

Integrated Energy Storage Systems to Optimize Payback Period of Hybrid Vehicles

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ABSTRACT

Enhancements of today's Micro-Hybrids based on stop-start systems with and without coasting and energy recuperation show a positive cost-benefit and a much shorter payback period compared to more complex and expensive Full-Hybrid concepts. However, improved Micro-Hybrid functionalities have a higher demand on the vehicle's electrical power network, which cannot be covered with traditional topologies alone.

To enable the advanced Micro-Hybrid features, additional energy storage elements like second lead acid batteries, double-layer capacitors or lithium-ion cell based storage systems will be integrated into the power network. This will stabilize the network and provide a reliable source of energy. To apply even further reaching measures like creeping (also called crawling), and high power recuperation, a dual voltage power network will be required. This can be achieved by adding a second voltage level to the traditional 12V power network.

In order to connect power networks with different voltage levels, DC/DC converters are required. This paper will discuss the constraints of a cost-optimum topology for each power class of DC/DC converter from Micro- up to Mild-Hybrid applications and present solutions to overcome these limitations. Furthermore, the different topologies are compared in regards of their economic benefit using the total cost of ownership model.

CITATION: Rosenmayr, M., Brown, A. and Schmidt, R., "Integrated Energy Storage Systems to Optimize Payback Period of Hybrid Vehicles," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-0341.

INTRODUCTION

Over the past years, both legal requirements for lower emissions as well as an increased awareness of the total costs of ownership have paved the road for more fuel efficient vehicles. As a result of this, most recent improvements in energy density and reliability of battery systems have proven the feasibility for alternative propulsion systems, in particular based on Hybrid Electric Vehicles (HEV) in a number of different topologies: Micro-Hybrid, Mild-Hybrid and Full-Hybrid, depending on the installed power and energy level.

While the Full-Hybrid concept shows a great success in reducing the dependency on oil-based fuels, it has not achieved a breakthrough in means of units sold due to the significantly higher costs. This leaves the absolute total emission reduction small compared with the vast potential of conventional vehicles with combustion engines in service. Therefore, the increase of fuel efficiency and reduction of CO₂ emissions of conventional vehicles remains a main challenge in the automotive development field. Due to the large production volumes still seen with combustion engines, a relatively small increase in fuel efficiency leads to a much larger overall reduction of emissions. However, such a

volume based effect will only be successful if it follows the most economic approach available.

I. MICRO-HYBRID

To increase fuel efficiency and to reduce CO₂ emissions, it is the goal to switch off the combustion engine whenever possible. Traditionally, the combustion engine is running during the complete drive cycle. As a first level of optimization, a stop-start system shuts down the engine as soon as the vehicle is at a standstill and automatically restarts when the driver desires to move on. This system, often referred as Micro-Hybrid, is based on a traditional 12V electrical power network [1]. The configuration of the power net for a Micro-Hybrid is shown in [Figure 1](#).

A stabilized 12V subnet is created for under-voltage sensitive loads such as infotainment systems or lights, to avoid driver noticeable effects during re-start. Such a subsystem operates as follows: An idle-stop engine start triggers a DC/DC converter (voltage stabilizer) to maintain the 12V power subnet voltage quality. After engine re-start is complete, the voltage stabilizer reverts to a passive mode

connecting the power subnet directly to the alternator power net to minimize efficiency loss during normal operation.

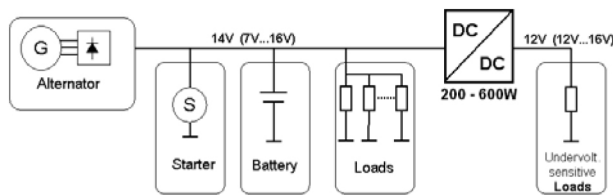


Figure 1. Micro-Hybrid idle-stop 12V subnet with DC/DC converter (200-600W)

The power class of the 12V voltage stabilizer is generally in the range of 200-400W. Higher power levels are possible but generally do not exceed 600W due to high input currents required to maintain the 12V output voltage level at low battery voltages. As the battery voltage level drops toward 6V the current required to maintain the 12V subnet can reach levels that further burdens the battery causing a positive feedback effect on voltage stabilizer input current. Since the voltage stabilizer converter is a power conversion device it requires higher current levels to maintain the fixed output power level given a lower input voltage level. Figure 2 from [2] shows the tipping point between the stable and unstable power range for a traditional 12V system as a function of the subnet power. System model includes affects from battery, starter, loads, voltage stabilizer and stabilized power system from a nominal vehicle with idle-stop system.

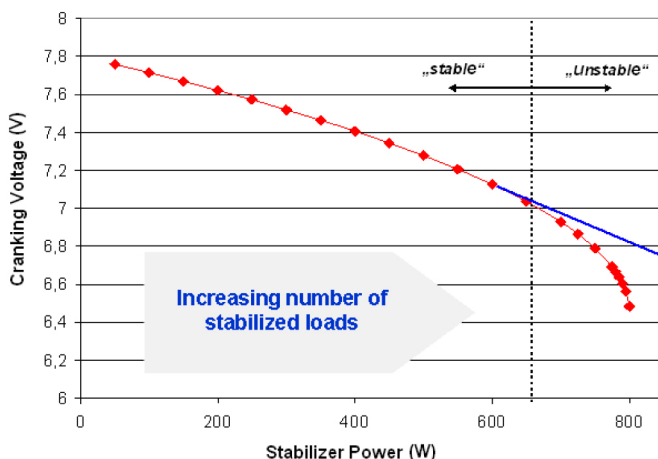


Figure 2. Voltage drop during warm cranking for different power classes of the voltage stabilizer

Usually an improved, more cycle-stable lead acid battery with excellent cranking performance is applied. The battery is discharged during stop mode and needs to be recharged when the engine is running, ideally during braking, so called recuperation or energy harvesting. The poor charge acceptance of lead acid batteries is today the limiting factor of recuperation in Micro-Hybrids

II. ADVANCED MICRO-HYBRID WITH ENERGY STORAGE

In order to further enhance efficiency of Micro-Hybrid vehicles, the engine must be stopped in more situations and over longer time periods. During coasting while approaching traffic lights or slower vehicles in front, the combustion engine is not required for propulsion. If the engine is switched off while the vehicle is moving, the battery remains the only source of electric energy. As there is a potential risk for sudden battery defect or disconnection, a backup power supply becomes mandatory. The backup power supply must be capable of supplying energy to safety relevant loads like electric power steering and stability control while the vehicle is coasting with the engine switched off or comes to a safe stop. Therefore, up to 1kW power needs to be provided for several minutes. The backup power needs diagnostic functionality to ensure that coasting is only enabled when the backup power is reliably available. Having such an additional energy storage module on-board for safety reasons, it can be utilized for further optimizations of the energy consumption. A bi-directional buck-boost DC/DC converter is placed between 12V alternator power net and an energy storage element as shown in Figure 3.

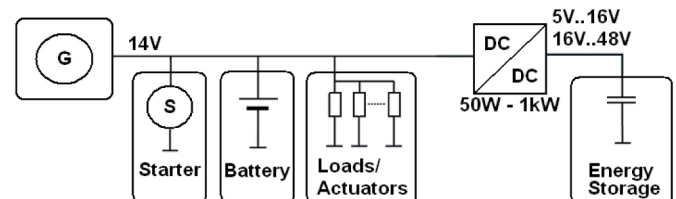


Figure 3. Low voltage Micro-Hybrid with recuperative energy storage (50W-1kW)

The addition of the DC/DC converter allows the flexibility to choose the voltage level of the energy storage element. A good charge acceptance is important to allow optimal recuperation. A high capacity of the energy storage module would be beneficial to maximize availability of electrical power. Cold cranking performance is not required, as cranking is still the duty of the lead-acid battery. A good cycle and lifetime stability is important to make the storage module last long. For selection of the right battery technology for the storage module battery performance parameters like cycle capability, energy density, power density, charge acceptance and last but not least cost vehicle architects need to trade-off those parameters. By combining the battery with a DC/DC converter, the system designer is free to choose the cell voltage level. This allows the integration of alternative technologies like ultra caps. Typically a standard single cell ultra-cap has a maximum voltage of 2.7V. The DC/DC converter therefore must provide 12V power to the alternator power net by boosting the ultra-cap voltage. This requires high levels of current to achieve the 12V / 1kW output power

level. DC/DC converters in this power class typically employ multiple power phases to provide the required power. It is also possible to place several ultra-caps in series to achieve a higher voltage level thus simplifying the design of the DC/DC converter.

The energy storage element is more optimally charged by energy recuperation during coasting or light vehicle braking if the SOC is at a good charge acceptance level. Excess power is fed via the DC/DC converter to the energy storage element charging system which monitors the individual ultra-cap cell voltages to insure proper charging. This is to prevent individual 2.7V cells from an over-voltage condition which decreases the capacitors usable life. Each 2.7V cell must be monitored to insure the voltage level is kept below a safe level. A bleeder circuit is employed across each 2.7V ultra-cap cell which effectively clamps the cell voltage when the cell is fully charged (see Figure 4).

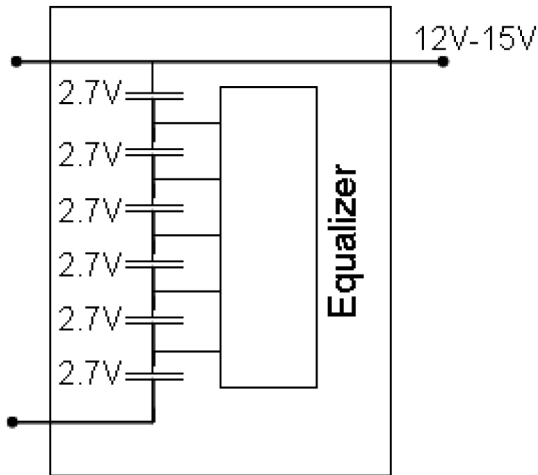


Figure 4. Ultra-capacitor charging equalizer

Figure 5 shows an energy storage device mated with a 60W DC/DC converter. This system offers higher efficiency and ease of integration when packaged together. Storage elements can include double-layer capacitors, lithium-ion batteries, lead acid batteries depending on the charge / discharge profile and the required stored energy. Higher power classes are also available up to 1.6kW and beyond using lithium ion cells or super caps.

An attractive concept is achieved by combining a lead acid battery optimized for cold and warm cranking with a battery storage module optimized for charge acceptance, cycle stability and backup capacity. The starter battery can be maintained at a high State-of-Charge (SOC) level for optimal cranking performance and long battery lifetime. The backup battery is re-charged preferably during recuperation. Given good cycle stability, it would also be beneficial to use this battery to supply loads when the engine is not running. The battery management of the storage module can be integrated into the DC/DC converter.

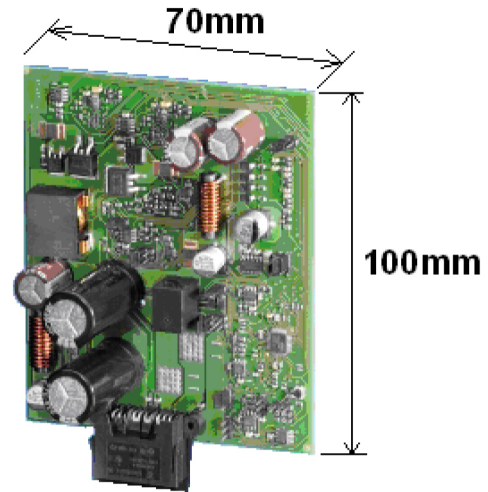


Figure 5. 60W DC/DC converter packaged with double layer capacitors as energy storage elements

III. MILD-HYBRID

In stop and go traffic, drivers with automatic transmissions tend to creep by just releasing the brake without actually using the acceleration pedal. In a Micro-Hybrid vehicle, after idle-stop, the combustion engine must be cranked again to creep forward. This is not optimal for overall efficiency. The power required for creeping is approximately 10kW, depending on the vehicle weight. Advanced starter/alternator machines can realize electric creeping functionality, but would require a higher voltage level for this power class. This high voltage power network would supply high power loads, in addition to propulsion such as electric heating for example. As the generator is at the higher voltage level, the energy must be transferred to the load side at the regular 12V power net. The traditional 12V network is supplied via a DC/DC converter. The bi-directional DC/DC converter as a replacement of the traditional alternator must support between 1.5kW and 3.0kW step-down performance in order to substitute the conventional alternator in most applications. The DC/DC converter must be able to transfer energy from HV to 12V with the maximum power rating at the highest possible efficiency, in order to maintain a high effectiveness of the whole recuperation system [2]. For backup reasons it must also be able to transfer energy in the opposite direction, for instance to charge the HV battery, or as a safety backup for the alternator. With the powerful starter/alternator and a high performance battery, recuperative braking allows additional increases in efficiency (see Figure 6). On the high voltage (HV) side there may be also loads, especially high power loads.