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SAFEDRIVE – A Full Series Hybrid Vehicle Drivetrain

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Abstract

SAFEDRIVE is a project funded under the European Union Framework Programme 7 (FP7) with the aim of providing the members of the European Association for Battery, Hybrid and Fuel Cell Vehicles, AVERE, with a Full Series Hybrid Vehicle Drivetrain, which may also be used in a Pure EV. This drivetrain is modular and scalable, and can be adapted to suit a wide range of vehicles, from small cars to heavy goods and utility vehicles. The project will also deliver to members a 'design toolbox' that allows computer configuration and simulation of a particular vehicle and drivetrain implementation, and a standard vehicle controller electronics package that is configured by the toolbox. [1] The technology uses far lower voltages than other hybrid drive systems in current use, so that the static (battery) voltages are comparable with those used in 48 Volt DC systems in fork lift trucks and other familiar utility vehicles, which have had such a good safety record over a 100 year history. Higher (but still comparatively low) voltages are only generated in the motor drives and generators when moving on the road. Research has demonstrated that the use of lower voltage systems also has cost and weight benefits; batteries and ultra-capacitor systems built out of smaller numbers of larger cells have less passive mass and thus higher energy density, fewer points of failure, and require proportionately fewer battery management components. The cost of thicker conductors is minimal and offset by the far less complex insulation and protection needs.This paper describes the project test vehicle, which will be a light 'car-derived' van and the implementations of the other technologies at this scale. It describes the high frequency, multi-phase, bidirectional, Boost-Buck 'Split-Pi' DC-DC controller which combines all necessary electronics functions, including regenerative braking, power distribution and charge control, in a single 64kW unit. This unit has high power efficiency of 95-98%, and only requires air cooling [5][6]. The paper will also outline the properties of the novel drive motors, which directly drive the wheels without any reduction gearing, giving comparable sustained hill climbing to that of a conventional IC engine vehicle.

Keywords: series HEV(Hybrid Electric Vehicle), DC-DC, AVERE, brushless motor, rare earth material

1 Introduction

There is increasing momentum behind the move to electric and hybrid cars, but whilst development activity is widespread, electric and hybrid vehicles still only represent a small fraction of total production. There are a multitude of reasons why this is so. On the engineering side the technology is complex, and will simply take time for it to be refined to the same level, and same cost base, so as to be competitive with IC based engineering, which has now had more than 100 years of evolution.

This situation manifests itself to the customer in simpler ways, these vehicles are generally more expensive, or have performance compromises, or require lifestyle changes. Moreover, the IC engine small vehicle market is almost global, with the same models selling widely across the world, with relatively little national or regional difference (with the exception of the US). By comparison hybrid and electric vehicles show up national differences stemming from national electrical energy policy, and from the nation's different energy sources, and so the CO_2 reductions that nations can achieve from a given technology will vary. Pure electric vehicles tend to suit city dwellers, and will directly reduce CO_2 emissions in countries with a lot of hydro-electric or nuclear sourced electricity (Scandanavia, Switzerland, France). In countries such as the UK which rely heavily on fossil fuels for electricity, pure electric vehicles have great potential in reducing CO_2 emissions by adaptation of the electricy mix towards the use of more renewable energy sources. Because even in the worst case scenario, when electricity is produced solely on coal, pure electric vehicles have CO_2 emissions that are comparable with an Euro5 petrol car. [2]

There are other factors around adoption of this technology concerning the established patterns of use of the car. The vast majority of cars sold embody the core attributes of the 'family car', and this is very significant: the life of the majority of vehicle users has evolved such that the car needs to be multipurpose. The same vehicle must take the kids to school, do the out of town shopping, carry bikes or skis, tow a boat or caravan and do the run to work. Once at work it may be expected to do the occasional long and unplanned trip. To support this, many (most?) car houses tend to operate on a personal use basis ('my car'/'your car', his/hers) not on a function basis (city car, people carrier). So widespread adoption of electric drive technology needs progress on both price and acceptability, and also needs consumer confidence, that can only be built up over time. Conversely, a new vehicle technology that has negative impact, that costs more, or requires life habit changes, or which imposes substantive restrictions (no ability to do long trips using established infra-structure, causing range anxiety) is not likely to gain acceptance, and thus will not yield any significant CO_2 reductions.

The 'Full Series Hybrid' vehicle is the candidate vehicle type that, if technology and price are right, will meet all consumer objectives, and allow widespread adoption without requiring changes to life habits. Moreover, it has the characteristics that can yield 'best outcome' to national governments attempts to reduce CO_2 emissions almost irrespective of the nation's energy mix. Wide adoption itself becomes a part of this 'best outcome', because a larger proportion of a nation's vehicle fleet will be able to deliver these results.

There is some minor variation in nomenclature, so for clarity by 'Full Series Hybrid' car, we here mean one that has a purely electrical drive train which has sufficient battery capacity for a 'significant' amount of pure electric mode driving, which is uncompromised in terms of hill climbing and acceleration when in pure electric mode, that may have a somewhat lower sustained top speed in pure electric mode, which has an IC generator on board capable of powering the vehicle for continuous sustained 'mixed' and level motorway driving, which doesn't rely on any external electrical recharging (and can therefore do long trips filling up only with conventional hydrocarbon fuel from the existing fuel distribution infra-structure), and which has also the capacity to recharge rapidly from external electricity sources (as per 'plug in hybrid') quickly when the opportunity presents itself.

As an observation, the total energy requirement to take a 1500kg vehicle from sea level to the height of an alpine pass (2000m) is about 10 kWHr and this is of the same order as 2 hours of slow city motoring. This is about the level of energy storage considered for such a hybrid vehicle, which is 25% to 50% of the level of storage in 'typical' pure electric vehicle. The alpine pass energy is significant because it gives a measure of the electrical storage necessary to allow use of an IC motor generator that is sufficient for steady level high speed motoring, but which would be inadequate for sustained high speed climbing. The reduction in battery size is significant because it is a major cost and weight item in a pure electric vehicle, and allows the inclusion of the motor generator, almost without impact.

In terms of national and international outcomes on CO_2 reduction, the pure EV is often cited as the only vehicle that is truly 'green', with the CO_2 to atmosphere emissions of the Hybrid seeming less good. However an examination of established driving habits would tend to suggest otherwise, with many small vehicles doing most of their mileage within a short range of the home base, but with a percentage of longer trips, beyond the range of pure electric vehicles. Thus if the battery capacity of a hybrid is sufficient to cover all of this local motoring, then all of that can be in pure electric mode. On long trips, when the IC motor generator is used, the hybrid drivetrain will deliver fuel efficiency in slower driving, and this and opportunistic external recharging will reduce hydrocarbon fuel usage even further over a conventional IC engined car [3] [4] [7]. It might be expected that total hydrocarbon fuel usage would fall to about 30% of that of a comparable IC car. If the Full Hybrid vehicle captured a high percentage of all small vehicle savings, then it can be argued that a reduction to 30% across the fleet achieves all of a governments' targets far earlier than would be possible by seeking pure EV adoption. Having a national hydrocarbon fuel requirement that is 30% of current levels makes substitution of a useful proportion of that by bio-fuels considerably more realistic, and the CO2 to atmosphere from motoring can be reduced further, without any loss of benefit to the driver.

It is for these reasons that the SAFEDRIVE project has set out to make a Full Series Hybrid test vehicle and drivetrain solution.

2 SAFEDRIVE's aim and potential

There is another factor in the emerging market for electrically driven vehicles, that of the 'early adopters' who will establish the initial market. It can be said that there are two main groups:

a) Green Enthusiasts in the general public
b) Commercial and public sector vehicle operators, who may have other factors at play, such as governmental directives or city centre emission restrictions, as reasons to move away from conventional IC engines

These two groups comprise an important part of the membership base of AVERE's network.

The 17 national associations, direct members of AVERE represent a large number of European companies which manufacture lower volume, more specialist vehicles, from city centre utility vehicles to sports cars. The conventional small volume vehicle market draws a lot of its components from the supply chain that supplies the volume car manufacturers. The equivalent supply chain for the electric vehicle sector is far from being fully developed, and so a core objective of the SAFEDRIVE project was to add to the drivetrain components that are currently available.

A final element of the SAFEDRIVE project was the observation that electrical voltages in most of the large car manufacturers' vehicles were very high. This appears to have three main causes

a) A lot of the technology was original derived from that used in the industrial sector, where such voltages, derived from mains supplies, were common, and had been in use for years
b) A widespread (but erroneous) belief amongst a lot of electrical engineers that high voltages were intrinsically advantageous in building high power electric motors: inside a motor it is only flux density (B) and current density (J) that matter, and the losses are material properties, and independent of operating voltage
c) A correct perception that, up until the development of high frequency MOSFET circuits, conversion efficiencies of low voltage electronic drive components was poor.

At the time that the SAFEDRIVE project was proposed, the 'Split-Pi' MOSFET based DC-DC controller technology was already in the 'green energy' market and demonstrating power efficiency of over 98% [5][6]. A low voltage, ultra high torque electric motor was in its infancy, but promised low cost, direct drive motors, which do not use permanent magnets, and which are not subject to strategic materials considerations that now apply to Rare Earth magnets, and the key element, Neodymium.

These two technologies offered the prospect of a lower voltage drivetrain for car scale and larger vehicles. A key consideration was that existing electric utility vehicles had built up an excellent electrical safety record using lead acid traction batteries, generally at 48 volts, generally considered to be at or near the upper voltage limit where there is little shock risk. Split-Pi technology, with Buck-Boost capability, can efficiently convert such a supply from zero to a small multiple of the supply voltage, and thus higher voltages that are convenient for high speed operation, can be generated when the vehicle is moving, but will be absent when the vehicle is at rest. A parked vehicle then has no more intrinsic risk from abuse (car thieves, vandals) or mishap, and so matters such as roadside assistance become easier.

There are many other considerations around the low-voltage/high-voltage question. In low voltage systems batteries and other storage components such as super-capacitors will be built with fewer but larger cells: these tend to have a higher proportion of 'active' mass because casings and separators are relatively less in bigger cells. Having fewer cells means that there are fewer points of potential failure and fewer (but bigger) battery management components. The requirement for electrical insulation and active protection will be less at lower voltages, and it is probable that the extra cost for thicker cables in low voltage vehicles is more than offset in savings in the complex cabling and protection systems now common in high voltage designs. As with all product engineering, there are trade-offs and so discussion around high voltage versus low voltage is complex and will be around for a long time. We expect that the SAFEDRIVE project will demonstrate that low voltage systems are fully viable, and thus contribute to the development of electric vehicle drivetrains

The SAFEDRIVE consortium brings together technology providers, vehicle builders, the academic sector and AVERE, The European Association for Battery, Hybrid and Fuel Cell Vehicles) as both the pan-European association, and two national associations (AVERE France and E'Mobile Switzerland). AVERE is the beneficiary of this project, on behalf of its members. Other partners of the project consortium can be found on the project website [1] and their role will be described below.

3 Materials and methods

There are four core technologies being developed within the project, other necessary elements will be bought in from external suppliers. These technologies are:

Split-Pi DC-DC converters: this technology is MOSFET based and so operates at a higher frequency (100 KHz switching) than the more conventional IGBT based controllers. As such it can achieve higher power densities (through smaller energy storing passive parts), and also achieve very high (in this instance 96-98%) power efficiency at low voltages [5]. Split-Pi allows both Up and Down voltage conversion (Boost and Buck), and an intrinsic regeneration mode, allowing voltages to be generated on the road that are higher than the main battery voltage, but with full control down to zero voltage at lower speed [6]. This technology is already in use in 'Green' applications, in Solar and Wind power generation, and with fuel cells and electrolysers. SAFEDRIVE will develop this technology to automotive standards.

Mutually Coupled (MC) motors: this is a new motor technology that does not use permanent magnets, and thus is not subject to the cost or strategic material restrictions that are now a concern around Rare Earth magnets. This is the newest element of the technology and still is a 'work in progress' and only the outlines will be revealed at this stage. Nonetheless early jig testing has confirmed that these motors can generate sufficient torque (1200 Nm) to directly drive the road wheels of a car scale vehicle, at a target weight of less than 60kg per motor. The other characteristics of these motors are ruggedness and relative ease of manufacture, from low cost materials. The motor and Split-Pi Controller technology is being developed by consortium partners Scimar Engineering Ltd, Metallisation Ltd and UK-ISRI.

Dynamic Vehicle Controller: this is a two part process, first the vehicle dynamics have been modeled mathematically, then a vehicle controller based on that model will be built on an industry standard platform.

Vehicle configuration toolbox: the technology in the drivetrain is essentially modular, and so allows scaling to different vehicle types. The toolbox will allow vehicle manufactures to configure drivetrains to vehicles, and to adjust the controller to suit. The vehicle controller and toolbox are being developed by the Croatian R&D organization, Novamina.

The project will incorporate the prototype motors and controller technology into a test vehicle, and a popular 'car derived' van has been chosen as the test vehicle. This will be modified to incorporate the SAFEDRIVE drivetrain by John Bradshaw Ltd in the UK, with input and assistance from the

Spanish specialist vehicle engineers Avia Ingenieria Y Disegno.

The test vehicle electrical and electronic components will be integrated, and the vehicle put through its paces at the Mobility, Logistics and Automotive Technology Research Centre (MOBI) which is a group in the Vrije Universiteit Brussel (VUB) (Free University of Brussels). The commercialisation and exploitation phase will be managed by Green Energy Technologies Ltd.

Table 1 below shows the main parameters of the test vehicle: this is in draft form, final parameters are being discussed at the time of writing. It is currently estimated that 250-280 kg of existing conventional drivetrain components will be removed from the demonstration vehicle, and that the additional mass of the hybrid drive train will thus reduce the payload from 800 kg to 670-700 kg. Two motors of 1200 Nm peak torque on wheels with 0.3m rolling radius will give a tractive effort of 8000 N, and so a slope climbing of 40% at GVM of 2000 kg.

The only parameter in this table that requires any comment is the power output of the motor generator which is currently too low for the model requirements of a family car with truly uncompromised performance. However it is considered to match well to a delivery van application, and to represent a realistic demonstration of capability using readily available components. The control system has been designed to accept up to 32 kW of motor generator input. Attempts are ongoing to find a higher power unit that will fit the size and weight profile.

Table 1 Main parameters of the SAFEDRIVE project vehicle.

Drive Motors	2 x 32 kW Each 1200 Nm max torque Liquid cooled, Gearless direct drive, 4 X 2 front wheel drive by shaft	2 X 60 kg = 120 kg
Split-Pi Power Controllers	2 Banks each 8 phase at 4kW = 64 kW max continuous Dynamic bank switching	2 x 12 kg = 24 kg
Batteries	2 x 100 AHr x 51.4 V (58.8 V pk) 14 series cell Lithium Ion 10.28 kWHr	2 x 40 kg = 80 kg
Ultra-Cap storage	158Wh storage at 96 V max voltage	55 kg
Motor Generator	15 kW 3 cylinder Diesel engine coupled to a single motor running as generator, between 30 and 90 volts DC	82 kg
Cable harnesses and Drive motor cooling	Controller, cabling, Cooling matrix for liquid cooled Drive Motors	19 kg
TOTAL WEIGHT		**380 kg**

The motor and electronic components of the system can be discussed in some greater detail in the context of this vehicle model.

3.1 MC motors

The MC motors are conceptually very simple, and are heavily reliant on modern switching electronics to make them viable. They are still under development, and thus discussion at this time is only in outline. They have an axial direction of magnetic flux, and this is in common with most modern high torque motors. They consist of interleaved rotor and stator discs, each with one or more serpentine electrical conductor path(s) forming the 'winding' between areas of low loss, high flux density soft magnetic material, as shown schematically in Figure 1, in which the grey areas are soft magnetic material, the outline is aluminium alloy, both as the structural and the conducting material, the black and red dots show (conceptually) the electrical connection points, and the blue line shows the serpentine electrical path. At the end of each stack the flux turns around and comes back down another axial path, as in any axial flux machine.

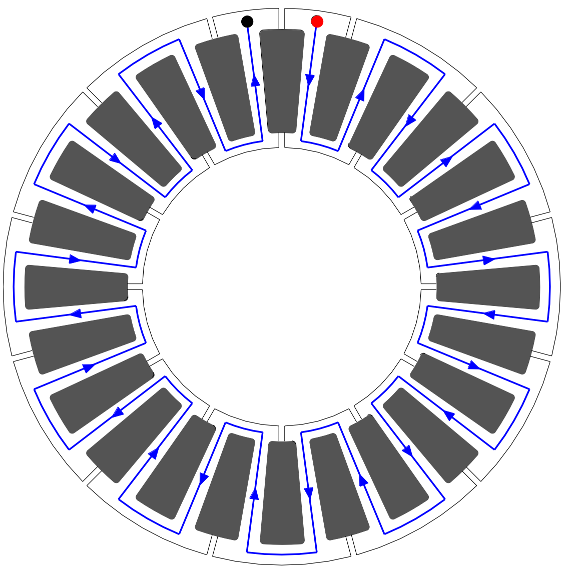

Figure 1 A rotor or a stator disk

There are a number of equivalent ways of describing the magnetic interaction. The most intuitive is to say that the radial part of the current flowing in each disc produces a field in its own magnetic sectors, and then is subject to a force from the field of the other. It is equally valid to say that the currents in both rotors and stators interact to produce fields in the magnetic parts, which then exert forces on each other. The 'Mutually Coupled' name is therefore direct and obvious. Since the field is produced by currents supplied directly (not induced) these motors have some similarity to conventional field wound DC motors, and so the field can be reduced for high speed, low torque running. The torque is proportional to the square of the current in the windings, and this is well matched to road vehicle use, where the main problem for direct drive without reduction gearing is the production of sufficient torque. These characteristics reduce the demand on the electronics, which do not have to either produce very high currents for high torque at low speed, or very high voltages for high speed operation. These motors are clearly distinct from conventional field wound motors in that both rotor and stator windings generate a 'motor e.m.f', and there is no electrical power lost in simply energising the field winding.

A very significant innovation in these motors is that the conductor is also the structural material, using a high strength grade of aluminium, and thus saving a lot of mass both by design and by material choice. Aluminium is not such a good a conductor as copper on a cross sectional area basis, but weight for weight the higher alloy grades are comparable (and low alloy grades better), and the higher volumes of aluminium alloy will conduct heat away better than copper. The interleaved disc construction has a very high surface area, and this greatly aids cooling. Continuous torque is produced by building a three phase machine, in a very similar fashion to some PM motors. Electrical power for the rotor is transferred by brushed slip rings in the prototypes, but will be by high frequency inductive (zero contact) couplers in production machines (thus truly 'brushless').

Each motor contains its own electronics, both for commutation, and for direction control, and is configured to present two terminal electrical connections very similar to those of a conventional DC motor, but with a current squared torque characteristic.

3.2 Split-Pi DC-D C converters

The ‘Split-Pi’ DC-DC converters have now been available in the market for green power conversion, and a typical current device, used in fuel cells, wind power, solar PV and electrolysers is shown in Figure 2 below

Figure 2 Current 4.5 kW Split-Pi controller as used in Green Power applications

MOSFET based Split-Pi circuits operate at around 100 kHz, 5 or 6 times higher than most IGBT based devices, and thus they are able to achieve a reduction of the mass and cost of the passive energy storage components by similar factors. At these high frequencies inductance is the main consideration, and there is an almost exact analogy with IC engines. You would not build a sports car by scaling up a single cylinder lawn mower engine, and so it is with high frequency electronics. A far higher power density is obtained by using multiple parallel units: they then ‘fire’ in sequence to deliver smooth power. Unlike in IC engineering, there is no increase in friction, and so use of multiple, small, high frequency units is always advantageous.

There are a number of very useful practical advantages: the electronics can be built on conventional PCBs and automated assembly process that are well developed in the electronics world. The modules represent a replaceable subsystem, and so maintenance is cheaper. The components used are not overly specialist and (thus expensive), but are those driven to minimum cost by bulk use in other applications.

3.3 Electric design of the demonstration vehicle

However the greatest advantage in vehicle engineering is that the modules can be operated with more than one power source, so that resources can be switched ‘on-the-fly’ as required. A hybrid vehicle may have three prime sources of energy

a) Main batteries
b) Ultra-capacitors
c) IC motor generator (or fuel cell etc)

Generally the main battery will be charged and discharged according to a regime that maximizes the use of external electricity. The Ultra-capacitors will be used for braking and acceleration, to extend the cycle life of the batteries, and the IC motor generator will be run to recharge the batteries if no external charging source is available, or continuously during high speed long distance travel. These modes will be modified if, for instance in a city centre, there is a demand for pure electric operation.

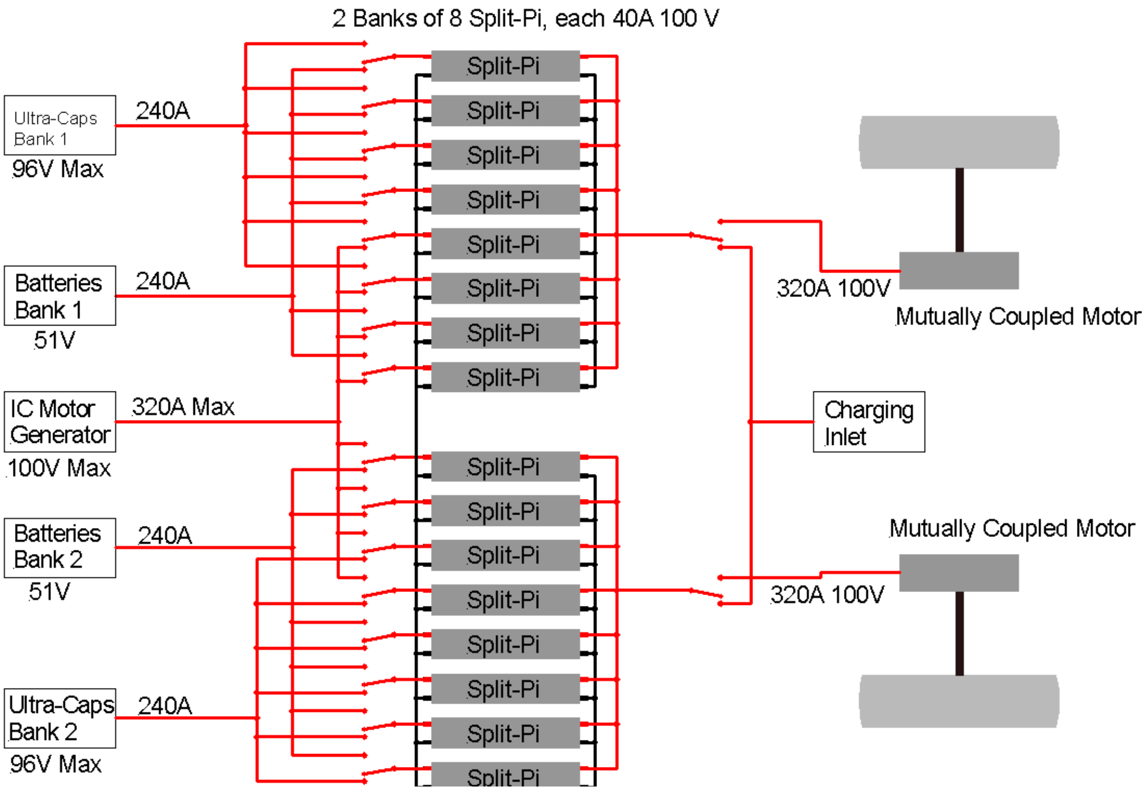

Figure 3 Interconnection between main electrical parts

Figure 3 shows the interconnection between the electrical parts in the demonstrator vehicle. It shows a front wheel drive configuration, with two motors each driving a road wheel through a conventional drive shaft. Each motor is controlled by an 8 module bank of Split-Pi DC-DC converters, each is bi-directional, and in SAFEDRIVE will be rated at 40 Amps per phase, and 100V maximum working voltage.

All of the motor side connections are connected in parallel to a bus, and a two pole master switch, which will be mechanically linked to the parking brake, connects this side either to its respective motor, or to a common bus which is the charging inlet. The connections only show the positive terminals for clarity, all the negative sides are connected together.

On the lefthand side, each Split-Pi module can be switched to connect to one of two power sources. These switches are again MOSFET based, and the complete cycle of disconnecting, adjusting to a new voltage and reconnecting happens in about a millisecond, and so is completely imperceptible, and can be done 'on-the-fly'. This allows the power electronics to reconfigure resources to different sources as required by the driving mode. With 8 modules per motor, this allows shifting in increments of 12.5% of the total available power control capability.

Table 2 gives an example of the allocation of the available power control capability to the different power sources for a number of driving modes. The given percentage corresponds to the fraction of the Split-Pi converters connected with the given source in that particular situation. If, for instance, 50% of the power control capability is allocated to the main batteries, this means that 8 out of a total of 16 Split-Pi converters are connected to the batteries. Total percentages not adding up to a 100% for some driving modes means that some of the converters are simply working on 'idle', i.e. are not connected to any power source. The architecture of the system allows a high flexibility of the allocation of the power control capability, and can therefore be set for the different driving modes according to the power strategy determined later in the project.

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Table 2 Allocation of power control resources for different motoring functions

Vehicle Mode	Driving mode	Main batteries	Ultra-caps	IC motor generator
HEV	Soft Acceleration		50%	
HEV	Hard Acceleration		75%	25%
HEV	Flat cruise			37.5%
HEV	Hill climbing	50%		50%
HEV	Hill descent	62.5%		
HEV	Hill descent and braking	37.5%	62.5%	
Pure EV	Soft Acceleration		50%	
Pure EV	Hard Acceleration	25%	75%	
Pure EV	Flat cruise	25%		
Pure EV	Hill climbing	62.5%		
Pure EV	Hill descent	62.5%		
Pure EV	Hill descent and braking	37.5%	62.5%	

It should also be noted, that as with any electronics, each module will have both voltage and current limits, and so the power that can be delivered from a particular source will depend on its voltage. Thus the power from the batteries per module can never be as high as that from the motor generator, which can operate at a higher voltage, and the power from, or into the Ultra-caps, is actually proportional to their voltage.
The interconnection shown in Figure 3 allows for other functions. Because Split-Pi is truly bi-directional, and produces virtually 'pure' DC (very low open circuit ripple) it makes the perfect battery charge controller. With the relatively small battery packs that specified here, by simply running the motor controller in reverse there is a built in 480A total charging capability, sufficient to fully charge the batteries within 20 minutes (battery technology allowing) from an external DC source. Split-Pi is also not ambivalent about the voltage; anything up to 100V will do, with the charge time just extending for low external voltages.

The motor bus connections also allow this configuration to discharge the ultra-caps back to the main batteries, to pre-charge them on switch on for better initial acceleration, and to start the motor generator by running the generator as a starter-motor.

4 Results and discussions

The SAFEDRIVE project is now a little over half way through its 36 month duration, and we are entering the testing and evaluation phase. So far progress has been very good, parameters that were uncertain at the start are now known, and there has been excellent correspondence between theory and measurement so far. We hope that that trend will continue.

Whilst this is a large project for AVERE and some of the smaller partners, in reality, it is only a small, but hopefully a significant, contribution to the field. We hope to be able to demonstrate both the viability of low voltage drivetrains at power levels of several tens of kiloWatts, and the functionality of a Full Series Hybrid Drivetrain (which of course can be used directly in pure electric vehicles if so desired) in a vehicle which is fully comparable to its IC engined sisters, and at a cost base that AVERE member companies can use commercially in the near future.

The consortium will be working actively to find further partners for the full commercialization phase, and we hope that this technology will become an important part of the automotive scene within a very short period.

Acknowledgments

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- Association Europeenne des Vehicules Electriques a batteries, hybride et a pile a combustible (AVERE)
- Association Suisse de vehicules routiers electriques et efficient, e'mobile
- Association Europeenne des Vehicules Electriques Routiers (AVERE France)
- John Bradshaw limited
- Avia Ingeneria Y Disegno
- Metallisation limited
- Vrije Universiteit Brussel (VUB)
- The Uk Intelligent Systems research institute limited
- Novamina centar inovativnih technologija doo
- Scimar Engineering Limited
- Green Energy Technologies Limited
- Moravian-Silesian Automotive Cluster

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Prof. Dr. ir. Joeri Van Mierlo obtained his Ph.D. in electromechanical Engineering Sciences from the Vrije Universiteit Brussel in 2000. He is now a full-time professor at this university, where he leads the MOBI - Mobility and automotive technology research centre (http://mobi.vub.ac.be).Currently his activities are devoted to the development of hybrid propulsion