

# Efficient Vehicle Power Supply by Adaptive Energy, Charge and Heat Management of an Alternator - Super Capacitor System

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## ABSTRACT

The power requirements of future vehicle electrical distribution systems will increase considerably. Consequently, electrical energy has a major impact on the overall vehicle energy balance, so its generation and storage must be as efficient as possible.

The presented concept is based on a voltage-controlled alternator in combination with super capacitors and a corresponding energy management system. The focus is energy efficiency, recuperation, and the use of standard components. A specific hardware in the loop based test set-up was built that allows the control and monitoring of the mechanical and electrical energy flows. Besides the theoretical description, the paper presents first experimental data and results followed by a discussion of the next steps and future potentials.

## INTRODUCTION

A well-known approach to enhancing energy efficiency is recuperation, which limits the mechanical/electrical energy conversion to phases of only negative acceleration or downhill driving. If there is no electrical traction component, the recuperated energy can be used only by the other electrical vehicle systems. Thus the efficiency of recuperation improves with the increase of electrical vehicle power consumption, which is to be expected due to additional electrical features as well as due to the conversion of current mechanical and hydraulic actuators into mechatronic systems.

First vehicles already in production are using standard or improved alternators and batteries in combination with an energy management which takes into account the current driving condition. The downside of this concept is that the alternator operates on battery voltage level and that the frequency and depth of charge cycles is increased. As a consequence, the maximum power of the alternator is limited and the lifetime of the battery may be shortened.

Other approaches address these disadvantages by adding super capacitors to handle the critical charge cycles and by operating the alternator at higher voltages. These concepts require DC/DC converters and optional switches and cause negative design impacts on packaging, weight and costs. On the other hand, these concepts have the potential of a higher recuperation rate, of an improved stabilization of the supply voltage, and of downsizing the battery, e.g. by using the super capacitor as a starter power supply.

Different architectures were realized or have been proposed. The one described in this paper is designed to minimize the power requirements to be met by alternator, electrical storage devices and converter, thus reducing the cost impact under the boundary condition of improved energy efficiency.

The presented concept is based on a voltage-controlled alternator and a new charging strategy for a combination of super capacitors and battery. The corresponding energy management takes into account the drive cycle and -status, the electrical power consumption of the vehicle and the thermal characteristics of the components, especially of the alternator.

## ARCHITECTURE

The architecture depends on various parameters such as

- battery type and performance,
- alternator type and voltage control,
- use and performance of an additional storage device,
- use and performance of DC/DC converters,
- power loads and their voltage range,
- energy management and
- topology.

Furthermore, the architecture is determined by the technical and economical targets and boundary conditions such as efficiency, voltage stabilization, weight, reliability or cost. As a consequence, there are a high number of possible architectures of which some are already in production or are under investigation, e.g. [1-6]. The following block diagrams should give a systematic, but not complete overview and illustrate the particular pros and cons of each.

The first approach is to obtain maximum use and functionality by employing regular or improved standard batteries and by applying minimum design changes. For example, the solution as in Fig. 1b allows the realization of a low cost start-stop function by simply adding a DC/DC converter to a current architecture as shown in Fig. 1a. Based on the higher voltage level, even a belt-driven starter is sufficient for smaller engines.

The architecture presented in Fig. 1c utilizes the voltage control of the alternator  $G_2$  and an appropriate energy management to render possible fast charging of the battery during vehicle braking and thus to allow a moderate recuperation. As figured, an additional DC/DC converter may be necessary to stabilize the voltage supply of sensitive electrical components.

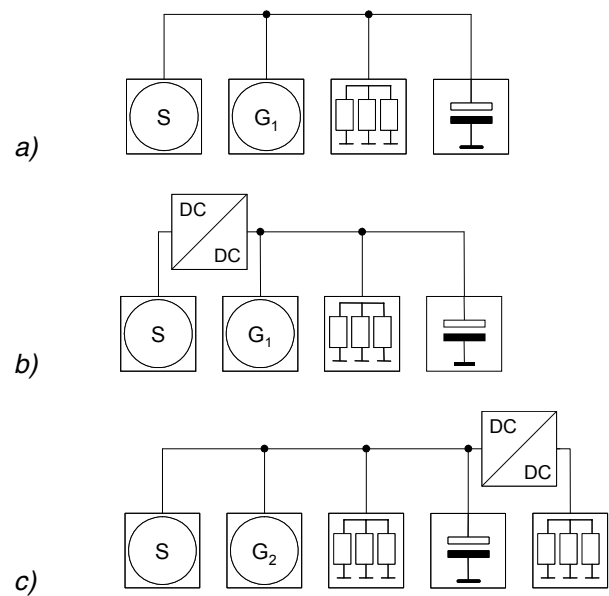


Fig. 1a,b and c, see text

Another approach addresses the limitations of current batteries, either by applying a more innovative technology such as Lilon or by adding a second energy storage. In particular, the technical characteristics of ultra capacitors, e.g. high charge and discharge currents and frequencies, but low specific energy, are very complementary to those of batteries and thus the combination of both is very interesting.

Already a simple architecture as presented in Fig. 2a provides several advantages: The supply voltage is stabilized even if there are dynamic power actuators in the EDS, no DC/DC converter is necessary, and the starter can be supplied by the ultra-capacitor. The downsizing of the battery, and, in a decentralized topology, of several wire cross-sections, is possible.

As the energy content of a capacitor is  $CU^2/2$  and the voltage change is marginal because of the parallel battery, the described architecture has the disadvantage of using the ultra-capacitor only partially. A solution as shown in Fig. 2b overcomes this drawback by applying a DC/DC converter to the ultra-capacitor. In some cases, such a configuration is also used to provide a power supply with a higher voltage and a low internal resistance for certain actuators.

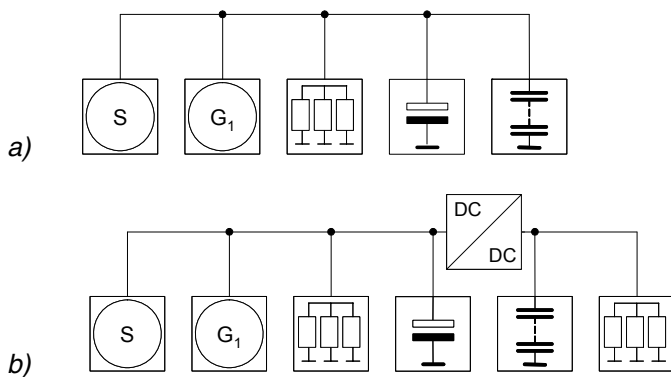


Fig. 2a and b. see text

All presented architectures have in common that the alternator voltage is limited by the battery. An obvious alternative is to let the alternator charge the ultra-capacitor directly and to utilize an adapted voltage control. The advantages are that at higher voltages the possible alternator power output increases considerably and its energy efficiency improves slightly. In combination with the higher charging currents of the ultra-capacitors (low internal resistance), this offers an interesting potential for recuperation.

Fig. 3a shows such an architecture using a starter alternator (SG). Of course, the battery and the remaining electrical distribution system (EDS) must be supplied via a DC/DC converter. Considering all operating states of the vehicle, this converter must be bidirectional and has to be specified for strong energy flows, which is certainly a drawback. An architecture as presented in Fig. 3b utilizes an active cooled linear power switch and a diode to keep the requirements to the DC/DC converter within an acceptable range.

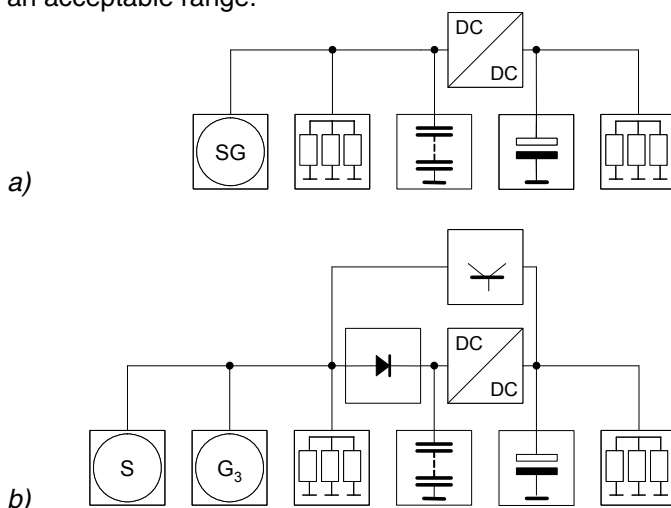


Fig. 3a and b, see text

The architecture presented in this paper (Fig. 4) is based on the type shown in Fig. 3 a,b but uses two relays (or optionally just one, see below) which leads to a very different type of control. The basic idea is to switch between two modes of operation (see table 1). If switch *a* is open and switch *b* is closed, the proposed architecture corresponds to the one shown in Fig. 3a with all advantages and functions already described there. This is the regular mode of operation, where the alternator is active only during negative acceleration or downhill driving or if the capacitor voltage  $U_c$  is below a given minimum level  $U_{cmin}$ .

The DC/DC converter should be designed to meet the mean instead of the maximum power requirements. Thus on one hand the converter costs are reduced, but on the other hand scenarios are possible where the required power exceeds the maximum rating  $p_{DC/DC}$  of the DC/DC converter. For example, the power consumption  $p_{Load1}$  is high and the SoC of the battery is below a critical value  $SoC_{crit1,2}$  or, another scenario, the power consumption  $p_{Load2}$  is high, the ultra capacitor is not charged and the alternator rotational speed  $n_{alt}$  is below its minimum value  $n_{alt,min}$ , e.g. the engine is at idle speed. In such cases the second operating mode (switch *a* closed and switch *b* open) has to be applied. This configuration corresponds to the architecture shown in Fig. 2b.

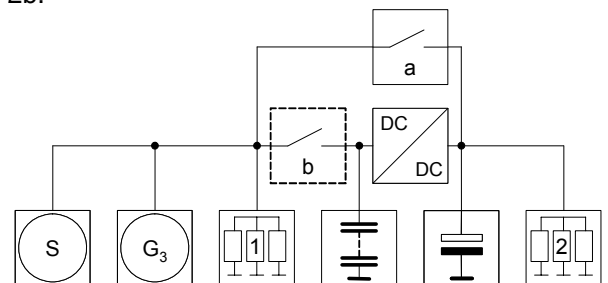


Fig. 4, Proposed Architecture

| Source:                                                                                | Supply via:                   |                    | Switch |        | Condition:                                                                                   |
|----------------------------------------------------------------------------------------|-------------------------------|--------------------|--------|--------|----------------------------------------------------------------------------------------------|
|                                                                                        | direct                        | DC/DC              | a      | b      |                                                                                              |
| (A) $(SoC \geq SoC_{crit2} \wedge p_{DC/DC} \geq p_{Load2}) \vee SoC \geq SoC_{crit1}$ |                               |                    |        |        |                                                                                              |
| Alternator                                                                             | Loads 1<br>U-Cap              | Loads 2<br>Battery | open   | closed | $n_{alt} > n_{alt\_min} \wedge$<br><i>(Recuperation <math>\vee U_C \leq U_{cmin}</math>)</i> |
| U-Cap                                                                                  | Loads 1                       | Loads 2<br>Battery |        |        | $n_{alt} \leq n_{alt\_min} \wedge$<br>$U_C > U_{Cmin}$                                       |
| Battery                                                                                |                               | U-Cap              |        |        | <i>Start</i>                                                                                 |
| Battery                                                                                | Loads 2                       | Loads 1<br>U-Cap   | closed | open   | $n_{alt} \leq n_{alt\_min} \wedge$<br>$U_C \leq U_{cmin} \wedge p_{DC/DC} > p_{Load2}$       |
|                                                                                        | Loads 1<br>Loads 2            | U-Cap              |        |        | $n_{alt} \leq n_{alt\_min} \wedge$<br>$U_C \leq U_{cmin} \wedge p_{DC/DC} \leq p_{Load2}$    |
| (B) $(SoC < SoC_{crit1} \wedge p_{DC/DC} < p_{Load2}) \vee SoC < SoC_{crit2}$          |                               |                    |        |        |                                                                                              |
| Alternator                                                                             | Loads 1<br>Loads 2<br>Battery | U-Cap              | closed | open   | $n_{alt} > n_{alt\_min}$                                                                     |

Table 1, Modes of Operation