Evaluation of the benefits of using dual-source energy storage in hybrid electric vehicles

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Abstract **– Batteries are often used as energy storage in hybrid and electric vehicles. Despite of the development, technical characteristics of batteries are the most limiting factor for further increasing the energy conversion efficiency and pure electric operation of these vehicles. In this research, dual-source energy storage system, a battery pack and ultracapacitors, has been studied by simulation of hybrid city bus models. These two different types of energy storages have complementary characteristics therefore their combination provides both high energy and high power to weight ratio. Based on the simulation results, the benefits of using dual-source energy storage in hybrid city bus are evaluated demonstrating the advantages of the proposed energy storage system.**

I. INTRODUCTION

Hybrid and electric vehicles have a lot of potential for better fuel economy than the conventional vehicles. Nevertheless, even if the hybrid technology viability has been proven and several commercial hybrid vehicles are in the markets, there are still technical challenges to be overcome. Especially for electric vehicles, the role of the energy storage system (ESS) is crucial to have a sufficient operation range for easier customer acceptance. Lot of research has been done to improve the specific energy and power as well as other technical characteristics of batteries. Furthermore, the lifetime of a battery can be drastically shortened under hard and unsteady solicitations.

For having a good practical performance, by combining two different types of energy storages seems to be an interesting and useful solution. Research has been made with rising activity in this area in recent years [1]-[6] and particularly for electric car applications [7]-[9]. For using of batteries as sole energy storage has been widely researched and there is a growing interest for development of more suitable batteries for hybrid vehicles [10], [11]. As batteries are usually sufficient energy storage for passenger cars, the use of ultracapacitors has not been considered such an interesting solution because of their lack of energy capacity. However, ultracapacitors have been studied in various city bus applications, for example in [12] and [13]. Most of the research in this area has been focusing on electrochemical components but also other types of energy storages have been studied, for example, hydraulic accumulators [14], [15] and flywheels [16]. Additionally, pneumatic accumulators have been studied in hybridization of internal combustion engines [17].

II. PROBLEM DEFINITION

The important technical characteristics of three types of energy storages are presented in Table 1 and 2 [1]. Even the most advanced batteries cannot offer a very high power to weight ratio and are vulnerable for unsteady power solicitations therefore a combination of a battery pack and ultracapacitors is interesting solution for having complementary characteristics. Besides electrochemical energy storages, hydraulic and mechanical storages have been studied for use in hybrid electric vehicles [14], [15] and [17]. Especially with heavy vehicles, these alternatives can be interesting solutions but more research has to be done in this area for verifying their suitability and usefulness.

TABLE I
TECHNICAL CHARACTERISTICS OF LITHIUM-BASED BATTERIES [1].

	LiIon: Power	LiIon: Energy	LiPolymer
Energy [Wh/kg]	70 – 130	110 – 220	100 – 180
Energy [Wh/l]	150 – 450	150 – 450	100
Power [W/kg]	600 – 3000	200 – 600	300 – 500
Number of cycles @ 80% DOD	800 – 1500	800 – 1500	300 – 1000
Efficiency [%]	85 – 90	85 – 90	90 – 95
Temperature range [°C]	-20 – 60	-20 – 60	-110

TABLE II
TECHNICAL CHARACTERISTICS OF ULTRACAPACITORS AND FLYWHEELS [1].

	Ultracapacitor		Flywheel
	Power	Energy	Power
Energy [Wh/kg]	3 – 5	12 – 20	1,8 – 3,7
Energy [Wh/l]	3 – 10	3 – 6	7 – 17
Power [W/kg]	2000 – 10k	2000 – 10k	100 – 1000
Number of cycles @ 80% DOD	500k – 1M	500k – 1M	10k – 50k
Efficiency [%]	95 – 100	95 – 100	90 – 95
Temperature range [°C]	-20 – 90	-20 – 90	-20 – 50

The pure electric operation range of a hybrid vehicle is dependent on the power and energy capacity of the energy storage. Because in accelerations a high peak of power is often needed and the braking energy is usually recovered by high peaks of power, the power limitations of batteries can easily be exceeded. By using a combination of a battery pack and ultracapacitors, the ESS can accept high peaks of power and provide a considerable energy capacity.

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III. Research Objectives and Method

The objective of this research is to evaluate the benefits of using dual-source energy storage system, a battery pack and ultracapacitors, in a heavy hybrid electric vehicle. The focus of the evaluation was in the energy consumption in different driving cycles. The research case was chosen to be a hybrid electric city bus. This was a logical choice because modeling and simulation based research had already been done in this area at the Aalto University and its predecessor Helsinki University of Technology (TKK). For having deeper understanding of the benefits, two different hybrid bus topologies were used, a parallel and a series hybrid.

The research work was carried out by different simulation studies and a comprehensive energy analysis of the simulation results. For both hybrid bus models, a combination of a battery pack and ultracapacitors with power converters was modeled and control strategies were developed for efficient use of the ESS. The dual-source ESS model was also simulated with a specific control strategy where battery solicitations were limited.

The studied hybrid topologies are presented in Fig. 1. The parallel hybrid bus is called a post transmission parallel hybrid because the electric motor is placed after transmission in the power train. The model of series hybrid has a traditional topology of the series hybrid vehicle. Simulations were also performed with models having single-source energy storage for comparison purposes. All simulations were performed in three different bus driving cycles.

IV. Configuration of Simulations

A. Background

As ADVISOR program had already been used in TKK heavy vehicle research, it was the logical choice for the simulation model development. ADVISOR is designed for rapid analysis of the performance and fuel economy of conventional and advanced, light and heavy-duty vehicle models as well as hybrid electric and fuel cell vehicle models [18], [19]. The parallel hybrid bus simulation model is based on the prototype hybrid bus built by a Finnish bus manufacturer, Kabus Oy. The series hybrid bus model is a modified model of the standard series hybrid bus model in ADVISOR program. The technical specifications of the buses are presented in Table 3. Simulations were performed with bus mass of 10000kg. The added load of 1500kg corresponds to about 20 passengers.

TABLE III
Technical Specifications

Parameter	Value	
General specifications		
Curb weight (kg)	8500	
Vehicle frontal area (m2)	6.2	
Drag coefficient	0.6	
Rolling resistance	0.01	
Wheelbase (m)	6.5	
Front weight fraction	0.34	
Centre of gravity (height) (m)	1.0	
Powertrain specifications		
	Parallel	**Series**
Engine max power (kW) @speed (r/min)	162@2250	
Engine max torque (Nm) @speed (r/min)	820@1500	
Electric motor nominal power (kW)	75	187
Electric motor nominal torque (Nm)	271	678
Generator max power (kW)	---	165

Part of this research was carried out in collaboration with the heavy hybrid development project called *HybLab* where an underground mining loader will be hybridized [6]. The loader will also have a combined battery-ultracapacitors energy storage system.

B. Energy Storage System Dimensioning

Except for the ESS components, the same component dimensioning was used for the hybrid buses than in previous research (Table 3). The dimensioning of the ESS power output and energy capacity was based on the parallel hybrid bus performance. For the battery only solution, the battery pack size was determined according to the required power output because it is the limiting characteristic for the battery. For ultracapacitors only solution, ultracapacitor unit size was dimensioned according to the required energy capacity. The battery pack was constructed from Kokam modules that have seven 40Ah lithium polymer cells, nominal voltage of 25.9V and continuous current of 200A.

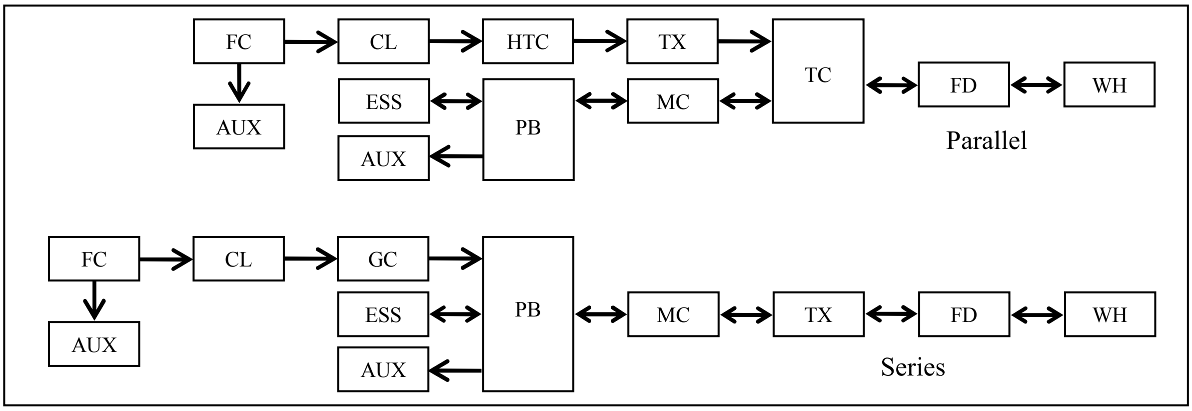

Fig. 1. Studied vehicle topologies: the parallel hybrid and series hybrid. (AUX = Auxiliary devices, CL = Clutch, ESS = Energy storage system, FC = Fuel converter, FD = Final drive, GC = Generator, HTC = Hydraulic torque converter, MC = Electric motor, PB = Power bus, TC = Torque coupler, TX = Transmission, WH = Wheels)

The total amount of modules was calculated with (1).

$$N_m = \frac{P_{mc}}{U_m \cdot I_{nom}} \quad (1)$$

where N_m is the number of modules, P_{mc} electric motor nominal power, U_m nominal voltage of the module and I_{nom} maximum continuous current. The required module number is 14 which results in battery pack voltage of 362.6V.

The required energy capacity for ultracapacitor unit, when using only ultracapacitors, was determined according to the pure electric acceleration where the nominal power of the electric motor is used. The energy storage should provide enough energy for acceleration from stand still up to 80 km/h. The Maxwell Boostcap ultracapacitor unit, which is used in *HybLab* project, has available energy capacity of 282Wh or 1000kJ. The required number of these units was calculated with (2).

$$N_u = \frac{P_{mc} \cdot t_{acc}}{E_{uc}} \quad (2)$$

where N_u is the number of units, t_{acc} acceleration time (53 seconds, calculated by using the vehicle parameters presented in Table 3) and E_{uc} available energy of one ultracapacitor unit. The required unit number is 4.

For the dual-source ESS, the maximum available braking energy in deceleration was used for dimensioning the size of the battery pack and the ultracapacitors. This energy was calculated from deceleration starting from 80 km/h to stand still where nominal electric motor power is used for braking. As the same battery pack size, than defined for the battery only solution, was used for dual-source ESS, only the size of the ultracapacitors needed to be defined. This was calculated with (3).

$$N_u = \frac{E_{br} - E_{bat}}{E_{uc}} = \frac{(P_{mc} - U_{nom} \cdot I_{chg}) \cdot t_{dec}}{E_{uc}} \quad (3)$$

where E_{br} is the recoverable braking energy, E_{bat} maximum regenerated energy into the battery pack in deceleration, U_{nom} nominal voltage of the battery pack, I_{chg} the maximum charging current (80A) and t_{dec} deceleration time (26 seconds). According to this calculation, one ultracapacitor unit is enough.

The same energy storage sizes were used in simulation with the series hybrid bus. This dimensioning is not necessarily optimal for the series hybrid bus but because the focus is on the comparison of the different ESS topologies, it was considered to have a minor impact on the simulation results.

C. *Dual-Source Energy Storage Configuration*

Fig. 2 shows the developed dual-source ESS model in ADVISOR. Both energy storages are connected to the power bus via a power converter which is in this case a DC/DC converter. The power bus operating nominal voltage is 650V.

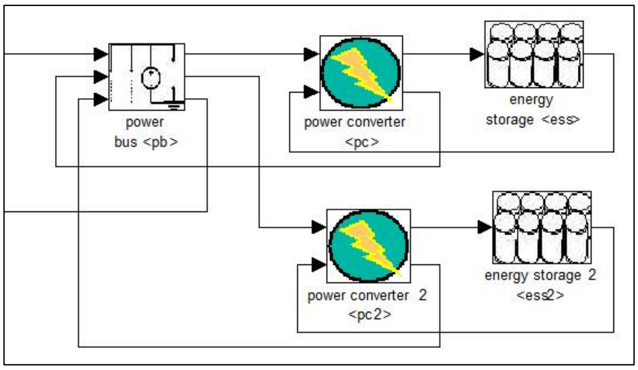

Fig. 2. Dual-source energy storage system model.

The control of the energy storage was implemented in the power converter model. The battery pack is the primary source and ultracapacitor unit is used as load leveling for smoothing the power demand of the battery. Because of the lack of thermal parameters for batteries and ultracapacitors, thermal behavior was not taken into account. Presently, the battery pack is being measured for modeling and cooling system development purposes in the project *HybLab*.

D. *Driving Cycles*

Simulations were conducted in two measured (L03, L05) and one standard bus driving cycle called Braunschweig (BR). The measured cycles represent typical city bus driving in the city of Lahti in Finland. The main characteristics of the driving cycles are presented in Table 4. The elevation profile has also been taken into account in the measured cycles. In simulation, the cycles were repeated many times in a row for minimizing the impact of control strategy on the simulation results.

TABLE IV
CHARACTERISTICS OF THE DRIVING CYCLES

	L03	L05	BR
Maximum speed [km/h]	66,1	58,2	57,9
Average speed [km/h]	33,1	28,0	29,0
Distance [km]	22,9	10,8	13,5
Number of stops	24	15	28
Time at stand still [%]	17,3	24,1	18,8

E. *Energy Management Strategy*

Energy management strategies for the parallel and series hybrid bus simulation model were developed. Both strategies are rule-based charge sustaining strategies. The focus was on the development of robust and adaptive strategies. This means that the strategy can be used in different bus driving cycles and it can maintain the state of charge (SOC) of the energy storage(s) in predefined limits.

The operation of the engine was optimized in respect of fuel consumption when it was possible. In this case, the ESS is used for load leveling either charging or discharging depending on the operation of the engine. The functioning of the strategies was verified by numerous simulations and by analyzing the energy consumption and losses in different components and operating modes. The strategies also ensure similar performance of the bus when using different ESS topologies. Fig. 3 and 4 illustrate the operation of the control strategies by describing the operating mode control as function of required driving power and SOC. The SOC levels “low soc” and “high soc” correspond to predefined state of charge levels for energy storages. In the middle area of the Fig. 3 and 4, the operating mode can be either electric or hybrid depending on the previous operating mode.

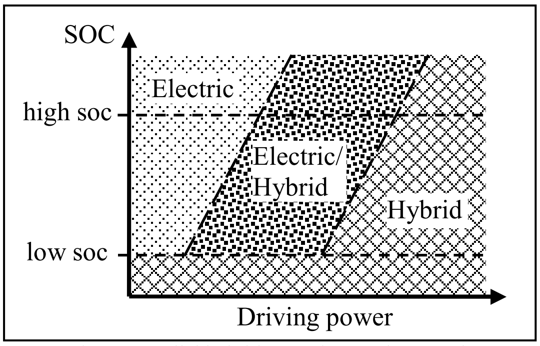

Fig. 3. Parallel hybrid operating mode control.

The biggest different between the two hybrid topologies is that pure electric operation of the parallel hybrid bus is more limited than in series hybrid. This is because of the electric motor smaller power capacity.

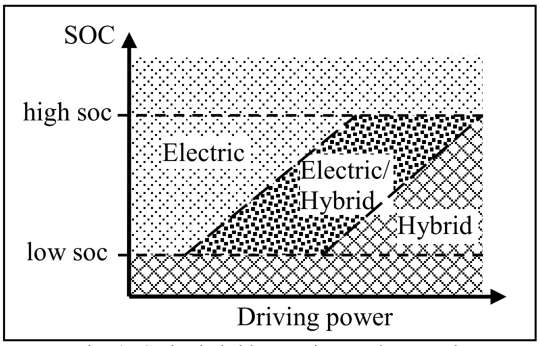

Fig. 4. Series hybrid operating mode control.

Two strategies were developed for controlling the dual-source ESS. The first is a standard strategy as it is described before and the other one is particularly developed for controlling two different energy storages together. In the latter case, the idea is to limit the solicitations of the battery pack by using the ultracapacitor unit for load leveling also in pure electric mode.

V. Analysis of Simulation Results

A. *Energy conversion efficiency*

The energy conversion efficiencies of different ESS topologies were evaluated in the vehicle level. Fig. 5 and 6 presents the tank-to-wheel (TTW) energy conversion efficiencies of the buses in three driving cycles. In all result figures the following names have been used for the different ESS topologies; DUAL = dual-source, BAT1 = battery only and UCAP = ultracapacitors only.

The dual-source ESS gives clearly better TTW energy conversion efficiency than the battery only ESS. Ultracapacitors performs also well but that can be considered normal because of the chosen relatively large energy capacity of capacitors in reference to the ultracapacitors of the dual-source ESS topology.

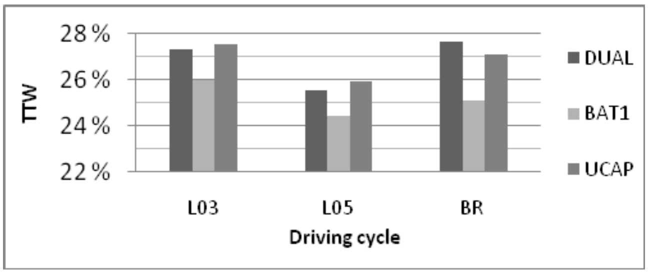

Fig. 5. Tank-to-wheel energy conversion efficiency of the parallel hybrid.

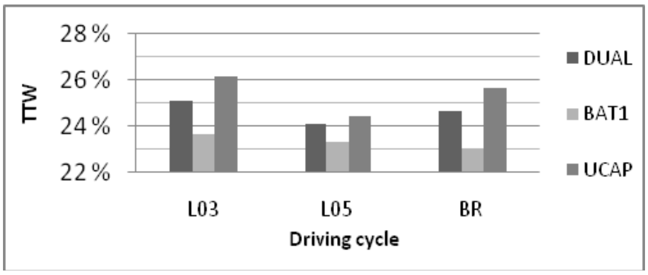

Fig. 6. Tank-to-wheel energy conversion efficiency of the series hybrid.

The parallel hybrid bus has a slightly better TTW efficiency than the series hybrid. This is mainly because there are less energy conversions and therefore less energy losses in the powertrain of the parallel hybrid than the series hybrid.

B. *Breaking energy recovery efficiency*

The braking energy recovery (BER) efficiency was calculated with (4) where E_{br} is the recovered braking energy in the storage and E_{veh} is the total required driving energy at the wheel.

$$\eta_{ber} = \frac{E_{br}}{E_{veh}} \tag{4}$$

Fig. 7 and 8 present the BER efficiencies for the parallel and series hybrid bus. Ultracapacitors accepts high currents and therefore high power recovery is possible in braking which can be seen in these BER efficiency results. Good BER efficiency also improves the TTW energy conversion efficiency.

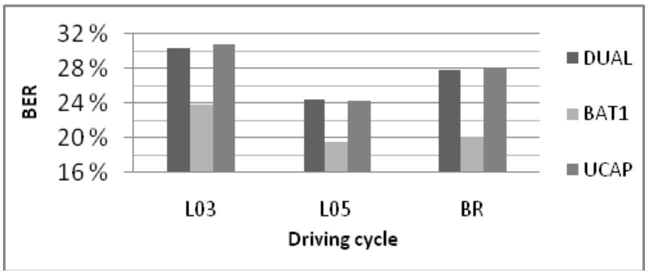

Fig. 7. BER efficiency of the parallel hybrid bus.

The limited charging power of the battery pack weakens substantially the BER efficiency of the battery only solution. On the contrary, even with one, relatively small, ultracapacitor unit, the dual-source ESS has about the same BER efficiency than the ultracapacitors only topology. This highlights the usefulness of the ultracapacitors' power capacity.

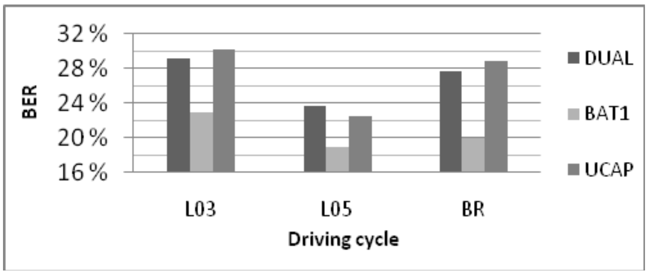

Fig. 8. BER efficiency of the series hybrid bus.

The BER efficiency is obviously dependent on the driving cycle as there are rather big differences between the cycles. The impact of the driving cycle is the same in both vehicle topologies.

C. Electric Operation

Different ESS topology choices were compared in terms of electric operation. Fig. 9 and 10 present the time portions of pure electric operation of the buses in three driving cycles.

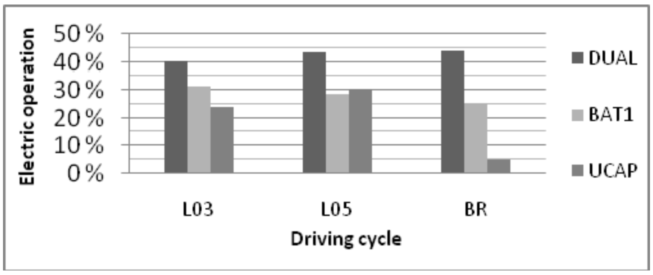

Fig. 9. Pure electric operation of the parallel hybrid bus.

Dual-source ESS provides, especially with the parallel hybrid bus, much longer range of pure electric operation than battery only ESS. Because of the lack of energy capacity, ultracapacitors only ESS has much less pure electric operation than the other ESS topologies in series hybrid bus operation. It is also worth to notice that with dual-source ESS in parallel hybrid bus, the pure electric operation can be extended up to the same level as in series hybrid bus.

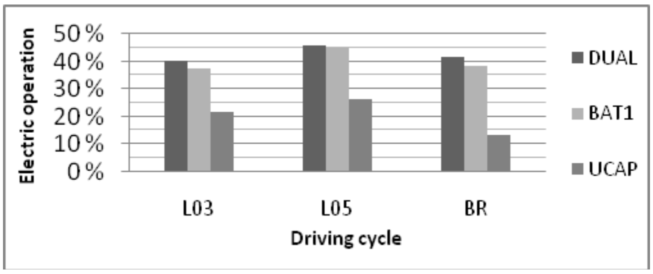

Fig. 10. Pure electric operation of the series hybrid bus.

D. Energy storage system solicitation

The solicitations of the energy storage systems were evaluated. Fig. 11 and 12 present the effective discharge currents (I_{rms}) of the battery pack in dual-source and battery only ESS topologies. The results of specific control strategy of the dual-source ESS are marked with "D2".

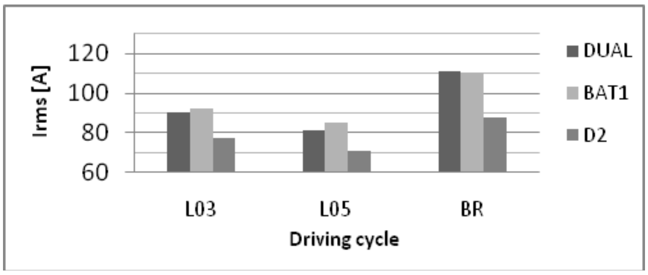

Fig. 11. Effective current of battery pack in parallel hybrid bus.

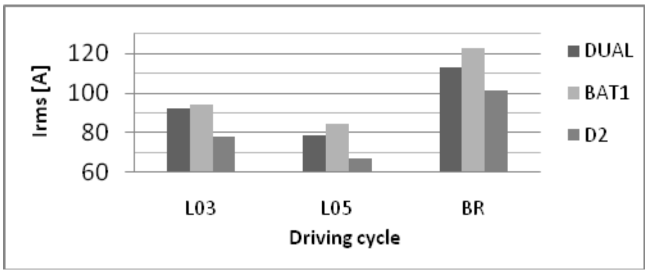

Fig. 12. Effective current of battery pack in series hybrid bus.

With the standard control strategy of the dual-source ESS, there is only a minor advantage for dual-source ESS in respect to the battery only solution. On the contrary, when the dual-source ESS operation is specifically controlled (limited battery pack solicitations), the effective current is about 20 percent less than in battery only solution. At the same time, the performance and energy efficiency of the bus is not severely sacrificed. This can be seen in Table 5 where the impact of the specific control strategy is presented for parallel hybrid bus.

TABLE V
SPECIFIC CONTROL STRATEGY IMPACT ON PARALLEL HYBRID BUS PERFORMANCE WITH DUAL-SOURCE ESS

Evaluation	Control strategy	Driving cycle		
		L03	L05	BR
TTW	Standard	27 %	26 %	28 %
	Specific	27 %	25 %	26 %
BER	Standard	30 %	24 %	28 %
	Specific	30 %	24 %	27 %
Electric operation	Standard	40 %	43 %	44 %
	Specific	40 %	35 %	36 %

VI. CONCLUSIONS

This research evaluates the benefits of using dual-source energy storage system in a hybrid city bus. The work was done by simulation where real component data were used for powertrain and energy storage components. Simulations with a parallel and series hybrid bus in three different driving cycles provided valuable results. Based on these simulation results following conclusions can be done.

The simulation results demonstrate that the use of dual-source energy storage in a hybrid city bus can offer several benefits. Overall, a hybrid city bus equipped with a combination of a battery pack and ultracapacitors as energy storage can reach better TTW energy conversion and breaking energy recovery efficiency than a hybrid bus with only a battery pack as energy storage. In addition, solicitations of the battery can be controlled by making them more steady and continuous which can prolong the battery lifetime. With parallel hybrid bus topology, also the pure electric operation range was extended in reference to the battery only ESS.

When comparing dual-source ESS to ultracapacitors only solution, the energy efficiencies are about the same level but the pure electric operation range can be substantially prolonged. As ultracapacitors can attain high efficiency and are capable of accepting high currents, it is possible to reach energy efficiency as good as with dual-source ESS. However, relatively low energy capacity of ultracapacitors, when comparing to batteries, does not allow very long distances for pure electric operation. Moreover, the ultracapacitors only solution used here is not necessarily a cost effective solution in a real application because of the large amount of the ultracapacitor units.

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