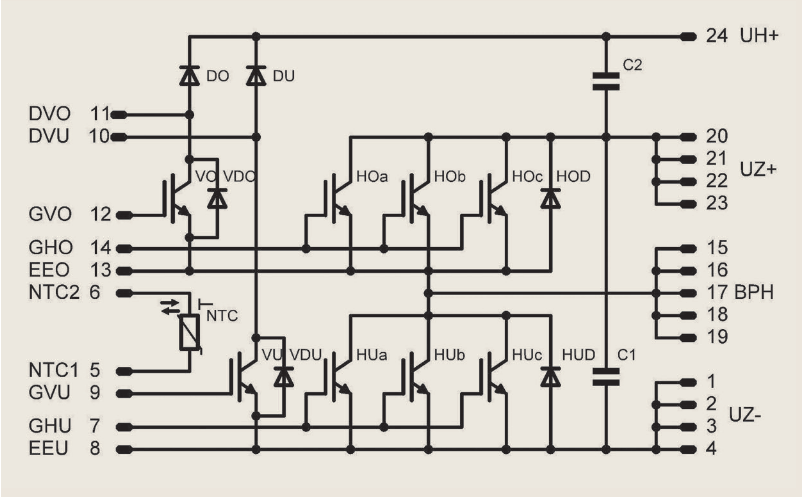



**Figure 6: Module schematics**

## Module definition

To be developed is a power integrated module with lowest possible inductances, in order to achieve subsystem levels which can be tested, qualified and produced at constant quality levels, using state of the art technologies and fabrication processes. The repeating structure for drives and bi-directional DC/DC converters is the phase leg topology. To achieve maximum flexibility, the phase leg function with incorporated SoftSwing topology is integrated into a single module (Figure 6).

The module is realised on a DBC substrate, which is directly mounted onto the system heatsink. For a better thermal interface to the cooling medium, AlN was chosen as substrate material. For applications with lower power demand, the standard $Al_2O_3$ DBC can be used. A baseplate-less solution is preferred, due to the outdoor usage with harsh requirements with regard to thermal cycling capabilities.

In order to achieve the required performance levels, the module's main power bridge consists of paralleled high speed IGBTs, designed for fast switching applications, with a given total nominal current of 150A (600V: 3 x 50A trench-field stop-IGBT + 100A ultra-fast recovery FRED. 1200V: 3 x 25A planar-field-stop-IGBT + 75A ultra-fast recovery FRED). The challenge for this pre-switch IGBT is the high current in short time. The device is far away from the thermal limits because of the short duration time of 1µs. But this component has to carry the complete phase current plus the reverse recovery current of the main diode at switch-on. IGBTs are rated only up to three or four times nominal current. It is likely that the IGBTs will work also with higher current during the 1µs period but, in this case, the component would be out of specification. The short circuit rating will not help, because the specified 10 times nominal value is only allowed for non-repetitive short circuit conditions.

The integrated capacitors are SMD components, specified for the required power and voltage levels. An SMD temperature sensor for monitoring of the module temperature is integrated as well. Three such modules represent a complete power kit of 40 kW continuous electrical output power. Higher power ratings are possible by paralleling. It is now possible to achieve 40, 80 and 120kW with the same components (Figure 7). The two different chip technologies (600 and 1200V) support DC voltages up to 900V.

A first application is a rail-based electric vehicle with 6 to 8 seats and its own drive mechanism with energy storage on board (energy recovery), a maximum incline climbing ability of 55%, maximum travel speed of 80km/hr, and capacity of 3000 people/hour/direction. The vehicle's batteries are only fully charged overnight. Thus, it is possible to use a high amount of cheap off-peak mains power.

## Conclusion

The softPHASE 0 modules are easy to use components for designing high efficient inverter and DC/DC converters in SoftSwing resonant topology. The phase leg concept provides the flexibility to distribute the inverter over the available volume in the application. The scalable power by paralleling multiple modules is a further advantage of the presented solution. The power modules are designed under the maxim of gaining highest power density as well as lowest stray inductances. High switching frequencies enable even special e-motors with extremely low leakage inductance to perform well. This is particularly beneficial for ultra-high speed drives or motors with a high pole pair number.

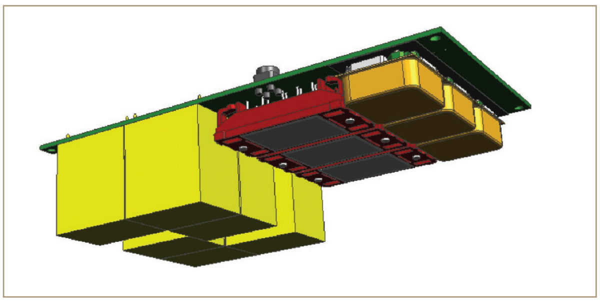


**Figure 7: Power PCB with three modules**

**Figure 8: Passenger transportation system application**