Specialized Battery Emulator for Automotive Electrical Systems

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Abstract—**Complexity of the automotive electrical power system is continuously increasing. Greater amount of higher loads is added and active energy management is being introduced. The whole design of such power systems depends on the batteries being used. Since safety-related systems also need power to function, special care has to be taken considering voltage quality. However, there are a lot of parameters that can be modified, and all configurations need to be tested. Since testing is time consuming, the right tools must be used during different phases of the design process.**

Specialized battery emulator is a combination of a power electronics device with an advanced battery model. It is used for testing and verification of the vehicle electrical system at various battery behavior or ambient conditions. Design requirements for the hardware were identified by observing occurring current and voltage ranges as well as considering special needs in the automotive environment.

I. Introduction

The desire for safety and comfort leads to an increasing amount of electrical units within a modern car. Components that were previously supplied with mechanical or hydraulic energy are replaced by electrically supplied appliances. In addition to the increase in the net electrical energy consumption, this also leads to growing peak power requirements [8,9]. Pulses drawn by several actuators are a problem for the electrical system. However, using a larger battery for compensation would introduce additional cost and weight.

Besides the battery size, there are many other degrees of freedom. All the aspects of the design, including chemistry and construction, can be optimized for different objectives. For micro hybrid applications, for example, it is important to take charge acceptance into account [7,10]. Charge acceptance limits the amount of energy that can be regenerated during braking and thus influences fuel efficiency. Choosing the best trade-off between these parameters is a challenge.

Since vital systems need to be supplied with necessary power at any time, verification of the chosen configuration is a key issue in the development cycle. Since batteries change their behavior with changing state of charge, temperature and age, tests have to be carried out under all possible conditions, to verify the correct functioning. Active power flow management, used in micro hybrids, not only allows better flexibility to optimize the system for fuel savings, but also increases its complexity.

In the following chapters, the tools, currently used to help with proper design and verification, are shown. Then a missing link in the verification algorithm is identified. Finally, by investigating the electrical behavior of standard lead-acid SLI batteries, the requirements for the missing tool are defined and one possible solution is presented.

II. Currently Used Tools

There are several tools used at the moment. At the first stage there is usually a simulation model of the whole electrical power system. In order to keep the simulation time within reasonable bounds, complexity of different parts of the model has to be small. Therefore, simple, idealized models of the system parts are used. For the battery simulation, often a state of charge dependent voltage source with an inner resistance is used. A disadvantage of this model is that several effects, like charge carrier depletion, are neglected. The simulated behavior often derives too much from reality, especially in edge cases. A statement about voltage quality cannot be derived solely using this approach.

The most accurate way to perform verification tests is to use a regular battery, loads and a generator. But since the power system has to be stable at all possible battery conditions (e.g. after a long standing time with an old battery), many batteries are required and they need to be preconditioned (adjusting state of charge, aging, temperature) as well as mounted and dismounted on the test car. This procedure is time consuming and costly. Another problem is that the battery changes its state with every test drive and, therefore, the behavior is not reproducible. Effects of the changes are especially hard to compare during the optimization of a parameter from an active power management.

Between the simulated and hardware environments there is a hybrid level. The device to be examined is simulated while all other parts are used as hardware. For this purpose an interface is needed between the real and the virtual environments. The combination of a simulation model and interface-hardware is called emulator. A benefit of this

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approach is that the model detalization can be significantly higher, since only one device needs to be simulated. The accuracy can thus be increased while retaining flexibility.

There are laboratory type battery emulators that take a controllable voltage source to produce a virtual battery (e.g. [1]). They measure the output current and calculate the optimal voltage for the provided battery model. However, in most commercially available systems, the model is as simple as used in the overall simulation. Moreover, these systems are mains-operated and housed in big size cabinets and thus can only be used on stationary test stands. Test with the complete car can only be done at roller type test stands. However, on these stands it is not possible to apply dynamic driving conditions where, for example, the stability program will become operative and draw excessive power from the electrical power system.

From the previous remarks it can be recognized that the optimal tool would be a specialized battery emulator. It has to be mobile to permit usage in driving tests, include an advanced battery model and be able to provide the dynamic current and voltage behavior of a real battery.

III. BATTERY BEHAVIOR

To identify the needed performance characteristics of the emulator, the characteristics of a real battery and the usage scenarios within the car have to be identified first.

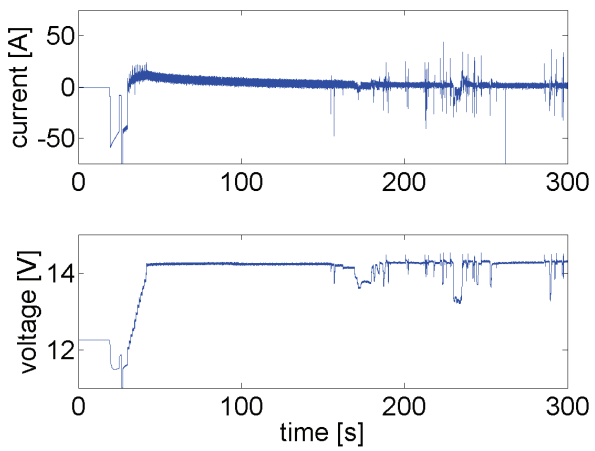

Figure 1. Current and voltage profile of an exemplary five minute drive cycle with a diesel engine car

In Figure 1, the current and voltage profile of the first five minutes of an exemplary drive cycle of a diesel engine car equipped with a lead-acid battery are shown. After about 20 s the ignition is turned on and the battery is being discharged while the preheat cycle starts. Then a cranking pulse follows which is cropped in the figure. Afterwards, the generator recharges the battery and different loads draw more or less power out of the power system. The voltage range is defined by the battery and lies in the range of a few volts (during cranking) up to about 15 V at some peaks. The current can be divided into continuous currents up to 100 amps during charge and discharge and the cranking current (discharging) that can go up to more than 1000 amperes. The continuous current range should be extended to account for micro hybrid systems, where the generator power is reduced in some periods (higher power draw) and boosted during braking to recover kinetic energy (higher charge currents).

The dynamics of the current within the profile are quite high. From the cranking pulse (Figure 2), it can be seen, that the battery has a low inductance and can therefore supply currents with fast rise times. The dynamics of the voltage corresponds to the current dynamics, because the voltage drop caused by the internal resistance is instantaneous.

Besides the electrical behavior at the terminals, which sets the needed performance of the emulation hardware, the complexity of the simulation model plays an important role. A simple model with a state of charge dependent voltage source and an internal resistance does not account for effects with time constants in the range of one second to several minutes that can be observed in real batteries. There are more effects that need to be monitored. For example, to get a correct state of charge calculation, side reactions needs to be taken into account. In lead-acid batteries especially the gassing reaction has a huge effect.

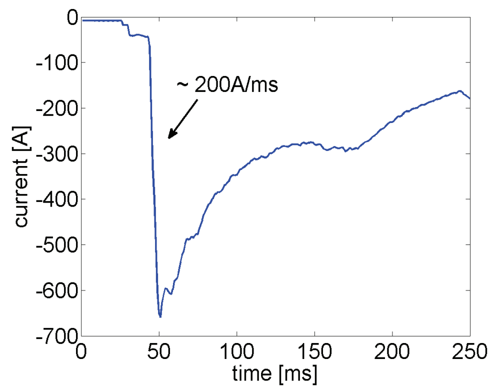

Figure 2. Exemplary cranking current profile

To reach a close match between the behavior of the emulator and a real battery, the precision of the input measurement, model computation and output accuracy have to be optimized.

IV. BATTERY EMULATOR

The presented solution is a combination of a power electronics device with a specialized battery model. With such equipment it is possible to have a virtual battery, where state of charge, temperature, age etc., can be adjusted just by pressing a button. Furthermore, the model can be repeatedly reset to have the same deterministic behavior. The system is supplied by two lead-acid starter batteries connected in series and, hence, is independent from the mains. The hardware size is optimized to fit easily within the test vehicle. The prototype, with all components except the supply batteries, is housed in a 19” 3HE rack (485x300x135 mm). With this setup it is possible to conduct dynamic drive tests.

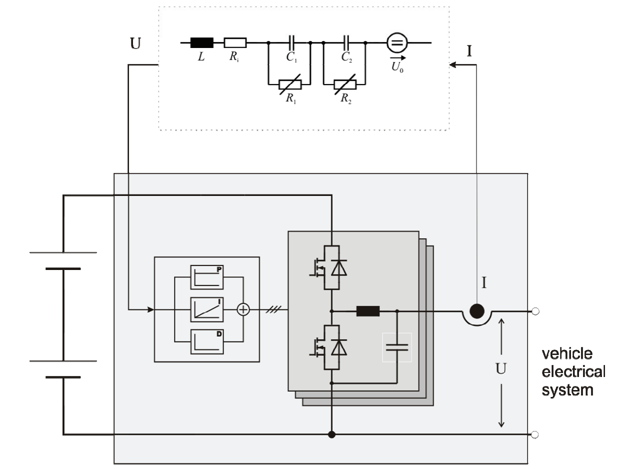

Figure 3. Battery emulator system diagram

A. Power Electronics

A bidirectional DC/DC converter is used. A galvanic isolation is not necessary. On the high voltage side, two batteries are connected in series; the low voltage side is connected to the electrical power system of a vehicle. A challenge in this scheme is an unusual combination of low voltages and high currents. To be able to supply the cranking current, all electrical components (e.g. saturation current of the inductor) have been chosen to withstand its maximum value. To keep the system compact, the thermal design was optimized for the maximum continuous power transfer. During cranking, the heat capacitance of the MOSFET casing is utilized to buffer the excessive heat.

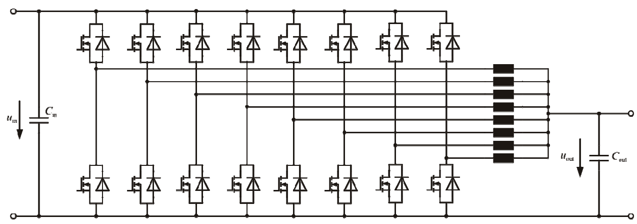

Figure 4. DC/DC converter topology

To achieve the desired current raise times, the inductance has to be kept low, even at small voltage differences between input and output. A negative consequence of this approach is a large current ripple. To compensate for this effect, switching frequency could be raised. However, this method is limited by switching losses, which also increase along with the switching frequency. Therefore a multiphase topology, as shown in Figure 4, is employed [5].

The eight phases are driven with a phase shifted PWM signal. Programmable logic (FGPA) is used to generate eight PWM signals with a frequency of 125 kHz, 10 bit resolution and the needed phase shift. But FPGA is not only used to generate the PWM signals, it also incorporates the control algorithm, sensor data input and validation and error checks. A simple PID controller is used and dynamics of the control is achieved by a high controller frequency, rather than a complex algorithm. An A/D converter samples the output voltage with 222 kSPS and the control runs at the same frequency. By choosing a fractional multiple of the PWM frequency, limit cycling is prevented [5]. Since one timing circuit generates all PWM signals, the difference in phase currents is small. To reduce the remaining inhomogeneity, a secondary controller adjusts the duty cycle proportionally to the current difference.

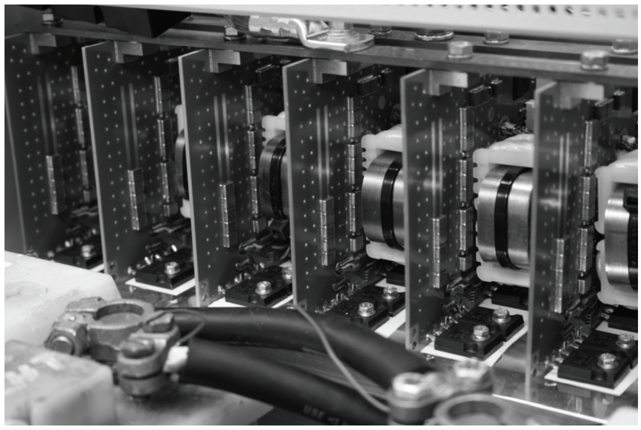

Figure 5. Battery emulator hardware prototype

Because all fast control processes are incorporated into the FPGA, all processing power of the DSP is free to be used by the simulation model. Only the CAN communication channel to the control PC is using some processor cycles.

B. Model

The model is the key part of the emulator. The virtual battery can only be as good as the model. An already existing lead-acid model was implemented, since this is the chemistry that is currently used in cars. The modeling approach is impedance based [2], where the behavior at the terminals is reproduced, rather than physical and chemical processes. An equivalent circuit is selected whose parameter-fields are identified by fitting of several impedance measurements. The model still needs to be extended with some physics based additions, since, for example, open circuit voltage is not included in the impedance measurements [3]. In addition some time domain effects, like gassing and overcharging, are present and have to be accounted for [4].

Despite all the complexity, the model has to be computable on a signal processor in real-time. Therefore the model was changed for time discrete execution. Then fast and slow changing processes were identified and divided into tasks with different execution frequencies for optimized runtime.

The model can be used with different parameter settings to simulate different lead-acid batteries. The values are identified by measurements; it is thus possible to copy behavior of a given battery to the emulator. From measurements of a series of batteries with the same type, but different nominal capacities, the dependency of parameters on nominal capacity was identified. With this knowledge it is possible to measure just one battery of a given set and change the nominal capacity of the emulated battery in a specific range.

During the simulation, internal states, like cell temperature and state of charge, can be accessed and logged. It is thus even possible to use this data as a reference for battery monitoring systems under tests.

V. Operational Test

For a first operational test the emulator was connected to a car. Motor cranking was repeatedly executed with varying simulated battery size and temperature, resulting in different durations for the starting procedure due to the limited power capability. Even aborted starts could be obtained.

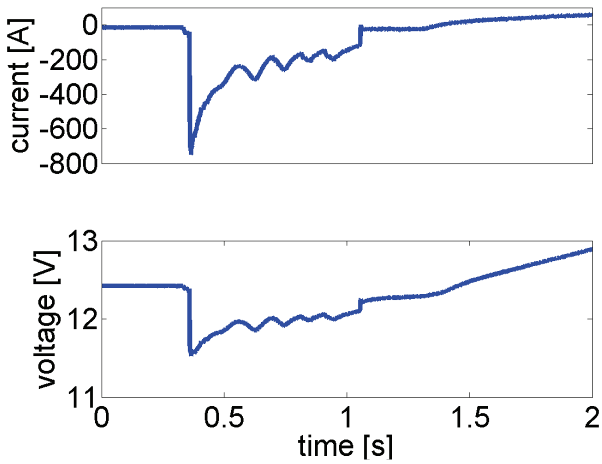

Figure 6. Current and voltage profile of a cranking pulse at the emulator

Further tests with more complex usage scenarios still need to be conducted. Likewise the used model needs to be verified.

VI. Conclusion

The specialized battery emulator serves as the missing link in the verification tool chain. Nevertheless, the emulator is only as good as its model, which will never be a perfect copy of a real battery. Therefore, tests on real batteries are still necessary. However, a lot of test cases can be covered by the emulator, reducing the time for battery preconditioning and setup, as well as significantly reducing the costs. It allows to verify the automotive electrical system in a convenient and reproducible way.

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