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HYBRID DRIVES FOR OFF-ROAD VEHICLES

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Abstract:

Nowadays, parallel hybrid electric drives are used in series production and therefore well known among the specialists of automotive technology. But there is a least known field of off-road uses of electric transmissions and hybrid technology. Especially for heavy vehicles like mining trucks electric transmissions are quite common and recently important steps were taken concerning military vehicles, multi-purpose vehicles, tractors and mobile working machines. The paper presents the state-of-the-art of these vehicles and shows the possibilities electric transmissions and on board supply systems of a higher voltage offer. At this, main focus is laid on the power supply of auxiliary drives.

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INTRODUCTION

The use of electric drives in vehicles started in 1900 with the presentation of the Lohner-Porsche at the world exposition in Paris. This car, designed by Ferdinand Porsche for the “Lohner Motor Vehicle and Automobile Factory”, was equipped with two hub motors in the steering wheels on the front axle. The electric power was supplied by lead storage batteries. In September 1900, the first Lohner-Porsche with functioning four-wheel drive was already sold for sports and racing purposes. In 1902, Lohner even equipped cars with internal combustion engines and generators to supply the batteries. Therefore, the Lohner-Porsches with this so called “Mixte”-principle were also the first vehicles using a serial-hybrid electric drive system, like it would be called today (1), figure 1a. Moreover, the Lohner-Porsche was not only the first electrically driven vehicle but also the first electric vehicle, which was used off the road, e.g., for racing or military purposes.

During the First World War, the Germans used electric hub motors for several applications and in 1916 already the first electric propelled tracked vehicle was released in France. The ground drive of this Saint-Chamond assault tank, figure 1b, was basing on the crawlers of an American Holt-tractor. A Panhard petrol engine drove these via a single dynamo and electric motors for each crawler (2).



Fig. 1. Lohner-Porsche (1) and Saint-Chamond assault tank (2)

Though, for a long time the main disadvantages of electric driven vehicles were the large volume and the heavy weight of the electric motors as much as the low efficiency of the whole drive system (3). Therefore, only few vehicles using electric drives were developed for series production. These have mainly been mining trucks used for open cast mining. In 1963 Unit Rig started installing diesel-electric drives in their mining trucks to raise the permissible overall weight and thereby the payload capacity (4). With common mechanical or hydrostatic drives it would have been very complicated to handle an engine output of more than 2000 kW and a total weight of over 540 tons then. To cope with these weights and powers e.g. eddy current retarders use up most of the braking energy and thereby the disc brakes are relieved. The whole drive motors are placed in the rims of the rear wheels and do not need any additional space within the frames of these trucks.

Nevertheless, until the early 1990's, electric power transmission was only used for very heavy off-road vehicles, that could be build without setting a high value on the weight of the machine.

Then, different alterations appeared, which led to an increasing effort in the field of research on electric vehicles. These were:

- the availability of water-cooled electric machines (which have a higher power to weight ratio than air cooled machines)
- the increasing effectiveness of programmable power electronics (5)
- the development of new electric machines (permanent magnet machines, reluctance machines, transversal flux machines (3))
- the appearance of new electronic elements (e.g. IGBT (Insulated Gate Bipolar Transistor) replacing GTO (Gate Turn Off Thyristor))
- the Californian anti-smog legislation (Air Resources Board approves standards for low and zero emission vehicles in 1990)

GROUND DRIVE

All these aspects led to a larger availability of more efficient electric components at lower prices. Therefore, especially the car manufacturers laid a main emphasis on the research on electric drives. This led to a multitude of concepts using electricity within the ground drive system, figure 2.

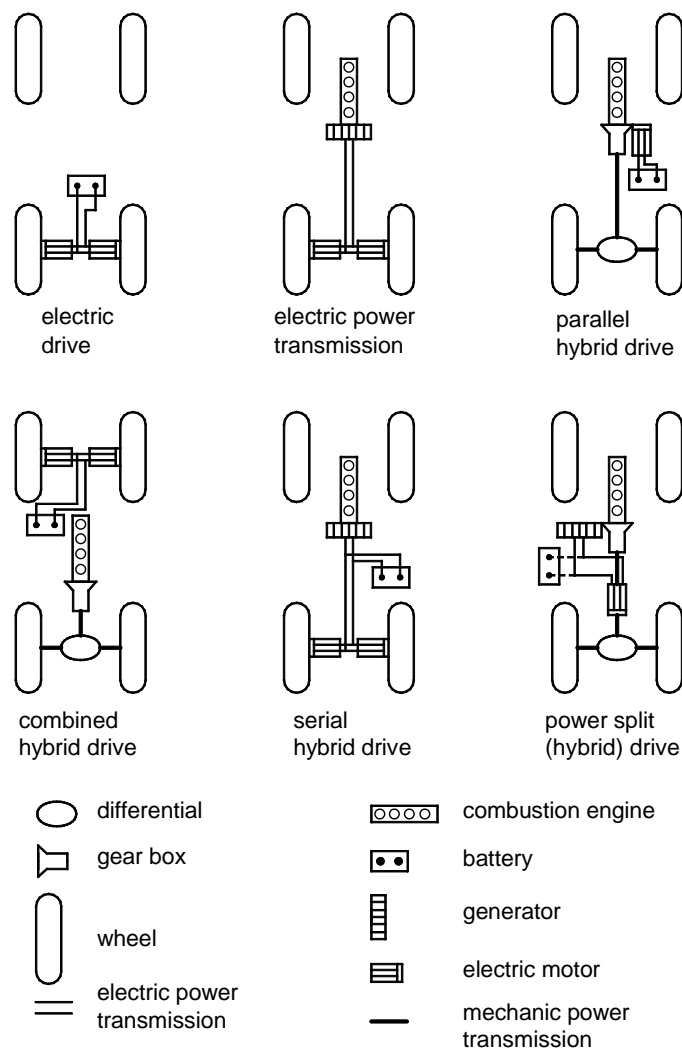


Fig. 2. Drive systems using electricity [according to (4)]

The pure electric drive only consists of a battery driving the electric motors. Examples for the use of pure electric drives in run production are forklift trucks or tow trucks for special indoor-use. Due to the huge batteries pure electric drives would need to reach larger cruising ranges, they have not been used for other purposes. Combined hybrid drives provide the possibility to drive either electrically or mechanically, depending on the usage site, since they consist of two separate drive systems. Moreover it is possible to combine the power of both drives while accelerating, or if an extraordinary situation occurs that demands additional power. The main disadvantage of combined hybrid drives is the fact, that the battery has to be transported all the time - solely to be used for these rather short operating times. This can also be considered the main reason why no series production use of a combined drive is known by now.

Electric power transmission is characterised by the fact that all power supplied by, e.g., a combustion engine is transferred into electricity by a generator and retransferred into mechanical power next to the consumers by electric motors, like it is done at the above mentioned mining trucks. For electric transmission, no battery is required. Moreover, the system of electric transmission can easily be extended by the use of additional consumers. This was done, for instance, to the design of the Vögele Super 1800 DE road paver, which used as many as seventeen electric motors in the circuit of the electric transmission (6).

Hybrid drives are defined as drives which use at least two different types of power converters (mechanical, hydrostatic, hydrodynamic, electric or pneumatic converters are possible) and two different energy storages to drive the vehicle (7). In the most common way, these energy storages are fuel tanks and batteries as far as hybrid electric drives are concerned. Since it is not the only power source, the battery can be dimensioned much smaller for a hybrid drive than it has to be for a fully electric drive.

The use of parallel hybrid drives is very common for cars (Audi duo, Toyota Prius, Honda Insight, Honda Civic IMA), because this drive system uses an electric motor to give an additional power push while the car is accelerated and recovers energy while the car is decelerated by using the electric motor as a generator and this way recharging the battery. This way, the same acceleration can be reached with a smaller combustion engine, which means that a comparable performance goes along with lower fuel consumption. Due to the use in cars, the parallel hybrid drive is the one most frequently used in nowadays series production.

The serial hybrid electric drive is a combination of an electric drive and an electric power transmission and therefore uses no mechanical power transmission. The required electric machines of course have a much higher capacity than those used for parallel hybrid drives to generate the complete power for driving. This kind of drive is either used if a vehicle can recover a lot of energy, like city busses that have to stop every few hundred meters, or they are used for vehicles for which a mechanical transmission could be achieved only very difficultly, like kneel busses. Furthermore, serial hybrid drives provide the possibility to expand the system by additional consumers just as electric transmissions do. The Unimog UX 100 vario drive, which had three consumers connected to the power circuit via power electronics may serve as an example for this (8).

Another more complicated application of electricity for drive systems are the power split drives (without the use of a battery) or power split hybrid drives (like they are

called, if an additional battery is used to store recovered energy). These systems transmit part of the power of the combustion engine mechanically to the drive wheels, whereas the other part is removed from the combustion engine by a generator and added to the mechanical power train again by an electric motor via planetary gear. Using this design, the power split (hybrid) drives can operate like an infinitely variable transmission. Due to the partially mechanical transmission, the efficiency of these drive systems is often higher than that of electric transmissions or serial hybrid electric drives (9). Nevertheless, power split (hybrid) drives have not been used in series production so far.

AUXILIARY DRIVES

The electric drives currently used in vehicles can be divided into four major categories. The first is extra-low direct current, used at 14 V in cars and at 28 V for the on-board supply system in trucks. The second is single-phase alternating current (120 V in the U.S./ 230 V in Europe), which is only produced by vehicles to supply external machinery normally driven by the stationary power supply. One example of this is the Dodge Ram Contractor Special (7). The third category is three-phase alternating current, which is used in electric, or hybrid cars and busses at about 110 to 600 V to power the electric drive motor. The fourth category is direct current, which uses from about 130 up to 700 V in the power circuits of vehicles with electric transmissions or hybrid drives. Figure 3 shows the current and the cross section of the necessary conductors versus the electric power, which can be transmitted at different voltages.

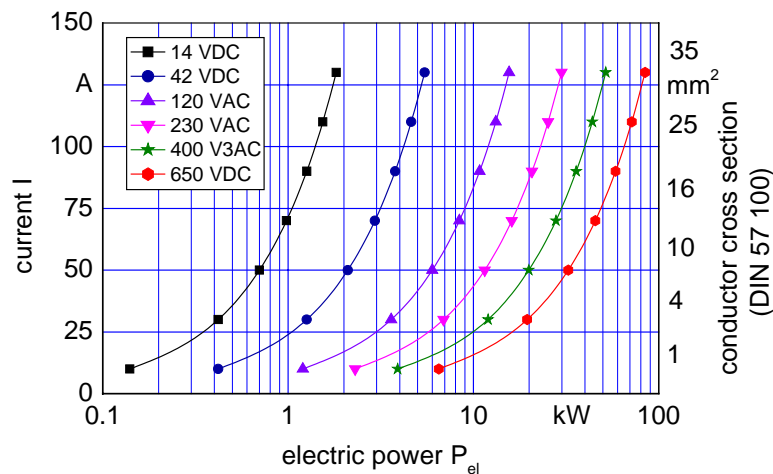


Fig. 3. Relation between current and power at different voltages [according to (10)]

To transmit a current of up to 100 A, any PVC-coated wire can be used and, even more important, can be installed loosely and flexibly. Beyond about 100 A, installation becomes more demanding and the wires have to be fixed (according to the German Association for Electrical, Electronic & Information Technology (VDE)). For this reason, 100 A should generally be used as a limit for the transmitted current and only be exceeded for special purposes where outstanding power is necessary. With 14 VDC like used for the on-board supply system of most cars and self-propelled working machines, the transmission of up to 1.5 kW is possible. The use of conductors with a cross section of 10 mm² or more to transmit power of this level is, however, unrealistic. The weight of the wires would be out of scale compared to the transmitted power.

For this reason, the power, which is supplied by a 14 V system, is permanently limited to about 1 kW. For some years, the automotive industry has been planning to introduce a 42 VDC supply system to power the multitude of servomotors installed in modern cars. With a 42 VDC system it would be possible to transmit 3 to 4 kW of power within the same restrictions. For the transmitting more power, the use of alternating current is reasonable. 120 VAC and 230 VAC are standardized and would be possible. But with the use of three-phase alternating current (3AC), an increase by factor $\sqrt{3}$ compared to single-phase alternating current can be transmitted. The current and the voltage for each conductor stay the same. Only one additional conductor per circuit has to be installed; therefore, Teichmann (10) recommends the use of 3AC commencing at a power demand of 5 kW. With the use of 400 V3AC and the appropriate inverter modules, about 40 kW can be transmitted at 100 A. Furthermore, special safety measures have to be considered. Basically, all the 3AC drives on mobile machinery have to be supplied by a DC power circuit if the speed should be controlled. This DC circuit is the basis for the supply system.

The standardized voltages for current and upcoming electric machines are or will be 14 VDC, 28 VDC, 42 VDC, 120 VAC, 230 VAC and 400 V3AC. These machines are or will be adequately available and reasonably priced. Because of this, these voltages should also be used in the development of mobile off-road machinery. In his analysis of the German market for electric motors, Mugrauer (11) detected that standard components fulfilling the requirements to propel each rotational drive on a combine harvester are already available. Indeed, for most purposes additional planetary or bevelled gears would be necessary. Therefore, the main disadvantage of a fully or mostly electrically driven combine harvester would be the higher initial costs and the greater weight of the machine. But such a machine offers the possibility to control every single drive, concerning power and speed, and to reverse them if necessary. Moreover, the power can be distributed to the single drives according to the momentary demand.

RESULTS

For off-road vehicles, which need not to be accelerated very fast or have to change driving speed permanently, the use of batteries is not reasonable since the weight of the batteries has to be transported all the time, while they can be used to restore braking energy quite seldom. Therefore, the first approaches made with agricultural prototypes use electric transmissions.

The Schmetz “Eltrac” tractor released in 1998 is the first agricultural machine, which can be indicated to use such an up-to-date drive system, figure 4a.



Fig. 4. Schmetz “Eltrac E135” and Hohenheim Test Combine “Magda”

This tractor is equipped with an electric transmission. The air-cooled AC generator is fixed to the crankshaft of the diesel engine and a water-cooled AC motor propels the axles via gearbox. The link between generator and motor consists of a rectifier, which supplies a DC (direct current) power circuit and a converter, which transfers the current to AC again. Moreover, the converter controls the performance of the asynchronous motor. The braking energy is used up by braking resistors. An air-cooled box on the roof of the tractor houses the electronic control system and the braking resistors. The p.t.o. is propelled mechanically by a direct drive from the diesel engine (12), (13).

The automation of processes on agricultural machinery to relieve the machine user gained more importance in recent years and especially electric drives offer a high potential for automation since they are easy to control by programmable inverter modules. Moreover, these inverter modules also offer an infinitely variable adjustment of rotational speeds. To use this potential on a machine with a multitude of separate drives, the University of Hohenheim started a project to equip a combine harvester with an electric transmission, figure 4b. Until now, just the wheel drive system was altered to electric transmission. The combine uses a permanent magnet synchronous machine driven by the diesel engine via v-belts to provide the electric power and an asynchronous machine to drive the wheels on the front axle. Two inverter modules and an in-between DC power circuit link electric motor and generator. To brake, the power flow is reversed. The generator performs as a motor and the electric motor performs as a generator. This way, the power is re-transferred to the crankshaft of the diesel engine and no braking resistors are needed. While moving the machine on the road, automotive driving is possible. This means that the rotational speed of the diesel engine is adapted to the momentary power requirement of the wheel drive system. Thereby, unnecessary fuel consumption is prevented. For the electric transmission only water-cooled components have been used to prevent the machine from failures caused by dust pollution. Apart from the wheel drive system, auxiliary and additional drives are to be added to the electric transmission. Due to this fact and to the general set up a combine harvester, the installation of a split power drive in the machine was impossible, even though it surely would have had a higher absolute efficiency. Nevertheless, if compared to hydrostatic wheel drive systems, which are commonly used for combine harvesters, the electric transmission outperforms them especially in the range of partial loads.

As far as the multi-purpose vehicles are concerned, two prototypes were presented recently, figure 5.



Fig. 5. DaimlerChrysler Unimog UGN E-Drive (7) and John Deere Fuel Cell Hybrid CWV (Commercial Work Vehicle) (14)

Like the above-mentioned agricultural machines, the Unimog UGN E-Drive is equipped with an electric transmission. But in addition, not only the installed working devices like the hydraulic pump are propelled electrically but also implements, which can be coupled to the machine, are driven by electricity (7). Therefore, the Unimog UGN E-Drive can work with optimum diesel engine performance at any application. The prototype of the John Deere Fuel Cell Hybrid CWV, presented last year, marks the latest stage of development for electrically driven off-road vehicles. The CVW is equipped with a Hydrogenics fuel cell supplying 20 kW of electric power. Thereby, a pure electric drive system was put into practice. By the use of a centralized belt drive system, a centralized cooling system and an independent component management a large reduction of internal energy consumption is anticipated, since components like the alternator, the engine coolant fan or the engine oil pump became dispensable (14).

In January 2003 UQM published a press release announcing that a HMMWV, figure 6a, equipped with one UQM generator and two UQM electric motors, one per axle, has begun cold weather evaluation testing. In 2000 an earlier feasibility study of a hybrid electric HMMWV had already proven test readiness by crossing North America. If the harsh terrain and cold weather testing will be passed successfully a potential series application of hybrid electric drives in this class of military vehicles becomes more and more likely (15). The alteration of these HMMWVs is part of a U.S. Army program called the Future Combat Systems (FCS). One main demand on the FCS is that the ground drive has to be a hybrid electric system. Also in January 2003 United Defense company was chosen by the U.S. Army to achieve the First Unit Equipped (FUE) of eight variants of Manned Ground Vehicles by 2008. At this time, United Defense had already finished a prototype of a wheeled FCS platform and a prototype of a tracked FCS platform, figure 6b (16). Unfortunately, no technical details are known by now.



Fig. 6. Hybrid Electric HMMWV (14) and Future Combat System-Tracked prototype FCS-t (15)

CONCLUSIONS

A further step to electrify off-road vehicles may be the use of all-wheel-drives with hub motors or the use of ultracap condensers to recover the braking energy. As far as the main drive system like the wheel drive of a tractor is concerned, drive systems using electricity today have to compete with mechanical or hydro-mechanical drive systems. In this case, they hardly reach the demanded efficiencies and are still more expensive. Therefore, apart from the discussion about raising the efficiency, the surplus value, that can be attained by electric drive systems has to be put in perspective. Electric drives seem to be very promising for machines with many auxiliary or additional drives, since

they are more flexible to install than the mechanical drives, which are mainly used in nowadays practice. Additionally, there is a constant rise in demand for electric power for comfort and productivity related features like lighting, air-conditioning and GPS-devices, which could be supplied easily if electricity was used for the main drives anyway.

Indeed, in run production of off-road vehicles, electricity is not used for the main power transmission but only for the small DC drives, which are connected to the 14 V on board supply system. Therefore, initially improved on-board (electrical) power systems seem to be necessary, since the first step towards electrically driven agricultural machinery for series production will most likely be a partial electrification e.g. of installed working units or equipment with lower power requirements which today typically use hydraulic or pneumatic drives. The ability to be turned on and off depending on a certain operating state of the ICE (Internal Combustion Engine), might also further promote the electrification of ICE subsystems, such as coolers and pumps, to reach higher environmental standards. During the next years, the development of electric drives therefore will be one of the main fields in automotive engineering. This can be stated since not only different university institutes but also most of manufacturers show a rising interest in electrically driven machinery.

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