Environmentally friendly hybrid vehicles in commercial service

Hybrid drive lines – a combination of electric motor and internal combustion engine – mitigate the environmental impact of road traffic by reducing vehicle emissions. ABB has unique experience in this area and is working together with Volvo to evaluate the technology during a three-year trial with two hybrid trucks in normal commercial service in Gothenburg, Sweden. Simulations have shown that fuel consumption is reduced and emissions considerably lower with the hybrid truck. In addition, hybrid trucks can be run with zero emissions in environmentally sensitive areas.

ABB began research into small high-speed power plants and their possible use in hybrid drive systems at the end of the 1980s. Such drive systems could help to lower CO_2 emissions, which come mainly from road vehicles and are a major contributor to the greenhouse effect. The hybrid drive line – a combination of electric motor and internal combustion (IC) engine – is designed primarily to reduce emissions, but also allows vehicles to run entirely without emissions in particularly sensitive areas. This will enable it to comply with the zero-emissions standards that are likely to be introduced in certain urban areas in the foreseeable future.

Hybrid vehicles are intended primarily for transportation in areas which are particularly sensitive to exhaust gases or engine noise. All drivers of hybrid vehicles have to do when passing through such areas is switch to the electric mode in order to lower the noise level and stop emitting pollutants.

The first practical application of the hybrid drive line was demonstrated in 1992, when ABB and Volvo jointly developed a specially built vehicle called the Environmental Concept Car, or ECC [1]. This was equipped with a gas turbine and a directly driven high-speed generator. The same concept was also used later as the basis for two other projects: a truck used in distribution service, and a bus [2].

The third hybrid vehicle concept has now been introduced and is currently being demonstrated 1 by the haulage company TGM AB in the city of Gothenburg, Sweden. During a trial period that will last three years, the company will operate two trucks in regular distribution service, transporting goods every day in the city center and suburbs. The trial period has already begun and fuel consumption, emission and noise level data are being recorded. Other factors which are being studied and evaluated include driver acceptance of the new technology, road handling and vehicle response in everyday traffic situations (eg, acceleration capability in electric mode), service needs and other practical details.

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New concept has a range of objectives

The advantage of hybrid vehicles is that, by switching to the electric mode 2, drivers can run them in sensitive areas without emissions, the traction power being supplied by just the batteries. The vehicles are designed to simplify driving; no special skills are required. A brief, introductory training session should be sufficient to ensure that the vehicle's capabilities are efficiently utilized.

In the concept chosen for the two trucks, a diesel engine drives two permanent magnet generators, with the wheels driven by two induction motors via reduction gearing, a propeller shaft and a differential. ABB supplied the complete electrical drive line, including the equipment for monitoring and control.

Hybrid vehicles used during the three-year trial

The hybrid vehicle is built around a standard Volvo FL6 truck, the electrical equipment being mainly located along its sides 3. The extra weight of the hybrid truck, compared with a conventional vehicle, is approximately three tonnes. Since the trucks will operate for several years in commercial traffic, components and technologies of proven durability and reliability are used as far as possible.

For the development and evaluation of hybrid vehicles, it is important to be able to collect component data which is based on service under everyday, real-world conditions. This information will be provided by the three-year trial now under way. The project stipulates that each vehicle is to travel an average distance of about 150 km per day, which is equivalent to a typical city distribution cycle. Of this distance, a total of 30 km can be run entirely in electric mode. *Table 1* shows the main vehicle data.

One of the two trucks fitted with a hybrid drive and now taking part in a three-year trial in central Gothenburg, Sweden, where it is being used to distribute goods **1**

Drive line

The Volvo FL6 Hybrid is a series hybrid vehicle with the drive line shown in **4**. An auxiliary power unit (APU), consisting of diesel engine and two permanent magnet generators with rectifiers, provides power to an intermediate DC bus. The two strings of batteries are connected to the DC bus via two DC/DC converters. Nickel-cadmium (NiCd) batteries are used. They also supply power to the auxiliary power system, which includes chargers for the 12-V and 24-V batteries and a DC motor that drives a brake compressor and the steering servopump. The truck is driven by two induction motors.

The two sources of energy (ie, the diesel engine and batteries) can be combined in different ways. Operation of the drive line can be either in electric or hybrid mode. In electric mode all the power is provided by the batteries, in which case the vehicle range and performance are limited by the capacity of the batteries. The batteries are recharged during braking, when the electric motors act as generators. In hybrid mode, the mean power demand is met by the APU and the unit's surplus power is used to charge the batteries. During periods of high power consumption (eg, during acceleration) the batteries provide additional power to the electric motors. Control of the diesel engine is based on the total power needs of the vehicle. *Table 2* gives the drive line specification for the Volvo FL6 Hybrid.

Table 1:
Main vehicle data

Top speed	90 km/h
Range in electric mode	15–30 km
Total weight, chassis	8,300 kg
Additional weight for hybrid vehicle	3,400 kg
Payload	4,600 kg
Gradeability (at full load)	16%
Vehicle length	8.6 m
Vehicle height	3.3 m

Controls in the truck cabin **2**

The truck's vehicle management unit (VMU) is mainly responsible for controlling the drive line, which it does by influencing the subsystems in response to the commands from the driver. An instrument computer unit (ICU) controls the dashboard instruments in the cabin, and also interfaces with the diesel engine control unit. The battery management unit (BMU) monitors the condition of the batteries and also communicates with the VMU.

The diesel engine is located in the same position as in a standard truck. All the additonal units are placed behind the driver's cab, underneath the cargo body **3**.

The electric motors and generators are mounted in a subframe in the mid-section of the truck. The inverters are located on the right-hand side of the vehicle, and the two battery units are mounted on each side. The power electronics equipment for the auxiliary power system, the DC/DC converters, the VMU and other electrical apparatus are installed in a special box behind the rear axle.

Table 2:
Specification of the hybrid drive line

Total motor output	130 kW cont, 370 kW peak
Nom battery voltage	2 strings at 216 V
Nom battery capacity	100 Ah/string, total 43 kWh
Total generator output	110 kW
Max diesel engine output	154 kW at 2,400 rev/min

Control

When the truck is driven in electric mode, all the power is taken from the batteries. The DC/DC converters keep the DC bus voltage constant at 600 V. In hybrid mode, the motor power is supplied by the APU and, when required, from the batteries. The power flow follows the formula:

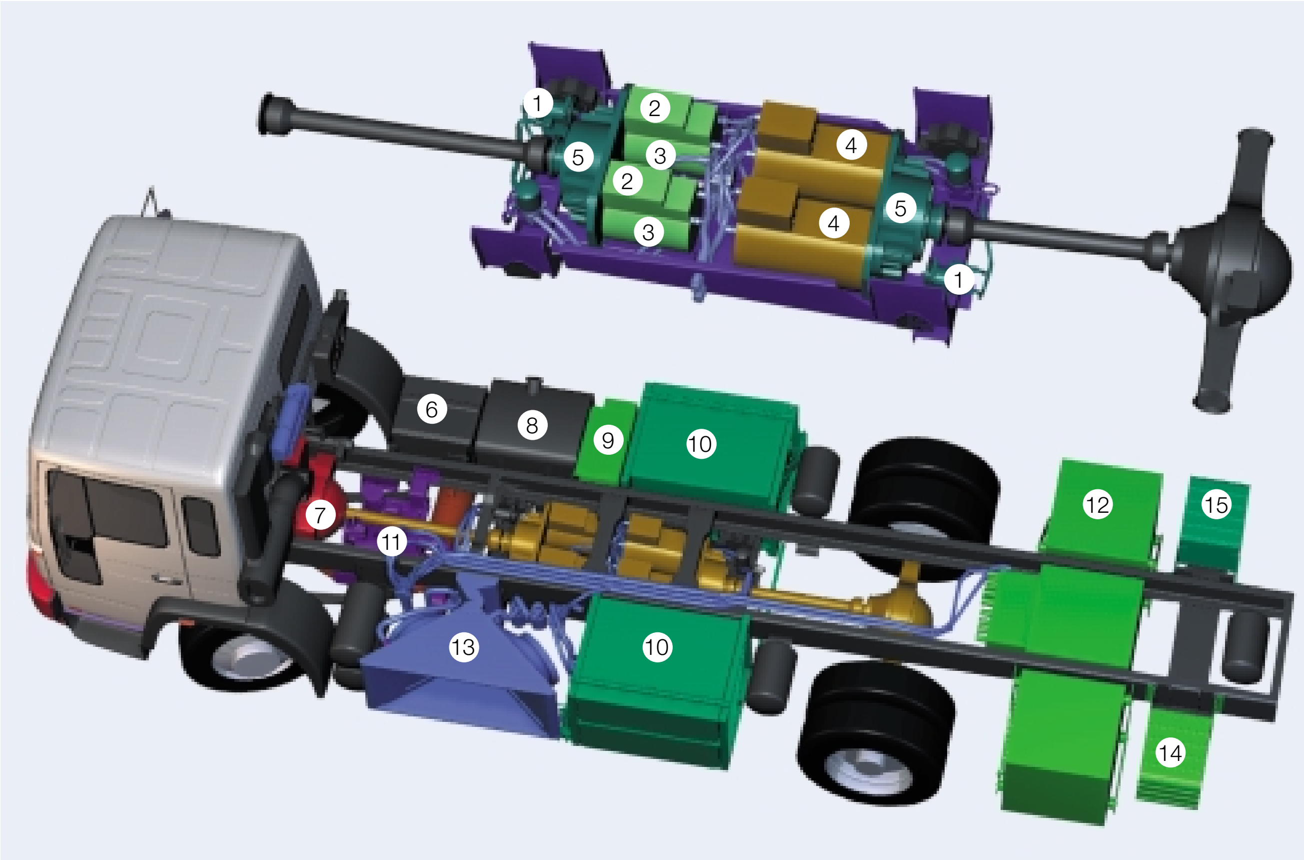
$$P_{eds} = P_{gen} + \eta_{dcdc} (P_{bat} - P_{aux}) \qquad (1)$$

P_{eds} Total power fed to electric drive system
P_{gen} Power generated by APU
η_{dcdc} Efficiency of DC/DC converters
P_{bat} Battery power
P_{aux} Auxiliary power

In hybrid mode, the DC bus voltage is controlled such that it always lies between 400 and 650 V DC, depending on the power taken from the generators and their speeds and temperatures.

To limit noise emission when the vehicle brakes at pedestrian crossings or traffic lights, etc, the VMU reduces the speed of the diesel engine and the generator output at speeds below 7 km/h and when the accelerator pedal is not operated. The VMU limits the power taken from the auxiliary power unit (APU) to the range of 0–110 kW.

Battery undervoltage is avoided by gradually limiting the possible power output of the electric drive system whenever the battery voltage becomes too low. Battery overvoltage, which could damage the battery, is avoided by reducing the maximum APU power and the regenerative power from the electric drive system when the battery voltage becomes too high. The system automatically gives priority to the requirements of the electric motor (mainly during acceleration) rather



Location of various components in the drive line and chassis of the hybrid truck **3**

1 *Oil pumps*
2 *Rectifiers*
3 *Generators*
4 *Motors*
5 *Transmission*
6 *24-V battery*
7 *Diesel engine*
8 *Diesel tank*
9 *Inverters*
10 *Batteries*
11 *Auxiliary power unit*
12 *HV box, with DC/DC converters*
13 *Cooling systems*
14 *12-V battery*
15 *Battery management unit*

than to battery charging. This enables the driver to utilize the vehicle drive systems to the full when the traffic situation requires or allows it.

Regenerative braking, ie braking with the electric motors working as generators and producing electrical energy, is also utilized to obtain the best possible fuel economy.

Electric motor drive

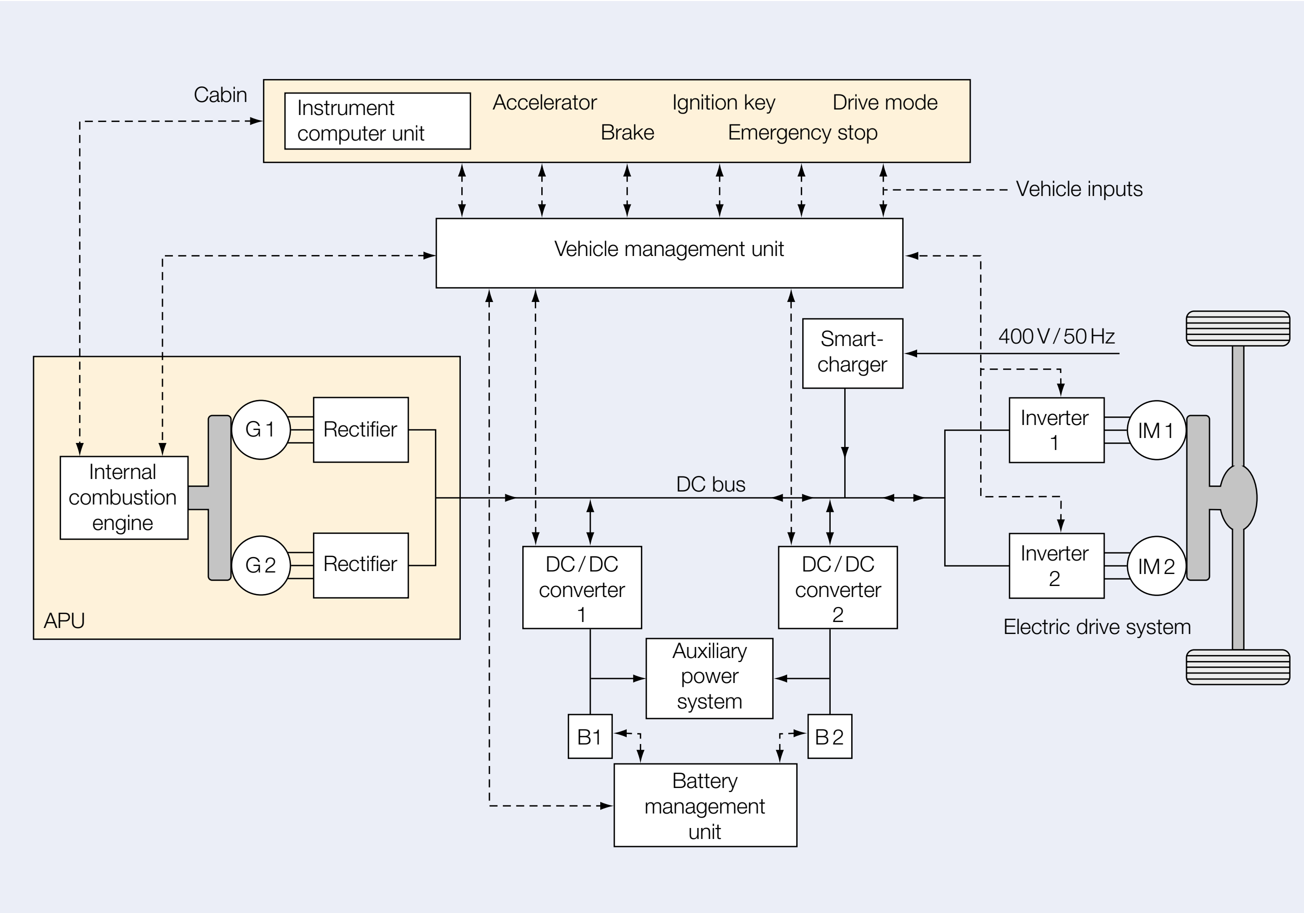
For its propulsion, the truck uses two water-cooled induction motors with inverters. The electric motors act on the rear axle via reduction gearing, a propeller shaft and differential. The total continuous electric motor output is 130 kW. The motors can reach 370 kW momentarily, but are limited in this application by the total power available of around 250 kW.

5 shows the maximum measured torque and power output values for one of the electric motors when it is coupled to the reduction gear and fed by its converter. The efficiency measured in such a case is shown in **6**. An efficiency in excess of 92 percent is achieved for most parts of the drive cycle. The efficiency of the inverter is steady at around 97 percent, except when the motor speed and torque values are low.

Battery system

The installed NiCd batteries weigh 940 kg and have a total energy storage capability of 43 kWh. Water-cooling ensures an efficient working temperature at all times. The batteries are divided into two strings with a nominal voltage of 216 V per string. The DC/DC converters, which connect the batteries to the intermediate DC bus, control the DC bus voltage independently of the actual battery voltage. This enables an optimum working point to be achieved with respect to the APU, so the diesel engine can be operated at speeds that ensure low emissions and maximum efficiency, ie reduced fuel consumption.

The BMU calculates and transmits



Block diagram of the electrical drive system used in a hybrid truck with diesel engine **4**

APU *Auxiliary power unit*
B1, 2 *Battery 1 and 2*
G1, 2 *Generator 1 and 2*
IM1, 2 *Induction motor 1 and 2*

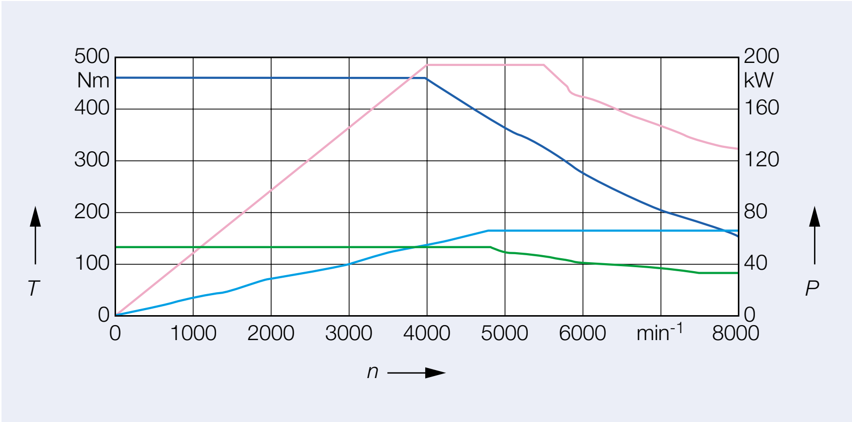
battery limit and reference values to the VMU. Via the BMU, the vehicle seeks optimum running conditions that will not cause the batteries to age too quickly. It also monitors battery charging. An ampere-hour-based algorithm calculates the level of the charge in both battery units. The BMU, which was developed by Volvo, also makes incremental changes possible, so different traffic situations do not cause sudden alterations in the vehicle's performance. For example, battery current limitations due to abnormal battery temperatures are introduced gradually to ensure that there is no sudden change in the motor torque, and therefore in the vehicle's behaviour. The operation of the BMU is shown in **7**.

The vehicle's batteries are charged from the mains by a unit known as the Smartcharger. This is fundamentally an on-board charger, but with the difference that there is no special charging unit on board. Instead, parts of the vehicle's drive line are used for charging from the mains. A 400-V, three-phase terminal rated at a minimum of 16 A is required for charging purposes. Charging begins automatically when the vehicle is connected to the mains and is terminated when the mains lead is disconnected or after the BMU has indicated that the batteries are charged.

Auxiliary power unit

The auxiliary power unit is linked to the DC bus via the generator rectifiers. The efficiency of the diesel engine is high and fuel costs are low compared with vehicles with petrol engines. The engine in the trucks now in trial operation is the standard six-liter, six-cylinder, direct injection turbocharged diesel engine used in a conventional FL6. Its maximum output is 154 kW at 2,400 rev/min. The engine is equipped with a continuous regeneration trap (CRT) filter on its exhaust side. This filter reduces the hydrocarbon (HC) content of the gas to about 20 %, the carbon monoxide (CO) content to less than 10 %, and the suspended particles to a quarter of the data for an engine without filter. Another advantage of the filter is that it reduces engine noise.

The generators are water-cooled, three-phase synchronous machines with permanent magnets, and are coupled to the diesel engine via a gearbox. The generators each produce 55 kW at approximately 550 V and 6,000 rev/min, corresponding to a diesel engine speed of 1,700 rev/min). **8** shows the estimated generator output/efficiency curves. The measured values of power output agree closely with the calculated ones. As is seen, the generators work at an efficiency of over 94 percent. Losses in the rectifiers are less than 1 percent.



Measured maximum output torque T and power P versus speed n for one motor **5**

Red	*Maximum power*	Dark-blue	*Maximum torque*
Light-blue	*Continuous power*	Green	*Continuous torque*

Measurements and simulations

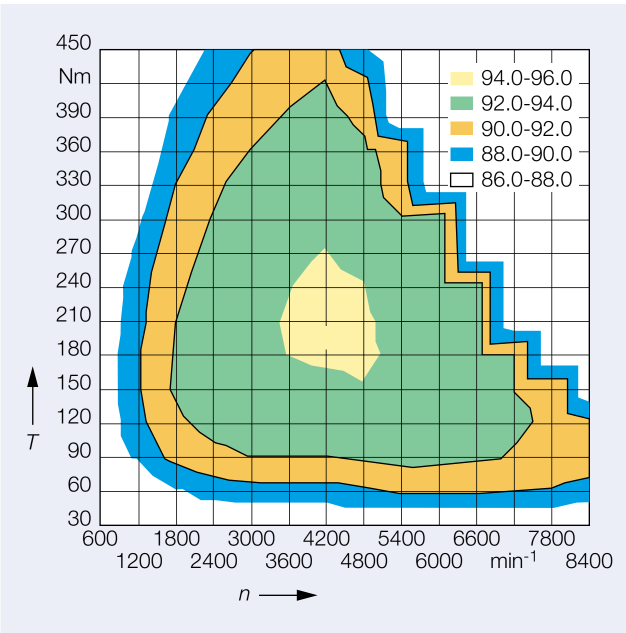
Measurements of the total power output of the electric drive system and the generator and battery output in relation to the vehicle speed in hybrid mode, are shown in **9**. The power from the generator follows the motor load reference value. The batteries are charged by the generators, except when the power needs of the electric motors are greater than can be met instantaneously by the generators. The batteries then supply power, eg to assist acceleration.

Fuel economy and pollution

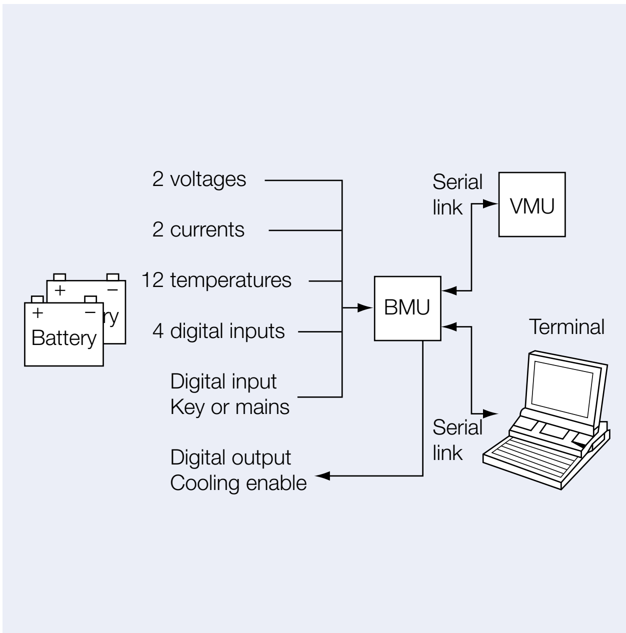
During the specification of the hybrid vehicle environmental considerations were given priority over fuel economy. Volvo has performed simulations that allow a comparison of the hybrid vehicle with a conventional truck in identical city distribution cycles with the vehicles carrying approximately the same payload. **10** shows simulated values of fuel consumption and emissions for a total distance of 71 km (140 km) per day, 15 km of which

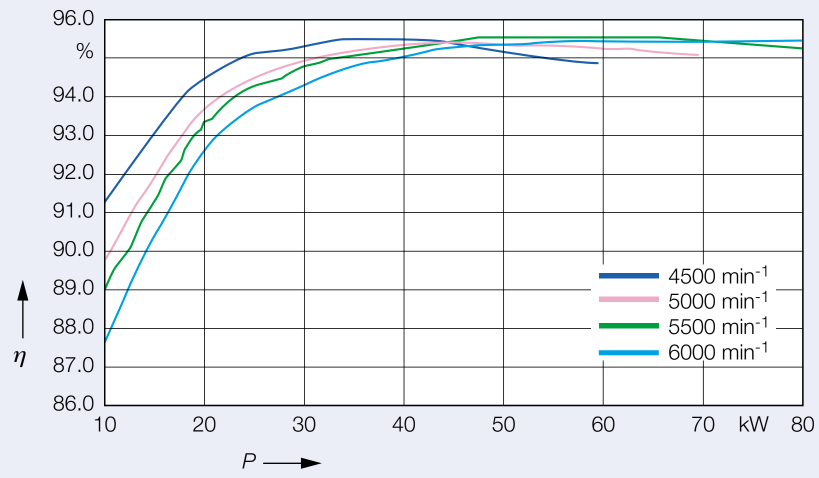
Measured efficiency (colour chart) of one motor and reduction gear, with the motor fed by its inverter **6**

n *Speed* *T* *Torque*



The battery management unit (BMU) calculates and transmits battery limit and reference values to the vehicle management unit (VMU **7**





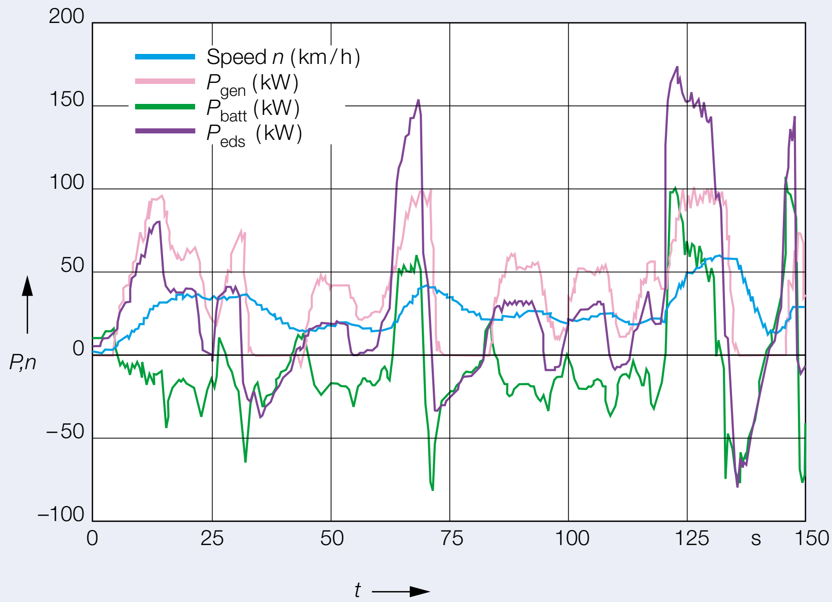
Generator efficiency η versus power output P, calculated for different speeds **8**

are driven in electric mode, with the batteries charged every night with 39 kWh. The calculations show that the fuel consumption and emissions of nitrous oxides (NO_x) are lower for the hybrid vehicle than for a conventional truck.

Vehicle speed n, motor/engine output, battery output and generator output for the Volvo FL6 Hybrid truck **9**

P *Output*

t *Time*



Two main types of hybrid vehicle

Hybrid vehicles can be divided generically into two types: series and parallel.

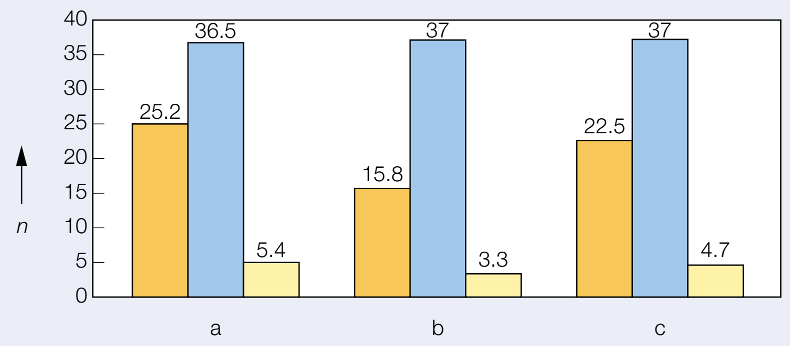
In the series hybrid vehicle the wheels are always driven electrically. The energy sources of this vehicle are some type of internal combustion engine (eg, gas turbine, diesel or petrol engine) and an energy storage unit (eg, in the form of a battery or flywheel). Since the wheels are always driven electrically, the electric motors must be sized for the full performance of the vehicle, taking into account the acceleration and top speed, etc. The IC engine can be sized according to the average power needs of the vehicle, and thus made smaller than if it were to drive the wheels directly. The power balance that every electrical system requires also applies to a hybrid vehicle. In the case of high power demand, the energy storage unit provides the extra power required. When power demand is low and regenerative braking takes place, the energy storage unit can be charged or boosted.

In the parallel hybrid vehicle, the wheels are driven electrically and/or directly by the IC engine, since the electric motor and the engine are coupled mechanically to the vehicle wheels via the same transmission system. Transmission of this type has tended to become rather complicated technically. The energy sources and the means of storing the energy are the same as in the series hybrid vehicle. In a parallel hybrid system, it is most usual for the IC engine to be sized for the full performance of the vehicle, with the electric motor sized for lower performance. The power balance is dealt with in the same manner as in the series hybrid vehicle.

It is not easy to say exactly when a series hybrid vehicle is to be preferred to the parallel hybrid alternative, or how an energy storage unit should be sized. The selection can be based on system simulations, with various requirements taking into consideration, for example:

- Is the range of the vehicle to be given priority over its performance in zero-emission zones?
- Under what environmental conditions (environmentally sensitive zones, night-time driving, etc) are the vehicles to be driven?

The series hybrid solution has been chosen for the system supplied by ABB Hybrid Systems, since the demands of operation with zero emissions are stringent (the vehicles are to run in distribution service with loading and unloading in the city center) and since the vehicles will not be run for long distances on highways. The zero-emission requirement also means that the batteries are sized according to the energy demand (vehicle range) rather than the power requirement (additional power), but without cutting back on the acceleration requirement.



Comparison of simulated values for emissions and fuel consumption for a conventional Volvo FL6 truck and a hybrid truck built on the same chassis. Driving is simulated for typical distribution services in a built-up area. **10**

a *Standard Volvo FL6, 11,000 kg*
b *Volvo FL6 Hybrid, 14,000 kg, 71 km/day, charged with 39 kWh per night*
c *Volvo FL6 Hybrid, 14,000 kg, 140 km/day, charged with 39 kWh per night*

n *Speed in km/h*

Orange *Fuel consumption (liters/100 km)*
Blue *Mean speed (km/h)*
Yellow *NO_x emissions (g/km)*

Summary and outlook

A development goal of the hybrid truck was to base the solution on a standard vehicle equipped with an electrical drive line from ABB.

In hybrid mode, the diesel engine is operated at speeds that afford optimum efficiency (ie, fuel consumption) and low emissions. Also, in hybrid mode the vehicle's average power requirement is generated by the APU and the surplus power charges the batteries. Whenever higher output is needed, the batteries provide the extra power.

Simulations show that fuel consumption is lower and emissions considerably lower with the hybrid truck than with a conventional vehicle. The possibility of running the truck entirely without emissions is a further environmental benefit.

The two hybrid trucks used for the three-year trial will provide valuable data based on commercial distribution service and real-world traffic conditions. One of the purposes of the trial is to evaluate customer acceptance of the new technology. In addition, the experience that is gained will point to any parts of the hybrid system that may need to be improved.

The additional weight of the vehicle compared with a conventional Volvo FL6 is slightly more than 3 tonnes. This is due to the extra weight of the drive line, including the batteries. In the long term, this weight will be reduced as the components are further developed.

The Volvo FL6 Hybrid has a total load capacity of about 5 tonnes. The additional weight of the vehicle has no effect on the payload volume, so that the vehicle offers unrestricted load capacity for a distribution vehicle.

Today, the electrical drive line is expensive, but this is largely due to the fact that its components are produced in a small series. With mass production, these costs will be considerably reduced, and studies indicate that the price of an electrical drive line in the future will not be higher than that of today's conventional drive systems.

References

[1] P. Chudi, A. Malmquist: A hybrid drive for the car of the future. ABB Review 9/93, 3–12.
[2] P. Chudi, A. Malmquist: Hybrid drive for low-emission trucks and buses. ABB Review 6/7-96, 12–18.

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