Electrification of a commercial vehicle’s auxiliaries: A chance of reducing fuel consumption and CO_2 emissions

S. PRETSCH
Magna Powertrain Engineering Center Steyr
Austria
Obtained M. Sc. in Engineering from the University of Applied Sciences Upper Austria. Joined Magna Powertrain Engineering Center Steyr in 2011 as Project Engineer.

M. WINTER
Magna Powertrain Engineering Center Steyr
Austria
Obtained Dipl.-Ing. in Engineering from the Technical University of Graz
Department Manager Vehicle Systems at Magna Powertrain Engineering Center Steyr

Abstract

This paper deals with the electrification of commercial vehicle’s main auxiliaries in order to minimize fuel and energy consumption and the upcoming CO_2 emissions. This approach is already state of the art regarding passenger cars and vehicles with a gross vehicle weight below 3.5 tons, but hasn't yet reached commercial vehicle engineering.
The Engineering Center Steyr (ECS) entered this field of innovation by analyzing the potential fuel savings of a heavy commercial vehicle’s steering pump and air compressor and arrived at good results: Simulations show that the total fuel consumption of a commercial vehicle at long haul driving can be reduced by 1% on average owing to electrification of the hydraulic steering pump and by about 2% due to electrification of the air compressor unit.

Keywords: commercial vehicle, auxiliaries, steering pump, air compressor, fuel reduction, electrification

1. Introduction and Motivation

As statistics show, the transport sector is Europe's greatest CO_2 driver by producing approximately 25% of all national greenhouse gas emissions. What's more, this sector reports the highest emission increase of 68% from 1990 until now [1].
This set of problems – caused by increasing numbers of vehicle registrations and the rising of long-distance traffic – inevitably leads to the need of reducing fuel consumption and CO_2 emissions of vehicles. In the last years engineers tried to achieve fuel and emission reduction by developing alternative propulsion systems like hybrid drive or pure electric drive or by downsizing the combustion engine, both for passenger cars and commercial vehicles.
However, until now only few attempts have been made to electrify and downsize the main auxiliaries which are driven by a commercial vehicle's engine – being: steering pump, cooling fan and air compressor – in regard to fuel consumption and greenhouse gas emissions, although there's great potential. Driven by - and therefore dependent on - the combustion engine, auxiliaries are enormously oversized to supply high power and reliability at engine idle, too. The electrification and demand-actuated control of those components leads to independence from the combustion engine and furthermore to a possible downsizing and power saving.
As an additional benefit, electric vehicles (EV) and hybrid-electric vehicles (HEV) which have implemented functions like "Start/Stop" and "Zero Emission Driving" need to be equipped with electrified auxiliaries as there's no combustion engine to drive them.

2. Initial situation

"Steer-by-wire" and "Brake-by-wire" are no longer foreign words regarding passenger cars and commercial vehicles with a gross weight below 3.5 tons. Due to the last revision of the standard ECE-R 79 in April 2005 even the homologation of a steer-by-wire system is possible [8].
In the range of heavy commercial vehicles auxiliaries are mainly driven by the combustion engine via gear case housings. Exceptions are some hybrid-electric vehicles, where at least one auxiliary unit is electrically driven via the vehicle's high voltage power supply and a DC/DC converter.
Electric auxiliaries that are optimized and downsized to be driven by a commercial vehicle's 24V power supply are – in opposition to passenger cars – not available nowadays and represent a gap in the market.

2.1 Steering System

A commercial vehicle's state – of – the - art steering system is a hydraulic power steering (HPS) system, where the driver's steering torque at the steering wheel is supported by a hydraulic circuit. The mechanical linkage between steering wheel and steered wheels still exists, as can be seen in Fig. 1.

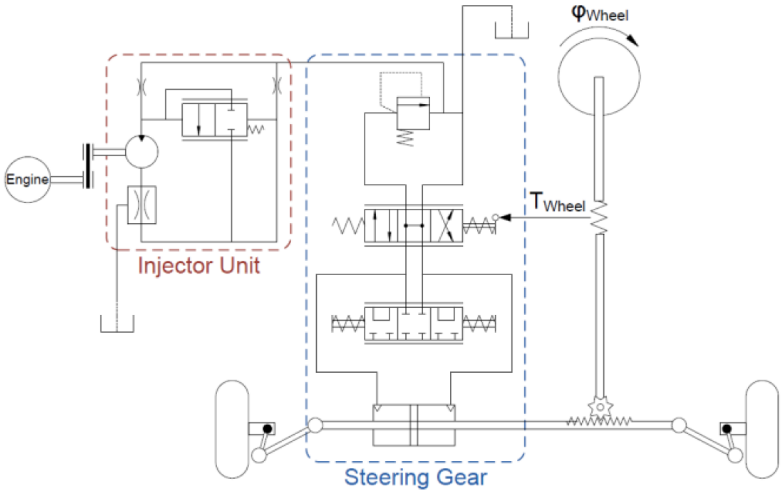


Figure 1 – Diagram of an HPS system

The hydraulic pump is driven by the combustion engine via gear drive housing or a belt drive and is equipped with a volume flow relief valve, which keeps the volume flow at a constant value over the full engine speed range from engine idle to maximum engine speed. To guarantee high steering dynamics also at engine idle, the volume flow and therefore the displacement of the pump needs to exceed a certain value: on average, the constant volume flow for a commercial vehicle with a gross weight of approximately 18 tons is around 20 l/min and the pump displacement is between 15 to 20 cm³/rev. On one hand this leads to high dynamics at engine idle speed but on the other hand you have to face high power losses at high engine speed (see Figure 2). The power to drive the hydraulic pump raises proportional to the pump input shaft speed – assuming a constant oil pressure and therefore a constant pump input shaft torque. On the contrary, the hydraulic output power is limited due to the volume flow relief valve.

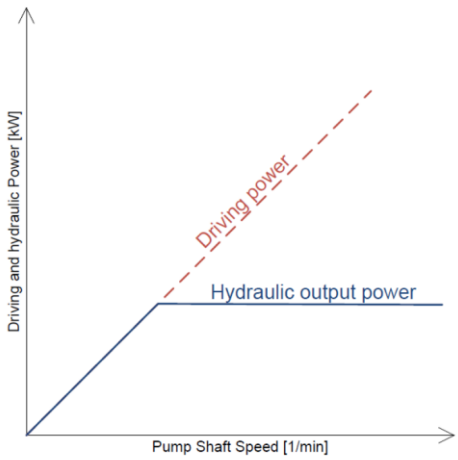
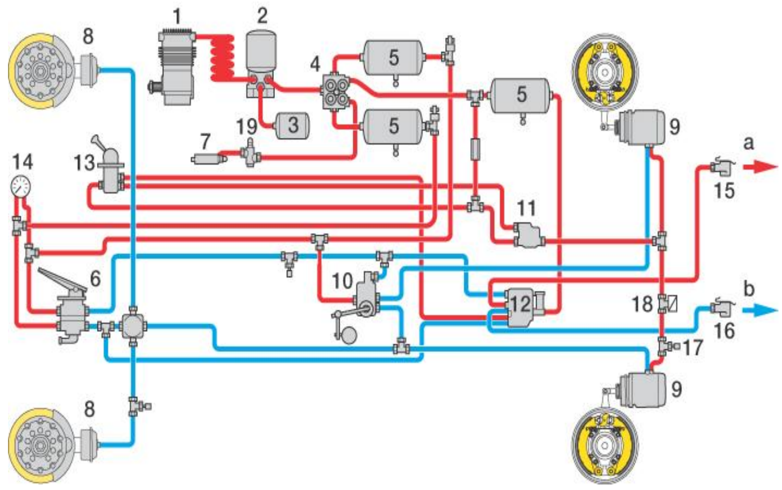


Figure 2 – Power bilance of a conventional hydraulic power steering pump

On average the hydraulic pump, including the relief valve, has an efficiency of 20%, the HPS system’s portion of total fuel consumption is approximately 1.5% at long haul usage.

2.2 Air compressor unit

In conventional commercial vehicles the air compressor is, like the steering pump, driven by the combustion engine and delivers air pressure for the braking system, the air suspension system and clutch actuation. The layout of an average air compressor unit can be seen in Fig. 3.



1 compressor
2 air dryer
3 regeneration tank
4 four-circuit protection valve
5 air tank
6 service brake valve
7 actuator of retarder
8 brake cylinder
9 spring brake cylinder
10 control valve
11 overload protection valve
12 trailer control valve
13 hand-brake valve
14 double-strike manometer
15 + 16 brake couplings
17 test connection
18 warning switch
19 air inlet valve

Figure 3 – Diagram of an air compressor unit [2]

The compressed air is delivered via an air dryer into a pressure reservoir, the operating pressure lies between 10 and 12 bar. Due to the dependency of the compressor on the combustion engine, the air is supplied at every time, leading to an enormous loss of power. In case that the air tank is already full and the system pressure has reached the final value, an overpressure valve releases the compressed air to protect the system against overpressure. Manufacturers of automotive compressors counteracted by developing energy saving air compressor systems. Those systems are designed in a way that they switch to idle position, when the operating pressure is reached. At system idle the compressor delivers compressed air against atmospheric pressure, additionally leading to an idle power reduction of 30% to 60%, depending on the breaking time in comparison to the system operating time [3]. Another solution to reduce the power losses of the system is a compressor with an integrated electro-magnetically actuated clutch, which is however still driven by the combustion engine. When the operating pressure is reached, the clutch will be opened to disconnect the actuator from compressor to stop the air delivery. When air delivery is needed again, the clutch will be closed [5]. The disadvantages of this system are the additional weight and also the component size of the compressor unit.

For hybrid-electric and electric vehicles electrified compressors have already been developed. Those systems are operated on the vehicle's high voltage power supply. An integrated energy management activates the compressor only if the operating pressure decreases and compressed air needs to be delivered [6].

The conventional engine driven air compressor's portion of total fuel consumption is approximately 4%. Equipped with a power reducing unit or the clutch, the portion of total fuel consumption can be reduced to approximately 2% at long haul usage.

3. Concept development

The goal of the concept development is to reach an independency of the combustion engine, what in turn delivers the opportunity of implementing a demand-actuated operating strategy and to carry out a possible downsizing of both the steering system and the breaking system.

3.1 Hydraulic steering pump

The first step towards optimization is the analysis of measurement data. The conventional system, as already mentioned before, delivers a constant volume flow over the whole engine speed range. The actual volume flow demand can be calculated from the steering gear's geometry and the steering wheel angular velocity, as shown in the formula

$$Q = \frac{A * k}{2 * \pi} * \omega \qquad (1)$$

In equation (1) variable Q describes the demanded volume flow, A describes the piston surface in the steering gear, k is the travel of the steering gear piston per steering wheel turn and ω describes the angular velocity of the steering wheel.
Using this volume flow demand and the steering pressure values from the measurement data it is possible to calculate the actually demanded hydraulic power of the system. In Fig. 4 the operation points of the conventional steering system are shown.

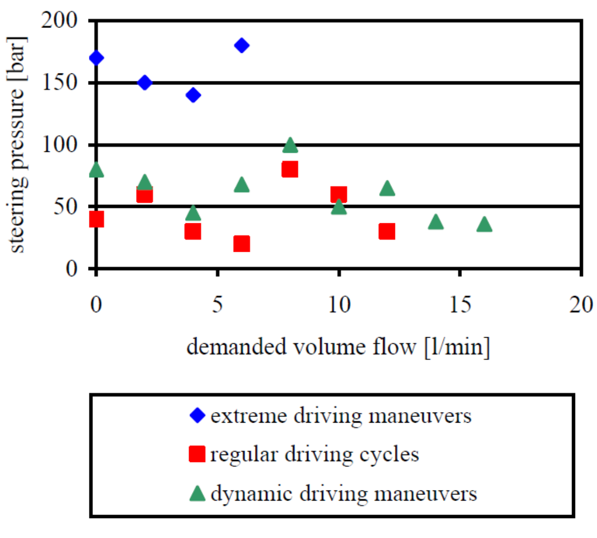


Figure 4 – Operating points of the HPS system

Extreme driving maneuvers are steering at standstill, where high steering power and high steering pressure are necessary, and steering against kerb, what is more or less a rare and

extreme use of the system, but needs to be considered nevertheless. Regular driving cycles are highway driving, urban and suburban driving cycles. Dynamic driving maneuvers would be lane change, figure 8 diving or accelerated or steady state cornering. At these maneuvers a high flow rate is required to achieve high steering dynamics.
To achieve the required pressure and volume flow values, a demand actuated control strategy has to be developed. This control strategy consists of three modules: a driving state detection unit, a pressure observer unit and the calculation unit for the required volume flow and subsequently for the required electric motor speed. The volume flow is calculated depending on the driving state, which is highway driving, standstill or regular driving. At highway driving the system performance will be turned down to idle, at standstill the system will deliver as much power as possible and at regular driving the system will deliver a demand actuated volume flow dependent on the steering wheel angular velocity to reach the operation points shown in Fig. 4. The steering pressure will be built up in the system in dependant on the volume flow

$$\mathrm{p(t)} = \int \frac{\mathrm{E}}{\mathrm{V_0}} * \mathrm{Q(t)} * \mathrm{dt} \tag{2}$$

In equation (2) variable p(t) is the steering pressure, E is the E-modulus of the hydraulic oil, V0 is the initial volume of the hydraulic oil and Q(t) describes the delivered volume flow.
Via the pump’s displacement, the size of the electric motor can be influenced. By using the formulas

$$n = \frac{Q}{V * \eta_{vol}} \tag{3}$$

and

$$M = p * \frac{V}{2 * \pi * \eta_{mech}} \tag{4}$$

the optimum displacement can be calculated. In formula (3) and (4) n is the motor speed, M is the motor torque, V describes the displacement, η_{vol} is the volumetric efficiency of the pump and η_{mech} describes the mechanical efficiency of the pump. The maximum motor torque shall be as minimal as possible to keep the electric motor as small as possible, too.
The system package, consisting of hydraulic pump, electric motor and connectors, can be seen in Fig. 5. Due to the downsizing and the demand actuated control strategy it is possible to supply the system with the vehicle’s 24V on-board power supply.

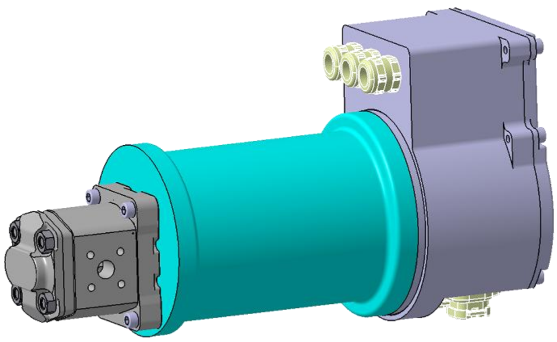


Figure 5 – CAD package of the electrified pump (functional sample)

3.2 Air compressor

Measurement data of different driving maneuvers have been analyzed for the air compressor unit, too. The pressure in the air tank is between 10 and 12 bar, the mass flow delivered by the air compressor correlates with the engine speed.
Depending on the breaking intensity, the air tank has to be filled up accordingly very often and correspondingly the system need more power. This breaking intensity differs in dependence of the driving maneuvers, what can be seen in Fig. 6. At highway driving the breaking intensity is very low, while at urban drive it is very high due to stop and go traffic.

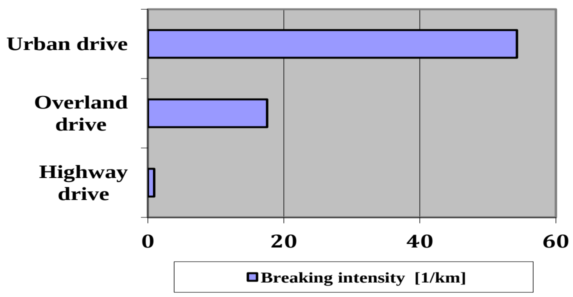


Figure 6 – Breaking intensity at different driving maneuvers

The system is equipped with an air tank and due to the electrification - and therefore independency from the combustion engine - it is possible to switch off the electric motor completely at system idle. At system operation, the control strategy decides the required mass flow to build up the pressure in the air tank in dependence of the driving maneuver according to

$$\dot{p} = \frac{R_L * T}{V} * \dot{m}. \tag{5}$$

At highway drive the breaking intensity is low, leading to the fact that the air tank can be filled up slower than at urban drive with a comparatively high breaking intensity. Therefore the compressor can deliver lower mass flow what leads in further consequence to lower power consumption [6].

4. Simulation Results

Both the steering system and the braking system have been built up in a simulation model using MATLAB® Simulink® to analyze the potential energy saving. The built up was done using differential equations and mathematical relations that show the interaction between the systems' components mechanics, electronics, hydraulics and pneumatics. The model parameters are extracted from datasheets and measurements on several experimental vehicles. The development of energetic simulation models may be time-consuming and complex at some point, but at the initial stage experiments and tests can be done much easier in simulation than on test benches.

4.1 Electro-hydraulic power steering system

The simulation model of the EHPS system consists of 4 sub-models, which can be seen in Fig. 7. The input data for the plant model and the operating strategy are extracted from measurements. The block "operating strategy" calculates the target value for the motor speed and therefore for the volume flow. This motor speed value is the input for the next block, the "E-motor and control" block. A state controller translates the motor speed target value into a controlled output variable. With the aid of the plant model it is possible to analyze if the delivered volume flow is sufficient to build up the required steering pressure in time. The necessary energy and power consumptions are evaluated and analyzed in the block "energetic considerations".

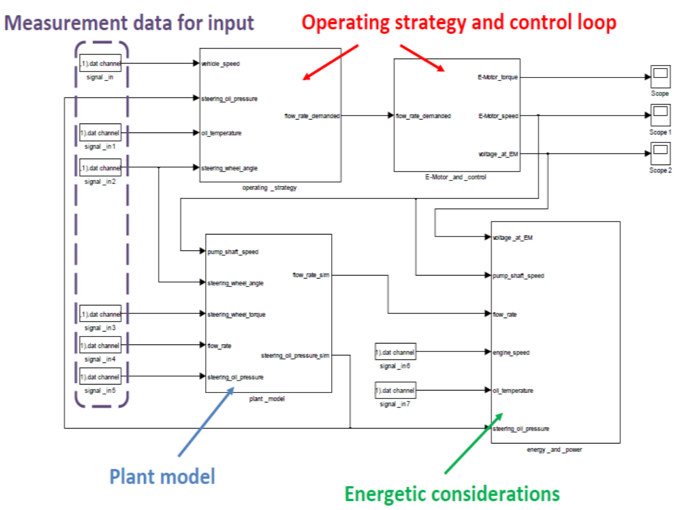


Figure 7 – EHPS simulation model

Irrespective of the driving state the electrification shows very good results in the simulation (Fig. 8).

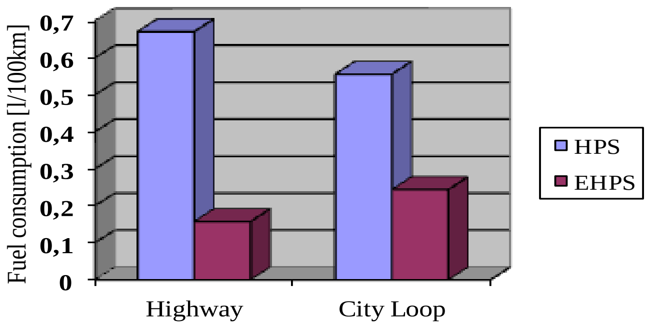


Figure 8 – Simulation results of the EHPS

When driving on a highway, the steering efforts are very low, while the driving energy of the conventional HPS system is high due to the high combustion engine speed. By electrifying the system and implementing a system idle mode, the driving energy can be reduced by 75%, what equates to 0.5 l/100km. When driving in urban and sub-urban areas the independency of the combustion engine and the demand actuated control strategy leads to a potential saving of 50% or 0.3 l/100km.

4.2 Electrified air compressor unit

The simulation model of the electrified air compressor unit is shown in Fig. 9. The first block includes the operating strategy, the controller model and the electric motor model. The operating strategy calculates the required motor speed, which is controlled using a PI controller with a pilot control. The air compressor model calculates the mass flow and the load torque of the system. The mass flow gets distributed to the different pressure chambers – front axle, rear axle and auxiliary consumers – by the 4-circuit protection valve. This block also includes the model of the air tank. The models of the pressure chambers are used to analyze if the mass flow is sufficient to build up the needed pressure in the pressure chambers [6].

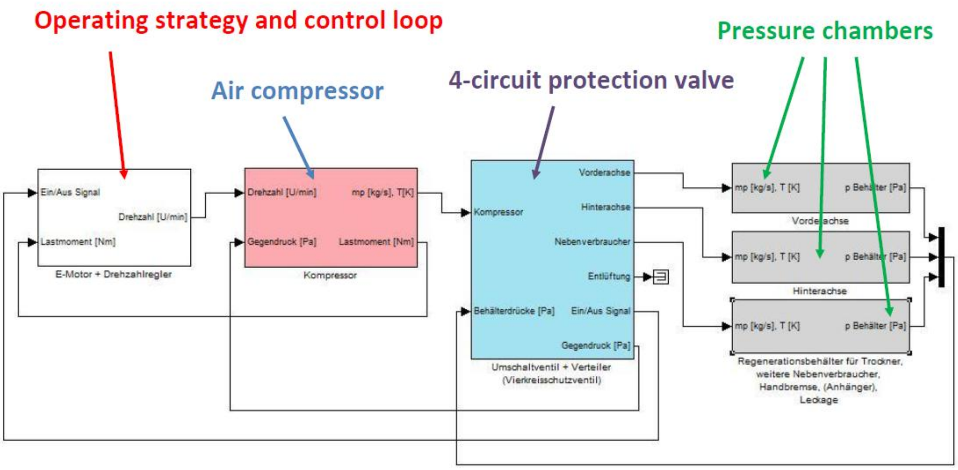


Figure 9 – Air compressor unit simulation model [6]

The electrification of the system leads to good energy savings, what can be seen in Fig. 10. Regarding highway driving, the conventional system has a fuel consumption of approximately 0.9 l/100 km, the compressors equipped with an energy saving system showed a reduced consumption of at least 0.3 l/100km. By electrifying the system, the operating time of the compressor can be pared down to a minimum and the fuel consumption can be decreased by 85%, compared to the conventional system. When driving in urban and sub-urban areas the start-stop operation leads to even higher fuel consumption. The independency from the combustion engine and the demand-actuated delivery of the mass flow lead to a consumption reduction of approximately 55% or 0.9 l/100km [6].

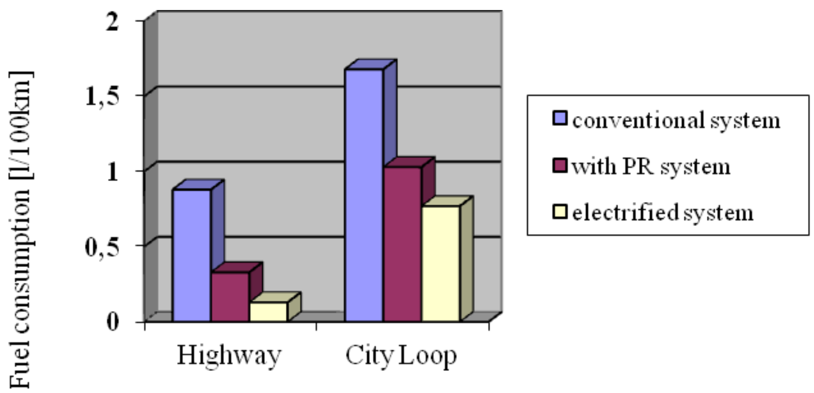


Figure 10 – Simulation results of the air compressor unit

5. Functional safety and Homologation

Some people may claim that especially the steering and the braking system of a heavy commercial vehicle entail huge risks and those systems which have been working reliably for decades shouldn’t be changed.
However, a hazard and risk analysis (HARA) according to ISO 26262 [7], which was performed on the electro-hydraulic steering pump, showed that the loss of assisting power can be evaluated with QM (quality management). This means that there’s no requirement to comply with the standard and that the system is not safety relevant. The reason for this lays in the fact that power-assisted systems – regardless of the source of the assisting power – need to be equipped with a mechanical fallback level. In case of the electro-hydraulic steering system it means that the driver must be able to overrule the assisting power at any time and must also be able to steer the vehicle purely mechanically in case of assisting power failure [8].
Regarding the braking system, the mechanical fallback level is defined by the air tank, which must be sufficiently dimensioned to contain enough compressed air. So the driver is able to actuate the service brake entirely for twenty times and for twenty seconds each time in case of a pneumatic or an electric failure. Additionally to that mechanical fallback level a warning lamp has to indicate the failure of the assisting power [9].

6. Conclusion

The simulation shows that the electrification of both the steering system and the braking system leads to an enormous energy saving potential, whereby the energy of the electric motor is sufficient to deliver the required pressure in both cases. The subjective and objective steering convenience of the electrified systems has still to be tested on demonstrator vehicles. Due to the downsizing it is possible to operate the steering system with a maximum power of 2 kW and the compressor unit with a maximum power of 3.5 kW. These power levels lead to the possible operation of the EHPS on the 24V on-board power supply of a commercial vehicle and the electrified brake air compressor to power by an additional 48V or HV power supply. So the installation of the EHPS is not limited to HEVs and EVs equipped with a high voltage power supply.
The concept of the EHPS system will currently be tested and evaluated on a prototype. An appropriate hydraulic pump has been chosen for this purpose and a synchronous machine has been designed and manufactured, too, which can be seen in Fig. 11.

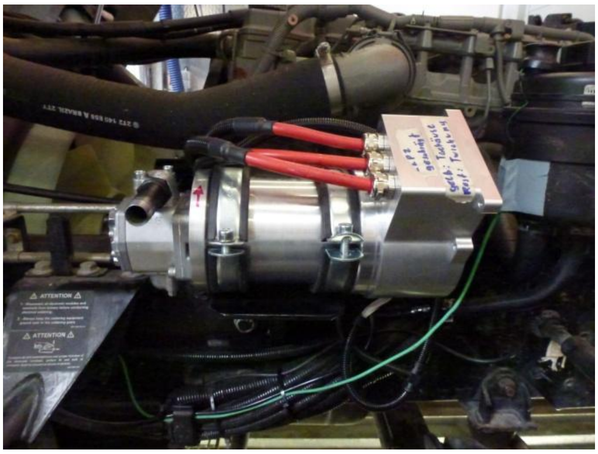


Figure 11 – Synchronous motor and hydraulic pump for EHPS system built-in in a CV

The prototype system will be implemented in an experimental vehicle to validate the simulation results and to evaluate the subjective steering convenience of the downsized EHPS system.

7. References

[1] J. Schneider et al., "Climate Protection Report 2010", Report, Umwelt-bundesamt GmbH, Vienna, 2010.

[2] MAN Nutzfahrzeuge Gruppe, "Grundlagen der Nutzfahrzeugtechnik", Marketing Training, Munich, 2004.

[3] "Air compressors 1- and 2-zylinder", datasheet, WABCO, American Standard Companies Inc., Brussels, 2004.

[4] "c-comp: Air compressor with integrated Clutch", http://www.wabco-auto.com/en/products_wabco/air_management/compressors_wabco/c_comptm_air_compressor_with_integrated_clutch, 04/12/2012.

[5] "e-comp: Electrically driven air compressor", datasheet, WABCO, American Standard Companies Inc., Brussels, 2010.

[6] G. Wagner, "Analysis and development of a demand-actuated operating strategy for a commercial vehicle's air compressor unit", Master Thesis, Johannes Keppler University Linz, 2012, unpublished.

[7] Standard ISO 26262, "Road vehicles – Functional safety", Nov. 2011.

[8] Standard ECE-R 79, "Steering Equipment", Revision 2, April 2005.

[9] Standard ECE-R 13, "Braking", Supp. 7, Oct. 2011.