EVS24
Stavanger, Norway, May 13-16, 2009

Series-Parallel Hybrid Using Axial Flux Motors

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Abstract

Hybrid vehicles make use of multiple power sources to optimise the efficiency of the overall power-train. The majority of the hybrid power trains are optimised for operation in urban driving and drop efficiency when operated on extra-urban or highway conditions.

The DuoDrive is a hybrid-electric drive-train that can be fitted in place of the gearbox in a conventional vehicle, offering series and parallel hybrid operation without the need of complex gearing as used in power-split devices. The DuoDrive system is especially relevant to vehicles operating in start/stop urban drive cycles, such as taxis and delivery vans.

Due to the dual mode operation which allows series or parallel operation the system offers best efficiency for all driving conditions. This system is only possible due to the high torque axial fluxes machines developed which allow a system without gears.

Keywords: list 3-5 HEV hybrid electric vehicle, power train, permanent magnet motor, series HEV, parallel HEV

1 Introduction

The DuoDrive Series-Parallel Hybrid System is especially relevant to vehicles operating in start/stop urban drive cycles, such as taxis and delivery vans.

Key Features:

High efficiency: The DuoDrive hybrid-electric drive train solution combines the advantages of series hybrids (e.g. high efficiency in stop-and-go driving) with those of parallel hybrids (e.g. high efficiency on motorways). The system will switch between each mode as needed, as well as giving the potential to operate in all-electric/zero-emission mode when appropriate. ‘Plug-in’ capability is also available to enable further increases in fuel economy and reductions of CO2 emissions.

Full functionality: Whatever mode is chosen, full functionality of conventional diesels (acceleration, speed, driving range, climbing ability, etc.) is retained throughout the driving cycle.

Compact design & ease of integration: EVO Electric motor/generators have exceptionally high power and torque densities (over 1.8 kW/kg and 5 Nm/kg, continuous). No gearbox is needed, reducing weight and efficiency losses. In fact, the DuoDrive system can be installed in the space normally occupied by the gearbox, and can thus be easily installed on existing vehicles.

Future possibilities: Improvements in energy storage technology are expected to further reduce costs as well as increase fuel economy to 100 mpg in the future.

2 WHY HYBRIDS?

One of the key challenges of this century is developing sustainable technologies for road transport, a key source of greenhouse gas emissions, air pollutants and geopolitical tension over scarce oil resources. Finding alternatives to the internal-combustion engine (ICE), which powers over 98% of current vehicles, is thus a key priority.

The main reason for the high fuel consumption of conventional vehicles is not only the low efficiency of ICE but also the inefficient way that these engines are used:

- ICE's are usually operated off their optimal design point resulting in less than optimal efficiency.
- Very often engines are idling and thus wasting fuel.
- Kinetic energy from braking is lost.

One alternative is the battery-powered, electricity-charged electric vehicle (EV). EVs do not have the aforementioned limitations and thus offer a much more efficient mode of transport. An electrically powered 3.5 tonne van can achieve equivalent CO2 fuel consumption up to 100mpg compared to about 25mpg for a diesel powered equivalent. Moreover, EVs emit no tailpipe emissions of NOx or other harmful air pollutants, and rely on domestically produced electricity. However, EVs have limited driving range due to the low energy density and high cost of current battery technology. These limitations will likely remain for the foreseeable future despite on-going improvements in battery chemistries.

Hybrid vehicles exploit the advantages of both EVs (high efficiency, low fuel costs, low CO2, low NOx, etc.) with those of conventional diesels (long driving ranges, rapid fuelling, etc.). Until now, the batteries in hybrids have been designed to be charged internally, i.e. by the ICE and through regenerative braking.

In the future, plug-in hybrids are likely to grow as yet another alternative to both EVs and conventional ICE vehicles. The only difference to conventional hybrids is that they can be charged by external (grid) electricity (in addition to regenerative braking and the ICE). Depending on how much batteries are added, plug-in HVs typically operate 20-40 miles in all-electric/zero-emission mode. Beyond this distance, the plug-in operates as a HV with power coming both from the ICE and motor.

3 SERIES OR PARALLEL?

There are two main hybrid architectures: The series hybrid is basically an EV with its own on-board power station e.g. a gen-set (ICE driving a generator) or a fuel cell. The parallel hybrid is a conventional vehicle assisted by an electric motor/generator (e.g. during acceleration). The ICE operates close to its optimal design point, but its speed will vary more than with a series. Both of these systems have particular benefits:

- The series hybrid is particularly well suited to 'stop and go' driving cycles in flat urban areas. Some operators report efficiency improvements of over 40%. However, these vehicles will be less efficient if driven in highway conditions and might not have sufficient power to climb steep hills.

- The parallel hybrid is less efficient in urban conditions (while still at least 20% more efficient than conventional diesels), but this limitation is overcome by its general usability and efficiency in 'cruising' cycles around motorways and other extra-urban driving.

The majority of commercial HVs for the car market (e.g. Toyota Prius, Honda Civic HV) are derivatives of the parallel hybrid while the bus market is currently dominated by series hybrids. Unfortunately, none of the currently available solutions can offer both high efficiency and universality of use.

The Toyota Prius is often called a 'Series-Parallel', and while it also combines some of the advantages of both types, the system continues to rely on gears and conventional electric machines resulting in a complex and expensive solution. While this results in relatively high efficiency (50-70 mpg depending on driving cycles), it's an expensive solution [1]. The Toyota hybrid models get larger, fuel economy falls (the Highlander Hybrid rates between 27 and 31 mpg). Similarly, the four-cylinder hybrid Ford Escape which achieves a combined urban-highway rating of only 34 mpg [1] In order to reduce complexity of the above systems more powerful motors are needed to avoid complex gearboxes

4 AXIAL FLUX ELECTRIC MACHINE

Axial flux machines comprise of disc type arrangements as compared to the drum type machines used in the vast majority of existing applications. The analogy between drum brakes – for conventional machines – and disc brakes – for axial machines often helps to visualise the difference between these two types of electric machines.
Underlining the analogy between disk brakes and drum brakes, an analysis of the geometry shows that the torque harnessed by a disc machine is much larger compared to that of a drum machine, especially if the ratio of diameter to length is larger than unity.

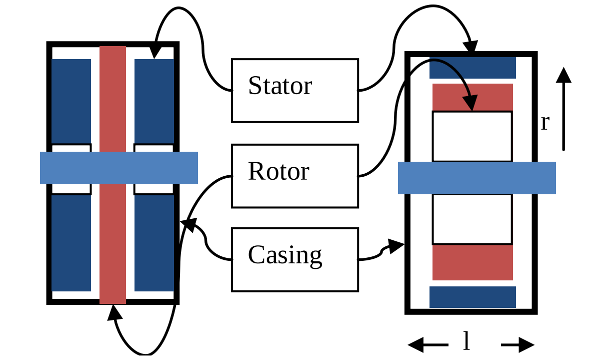

Figure 1: Comparison between Axial (left) and radial (right)

In the comparison shown in Figure1 it can be seen that the axial machine on the left makes much better use of volume inside the casing than the radial machine depicted on the right.
The concept in Figure 1 is one of many different ways of implementing an axial flux machine [2,3]. These comprise:

Internal rotor: As depicted, requiring a high strength, non-magnetic carrier material for the magnets.
Internal stator: Possibility to use magnetic retainer discs for the rotor at the cost of reduced cooling area.
Single sided: With one rotor facing one stator, results in high axial loads.
Multi stage: with more than one rotor per machine – increases the complexity of cooling.

It is also worth noting that the cooling area available for most effective cooling is the area behind the rotor and again this area is much larger for an axial machine compared to a radial machine. Simply put, the cooling area of the axial machine is twice the frontal area of the cylinder:

$$A_{c\_axial} = 2r^2\pi$$

while the cooling area of the radial machine is the circumferential area of the cylinder:

$$A_{c\_radial} = 2r\pi l$$

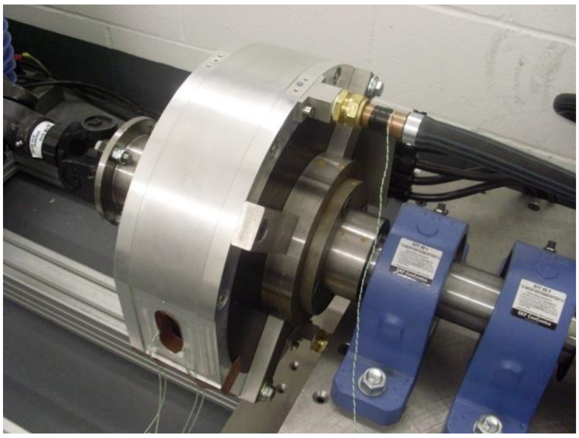

Figure 2: 70Kw Axial Flux motor on Testbed

This indicates that only for an aspect ratio of radius r to length l smaller than 1 will the conventional machine have more cooling area.
Moreover, the above analysis can be done for active motor volume and is can be shown that the axial machine increase its torque with the cube [2] of the machine radius, whereas the torque of a drum machine increases only with the square of the radius.
These benefits are purely due to geometry and not due to the electromagnetic topology. To further illustrate this, a simplified analysis is conducted.
For the radial flux (drum machine) the torque is proportional to the force generated at the interface between stator and rotor multiplied by the radius. Hence:

$$T_{radial} \propto \underbrace{2r\pi l}_{stator/rotorarea} r \propto r^2$$

For the axial machine on the other hand the area of the interface is given by the frontal area of the cylinder resulting in:

$$T_{axial} \propto \underbrace{r^2\pi}_{stator/rotorarea} r \propto r^3$$

The reason for the slow up-take of axial flux machines is to be found in the technical difficulties associated with manufacturing.
The higher power density can be achieved using permanent magnet machines. An example of a Axial Flux machine is shown in Figure 2.

5 THE DUODRIVE CONCEPT

EVO Electric has developed electric motors/generators with exceptionally high power density and very high torques. As will be shown, the characteristics of this motor make it possible to design a vehicle combining the benefits of both series and parallel hybrids (plug-in or not). A typical delivery van is propelled by the rear wheels via a differential which in turn has the prop-shaft as its input. The speed range of the prop-shaft is up to 3500 rpm depending on vehicle parameters. In a conventional vehicle the prop shaft is driven by the gearbox which in turn is driven by the engine. To get high torque at low engine speed, the gearbox reduces the engine speed by a factor of about 5 during start up and when climbing hills. At high speeds, the gearbox ratio is usually 1:1 so that the engine is directly linked to the prop-shaft.
Electric machines are characterised by a much better torque profile than IC engines. As a result most EVs use a fixed ratio gearbox in order to achieve high enough torque, and have traction motors run at high speeds of up to 10,000 rpm [4].

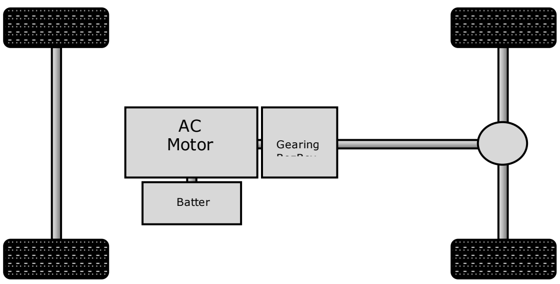

Figure 3: Conventional electric power train

EVO's Axial Flux Permanent Magnet technology allows the removal of the gearbox and the direct coupling of the motor to the prop-shaft. The elimination of the gearbox results in a 40kg weight reduction.

Table 1: Comparison of Induction and Axial PM motor

	Conventional [4]	**Axial PM**
Power:	54kW	65kW
Nominal Torque:	65Nm	200Nm
Peak Torque:	192Nm	>400Nm
Speed range:	0 to 10'000 rpm	0 to 4000rpm
Weigth:	49 kg	40 kg
Peak Efficiency	94 %	95 %
10% Speed eff.	50 %	70 %

The EVO electric motor/generator can be applied to a 'pure' EV, resulting in about 15% increased driving range and lower costs. However, as noted EVs have functional drawbacks such as limited driving range, and will thus not be attractive to many users and fleet operators. The application of the EVO DuoDrive system to hybrid vehicles is thus proposed. This would combine the benefits of series and parallel technology whilst maintaining good drivability.
Figure 4 depicts an electric driveline which is combined with a second electric machine which in turn is directly coupled to a combustion engine. Coupling the two electric machines together by means of a clutch enables the engine to be connected directly to the wheels.
This system can be used in the following modes:

- EV mode (ICE is stopped; all the power required for propulsion is supplied by an electric motor drawing current from a battery pack)
- Series hybrid mode (ICE powers a generator, which then drives the motor)
- Parallel hybrid mode (power is supplied by both the ICE and the electric motor)

In summary, the DuoDrive concept has the potential to provide significant efficiency improvements and carbon emission reductions compared to both conventional diesels and hybrids, as well as providing more functionality than parallel or series hybrids (not to mention EVs). It does this while eliminating rather than adding components, thus reducing costs and complexity.

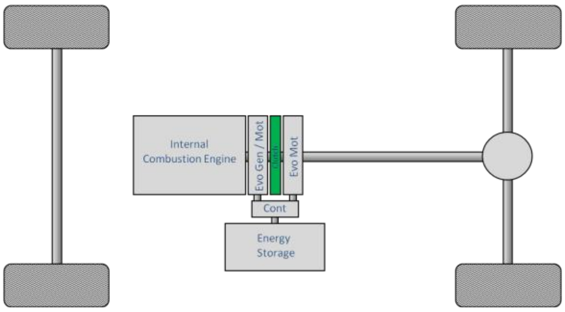

Figure 4. EVO DuoDrive

Table 2: Hybrid modes compared

Mode	**Power source**	**Primary energy source**	**Tailpipe emissions**
Parallel hybrid mode	ICE and/or Electric motor	Fuel* & regen braking	Low
Series hybrid mode	Electric motor		Very low
EV mode	Electric motor		Zero

* If plug-in capability is added, all or most of the fuel portion is substituted by grid electricity

6 INTEGRATION AND COSTS ISSUES

As highlighted by the recent King Review of low-carbon cars [5] one of the most critical issues of climate change is to find technologies that can be developed and deployed to quickly reduce CO2 emissions in the next few years.
A key characteristic of the EVO DuoDrive system is that is compact and light enough to be easily integrated into conventional vehicles in the space normally occupied by the gearbox. This is only possible due to the compact design and short length of EVO's machines allowing them to be configured back to back without major changes to the drive train. This will provide an opportunity for fleet operators to lower fuel costs and CO2 emissions without scrapping their current vehicle stock. Alternatively, it will enable vehicle manufacturers to quickly and cheaply convert existing models to hybrid operation. In contrast, the majority of conventional hybrid systems cannot be easily integrated into existing vehicles or models, thus slowing down the up-take of the technology. This is due to the fact that the whole driveline needs to be changed and space need to be found for the hybrid components.

7 SIMULATION

HEVSIM simulation software [6] was used to simulate the performance of the concept based on real driving cycles.
The cycle is depicted below and is characterised by frequent starts and stops. The simulation uses component models of each power-train part to simulate the performance of the whole drive train.

The drive cycle used in the simulation represented typical London traffic and vehicle duty. The simulation was run for a 3.5t van and the results show that this would achieve over 60mpg fully loaded using DuoDrive. Total Emissions are slightly higher than with the EV version but hybrids are more functional; they do not face driving range and charging time limitations. By comparison, conventional diesel vans (e.g. Ford Transit Tourneo) achieve less than 30mpg (220g of CO2/km) in urban cycles. Adding plug-in capability to this system further increases efficiency by about 10 to 20%, depending on the source of grid electricity. Operating costs savings may be quite substantial, especially in Europe where electricity costs much less than fuel. However, these savings need to be weighed against the extra cost of batteries (plug-in HVs require 3 to 5 times more batteries to provide meaningful all-electric/zero-emission range). The selection of plug-in capability will depend on usage patterns, corporate objectives and policy incentives

As shown in Figure 5, applying the EVO axial flux motor technology to electric vans or taxis results in major reductions in CO2 emissions, while applying the DuoDrive system to hybrids brings slightly higher emissions, but with the advantage of higher functionality.

These figures are preliminary and actual efficiencies may differ depending on driving cycles, vehicle weight and so on.

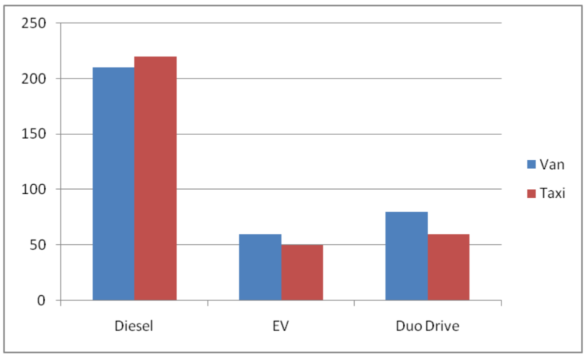

Figure 5: CO_2 Emissions in g/km for Van and Taxi in London

8 CONCLUSION

The current trend in hybridisation of commercial vehicles is towards parallel hybrid or pure electric vehicles. The Duo Drive concept has shown that a third way combining these is possible with affordable technology.

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