Modernization of Experimental Electric Vehicle Drive System

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Abstract — **Modernization consists of a new compact drive unit for the Citröen Berlingo Electrique electric vehicle. The drive unit integrates a power converter for the traction motor, a DC/DC low voltage converter, an on board charger and an electronic control unit (ECU). The new air-cooled power converter is lightweight and more efficient due to a modern equipment used. The new ECU uses controller area network (CAN) to communicate with the power converters and also collects all the measured data that can be transferred in real-time during drive. This vehicle also currently provides a test and measurement platform for Master's Degree students.**

Keywords — electric vehicle, drive, converter, electronic control unit.

I. Introduction

The goal was to design a compact drive unit for the experimental electric vehicle (EV) that will maintain original function [1] while increasing efficiency, decreasing weight and making the system more variable. The vehicle was purchased without the original converters or electronic control unit (ECU) and without traction batteries. For an experimental vehicle variability it is necessary to enable it to be used for various measurements in other projects such as testing newly designed EV drive components.

The suggested concept for a compact drive unit integrates the ECU together with the power converter for the traction motor, the DC/DC converter for the low voltage (LV) system and the on-board charger for the traction battery.

Multiple parts such as the power converter, charger, or any future installed devices are connected together with the ECU using controller area network (CAN). CAN enables fast, real-time sharing of measured and demanded values, commands, and error messages with all connected microcontrollers (MCUs).

The compact drive unit with completed motor converter and ECU was used in the EV Citroën Berlingo Electrique as a replacement for the damaged original drive unit. The EV is used as an experimental vehicle with students doing measurements on it during drive. All measured data such as currents and voltages in the traction power path together with EV velocity are transferred in real-time to a connected computer.

Using the measured data, the power and efficiency of each part of the power path can be calculated, including the total powertrain efficiency of the vehicle to compare it with other vehicles [2].

The main benefit of having the new ECU is that we can fully control the inner software and for example test various settings of regenerative braking to achieve comfortable drive or save a significant amount of energy [2] depending on the drive profile.

Also the motor converter software can be adjusted for example to achieve better efficiency during various speed and torque conditions. Generally the driving cycle can affect the converter efficiency significantly [3].

II. Compact Drive Unit

The goal was to integrate the most important electrical parts of the EV into one chassis. The block diagram of the designed compact drive unit is in Fig. 1.

The unit contains four main parts: on-board charger, ECU, DC/DC converter for LV charger and motor converter. It is connected to both the traction battery and the low voltage (LV) battery which power the vehicle electronics such as lights, steering and brake assists, traction motor cooling and also the ECU.

Because the LV battery is small, the DC/DC converter charges it from the traction battery.

The on-board charger offers the option to slow-charge the traction battery from the grid.

The motor converter is between the traction battery and the traction motor and controls flux and torque of the motor depending on the actual speed and demanded power.

The ECU controls the rest of the vehicle and also transfers values such as accelerator pedal position to the motor converter using finite state machines (FSM).

With the completed motor converter and the ECU, the compact drive unit is partly finished now to be able to drive the vehicle. The DC/DC converter and on-board charger are now designed and will be built by students.

A. Motor Converter

Traction motor nominal parameters are in Table I.

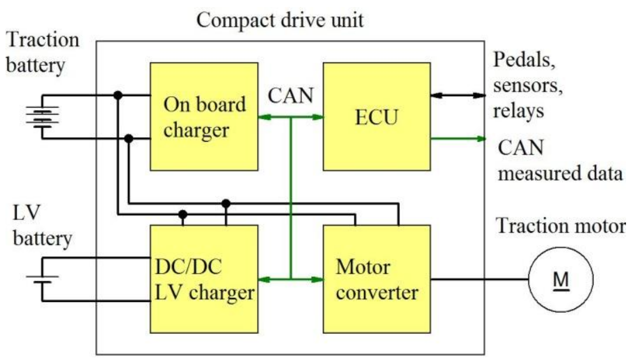

Fig. 1. Compact drive unit block diagram.

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TABLE I.
TRACTION MOTOR RATED PARAMETERS

Type	Leroy-Somer SA-18
Power nominal/max	15 kW / 28 kW
Speed nominal/max	1650 RPM / 8000 RPM
Armature	162 V / 110 A
Field	120 V / 9,5 A

The vehicle still has its original separately excited DC motor. This type of motor is not used in modern electric vehicles today but the control strategy applied is similar to drives with AC motors. The converter controls the torque and flux. The power stage of the converter is shown in Fig. 4. It is divided into two parts, the armature converter and the field converter.

The armature converter is a synchronous buck converter half bridge [4] where the working inductance is the parasitic armature inductance L_q.

The field converter is a full bridge to enable reversing the motor rotation direction.

Both converters are made using modern types of fast switching IGBT transistors. To decrease the iron loss in the rotor, the current ripple was decreased below 5 % by increasing the switching frequency up to 20 kHz.

Armature and field currents are measured using Hall sensors. The sensors' temperature offset is compensated in software by subtracting the value measured when the vehicle is idle.

The armature and field converter construction is shown in Fig. 2.

As it was a prototype, the motor converter is on multiple separate boards connected together.

An IGBT driver with fast desaturation protection [5] was designed for the armature converter half bridge to protect it against an overcurrent.

The fast driver enables the IGBT to operate at 20 kHz with low switching losses.

The parameters of both converters are in Table II.

The enclosed air-cooled compact drive unit is placed in the vehicle as seen in Fig. 3.

TABLE II.
MOTOR CONVERTER PARAMETERS

Nominal values	Voltage	Current	Switching frequency
Armature	200V	110A	20 kHz
Field	200V	11A	20 kHz

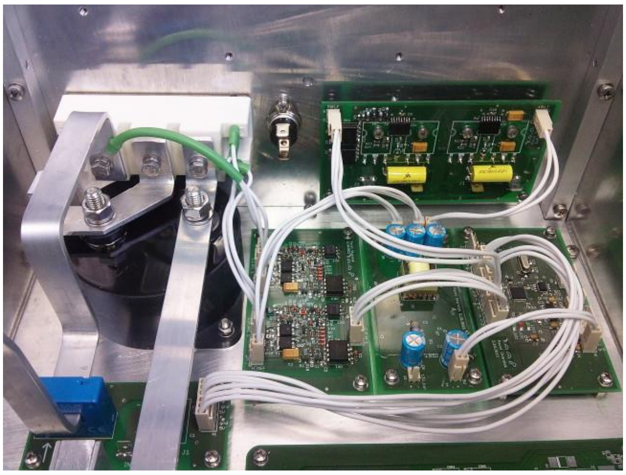

Fig. 2. Armature converter on the left and field converter on the vertical board on the right.

Fig. 3. Air cooled compact drive unit placed in the vehicle.

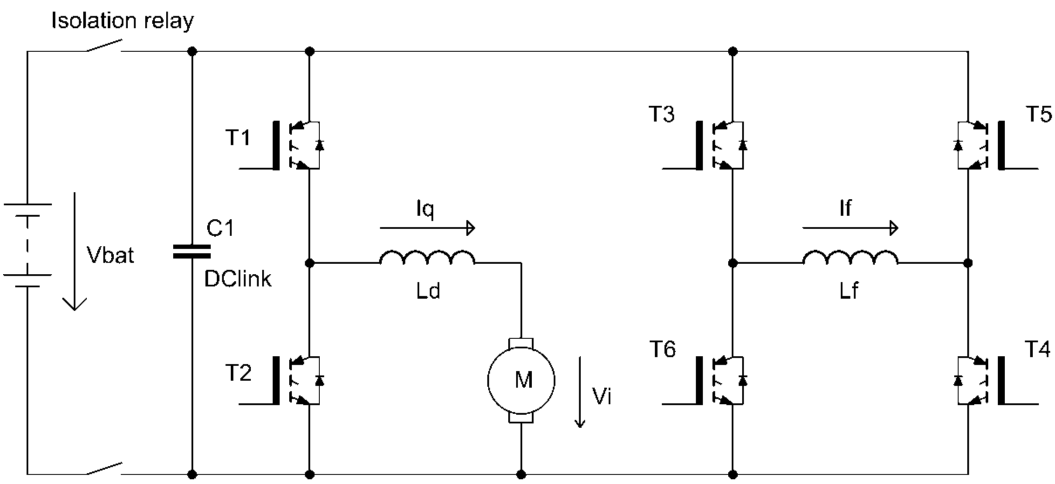

Fig. 4. Motor converter simplified diagram.

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The control strategy is pictured in Fig. 5. The torque depends linearly on the armature current and the accelerator pedal controls this current from negative to positive value. The positive armature current provides drive while negative gives regenerative braking. During the regenerative braking, the energy is returned to the traction battery through the armature converter.

For low speed the armature current is controlled by the I_qPS controller and the armature converter. The field converter is controlled by the I_f PS controller, allowing the motor to achieve the characteristic of a series motor, keeping the nominal armature to field current ratio.

For higher speed when the duty cycle of the armature converter is 100 % and the armature voltage is equal to the traction battery voltage, the motor is controlled in the field weakening region. The I_f^* PS controller sets the amount of the field current such as to achieve the armature current demanded by the accelerator pedal position.

The maximum field current I_{fmax} is defined as the ratio of the nominal field current I_{fn} to nominal armature current I_{qn} according to (1).

$$I_{fmax}^* = \frac{I_{fn}}{I_{qn}} \cdot I_q^* \tag{1}$$

This lowers the power consumption of the field winding during slow ride when the nominal torque is not needed.

III. Drive Measurement

The identified parameters of the motor are in Table III.

The battery power P_{bat}, converter power P_{con}, and motor power P_{em} are calculated according to (2) – (4). The mechanical power P_m [6] is calculated according to (5) from the vehicle velocity v, mass m =1400 kg, rolling resistance F_r = 300 N and drag resistance F_d = 0.4 N.

TABLE III.
Traction Motor Identified Parameters

Armature inductance L_q	(0.28 ± 0.2) mH
Armature resistance R_q	(17 ± 1) mΩ
Field inductance L_f	(15 ± 2) H
Field resistance R_f	(8,9 ± 0.2) Ω
Motor constant $k_{\Phi m}$	0.09 ± 0.01

$$P_{bat} = U_{bat} \cdot I_{bat} \tag{2}$$

$$P_{con} = U_q \cdot I_q + U_f \cdot I_f \tag{3}$$

$$P_{mot} = (U_q - R_q \cdot I_q)I_q \tag{4}$$

$$P_m = \left(\frac{dv}{dt} \cdot m + F_r + F_d \cdot v^2\right) v \tag{5}$$

The efficiency of the motor converter η_{con}, motor η_{mot}, mechanical η_m, and the total powertrain efficiency η_p are calculated according to (6) – (9).

$$\eta_{con} = \frac{P_{con}}{P_{bat}} \tag{6}$$

$$\eta_{mot} = \frac{P_{em}}{P_{con}} \tag{7}$$

$$\eta_m = \frac{P_m}{P_{em}} \tag{8}$$

$$\eta_p = \frac{P_m}{P_{bat}} \tag{9}$$

Measured data during the drive are presented in the following figures.

In Fig. 6 it is seen that at speeds below 20 km/h the motor is controlled in the constant current region as I_{bat} is lower than I_q. Above 20 km/h the motor is controlled in a constant power region with field weakening as $I_q = I_{bat}$ and I_f falls down as speed increases.

When regenerative braking is applied, I_q is negative and until enough power is generated, I_{bat} is also negative and decreasing with the speed as the generated power is also decreasing.

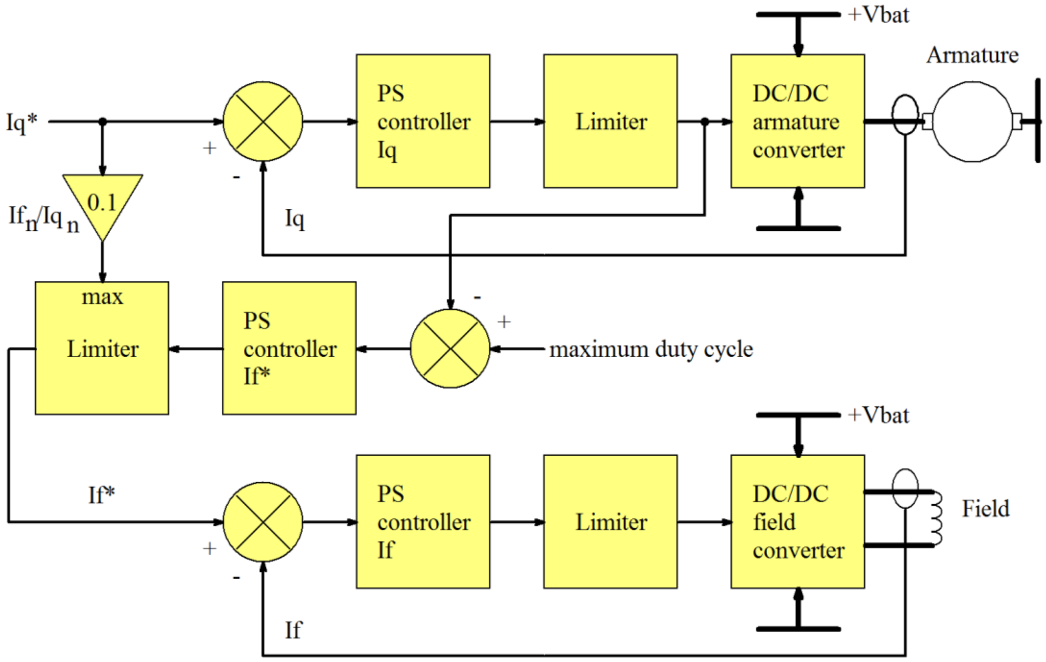

Fig. 5. Motor control strategy.

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The armature converter functions in the same way regardless of drive or regenerative braking and adjusts its duty cycle to maintain the demanded current.

Fig. 7 shows how the battery power is transferred with losses through the converter, traction motor and wheels to the actual mechanical power that moves the vehicle. During regenerative braking the mechanical power is the source of the energy and the power is transferred with losses in the system back to the battery.

The measured efficiencies of each drive component, together with the total powertrain efficiency, depend on the motor power according to Fig. 8.

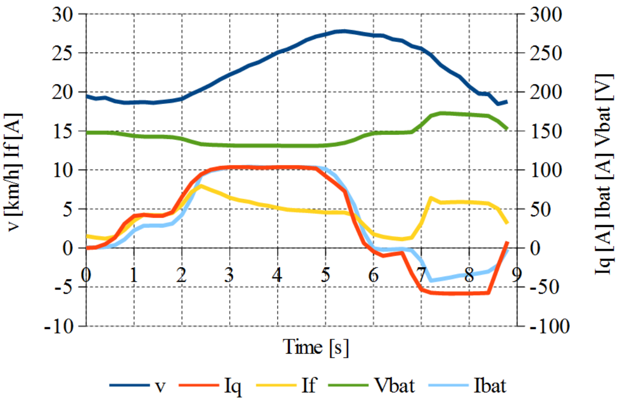

Fig. 6. Vehicle speed, traction battery and motor data during the drive (0 to 6 s) and regenerative braking (7 s to 9 s).

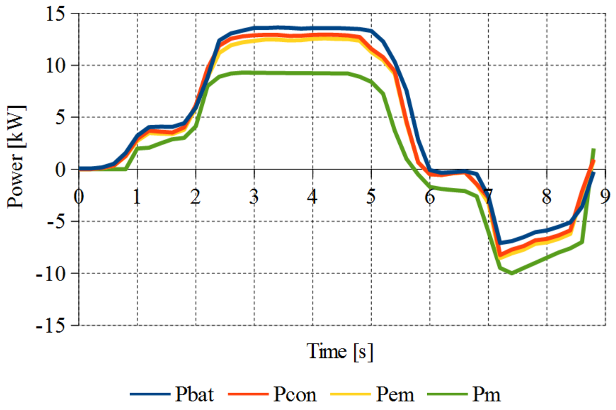

Fig. 7. Battery power, converter power, electromechanical power in the motor and mechanical power on the wheels during drive and regenerative braking.

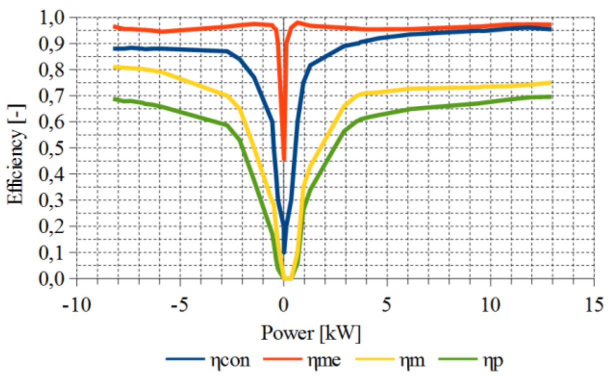

Fig. 8. Powertrain efficiency and its components depending on the motor power.

According to [2] we achieved comparable results; however, the motor and mechanical efficiencies depend on the velocity too. The plotted values were taken for low speed range only. The presented results show that the separately excited DC motor has relatively stable efficiency over a wide power range. Even though the development of EV drives brought various other solutions (usually with AC motors) in recent years [7], the DC drive can still compete.

IV. Conclusion

The designed compact drive unit was put into the Citroën Berlingo Electrique vehicle to replace the original drive system. It was tested to operate the motor in the range of nominal values while decreasing the power loss in the motor converter. The new unit allowed elimination of a water cooling system weight while also decreasing maintenance requirements.

The variability of the compact drive unit and our own software enables this experimental electric vehicle to be used in a variety of student research projects connected with the fields of electric drive, power converters and also battery management system technologies.

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