The Delivery of Magnetic Powersplit Technology Into Vehicle Powertrain Applications

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ABSTRACT: This paper will describe the journey of magnetic powersplit powertrain technology from its origins in new technology discovery through to packaged, design intent vehicle applications, describing the obstacles overcome and opportunities realised in the journey that delivered magnetic powersplit technology to Global Automotive OEM’s. Aspects of technology development, design for manufacture, capability proving and production feasibility will be described in order to demonstrate a credible, world class next generation hybrid powertrain.

KEY WORDS: power transmission, CVT, hybrid system, vibration, noise, and ride comfort, powertrain oscillation, powertrain start/vehicle start/shift, device technology, magnetic, powersplit, vehicle, torsional vibration, filter, Dedicated Hybrid Transmission, DHT [A2]

1. Introduction

The planetary gear based powersplit hybrid powertrain dominates the market, with 82% market share in the US in 2015 (1). The success of this Dedicated Hybrid Transmission (DHT) (2) architecture can be attributed to three main factors

1. The architecture is suitable for hybrid, plug-in hybrid and to a certain extent, for range extended hybrid vehicles with minimum engine size and large on board electrical tractive power capability, offering excellent scalability to different vehicles and vehicle capability requirements.

2. The hybrid driveline components in a powersplit DHT powertrain are substituting incumbent powertrain components, enabling a lower cost solution when compared with Px (meaning P0, P1 etc.) hybrid concepts, where hybrid components are typically added to incumbent powertrains (2).

3. Other factors such as good efficiency and the absence of gear shift dynamics also lead to enhanced customer acceptance. Although it must be noted that the control architecture of an integrated engine/DHT system can be a barrier to adoption by many OEM’s, leading adopters of power split argue that the upfront development effort is justified in terms of the cost / complexity improvements achieved in the powertrain hardware and real world fuel savings.

The Magnetic Powersplit Transmission is a new generation of DHT and has been in development since its original invention in 2006. During this time it has evolved from an integrated e.CVT powersplit device into a powersplit hybrid transmission system for automotive applications.

2. Overview Of Transmission System

The topology of a magnetic powersplit transmission in an automotive application is shown as Figure 1.

Whilst the principles of powersplit transmission, and specifically magnetic powersplit operation have been previously defined in other papers (3,4), a short review of the main functional elements and components will equip the reader for the detailed descriptions that follow. The main functional elements of the magnetic powersplit transmission are the magnetic powersplit device, the Traction Motor (TM) and the final drive/differential. The magnetic powersplit device itself consists of a permanent magnet rotor, a stator and a “pole piece rotor” (PPR) which enables the magnetically geared e.CVT function (Figure 3b).

3. Comparison With Alternative Hybrid Transmissions

Figures 2a-c show schematic diagrams of the magnetic powersplit transmission in comparison to current hybrid transmissions including one alternative DHT powersplit and one Px “add-on” hybrid in series production today. The schematics show the low complexity of DHT’s generally in comparison to Px but specifically the reduced complexity of the magnetic powersplit DHT in comparison to alternative DHT’s.
This is principally due to the integration of the incumbent CVT (typically a mechanical planetary gear) and variator motor/generator functions into a simple e.machine, eliminating the relatively complex 3-rotor planetary gear set and connected e.motor (with planet carrier and ring gear acting as input and output, and the sun gear with motor/generator performing the variator function).

4. A 3 Rotor System Achieved With 2 Rotors

Before the detailed component evolution is described, it is appropriate to discuss the delivery of the present 2 rotor magnetic powersplit device from its original 3 rotor embodiment. The original 3 rotor invention inverted a conventional magnetic gear and added a stator as shown in Figure 3a. In this first generation device, the stator operated the outermost rotor (analogous to the sun gear in a planetary gear arrangement) which acts as the variator to vary the speed ratio between the input (PPR) and output (magnet rotor). Whilst this device was successfully developed, an opportunity to eliminate the “sun” rotor was identified whereby the stator itself would directly generate the magnetic field for the variator function rather than there being a physical variator present in the assembly. This second generation device (Figure 3b) with its “virtual variator” being a massless magnetic field can react and position itself instantaneously and has been shown to successfully filter torsional vibration from engines\(^{(4)}\), eliminating engine damper systems, as can be seen in Figure 4 and Figure 5, in tests completed using a 2 cylinder diesel engine.
5. Magnetic Powersplit Device Developments

This section will show the component level development of the magnetic powersplit device specifically.

5.1. Stator Assembly

Following an increasing trend to maximize stator slot fill using methods that are appropriate to mass manufacture, initial prototypes of magnetic powersplit iterated from designs suitable for needle-wound production methods into bobbin-wound pre-formed coils. This increased slot fill to achieve high torque density, but the achievement came at the cost of incurring higher than expected losses due to the open slot nature of the stator to enable assembly of the coils. Alternatives including bobbin formed cables made up of pre-transposed conductors were also prototyped and delivered high performance and significantly reduced losses, but this was at the expense of stator scalability and suitability for economic mass manufacture due to the low integer number of turns with the pre-formed cable. The ability to scale the stator length and therefore torque capacity is considered key to leveraging a common “platform” electrical machine design to suit different engines and powertrains, thereby achieving a cost competitive solution. This led to the present design, which utilizes a segmented stator upon which coils are precision wound, achieving high slot fill, low losses (due to transposition of the conductors during the precision wind process) and high suitability for mass production. Scalability is also achieved through the specific winding design being accomplished with a high integer number of turns that is very scalable to different stator lengths and required torque capacities.

5.2. Magnet Rotor

The magnet rotor has iterated in a similar fashion through multiple development stages, with early designs featuring surface mounted magnets with filament wound magnet containment enabling high speed operation as required. As the magnetic powersplit design matured, a semi-closed magnet rotor design was successfully deployed (Figure 6), featuring laminated poles affixed to a central hub using mechanical retention features that, when assembled, created apertures into which the magnets were “posted” to complete the rotor assembly. The poles also featured short overhangs to mechanically retain the magnets. This rotor design represented a cost advantage in terms of magnet material usage and ease of assembly, but the mechanical retention features were identified as features not conducive to achieving a low cost design for high volume manufacture. This led to the development of the present magnet rotor design which has been successfully used on magnetic powersplit machines up to 800Nm, which uses an interior permanent magnet (IPM) configuration. With this configuration the requirements for the achievement of high performance with a design suitable for high volume manufacture was achieved.

5.3. Pole Piece Rotor Assembly

Having established that the magnetic powersplit stator and magnet rotor as discussed above uses design and construction methods that are well established in the automotive industry, we turn our attention to the novel pole piece rotor (PPR) component. However, the term “novel” in this case refers simply to the resultant functionality of the PPR rather than to the design or construction of the physical component. The philosophy of development of the PPR has endeavoured to utilize common production techniques to deliver novel functionality, which increases the credibility of the solution and provides a pathway to a low cost component development route using established volume manufacturing infrastructure.

The PPR contains the array of laminated steel pole pieces that enable the magnetic gearing function, held within a support structure that retains the pole pieces and provides a connection to the engine crankshaft. Whilst the pole pieces are by definition magnetically permeable, it is important that the support structure is magnetically impermeable to prevent unintended magnetic interaction, or that the structure forms part of the pole piece functionality in a way that enhances or at least does not reduce the performance of the pole pieces in the achievement of their primary function. In addition, as the magnetic powersplit has been shown to obviate the need for engine dampers\textsuperscript{[4]}, the PPR must be robust to undamped or minimally damped torsional vibration (TV) so that this benefit can be applied to target engine and vehicle applications. To achieve this, the PPR has benefited from a high degree of development effort, resulting in several viable solutions for the various potential applications of the transmission. In each case the pole pieces are steel lamination stacks that are readily produced using techniques similar to the stator and magnet rotors. The structures available include all metallic solutions, overmoulded solutions and filament wound composite solutions. The structural solution is selected depending on the requirement of the specific application, where volumes, performance, operating environment, duty cycle and cost will determine the optimum solution.

6. Standard Transmission Components

6.1 Traction Motor

The magnetic powersplit transmission, as with other powersplit transmissions, requires a Traction Motor (TM), which provides or utilizes the power requirements in a recirculating fashion, enabling the variator function within the magnetic rotation.
powersplit device. The performance, topology and location of the TM is dictated by the target application, primarily delivering required vehicle capability within the available packaging space. As permanent magnet (PM) e.machines and their construction are established automotive powertrain propulsion technology, for the purposes of this paper it will simply be stated that as vehicle performance and packaging space dictates, the magnetic powersplit transmission can make use of any incumbent motor technology available to perform this function. Specific TM positions and resultant sizing implications will be discussed further in Section 7.

6.2 Integrated Final Drive (As Required)

For Front Wheel Drive (FWD) and some All Wheel Drive (AWD) applications, a highly integrated transaxle configuration is desirable. To accommodate these powertrain variants, the final drive arrangement is integrated in a similar fashion as the same arrangement within a conventional FWD transmission, connecting the selectable gearing stages (or in this case the magnetic powersplit device / TM output shaft) to the input stage of the final drive reduction gearing. Once again, the specific design, construction and arrangement of the final drive gearing stages replicates that of a conventional incumbent transmission.

7. Integrated Transmission Assembly

7.1. xWD, Transverse and In-Line Suitability

The Magnetic Powersplit transmission is suitable for FWD, RWD and AWD configurations, with In-Line / Longitudinal (North-South) and Transverse (East-West) engine orientations, with component configurations as shown in Figure 7.

![Fig. 7 FWD, RWD and AWD Transmission Configurations](image1)

![Fig. 8 Magnetic Powersplit Transmission Assembly](image2)

7.2. TM Packaging Options

Magnetic powersplit answers this trend through the sizing and positioning of the TM to deliver an appropriate packaging solution. In the interests of overall simplicity, a co-axial transmission arrangement is preferred as shown in Figure 8.

![Fig. 9 TM Positioning for Parallel-Axis Configuration](image3)

However, where available packaging space precludes the use of a co-axial arrangement, a parallel-axis variant can be used, with the TM positioned alongside the e.CVT, delivering torque directly to the final drive gearing arrangement. Although this packaging flexibility comes at the cost of an additional gear mesh, the addition enables the TM to be downsized in terms of required torque output. Since a principal cost driver in e.machines is torque requirement, the achievement of the power requirements with a reduced torque/higher speed e.machine as shown in Figure 9 can equate to an overall cost reduction for the powersplit transmission assembly.

The flexibility in position is also enhanced further by flexibility in the TM aspect ratio, removing the necessity for an axially short, large diameter e-machine that is required for co-axial configurations.
7.3. Multi-Stage TM gearing

To resolve vehicle capability limitations afforded by single ratio gearing, such as achieving good gradeability / launch performance and one end of the performance requirements specification, and achieving a high Vmax at the other, some applications both in hybrid and EV powertrains have elected to include selectable gearing stages for the TM. The logic discussed in 7.2 above is also true in this case in that the cost of including the selectable gear stage can be offset by a reduction in TM torque output, since the peak torque is now provided via 2 ratio reduction gearing, with a higher ratio selected for high speed operation where the torque demands are lower as seen in Figure 10. Alternatively where e.machine downsizing is not the goal, a vehicle capability improvement can be realised for a relatively low on-cost.

Fig. 10 Effective TM Performance with Selectable Gear Stage

For magnetic powersplit transmissions, a 2 stage gearing system can be achieved for co-axial variants using an in-line gearing stage & brake similar to powersplit hybrids in series production today. For parallel axis variants, an upgraded final drive arrangements for 2 speed operation are available and also currently in series production.

8. Basic Transmission Sizing And Scalability

Transmission sizing must of course be considered in the context of the full powertrain specification. That said, where non-hybrid and Px “add-on” hybrid powertrains and their resulting control strategies must remain engine-focused in terms of the importance of good engine driveability for overall vehicle ride quality and refinement, powersplit hybrid powertrains, and particularly magnetic powersplit DHT’s are less reliant on engine driveability. This is because the engine is more purely functioning as a power generator, with the magnetic powersplit device capable of extracting the engine power to deliver the most useful balance of mechanical and electrical power to serve the needs of the powertrain at that moment.

Following the removal of the mechanical link between driver and throttle control pioneered in the 1980’s, now comes the removal of the functional link between driver and throttle control, as the driver of a DHT equipped vehicle now demands wheel torque and leaves the powertrain control system to determine the most fuel efficient method to deliver that demand, considering its own system constraints.

8.1. Magnetic Powersplit Transmission Sizing Approach

The starting point for magnetic powersplit transmission sizing is vehicle capability requirements. Additionally, where incumbent or legacy engines are available (which will certainly be the case during the initial implementation of DHT based powertrains), this will place a further constraint on the sizing specification. The pursuit of delivering real world fuel economy as part of the catalyst for mass adoption of DHT’s must also consider the optimization of the powertrain for typical usage cycles and high residency operating points such as motorway cruising. For magnetic powersplit transmissions, high residency operating points influence the selection of the powersplit’s “intrinsic ratio”, which is the gear ratio that requires no rotary movement of the variator field (initially described in Section 4) and is the base gear ratio about which rotary movement of the variator changes the speed ratio between the powersplit input and output within the transmission. This is important because the magnetic powersplit’s best efficiency points are where the required speed ratio corresponds to the intrinsic ratio (Figure 11).

8.1.1. TM Sizing

The TM sizing is guided primarily by vehicle capability requirements such as launch performance and extreme gradeability. Whilst a mechanical torque contribution from the engine via the magnetic powersplit device is also utilized during these events, the dominant provider of tractive effort in the cases above will be from the TM. Once these requirements are satisfied, vehicle usage data identifying high residency driving conditions (Figure 12) will then influence the shape of the TM efficiency map balancing high efficiency at high residency usage points with thermal stability at performance extremes. As TM sizing is driven by vehicle capability requirements, final drive sizing will also be considered in this phase, with the additional consideration of 2-speed gearing of the TM if required or desirable to do so.
8.1.2. Magnetic Powersplit eCVT Sizing

Concurrently with TM sizing, vehicle capability requirements and engines available, a basic sizing of the powersplit e.CVT can be completed. Here the peak electrical demands must be generated to enable full TM performance during vehicle operating extremes assuming limited or no energy is available from the vehicle’s on-board energy storage. As previously stated in Section 8.3, e.machine cost is dominated by torque requirement, meaning that with a free choice of engines to match to the hybrid system, an engine suited to efficient operation at higher speed, and lower torque is generally preferred. From the typical engine efficiency map shown in Figure 13, however, it can be seen that peak engine efficiency, and therefore the preferred operating zone for best vehicle fuel efficiency are not at the high speed / low torque areas. Some compromise must therefore be reached between cost, efficiency and performance in the requirements analysis and initial sizing stage of powertrain design.

8.1.3. Scalability

With hybrids making up a small part of the global powertrain mix\(^5\) (Figure 14) and the incumbent “add-on” Px powertrains benefitting from mass market economies of scale, the successful disruption of the market with magnetic powersplit transmission depends on its ability to commercially compete with the incumbents whilst not operating at comparable volumes for “carry-over” powertrain components.

Notwithstanding the preference stated above, mating of magnetic powersplit powertrains and specifically of the magnetic powersplit device to low speed, high torque engines is achievable, enabling high efficiency diesel engines to represent suitable choices for passenger car and particularly bus, truck and off highway powersplit powertrains. For the automotive passenger car and light commercial vehicle markets, it is also recognized that aggressive engine downsizing is prevalent with 3 cylinder gasoline and even 2 cylinder diesel engines available in current production vehicles. From the discussion in Section 4 demonstrating effective torsional vibration filtering with magnetic powersplit and Section 8 discussing the use of the engine more purely as a power source, it becomes evident that magnetic powersplit is well suited to being matched with this new generation of power dense engines facing refinement challenges for current conventional or hybrid powertrain applications. Furthermore, with significantly reduced dependency on the achievement of acceptable engine driveability and the associated use of complex damper systems, a renewed focus on engine efficiency improvements and narrow-banding the engine operating regime at the expense of engine driveability can be considered, removing a significant constraint on engine design.
To this end, effort has been invested in the design phases of the e.machinu development for the magnetic powersplit component to ensure the design uses a common, scalable cross section. Where appropriate, TM selection has been made with the same consideration such that tooling, manufacturing and logistical infrastructures for magnetic powersplit transmission mass production can be achieved together with reduced costs that offer OEM’s a strong incentive to change to DHT.

9. Magnetic Powersplit Vehicle Integration

The magnetic powersplit transmission has been developed and configured to enable a “transmission swap” hardware upgrade from the previous Px generation of “cost-add” hybrids. Existing hybrid vehicle infrastructure can therefore be carried over or in many cases simplified with opportunities available in required battery capacity and cooling system complexity for further cost reduction.

10. CONCLUSION

The development of the magnetic powersplit transmission has demonstrated that it represents a hardware and package compatible opportunity to upgrade incumbent Px “cost-add” hybrids to a full powersplit DHT based powertrain with the associated fuel saving and cost reduction opportunities. Looking beyond the incumbent hybrid infrastructure when designing new hybrid powertrains, additional benefits can be achieved including the use of power dense high efficiency gasoline and diesel engines which can be permitted to deliver improved efficiency at the expense of driveability characteristics with no resulting compromise to vehicle refinement. In addition, the ability of the magnetic powersplit transmission to filter torsional vibration from the engine, outputting a smooth torque signature simplifies or even deletes engine damper systems that are currently essential in the achievement of acceptable powertrain refinement.

The materials and manufacturing infrastructure required for series production of magnetic powersplit transmissions is based completely on established automotive manufacturing techniques, with the added ability to include existing mass market transmission components to achieve a functional powersplit system. The elements of the magnetic powersplit device itself have been shown to consist of components and sub-assemblies again well established in the industry, with recent developments taking advantage of cutting edge stator construction to balance cost, performance and reliability.

The resulting magnetic powersplit transmission leverages these common components to offer a solution that is scalable across a number of vehicle platforms, achieving vehicle capability requirements utilizing a range of engine solutions.

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Fig. 16 Magnetic Powersplit Transmission Boundary Diagram

The boundary diagram and electrical architecture diagrams are shown as Figure 16 and Figure 17, illustrating the ability offer a package compatible upgrade to a powersplit powertrain.

Fig. 17 Magnetic Powersplit Transmission Electrical Architecture