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Analysis of the ultracapacitor module in power buffering

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Abstract

This paper presents efficiency analysis of the power buffering in common voltage bus systems. Operation of the power buffering is briefly described with the power control experiments. The efficiency measurement setup and performed measurements from the charging and discharging events of the ultracapacitor module with the dc-dc converter are presented. As a result, the efficiency map of the dc-dc converter is gained and losses of the ultracapacitor module energy storage are differentiated. In addition, the efficiency map of the full charging and discharging cycle of the energy storage system is attained and the capacitance variation of the ultracapacitor module in the dc-dc converters operation area is presented. The operation areas of the energy storage system and variable speed diesel generator (VSDG) in series hybrid electric vehicle (SHEV) application are investigated in simulation case studies.

1. Introduction

This study is part of a duty vehicles hybridization project. Hybridization of vehicles and mobile machines aims to decrease emissions and fuel consumption by exploiting the kinetic and potential energy of the system, downsizing the primary energy source’s power rating, and by generating the primary power with the most efficient means.

Design of a hybrid vehicle, non-road mobile machinery (NRMM) or other hybrid power system is a very complicated task. Therefore, profound research relating to energy storing, hardware design and supervisory control is needed. This study focuses on the system efficiency of peak power buffering in common voltage bus systems. The system efficiency study utilizes the measured data, since it is not feasible to use too accurate system level models with a semiconductor switching events. The functional approach in system level models provides possibility to solve power train’s total efficiency efficiently. Also, characteristics of an ultracapacitor (UC) module in system level are considered [1].

The contribution and novelty of this article is in introducing the power buffering from the Original Equipment Manufacturer’s (OEM’s) from the NRMM industry point of view. This consists of presented measurements, analysis and case simulations for the UC module based power buffering in SHEV drive lines. Efficiency maps from charging, discharging, and full cycle are presented for the three-phase interleaved boost converter, [2] and [3]. Also, losses of the UC module are differentiated from the measurements. Furthermore, as a case example the operation area of an energy storage system in peak power buffering is described on a two-quadrant efficiency map and the affect of the dc-dc converter control strategy on the VSDG’s possible operation area is compared. This study completes the SHEV modeling studies presented in [4] and [5].

2. Power buffering in common voltage bus systems

Two different power control cases are presented in this chapter: case 1 presents the peak power cutting method and the case 2 presents the acceleration assistance and regenerative energy recuperation method. In addition, the latter can be separated into two sub cases depending on the source current during the regenerative load current. The current patterns and scheme of the experiment setup of these two power control cases are shown in Figure 1.

Fig. 1. The power control targets for two different cases: peak power cutting and acceleration assistance / regenerative energy recuperation.

2.1 Peak Power Cutting

Figure 2 presents the peak power cutting measurement. The dc-dc converter was controlled in the presented experiment with a constant power limit of 45 kW. After the load power exceeded the power limit value, the dc-dc converter discharged the UC module with a margin of the load power and power limit value. The continuous current of the dc-dc converter was ~80A, which limited the continuous power of the ultracapacitor module to around 15 kW. The minimum power limit, which is used for
charging of the ultracapacitor module, operates respectively during regenerative or low loads.

As features, the used dc-dc converter has overshot the reference current in the beginning of the discharge operation and minimum current limit (27 A), which alters the used power limit values with a variable depending on the UC module’s voltage. In the shown figure the minimum transferred power was ~5 kW.

2.2 Measurement setup in Peak Power Cutting experiments

The scheme of measurement setup is shown in Figure 1. The measuring hardware and software for this experiment consisted from dSpace MicroAutoBox 1401/1505/1507 (MABX) and dSpace Controldesk produced by dSpace GmbH, respectively [6].

The load power was calculated from the dc link voltage and the dc link current to load which were measured with AV100-750 and HTFS 400-P sensors. The ultracapacitor module’s voltage and current were measured with AV100-750 and LA 305-S sensors, respectively. All the used sensors are products of LEM [7].

The source power is calculated from the previous measured variables. The source was an active front end converter (AFE) NXA_0460 5 (Vacon Plc.), which regulated the dc link voltage and supplied the source current. [8]

The load was an electric drive system ELFA produced by Siemens [9]. The inverter (G650 D440/170/170) and electric machine (1PV5135-4WS28) of the loading system was operating against the NRMM’s disc brake on its shaft.

The dc-dc converter was a product of MSc electronics Plc. and the model was MSc200DCDC750 [10]. The UC was a product of Maxwell technologies®, with a nominal capacitance of 17.8 F and maximum voltage of 390 V [11].

2.2 Acceleration assistance / regenerative energy recuperation

Figure 3 presents the power control measurement with the acceleration assistance / regenerative energy recuperation method in the SHEV powertrain. Implementation, comparison to simulations and error estimation are presented in [4]. The hardware for the experiment is described in detail [2]. The presented power control experiment describes how primary source current can be ramped up in common voltage bus systems with the full-scale power transfer hardware for the primary energy source’s needs, [12] and [13]. The figure shows the load current, the Ucap current, the source current and the Ucap voltage during an ECE-15 based load cycle.

3. Efficiency measurements

3.1 Measurement setup

Equipment under tests (EUTs) includes the ultracapacitor module (17.8F, 390V) and the dc-dc converter. As a change for the previously described measuring setup all measurement sensors were replaced with a power analyzer. Figure 4 illustrates the schematic from the measurement setup.

Fig. 2. The peak power cutting control method with the ultracapacitor module. The dc-dc converter with 80A continuous energy storage current is controlled when the load exceeds the maximum power limit.

Fig. 3. The acceleration assistance / regenerative energy recuperation control method with the ultracapacitor module. The figure presents an experiment which was realized in the full-scale hardware-in-the-loop verification environment.

Previous experiments with the different types of load cycles illustrate how an UC module is a practical choice for power buffering in different applications.
The used power analyzer was LEM/Norma D6100 with its triaxial shunts for 6 to 300 A current measurements. The measuring accuracy for voltage channels in the frequency range of 0 to 15 Hz are ± (0.15 + 0.03) % for reading and range, respectively. The measuring accuracy for current shunts is ± 0.1% within a frequency range of 0 to 100 kHz [14].

Measurement data acquisition was performed via an RS-232 cable and the control of the dc-dc converter in the tests was performed with the MABX.

3.2. Measurements

Efficiency measurements were performed in the following means. The UC was charged and discharged repeatedly from zero voltage to its maximum voltage and back to zero voltage. The UC current was kept constant in one charge – discharge cycle, and afterwards the reference current was changed for the next repetition. The dc link voltage was kept within 650 to 655 volts with the AFE, according to the averaged dc link voltage measurement data.

Figure 5 illustrates the UC voltage measurement data with different charging and discharging currents. The legend represents the average ES rms current values during charge – discharge operations.

Fig. 5. Charging and discharging of the ultracapacitor module with different constant currents.

All measured variables in each charge – discharge cycle were the voltages in the energy storage and the dc link side, as well as the currents from both voltage potentials, respectively. All variables were taken as rms values. The measurement points are illustrated in Figure 4.

Measurement data sampling frequency in the power analyzer was fixed at 70 kHz. In addition, the measuring device averaged measured values over a 0.934 seconds time frame with a digital filter to avoid efficiency values from varying and to prevent an excess amount of data.

3.2. Measurement analysis

The measured data provides directly the efficiency maps of the dc-dc converters charge and discharger operations. The efficiency values (η) in different operation points are functions of the ES current (iES) and the voltage ratio (u_ratio) between the ES and the dc link. The efficiency maps for charge and discharge operations are calculated as in (1),

\[ \eta(u_{ratio}, i_{ES}) = \frac{u_{out} \cdot i_{out}}{u_{in} \cdot i_{in}} \]  

(1)

The in and out subscripts refer to power transfer directions.

Efficiency values corresponding to particular ES current and voltage ratio in two digits accuracy are averaged. This way the realized charge efficiency map is presented in Figure 6. Measurements were performed in two sets, firstly from zero current to 90 A, and secondly, from zero current to 200 A. Both measurement data sets are utilized in the results.

The total power buffering efficiency can be derived from the measurement results as in (2),

\[ \eta(u_{ratio}, i_{ES}) = \frac{p_{out}(u_{ratio}, i_{ES})}{p_{in}(u_{ratio}, i_{ES})} \cdot \frac{T_{out}}{T_{in}} \]  

(2)

In Equation 2, \( p_{out} \) refers to instantaneous power on the dc link side towards the dc link and \( p_{in} \), respectively, towards the ES. \( T_{out} \) refers to the total discharge time of the ES and \( T_{in} \) to the total charge time of the ES. In addition, \( u_{ratio} \) is used without the voltage drop over the equivalent series resistance (ESR) of the ES.

The previous equation leads to the full power buffering cycle efficiency according to the ES operation points. The full power buffering cycle efficiency map is presented in Figure 7.

Further, from the measurement data can be derived also the variable capacitance map over the UC module operation area. The variable capacitance map can be derived as in (3),

\[ C(u_{ES}, i_{ES}) = \frac{I \cdot \Delta t}{\Delta U} \]  

(3)

In Equation 3, \( C \) refers to capacitance, \( I \) to rms current, \( \Delta t \) to time change and \( \Delta U \) to change of voltage. The variable capacitance map is presented in Figure 8.
The modeling of the UC can be realized with the variable capacitance map and the ESR value of the module, [1] and [4].

The efficiency of the UC module, with the used dc-dc converter, can be derived from the total efficiency map by subtracting the charging and discharging losses of the dc-dc converter, and by assuming the UC module’s efficiency equal in charge and discharge operations, as contained in Figure 9.

\[
\eta(u_{ES}, i_{ES}) = \frac{u_{ES} \cdot i_{ES} - ESR \cdot i_{ES}^2}{u_{ES} \cdot i_{ES}}. \quad (4)
\]

Figure 9 can be compared to the efficiency contour pattern created by pure ESR losses for the UC module. The efficiency contours created by 65 mΩ resistance [11] is drawn in the background with black dashed lines as in (4).

The presented figure suggests that UC module’s losses are mainly caused by the dc current in the ESR of the UC module and the ripple current component of the dc-dc converter has only minor or insignificant effects on low ES currents. The change in the trend of the efficiency pattern of the UC module can be seen with less than 50 A values.

4. Simulations

An introduction to the simulated SHEV drive line is presented in Figure 10, which is an example of an ultracapacitor module power buffered SHEV drive line. The abbreviations in the figure represent generator (G), active front-end converter (AC/DC, AFE), dc-dc converter (DC/DC), inverter (DC/AC) and traction motor (EM). The control signals and actual values are speed reference \( (\omega_{ref}) \) for the VSDG electronic control unit, power limits of the AFE \( (p_{limit}) \), the dc link voltage reference for the AFE \( (u_{dc\ ref}) \), actual ultracapacitor module voltage \( (u_{es}) \), actual dc link voltage \( (u_{dc}) \), current reference for the DC/DC \( (i_{ref}) \) and actual load power \( (p_{load}) \).

Simulations illustrate how the operation points of the primary energy source and energy storage differ after hybridization from the conventional electric drive line. In the shown example, the drive line is considered to provide power for the ECE-15 drive cycle, with peak power equal to the diesel engine’s maximum. The operation area of the conventional VSDG use and hybrid power control method cases I and II are illustrated in Figure 11. The figure shows the operation points of the conventional electric drive line and the SHEV drive line with the UC module.
ratings of 17.8F and 390V. In the figure blue stars refer to operation points with the conventional VSDG use, green crosses refer to operation points in the SHEV drive line with power control case I and red circles refer to operation points with power control case II. Operation points are drawn on the static fuel consumption map (g/kWh), which is not exact during transitions. In addition, the black line depicts the maximum power of the VSDG, and the VSDG is assumed to operate with the speed reference as a function of transferred power.

![Figure 11. Operation points of the conventional VSDG and with the SHEV drive line during the ECE-15 drive cycle. The figure illustrates the primary source’s downsizing with two different power control methods. Blue stars refer to the operation points with the conventional VSDG use, green crosses refer to the operation points in the SHEV drive line with the power control case I and red circles to the case II, respectively.](image1)

Both SHEV drive line power control cases decrease the maximum power to approximately two thirds of the original. In addition, the power control case I provides the possibility to move the operation points of the VSDG from low load and low speed to higher load with low speed when compared against case II.

Figure 12 presents the VSDG’s power in the each simulation case, in the time domain.

![Figure 12. The loading of the VSDG in three simulation cases. The blue line refers to the conventional VSDG use, the green line refers to the SHEV drive line with the power control case I and the red dashed line refers to the case II, respectively.](image2)

Figure 13 depicts the operation points of the energy storage system on the top of its total efficiency map. The figure is two quadrant, such that the positive current is towards energy storage and negative current is towards the load. Figure 13 is derived by taking the square root from the full power buffering cycle efficiency map. The dc-dc converter is considered to transfer the current within its maximum current limit 200 A. Green crosses refer to the operation points with power control case I and red circles refer to the operation points with power control case II.

![Figure 13. Operation points of the ultracapacitor module in the SHEV drive line during the ECE-15 drive cycle. Green crosses refer to the operation points in the SHEV drive line with the power control case I and red circles to the case II, respectively.](image3)

Figure 13 illustrates that the energy storage system containing the dc-dc converter and the UC module operates mostly in area with 90 to 95 percent efficiency when power conversion efficiencies either from the dc link to the energy storage or to opposite direction is considered.

Figure 14 presents the UC module’s current in two power control cases, in the time domain.

![Figure 14. The ultracapacitor module’s currents in the SHEV drive line during the ECE-15 drive cycle presented in the time domain. The green line refers to values of the SHEV drive line with the power control case I and red dashed line to the case II, respectively. The positive current is towards the load.](image4)

4. Conclusions

This study describes two different power control methods for the SHEV drive line with experiments. Also, the efficiency measurement setup and efficiency
measurements for the energy storage system are described and results of the measurements are analyzed. The study is concluded with case simulations from the operation areas of the energy storage system and the VSDG in the SHEV drive line in contrast to conventional use. The approach to the system level models is a functional, which utilizes measurements presented in the study. The functional approach to system level modeling provides the efficient method to solve the power train’s total efficiency.

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