Abstract: Layshaft transmission designs have been modified to integrate electrical motors for hybrid vehicles for many years although it is typical for designers to couple conventional electric motors that are developed in isolation from the transmission system. The integration and optimization of the two components together leads to lighter, more compact and efficient hybrid solutions. Further benefits are realised if the electrical machine can be used to perform multiple powertrain functions such as input shaft synchronisation and electric creep alongside the normal hybrid functions: regenerative braking and torque support.

By using the electrical machine to displace existing components such as shift elements in the transmission, some of the additional cost and weight of these hybrid systems can be offset by savings in the mechanical components. This can lead to significant savings in package, weight and efficiency. To achieve the best integration the electric motor must be designed to support specific transmission functionality and the transmission adapted to better support the needs of the motor.

This paper will introduce the direct benefits of integrating an electric machine into a layshaft transmission, and the design of a bespoke electric machine design which complements the system requirements. The advantages of the lightweight and low-inertia machine design will be highlighted with respect to cost and additional vehicle features when targeting high volume in mass production.

Keywords: Hybrid, 48V, mass production, manual transmission, synchroniser, efficiency.

1. Introduction

Global CO2 reduction is currently one of the major tasks for OEMs, due to the short-term mandated CO2 emission targets for new passenger cars and light-commercial vehicles.

Significant global reductions in emissions cannot be achieved solely through the delivery of high-tech ultra-efficient hybrid and electric vehicles if they only account for small proportion of the vehicles on the road. For global benefits to be realized, CO2 reducing technologies need to find their way into the low cost, high volume market. This requires either significantly cheaper hybridization with a low impact on final price and/or the provision of value adding features which can justify additional cost.

Hybrid vehicles have demonstrated that they can satisfy requirements emission below 100g/km. However, with the current cost of battery technology, and the additional costs on top of the conventional powertrain, it seems that there is a need in the market to develop additional lower cost hybrid solutions focussing on higher production volumes. To gain wider market acceptance, costs of such systems would potentially need to fall to within 10% of the incumbent technology. Furthermore, in many European countries, governments have started to reduce incentives for new buyers and value-added tax exemptions for existing owners, hence, there is still high pressure for OEMs to reduce costs for these technologies in order to attract consumers.
Despite a steady growth in dual clutch, CVT and efficient automatic technologies, manual transmissions still make up approximately 40% of all transmissions produced worldwide [Figure 2]. In Europe this is even more apparent with about 70% of consumers preferring manual transmissions in their cars. This is largely driven by the cost - typically 1000€ additional cost to driver for an automatic/automated transmission.

![Global Production, by Design](image)

**Figure 2: Global transmission production by transmission type (Source IHS Markit Powertrain Forecast [10])**

Up to now, in order to bring hybrid technology into the manual driveline market many solutions have focused on integrating electric motors on the crankshaft or linked to it. A significant amount of detail has been published [5] regarding the optimum location of an electric machine in the drivetrain. A summary of some of these benefits are shown below.

<table>
<thead>
<tr>
<th>P2</th>
<th>Stop-start</th>
<th>Recuperation</th>
<th>E-Coasting/ Sailing</th>
<th>E-creep</th>
<th>E-launch</th>
<th>Power assist (boost)</th>
</tr>
</thead>
</table>

Table 1: Hybrid 48V Functions in M/T, (*) only possible with an automated clutch

Each of these additional functionalities reduce CO₂ and in some cases improve driver comfort. This paper will however concentrate on the other tangible benefits enabled by this technology choice that can reduce mass, lower drag loss and help offset the cost of the E-machine and therefore help pay for the addition functionality shown in Table 1.

E-machines have typically been developed as ‘bolt-on’ external components to transmissions. The expectation is that the damper and clutch would allow them to perform as a fully integrated system. Here the potential of an integrated system design approach to reduce costs compared to the conventional approach is investigated. Aiming at the volume market enables bespoke design of the system. Bespoke design of the system enables other further benefits to be realized, helping to achieve the cost targets and additional features. The key points for consideration are:

- 48V systems adoption: 48V network presents a good opportunity to benefit from significant complimentary power (15-20 kW) without specific requirements for a high voltage system such as safety, harness, battery, etc.
- Market forecasts predict that 25 per cent of newly registered cars will have an electrified powertrain by 2025 (Figure 3) and that almost half of these will feature 48-volt technology. From the year 2020 onwards, global potential for up to four million 48-volt systems could unfold.
- Additional vehicle features
- Downsizing possibilities

![Figure 3: Market forecast electrified powertrain (source ZVEI - German Electrical and Electronic Manufacturers' Association [1])](image)
2. The concept layout

Layshaft transmissions offer diverse opportunities for the integration of a custom e-machine into the transmission case, compared to an e-machine being arranged between the engine and the transmission (P0, P1). It is also possible for this layout not to have any impact on the overall powertrain length between the chassis longitudinal structure.

The baseline transmission used in this paper is a 6 speed 370Nm transverse manual transmission. The layout shown is just one possible embodiment of this concept. The electrical machine is incorporated in the P2 position as an additional parallel shaft in the transmission which takes advantages of the full length of the existing transmission space whilst not impacting on the overall installed length of the powertrain.

In order to avoid the cost and complexity of a disconnect device the motor is permanently engaged with the input shaft via a 1.5:1 ratio. This also avoids any additional costs associated with a disconnect actuator, its electronics and control. Careful design of the motor can ensure this approach is possible, and also means that power can potentially be put into or, recovered from the transmission independent of the selected gear.

In addition to the functions detailed in table 1 this layout could also be used to support typical synchronised shifts within the transmission, potentially leading to other efficiency savings and cost displacement.

As it is reasonable for the consumer to expect this new technology to perform as well as their existing manual transmission. It is key that the system does not delay shifting or increase the force required to shift during normal operation.

Figures 6 and 7 show manual up and down shifts for the baseline transmission. The particular transmission was originally designed to run with a diesel engine and therefore shift speeds towards the upper operating area of the engine have been chosen. It can be seen how once the clutch is opened the synchroniser is doing all the work to bring the input shaft to the desired target speed.
Table 2 shows the results of a shift time analysis based on an upshift at 4000rpm and a downshift targeting a 4000rpm final speed. Typical clutch opening and close times have been chosen as well as a typical inertia for an inline-4 cylinder diesel engine.

<table>
<thead>
<tr>
<th></th>
<th>1→2</th>
<th>2→1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift time (s)</td>
<td>0.138</td>
<td>0.2</td>
</tr>
<tr>
<td>Shift Impulse (Ns)</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 2: Performance targets based on baseline

These targets will be used to determine the performance of the new ‘supported shift’ design.

3. Supported shifting

In the concept layout with e-machine supported shifting, once the clutch is opened the P2 E-machine will accelerate the input shaft and its connected system to within a range of the target input speed. In the example shown here they achieve within 100rpm. The remaining speed delta is then reduced by using a low spec ‘economy’ single cone synchroniser. It is key here that the synchroniser functionality has been maintained: It results in not only an achievable motor design; but maintains the feel characteristics expected with a typical manual shift; It also gives the transmission the ability to shift in a limp home condition - albeit at a slower shift speed than typically acceptable in the event of an electrical fault with the e-machine.

Figures 8 and 9 show typical speed and torque profiles for an E-machine assisted shift. It can be seen that in addition to the ‘mechanical’ synchronisation phase there is now also an ‘electrical’ synchronisation phase.

By applying the same rules about rate of clutch engagement, engine inertia and the overall shift times from the baseline design, it is possible to arrive at a total synchronisation time for the system that needs to be split between the motor and the mechanical synchroniser.

\[ T_{\text{syncTot}} = T_{\text{syncEM}} + T_{\text{syncMech}} \]

It is clear from this that in order to meet the target shift time a very fast response is required from the electric machine. It is therefore critical that its inertia is minimised as much as possible as it too has to be accelerated in the short time window as well as the system coupl to the transmission input shaft.

Balancing the designed machine performance with the specification of the mechanical synchronisers is therefore of utmost importance and can only be done effectively by designing at a system level.

Assuming the E-machine operates at constant power during synchronisation, then a peak Torque of 35.6Nm (at 2080rpm) is required for the downshift, and a Peak of 40Nm (at 2180rpm) is required to achieve the same upshift time as the baseline.
The power required to perform each shift is 7.75kW and 9.1kW respectively. It will be shown later on how both are well within the capability of the designed motor. Indeed in this instance the motor has been designed with enough margin to be useful during more abusive shifts. It can be seen here that upshift requires more power. This peculiarity arises due to the relatively fast shift time achieved by the baseline design’s triple cone synchroniser.

Although the details of only the more arduous 1st and 2nd gear shifts have been included in this paper, the same operation can be utilised in all gear positions.

To put the results in perspective the differences between the mechanical synchroniser specification for the baseline and supported shift must be understood.

<table>
<thead>
<tr>
<th></th>
<th>No. of cones</th>
<th>Mean cone diameter</th>
<th>Friction material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 1st</td>
<td>3</td>
<td>83.26</td>
<td>Carbon</td>
</tr>
<tr>
<td>Economy 1st</td>
<td>1</td>
<td>65.5</td>
<td>Carbon</td>
</tr>
<tr>
<td>Baseline 2nd</td>
<td>3</td>
<td>83.26</td>
<td>Sintered</td>
</tr>
<tr>
<td>Economy 2nd</td>
<td>1</td>
<td>65.5</td>
<td>Sintered</td>
</tr>
</tbody>
</table>

Table 3. Synchroniser comparison.

Even with the significant downsizing in synchroniser shown in Table 3 the assisted up shift achieves an Impulse as low as 5Ns for the downshift and 1.4Ns for the up shift – a significant comfort improvement. Once the 3rd, 4th double cone sintered units, and 5th/6th single cone carbon units are also all replaced with single cone sintered items a cost saving in the region of €18 could potentially be achieved.

4. The Electric machine design

In order to integrate the machine as an additional shaft in the gear cluster it must have a small rotor radius. It has been discussed previously why minimising the inertia is critically important in ensuring a fast response of the machine. Indeed, this is a virtuous circle as in the event of an electrical failure, the mechanical elements must be able to overcome the inertia of the electrical machine in order to perform a shift. The additional low inertia of the machine makes this a possibility. An additional benefit of a low inertia machine is that it helps minimise rotor windage losses at higher machine speeds. This is very important for a machine which is permanently engaged with the transmission input shaft.

Eliminating the conventional cooling water jacket from the machine is essential for achieving this level of integration with the gear cluster. Cooling the machines stator windings directly with the transmission oil has the further advantage of improving the potential for a higher power density in the machine. To avoid the additional cost of active lubrication of the machines windings and stator, it is proposed that state of the art techniques for passive oil management within manual transmissions are applied [3,8] around the machine, to help distribute splashed lubrication over the end windings and take heat away from the active coils. It should also be considered that it is often required to use a low Sulphur transmission oil in such applications.

Further advantages of such an integrated machine include: the elimination of rotary seals on the motor shaft, providing some efficiency and cost reductions over conventionally coupled systems; and the potential to use the main transmission casing as the motor housing.

Whilst this layout can be adapted for different machine topologies it is felt here that a switched reluctance type rotor version with the following attributes best suits the system attributes:

- Simple and relatively low cost motor design with no permanent magnet materials and associated exposure to magnet price volatility.
- Simple and robust rotor design suitable for in oil environment.
- Has a safe and iron loss-free power-off state avoiding the necessity for a disconnect clutch to decouple the machine in case of electronic failure conditions.
- Design scope for short term high peak torque without concerns for demagnetization of machine magnets providing electrical system capability (battery and electronics can deliver the required currents).

Selection of the e-machine and its' operational speed range is critical in delivering the efficiency benefits of the system and the electric only driving performance. As a starting point the specification for a belt starter generator machine was taken. These machines are sized and geared for handling engine starting torques (100-150Nm at the crank shaft). Belt mounted machines typically have a belt ratio of 2.5 – 3:1 back to the crank shaft to achieve the required starting torque in a reasonable package space.

The P2 solution however does not necessarily need to start the engine if a conventional starter is retained or used in combination with a 12V starter-alternator equipped for fast starting. This removes the high-Torque load case associated with cold cranking. E-
Creep torque requirements are somewhat lower with a peak of 30Nm at the transmission input shaft sufficient to achieve a good creep performance in a C/D segment vehicle.

Whilst higher starting motor torques are desirable for improved engine off operation, the machine design and operational speed range (defined primarily by ratio selection) should be set primarily to meet the needs of on-cycle benefits, optimizing the efficiency of generating and motoring around the typical speeds seen on cycle circa 1500-2500rpm. It is also important to ensure max machine generating power in this speed range in order to maximize the potential for energy recovery in this range.

The requirement for providing electrically assisted shift synchronization adds a further requirement in the machine design and the operational speed range. Whilst adding ratio between the machine increases the available torque at the input shaft this also increases the reflected inertia of the machine at the input shaft by the square of the ratio. This needs to be carefully balanced to maximize the available electrical torque to synchronize, without significantly adding referred inertia to the input shaft from the machine and selected ratios.

Figure 11: Bespoke E-machine, by DSD

The performance of the bespoke machine used for this study is outlined in Table 4.

<table>
<thead>
<tr>
<th>Size (Diameter x Length)</th>
<th>70 X 250 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Torque Stall</td>
<td>80 Nm</td>
</tr>
<tr>
<td>Max Torque Peak</td>
<td>50 Nm</td>
</tr>
<tr>
<td>Max Torque Continuous</td>
<td>23 Nm</td>
</tr>
<tr>
<td>Max Output Speed</td>
<td>18000 rpm</td>
</tr>
<tr>
<td>Max Power</td>
<td>15kW</td>
</tr>
</tbody>
</table>

Table 4: Characteristics of bespoke 48v e-machine designed by DSD

Reducing interfaces between discrete components and designing the transmission as a single system reduces the numbers of components such as bearings, and minimize the size of other components such as casings by ensuring elements serve multiple functions. These steps can further reduce cost of the machine.

5. Additional benefits

During the down shift phase the P2 machine is recovering energy in order to slow the input shaft down. For the 2nd to 1st shift considered here this equates to 1.1kJ. This energy can be used directly to support upshifting (therefore providing this functionality for a negligible energy cost), and also to assist propulsion in certain operating modes.

Lowering the overall size and number of friction surfaces also contributes to a weight saving. Applying this technology to the baseline transmission has the effect of lowering the combined mass of the mechanical synchronisers by almost 1kg.

Finally reducing the number of friction cones in the transmission reduces their contribution to the overall transmission drag loss. In this application the choice of all single cone synchronisers has the effect of reducing the mean power loss of the transmission at typical city speeds by more than 14W. Reduction of the outer diameter of the synchronisers can also help to minimise churning losses.

6. Conclusions

Opening up the lower margin area of the market to benefit from the 48V network and hybridisation could have a significant effect on fleet average CO₂ emissions. At a consumer level the features introduced by this technology, in addition to lowering fuel costs, offer improved feature content and comfort.

Hybridising transmissions in such a competitive area of the market relies on maximising the cost benefit. Here Drive System Design have offered a solution to maximise the benefits of using a 48V electric machine in such an application. By designing the machine and transmission together at a system level significant cost savings can be realised alongside improved performance.

Not only can the cost of adding the machine itself be minimised by careful system level design, but by understanding its potential, in this case for synchroniser downsizing, cost can be displaced elsewhere in the transmission whilst enhancing the system performance, efficiency and overall mass reduction further. These savings can be directly used to help pay for the addition of the technology, helping their introduction in an area where cost is key.
7. References

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[8] Lubrication system efficiency – 13th International CTI Symposium 2014, Sam Thompson, Drive System Design