3.11 Hybrid Drive Systems for Industrial Application

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Zusammenfassung
Hybridantriebe bieten nicht nur im automobilen Bereich Vorteile, vielmehr kann dieses Prinzip im industriellen Bereich seine Vorteile sogar viel besser nutzen. Im Vergleich zu den etablierten Antriebssystemen sprechen zunächst die erhöhte Systemkomplexität, die Entwicklungskosten und das generelle Risiko beim Einsatz neuer Technologien gegen den Hybridantrieb, jedoch punktet dieser mit Einsparungen beim Kraftstoffverbrauch, beim reduzierten Aufwand der Abgasnachbehandlung und bei der zusätzlichen Flexibilität für die Anwendung. So kann sich der Hybridantrieb in der Industrie durchaus rechnen, insbesondere, wenn schnelle Lastwechsel vorliegen

ABSTRACT
Hybrid drives for automotive application are extensively discussed. In contrast, the company HEINZMANN, the University of Karlsruhe and the University of Applied Sciences Offenburg concentrate on hybrid drives for industrial, off-road purposes in a joint project. These applications promise a much higher fuel saving potential, particularly if highly frequent load cycles are present. Hybrid drive systems offer additional advantages including reduced exhaust aftertreatment requirements due to engine downsizing, better engine dynamics, emissions and noise reduction.

„Mild hybrid“ technology is currently the most promising version of hybrid technology for industrial applications. It combines an electric motor with a combustion engine. The electric motor is mounted directly on the crank shaft (substituting the flywheel) so that a very compact design is achieved. The electric motor has three functions: Boost, energy regeneration, start-stop. Combining the combustion engine with an electric motor on one shaft enhances greatly the performance: The combustion engine has its maximum torque at high speeds, whereas the electric motor provides maximum torque at low speeds. The addition of both units results in a powerful characteristics with high torque particularly in the starting phase at low speeds.

The paper presents the system architecture and the different applications with different engines of DEUTZ, VOLKSWAGEN-Industrial Engines and others. Heinzmann hybrid motors are installed in fork lifts and in construction equipment. The load profiles of these applications are most promising for the mild hybrid concept. Both load profiles are characterized by fast load changes with a high frequency of acceleration and braking. The braking energy is regenerated and stored in the battery. This energy is then used for acceleration periods by the electric motor. A lithium-ion battery is used. This type of battery can withstand the high frequency of charging/discharging cycles. Such micro cycles can work with a relatively low battery capacity of 4 to 8 Ah. The combustion engine can be downsized, as the short load peaks are taken over by the electric motor.

Heinzmann´s electric motors are available in power sizes up to 50 kW permanent power. They are of the latest brushless synchronous permanent magnets (embedded magnets) design. The system efficiency of motor and inverter exceeds 90 % over a large speed and torque range. It was found that the motor with a permanent power of 15 kW power and a peak power of 30 kW (for two minutes) is by far most asked for as it fits the majority of fork lifts and construction equipment like wheel loaders and excavators. A voltage level of 400 V is chosen for the electric motor to keep the currents low, resulting in a compact motor design.

Real operation cycles of the industrial vehicles are measured as a basis for the analysis of the fuel consumption of hybrid engines with regeneration. The fuel saving potential is analyzed. Based on the real practical data, the simulation software is developed to get reliable data for wide ranges of possible hybrid applications. The potential fuel savings will be presented for the different load profiles of working engines, in comparison to the experimental data.

Basis
HEINZMANN GmbH & Co. KG is a leading supplier of mechanical and electronic control systems for diesel, gaseous fuel and dual fuel engines as well as for gas, steam and hydro turbines. The range of system solutions offered by the company includes products for speed-load governing, air/gas mixture control, electronic injection systems in common rail technology and power management. These solutions are used in gen-set applications, ships, agricultural and construction machinery, locomotives, cranes and others. The electric drives division of HEINZMANN develops and manufactures DC disc motors with and without brushes and wheel hub motors for electric vehicles and hybrid drive systems. The Institute of Vehicle Science and Mobile Machines, University Karlsruhe is specialized in advanced drive systems for mobile machines, i.e. hybrid drives of different combinations.

Hybrid systems incorporate different engineering disciplines like vehicle technology, combustion engines, electric motors, inverters, control technology, battery systems. HEINZMANN has a strong basis for the hybrid drive technology due the expertise gained by its „Engine & Turbine Management“ and „Electric Drives“ divisions. The University Karlsruhe contributes by its theoretical and simulation capabilities as well as by its laboratories. The University of Applied Sciences is involved in the inverter development.

Hybrid Drive Systems for Industrial Applications

Motivation
Hybrid drive systems for passenger vehicles gained public interest worldwide. This triggered also the idea to use hybrid drives for industrial applications. The driving forces for the development have been:

– Scarcity of oil supplies and rising fuel prices.
– Stricter emissions regulations (TIER 4, EURO 5).

Hybrid drive systems may contribute to the solution for this problem. They represent the future of today's combustion-based drive systems and will also act as an intermediate step and link to solely electric drive systems.

Hybrid Drive Strategies

Hybrid drive systems for industrial applications must prove cost-effectiveness. This depends directly on the particular application. Forklift trucks (figure 3.11-1) and certain construction machines with a working profile made up of many short load peaks are ideal candidates [1].

The additional components required for a hybrid drive system result in greater initial costs. These additional costs must be compensated by the benefits of the hybrid drive system. These include:

- Savings through lower fuel consumption.
- Reduced exhaust after-treatment requirements through the use of smaller combustion engines.
- Additional functionality/application areas due to better dynamics of hybrid drive system.
- Noise and emission reduction.
- Further potential for electrically operated auxiliary units.

The most important cost factor is currently the battery. The latest developments in the automotive sector give cause for hope. Almost every automotive manufacturer is working to develop a hybrid vehicle. Accordingly, battery technology is sure to develop quickly, resulting in lower prices.

Mild Hybrid

„Mild hybrid" technology – based on the following concept – is most promising for industrial applications. An electric motor is combined with a combustion engine. The electric motor has 3 functions:

- Boost: The electric machine is switched on during load peaks to provide additional torque.
- Generator/regeneration: The electric machine switches to generator mode when the full output of the combustion engine is not required for the particular application. The electrical energy is then recharged to the battery. The system switches to generator mode during braking („regeneration") feeding the braking energy into the battery.

***Fig. 3.11-1**: Forklift application [3] with hybrid engine of Wand HEINZMANN*

- Starter: The relatively large electric machine can start the combustion engine very quickly, typically between 150 and 300 ms. This makes it possible to implement a start-stop function whereby the combustion engine is switched off when idling but is made immediately available when it is required for operation.

System Overview

Figure 3.11-2 shows an example of the mild hybrid system. The functions of the individual components are:

- Electric motor/generator or starter
- Hybrid system control unit: To control individual units. Activates boost, charge or start function.
- Diesel control unit: Governor of diesel engine
- Inverter: Speed/torque control for the electric machine
- DC/DC converter: Converts the 400V DC bus into the on-board electrical system voltage

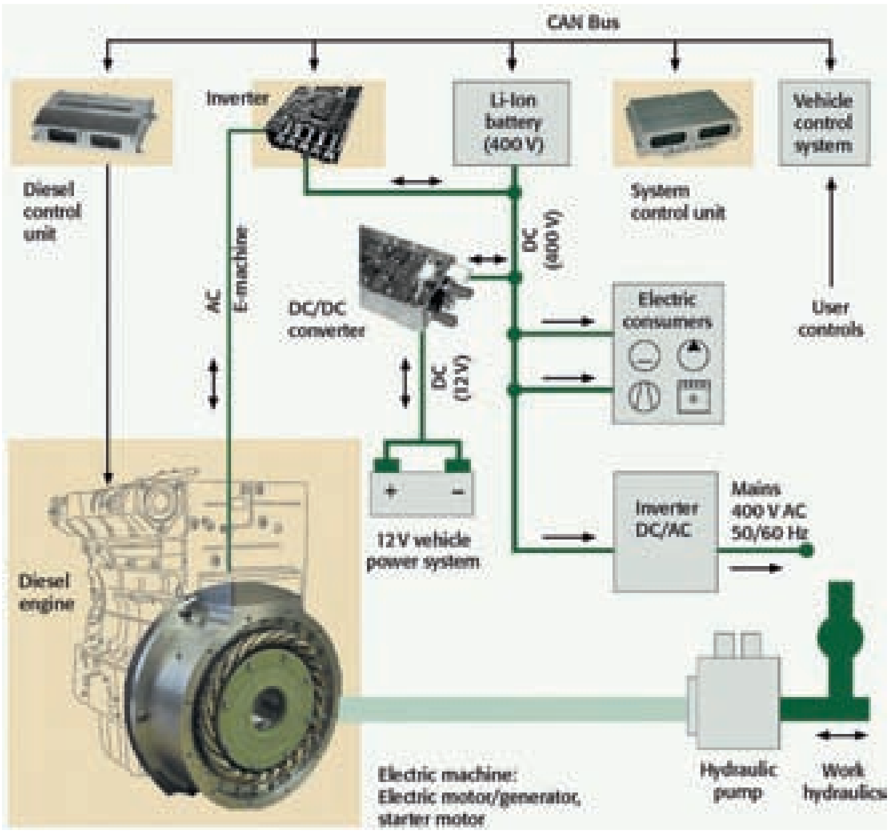

***Fig. 3.11-2:** System overview*

Torque Addition

The additional electric machine of the hybrid drive system provides a much higher torque. This makes it possible to use a smaller combustion engine, known as „downsizing" or "rightsizing" the diesel engine (figure 3.11-3). By combining the torque provided by the smaller combustion engine and the electric machine, it is possible to obtain the same or a slightly better performance than that of the original combustion engine, at least for short periods of time. The typical torque curve of a PSM (permanent magnet synchronous motor) provides advantages at low rpm.

In practice, the aim is to select a smaller combustion engine with reduced exhaust after-treatment requirements.

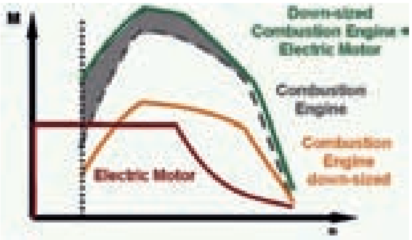

Fig. 3.11-3: Torque addition on a mild hybrid system [1]

Power Output versus Time

The diagram of power output versus time visualizes the mild hybrid strategy (see 3.11-4).

The start-stop function reduces fuel consumption drastically. For example, the vehicle equipped with a mild hybrid system will not be left anymore idling.

Load peaks -which the downsized combustion engine can no longer cover- are covered by the electric machine. In addition, the electric motor can be engaged right at the start of the load peak, providing a high level of torque, even at low rpm. This is the „dynamic boost", improving the dynamics, reducing the „roaring noise" of the diesel engine and the transient smoke associated.

If the particular load demand does not require the full output of the diesel engine, the electric motor charges the battery. The electric motor also recuperates the braking energy before the mechanical brake engages.

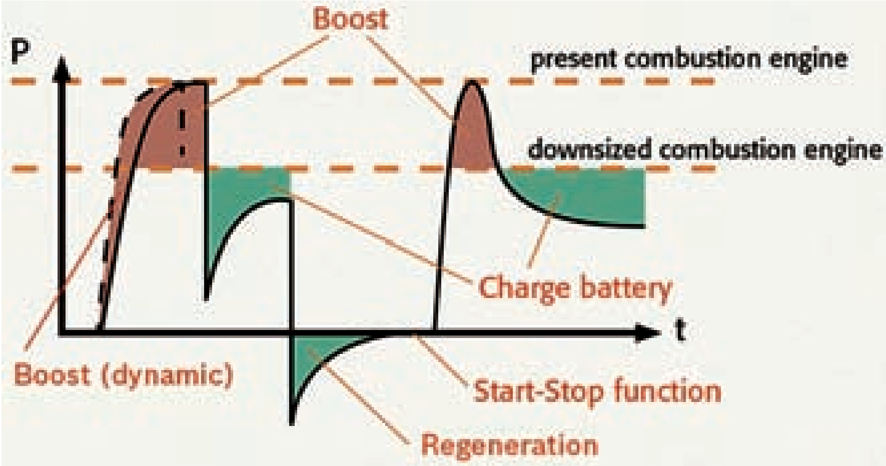

Fig. 3.11-4: Mild hybrid power output over time

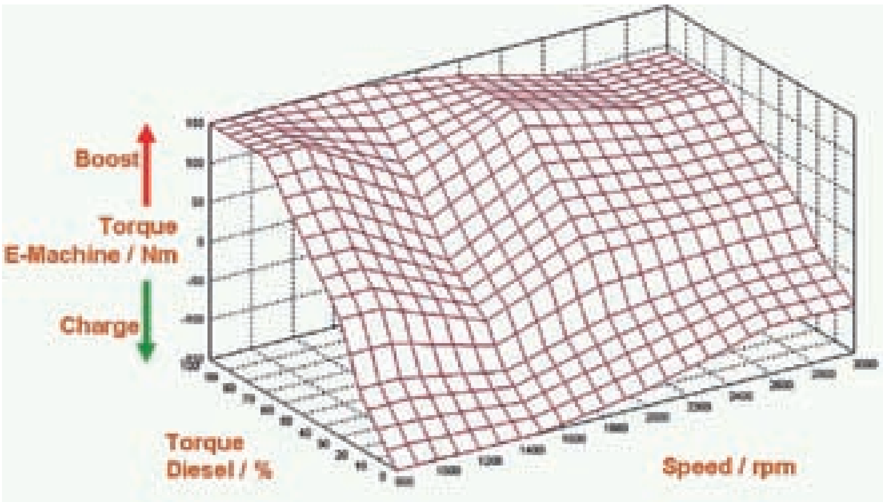

Fig. 3.11-5: Hybrid characteristic map

Figure 3.11-4 visualizes another advantage of this principle: The load pattern of the combustion engine is smoothened out when the system is tuned correctly (phlegmatisation). The load setup should be tuned to achieve either the lowest fuel consumption or the lowest level of emissions. The maximum output level of the diesel engine is exploited more, which should improve the service life of the combustion engine.

Hybrid Control Strategy

The hybrid control unit basically maps the e-machine´s operation. According the actual speed of the combustion engine and the actual combustion engine´s torque, a value for the torque of the electric machine is assigned.

The values "engine torque" and "engine speed" typically are transmitted from the diesel control unit via the SAE J1939 protocol. The torque of the e-machine can be either positive for boost-mode or negative for charging the battery. This torque of the e-machine must be limited by several parameters e.g. actual state of charge battery, temperatures of battery, inverter and e-machine.

A basic hybrid-map is shown in figure 3.11-5. The e-machine has to deliver the maximum torque at maximum load of the combustion engine. At reduced load, the torque of the e-machine will be negative – the battery is charged. The hybrid characteristic map has to be adjusted due to demands of the individual application. This strategy leads to a torque split between combustion engine and e-machine showed in figure 3.11-6 This picture is slightly different to the idealized schematic diagram Figure 3.11-4. The blue line shows the diesel torque: It can be seen, that there is a "phlegmatisation" of the combustion engine.

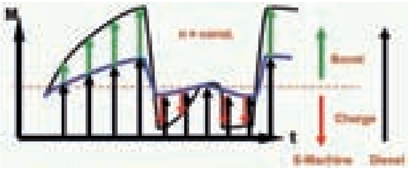

Fig. 3.11-6: *Torque split between combustion engine and e-machine*

Design of Electric Machine

Electric motors are usually categorized according to their rated output, which corresponds to allowed rotor/stator temperature. However, electric machines used in mild hybrid applications do not operate continuously – the short boost or regeneration phases generally last only seconds. Therefore, only the short-term power capacity of the electric motor matters for mild hybrid systems.

HEINZMANN thus specifies the „2 min peak output" of an electric motor in addition to its continuous output. Figure 3.11-7 shows an example of the torque characteristic of a HEINZMANN electric machine with 15kW continuous output. This electric motor can be overloaded up to 4 times for short periods. The peak output for 2 min is approximately twice that for continuous output.

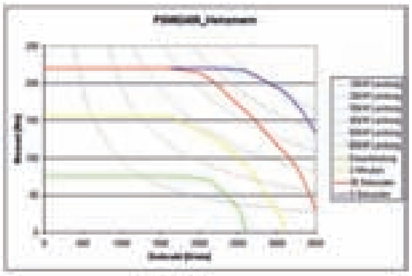

Fig. 3.11-7: *Torque split between combustion engine and e-machine*

Mechanical Integration

On the HEINZMANN mild hybrid, the rotor of the electric machine replaces the flywheel of the combustion engine and is bolted directly to the crankshaft. As a result, the electric machine uses the crankshaft bearing of the combustion engine (figure 3.11-8).

Fig. 3.11-8: *Electric machine*

The advantage of this arrangement is that the motor can be kept very compact and the overall drive train remains as short as possible (see figures 3.11-9 & 3.11-10). The manufacturer of the combustion engine must give its approval for the additional load placed on the crankshaft bearing by the electric motor.

Fig. 3.11-9: *HEINZMANN electric machine on DEUTZ 2011 diesel engine*

Fig. 3.11-10: *HEINZMANN's machine on VW SDI diesel engine with hydraulic pump*

Magnetic Pull

On a PSM, a magnetic force is generated which attempts to pull the rotor towards the stator. If the rotor is centred relative to the stator, these forces cancel each other out (see figure 3.11-11, left).

In a combustion engine, the ignition of the fuel/air mixture applies a force to the crankshaft. This causes the crankshaft to bend slightly. Since the rotor is directly bolted to the crankshaft, any bending of the shaft causes the rotor to wobble. The rotor is then no longer centered and the forces become unbalanced. This produces a force called „magnetic pull" (see figure 3.11-11, right).

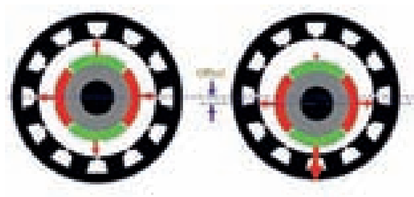

Fig. 3.11-11: *Magnetic pull of rotor*

This force also acts on the crankshaft bearing. For this reason, it is important to clarify the following points during the development process:

- What is the deflection of the crankshaft?
- Is the crankshaft bearing able to cope with the additional load caused by the magnetic pull?

Is the clearance between rotor and stator sufficient?

The magnitude of the force depends on the stator offset and the electric machine used. The figure 3.11-12 shows an example of the force for a 30kW (peak) electric machine.

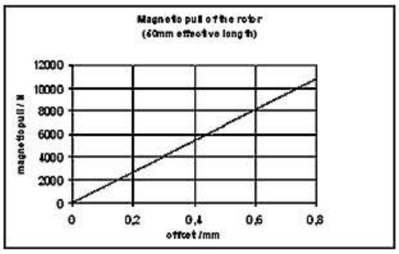

Fig. 3.11-12: *Magnetic pull relative to offset*

Battery Size / Battery Type
The minimum number of cells required depends on the system voltage of the DC bus. For example, a DC bus voltage of 400 V needs:

- 110 Li-Ion cells, or
- 125 LiFePO4 cells

Figure 3.11-13 depicts a battery for a mild hybrid system with a rated voltage of 400 V and a capacity of 4.5 Ah.

Fig. 3.11-13: *Battery for a mild hybrid [5]*

The minimum capacity of the battery is determined by the capacity of the individual cells. The battery capacity required depends on the application. E.g., the red colored area in figure 3.11-4 represents the energy consumed when the battery is used for a boost procedure. For this reason, the load profile for the application must be known in order to estimate the battery size. The selection of the battery size is based on the following conditions:

- Required capacity according to load profile
- SOC window within the battery is operated. A small SOC window (low discharge depth) is necessary if a battery a long service life is needed. Required battery current peaks (charge/ discharge)
- Space requirements
- Cost of battery

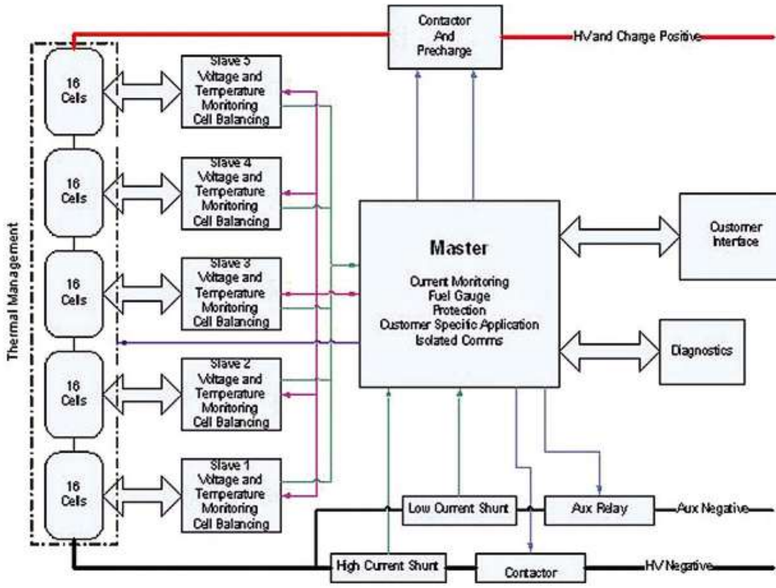

Fig. 3.11-14: *Schematic illustration of a Bm) MS (Batterie Management Syste[5]*

Battery Management System
Hybrid drive systems need a Battery Management System (BMS) to ensure that the battery remains in safe conditions. The BMS performs the following tasks:

- Monitoring of individual cells (voltage, temperature)
- Charge balancing
- SOC determination
- Insulation monitoring
- Safety shutoff

The BMS communicates with the system control unit over a suitable bus. For example, a CAN bus with SAE J1939 protocol can be used. Figure 3.11-14 illustrates schematically the BMS.

Test Runs
During the test runs various values were measured like vehicle speed, engine speed, instantaneous fuel consumption and the pressure in the hydrostatic transmission. Figure 3.11-15 displays some recorded cycles.

Simulation models
The simulation models for vehicles with and without hybrid drive were created in Matlab Simulink. Static efficiency maps *($b_e = f(M, n)$, $\eta = f(M, n)$)* are used for the internal combustion engine and the electric motor. The battery was implemented with constant efficiency. The transmission efficiency as well as losses in the tire and the tire-ground contact was modeled as a black box. The parameters of this black box were set within the validation process.

Simulation of the reduction in fuel consumption

Objective
Objective of the simulation approach is the estimation of potential fuel savings through hybridization. The first example which is investigated is the drive train of a municipal multi-purpose vehicle, figure 3.11-16.

Approach
- Driving representative test runs with the non-hybridized vehicle, thereby recording real data.
- Generation of a simulation model representing the conventional, non-hybridized vehicle.
- Validation -the term validitation is here used as defined in ISO 9000 3.8.5: "Confirmation [...] that the requirements for a *specific* intended use or application have been fulfilled."- of the simulation model based on the recorded measurement data.
- Extending the simulation model to represent the hybridized vehicle.
- Comparison of simulated fuel consumption of non-hybridized and hybridized vehicle.

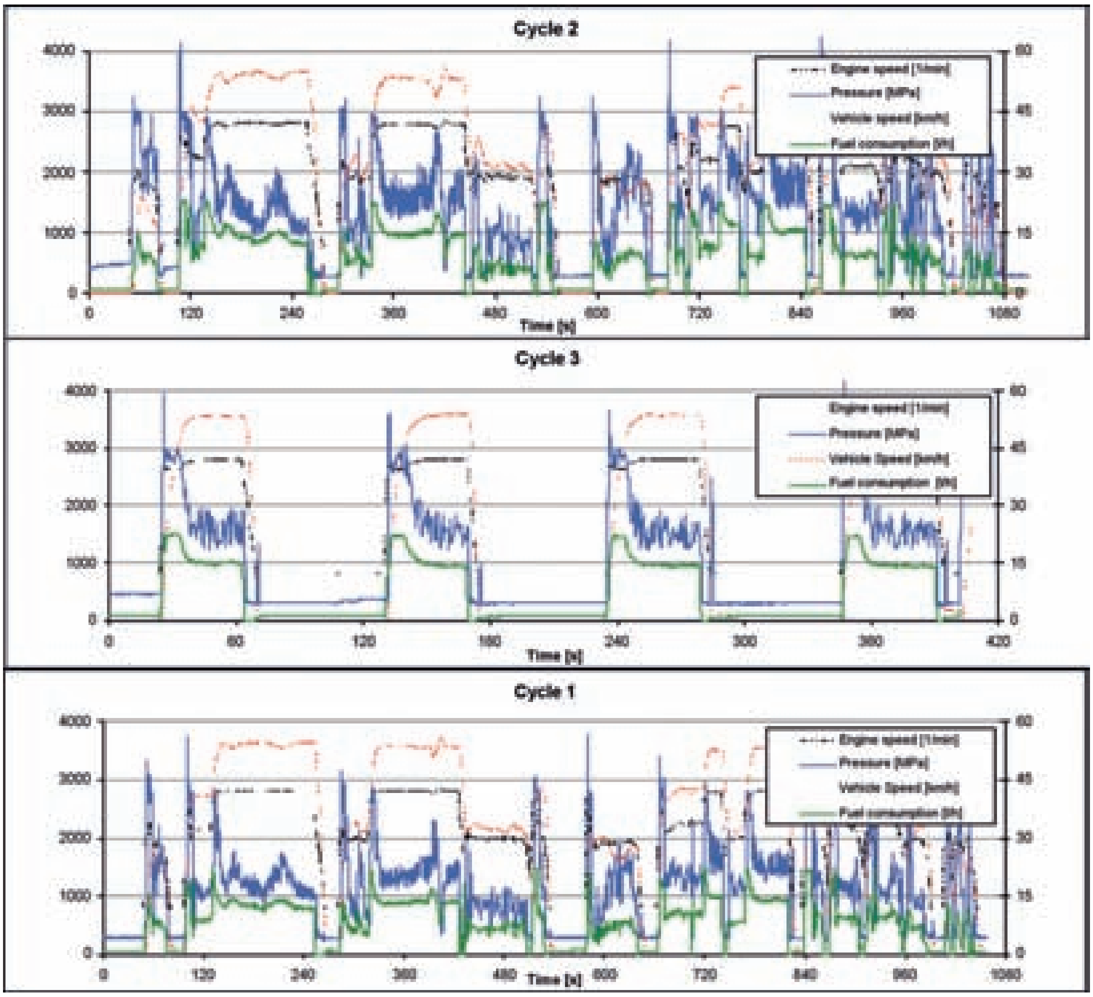

Fig. 3.11-15: *Measured values for 3 different cycles*

Description	Unit	Value
Vehicle weight	[kg]	2.950 (cycle 1) 4.600 (cycle 2) 2.800 (cycle 3)
Engine power (conventional)	[kW]	72
Engine power (rightsized)	[kW]	42
Motor power	[kW]	30
Top speed	[km/h]	53,5

Table 1: *Machine data*

Different drive train configurations and operation strategies (hereinafter called configurations) were investigated throughout the simulations. As a first step, the combustion engine and the electric motor were modeled via static efficiency maps $(M_{el} = f(M_{vkm}, n_{vkm}))$. In a consecutive step, the combustion engine was turned off during idling phases (start-stop). The third step modeled the possibility to recuperate breaking energy.

Simulations were conducted with both, the conventional 72 kW combustion engine and with the smaller, rightsized – The term "rightsizing" is used as defined in [6]: Matching the installed engine power to the actual need. – 42 kW engine. An overview of the fuel consumption with different configurations and cycles is presented in table 2.

Simulation Results

The battery's state of charge and the fuel consumption for each cycle and each configuration were simulated.

Fig. 3.11-16: *Testing vehicle*

Conclusion

As the results in table 2 show, the present application provides an enormous savings potential of over 20% under the assumed conditions. It also shows, however, that certain configurations only promise significantly lower savings. The main increase in efficiency derives from rightsizing the engine, while start-stop and recuperation have less influence. Further exploitation is under way.

Full Hybrid

The mild hybrid system can not be operated on a solely electrical basis. A full hybrid system is obtained by a disengageable clutch between combustion engine and electric machine. When the clutch is disengaged, the combustion engine can be stopped to allow solely electrical operation. When the clutch is engaged, the system can either be operated with the combustion engine alone or in combination with the electric machine, as on a mild hybrid.

A full hybrid has some advantages over a mild hybrid:

- Solely electrical operation feasible (usage in halls, tunnels etc.).
- Greater potential for fuel savings.
- Combustion engine can be downsized further.

The disadvantages compared to a mild hybrid are:

- A much larger battery is required.
- Larger electric machine and inverter are required.
- An additional clutch is required.
- The electric motor must have separate bearings.
- The mild hybrid is more compact.
- Higher system costs.

Conclusion/outlook

In the short to medium-term, mild hybrid systems will be a beneficial addition to the drivetrain for industrial applications. Mild hybrids have already been proven to offer positive benefits. On a long-term basis, full hybrids will eventually become cost-effective when battery prices fall as a result of the series production of hybrid vehicles in the automotive industry.

It is conceivable that these developments will lead to a battery-operated vehicle with a small, optimised genset diesel-generator which is used to extend the range of the vehicle and/or to supply base load energy.

Configuration	Engine =72 kW	Engine =42 kW	Efficiency map	Start-Stop	Recuperation	Fuel economy [%]		
						Cylce1	Cycle 2	Cycle 3
Conventional (measured reference)	x					0,0	0,0	0,0
Hybrid 1	x		x			0,2	0,3	0,4
Hybrid 2	x		x	x		3,1	3,4	9,8
Hybrid 3	x		x	x	x	5,7	5,3	13,4
Hybrid 4		x	x			16,7	14,6	15,7
Hybrid 5		x	x	x		19,0	15,5	19,0
Hybrid 6		x	x	x	x	21,6	17,6	22,8

Table 2: *Simulation results*

Literature

[1] R. Prandi, A True Heavy-Duty Hybrid – Deutz, Heinzmann, Atlas-Weyhausen team up to develop prototype hybrid wheel loader, Diesel Progress Int. Edition, Sept.-Oct., 2007

[2] T. van der Tuuk, Dieselhybridantriebe als alternative Antriebslösungen, Informationstagung des VDMA und der Univ. Karlsruhe "Hybridantriebe für mobile Arbeitsmaschinen", Karlsruhe 2007

[3] LINDE Material Handling GmbH, picture, 2008

[4] F. Böhler, R. Zahoransky (Interview), Industrial Engines Meet Hybrid Technology, Diesel Progress Int. Edition, March-April, 2008

[5] Axeon Power Ltd., picture credit, 2008

[6] Thiebes, P., M. Geimer and G. Jansen. Hybridantriebe abseits der Straße - Methodisches Vorgehen zur Bestimmung von Effizienzsteigerungspotentialen. In: 2. Fachtagung Hybridantriebe für mobile Arbeitsmaschinen. 18.02.2009 in Karlsruhe, S. 125-135.

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