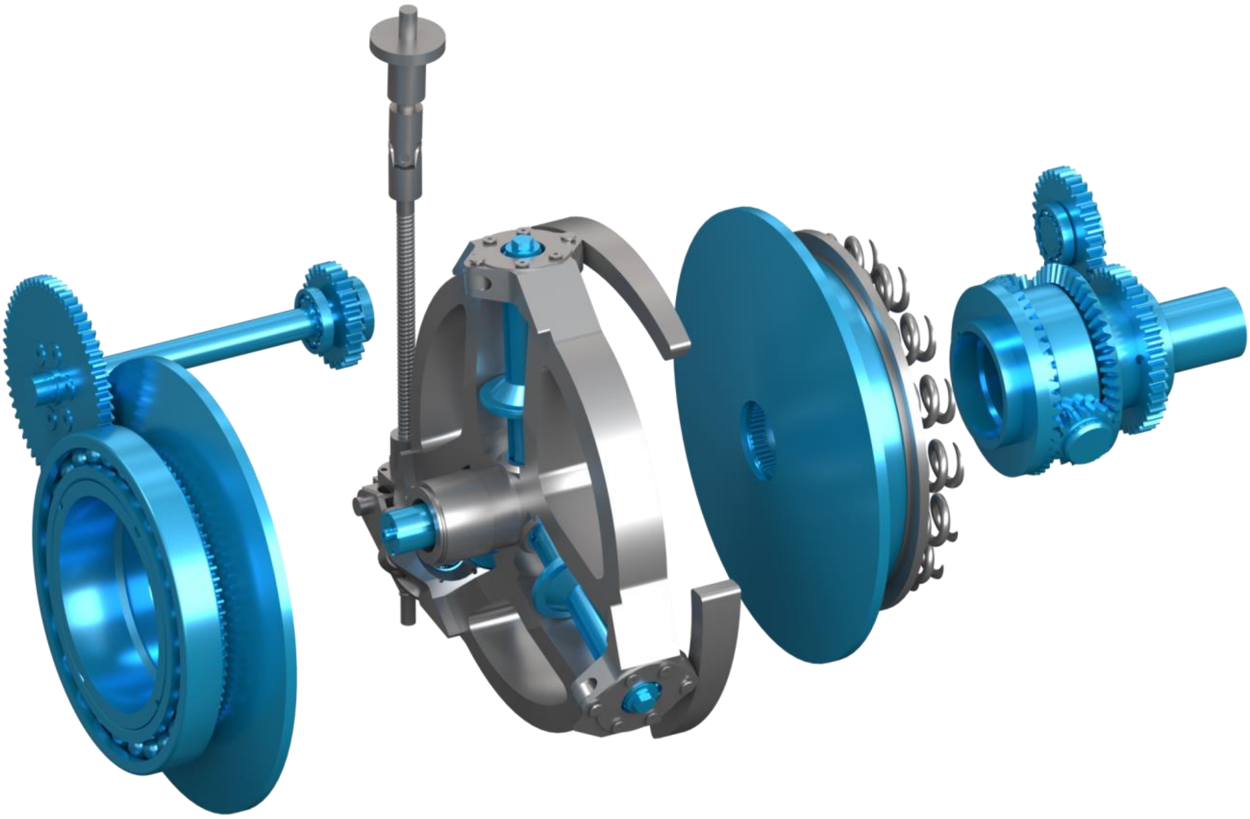
RADIALcvt as an ideal electric vehicle transmission



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1 Current status of electric vehicle transmissions

With the current drive towards electric vehicles, optimization of the various components contributing to the overall energy efficiency of the electric vehicle is becoming more important. As development to higher energy dense batteries and other energy storing devices continues it is a very high priority not to have inefficient components deteriorates any advances in this development. The norm for current electric vehicles is not merely a means to get from point a to b but includes super cars like Tesla and Nio and normal passenger vehicles which all demand, all the features as included in equivalent internal combustion vehicles. The pure electric vehicle is here to stay and will increase its stepped ratios to 3 and 4 and its market share will grow and development will continue as reported by ZF (Tom, 2014) and Bosch (Beissmann, 2014).

The primary power source in electric vehicles, the electric motor, however share some disadvantages with the internal combustion engine. This includes the fact that the electric motor and its drive/inverter are not equally efficient under different loads and speeds which is also the case for internal combustion engines. A typical electric vehicle, electric motor efficiency varies between about 92.5% and about 70% as reported by Antonov plc (David, 2011) and reproduced below in Figure 1 as well as by (Turner, Cavallino, & Viotto, 2011) and reproduced in Figure 2

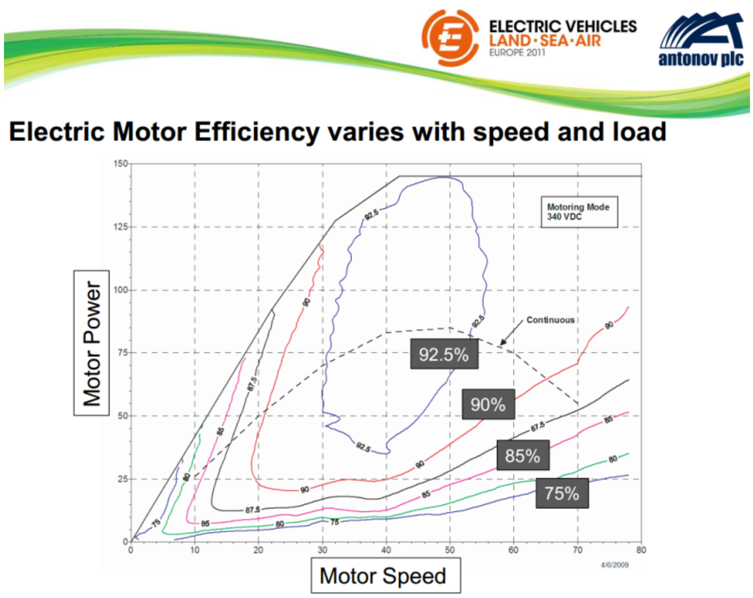

Figure 1 Electric motor speed vs motor power efficiency (David, 2011)

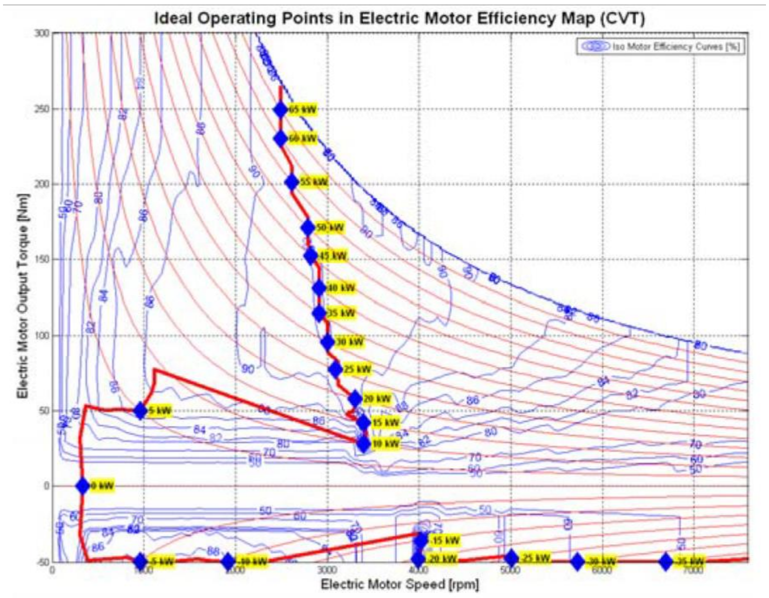

Figure 7. Graphical plot of the results of the automated procedure for the gearshift map selection for the CVT system

<u>Figure 2 Electric motor speed vs motor power efficiency (Turner, Cavallino, & Viotto, 2011)</u>

(Turner, Cavallino, & Viotto, 2011) indicated about 10% improvement in energy efficiency when utilising a 2 speed transmission in combination with the electric motor compared to the single fixed ratio. The 2 speed implementation added 19 kg of mass to the single speed transmission. A dry clutch, sprag and locking ring were added in the 2 speed implementation. Above was based on a 60 to 70 kW front wheel drive minibus implementation. The exact ratios for the motor to lay shaft reductions are not given in (Turner, Cavallino, & Viotto, 2011) but from their Figure 2, are estimated as about 3.5:1 for the first speed and 2.5:1 for the second speed, thus a ratio range of about 3.5/2.5=1.4, which is very low.

Antonov's dual clutch 3 speed transmission is presented in (David, 2011) as implemented in a Jaguar XJ known as the Limo Green (Case Study:Limo Green - eco-friendly Luxury Limousine), powered by a 170 HP (129kW) electric motor and reporting an energy saving of up to 14.7%.

Antonov also integrated their dual clutch 3 speed transmission into a 3.5 ton Smith Electric Vehicle, demonstrator known as "E-Van".

Typical ratios from (David, 2011) indicate that the 3 speed transmission has ratios of about 3.8:1, 2.3:1 and 1.7:1, thus with a ratio range of 3.85/1.7=2.3 which is also relatively low.

More recent publications on multi speed electric vehicles, which include mechanical variable speed transmissions (CVT), include (Wang, Liu, Liu, & Xu, 2016) and (Bottiglione, De Pinto, Mantriota, & Sorniotti, 2014).

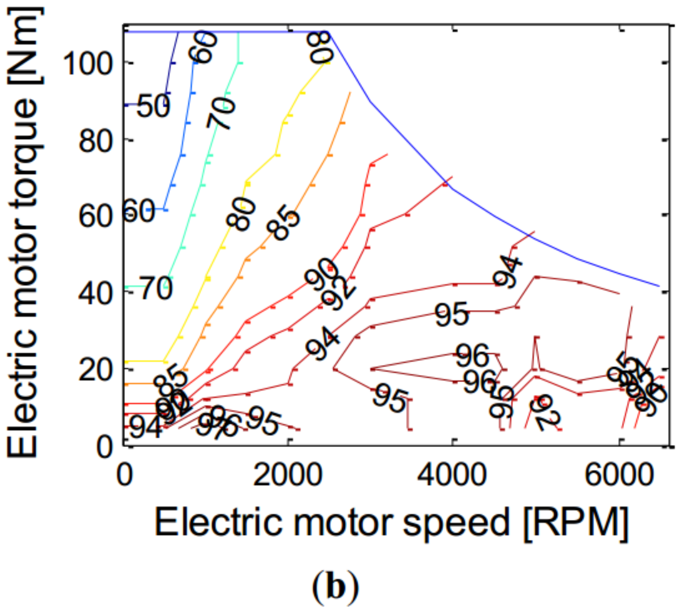

Figure 3 (Bottiglione, De Pinto, Mantriota, & Sorniotti, 2014)

The work of (Bottiglione, De Pinto, Mantriota, & Sorniotti, 2014) based on a 28kW, 108 N.m electric motor (motor efficiency presented in Figure 3) in a 872 kg vehicle compared transmissions that include, single and two speed, full and half toroidal, as well as two IVT (infinitely variable transmissions). The result show that at constant speed and load the single and two speed transmissions outperform (lower energy consumption) the variable ratio ones, as can be expected due to the lower mechanical efficiency of the latter. However in the UDC and the J10-15 drive cycle (city driving) the half toroidal outperformed the fixed ratios by 10% and 15% respectively. The advantage is gain by the variable drive, by being able to fully optimise the electric motor in drive conditions and well as in regeneration conditions.

As a very advanced four speed electric vehicle transmission example, Oerlikon Graziano, discusses their clutch less four-speed EV transmission in (Torrelli, 2012). This transmission called an e-DCT, presents a DCT but without the dual clutch. The clutch function is eliminated by using two motors, one coupled directly to the even ratios and the other directly to the uneven ratios. This transmission offers 15% improvement in vehicle efficiency and is intended for the high end EV vehicles.

Bosch also forecasts multiple ratios for electric vehicles and continued growth in their market share and development as reported by (Beissmann, 2014)

GKN was able to match the performance of a 100 kW motor downsized to 80 kW by replacing a fixed drive with a 2 speed eAxle. The 80 kW e-motor was 20% smaller and 28% lighter. The downsized motor with 2 speed also improved 0-50km/h acceleration by 36% and 0-100 km/h acceleration by 22% (Transmission Technology Magazine, 2017).

Simulations done by (Yulong Yin, 2017) on a 90 kW EV comparing a fixed ratio with a two speed ratio resulted in up to 29% energy saving in the ECE and EUDC driving cycles.

A single ratio vs CVT implementation in an EV was done by (Jiageng Ruan, 2015) and presented significant improvements on battery energy saving, range extension as well as vehicle cost with the implemented CVT.

Drive System Design and Dana commented that multispeed shifts need to be imperceptible as far as electric vehicle transmissions and general passenger vehicles are concerned (Transmission Technology Magazine, 2017).

In order to make the steel belt more attractive as an EV transmission Bosch is replacing the existing hydraulic clamping system with an electronic clamping system (Transmission Technology Magazine, 2017).

CVT volumes are increasing from 12 million units in 2016 to an estimated 18 million by 2020. This is further demonstrated by the cumulative sales of Bosch CVT, from 10 million by 2010, 25 million by 2012 and a total of 50 million by March 2017. The largest markets for CVT in order are USA, EU, China and South Korea (Transmission Technology Magazine, 2017).

In 2016, 31.6% of cars sold in the USA were equipped with CVTs, up from 10.2% in 2012 (Murphy, 2017).

2 Conclusions

When considering a transmission for a pure electric vehicle the following can be concluded for the above mentioned work which convers some electric vehicles in the range of 28kW to 129kW.

2.1 Single speed

A fixed drive (single speed) has the lowest cost and is the least complicated, requiring at most a locking ring (dog clutch) to tow the vehicle in emergency conditions. This configuration however have no means to optimise the overall vehicle energy consumption as far as configuration between electric motor and wheels is concerned, besides the optimized selection of the fixed gear ratio between motor and wheels.

2.2 Multiple stepped speed

When multiple stepped ratios (two and three speeds and more) are considered, the following issues arise, and the solutions to these exponentially increase the complexity if compared to the single speed case:

- Multispeed shifts need to be imperceptible by the driver.
- All the reviewed work indicates that ratio change synchronisation with a single electric motor is not possible without a clutch (except the Oerlikon 4 speed high end EV transmission which requires two motors). As a result all the reviewed multi speed transmissions functions as an AMT (automated manual transmission) or as a DCT (dual clutch transmission) as in the case of the Antonov transmission all using a clutch or dual clutch respectively.
- In order to realise above, a clutch system with automated clutch control is needed
- Also an automated ratio changing mechanism is required.

The upside to a stepped multi speed is that high mechanical efficiency is maintained if compared to the single speed and that the electric motor is partially optimised in driving and regeneration conditions to provide energy consumption up to about 15% compared to the single speed. It also allows for partial optimisation of the electric motor in terms of size, speed range and torque range.

2.3 Variable mechanical drives

All the reviewed work which considered CVT's/IVT's used existing well known systems limited to toroidal and belt/chain CVT transmissions as well as these transmissions in IVT/power split configurations. These transmissions are characterised by the following disadvantages:

- Much lower mechanical efficiency than a fixed ratio.
- All require a hydraulic control system.
- They are heavy and expensive.
- All toroidal and belt/chain CVT include an overdrive in their ratio range (output turns faster than the input) thus additional reduction gearing would be needed in electric vehicle implementation.

On the upside these transmissions provide the following advantages:

- Fully optimise the electric motor in driving and regeneration conditions.
- Provide better vehicle acceleration and gradient ability.
- Has the definite potential to provide better energy consumption than stepped transmission if its mechanical efficiency is within certain limits.
- They do not require a clutch, but only a locking ring/dog clutch, the same as for the single speed.

2.4 RADIALcvt as an ideal electric vehicle CVT transmission

The RADIALcvt is a new CVT transmission being developed by Varibox. Full details of the RADIALcvt simulation (Naude, RADIALcvt prototype design,simulation and testing, 2017) can be obtained from http://www.varibox.com/media/1195/radialcvtdesignver110-004.pdf The executive summary of this document is reproduced in Appendix A at the end of this document. It has a number of fundamental advantages over current commercial and developmental CVT's and if considering its use in above cited work (thus as an electric vehicle transmission), thus considering a power range of 30kW to 130kW with a maximum ratio range of 2.3, the following can be concluded, while using the same size RADIALcvt unit with a 292mm disk diameter:

- For a ratio range of 2.3 the RADIALcvt disk radius (R_B and R_C) will vary from 65 mm to 150mm.
- For the base case of a 30 kW configuration the variator contact efficiency will vary from about 97.5% to 98.7% as per (Naude, RADIALcvt prototype design,simulation and testing, 2017) Figure 12.
- For the case of 130 kW configuration the variator contact efficiency will vary from about 95.8% to 98.2% as per (Naude, RADIALcvt prototype design,simulation and testing, 2017) Figure 16.
- The RADIALcvt does NOT use a hydraulic control system.
- Ratio actuation is done via 12V PWM control of an estimated 150Watt electric motor.
- The clamping force related bearing losses in the above RADIALcvt is estimated at about 1.4% to 1.2% as per (Naude, RADIALcvt prototype design,simulation and testing, 2017) Figure 12.
- Above is realised while all maximum Hertz contact stresses are below 2 GPa, thus durability is not an issue.
- The RADIALcvt does not include an overdrive in its ratio range, thus its output can drive the wheels through the normal reduction to the differential.
- No clutch or clutch control system are required, but only a locking ring/dog clutch (for emergency towing) as is the case with all the other electric vehicle transmissions.
- The first RADIALcvt prototype mechanical efficiency tests were performed on 3 October 2017. See section 8 of (Naude, RADIALcvt prototype design,simulation and testing, 2017). The results are very encouraging as they are already in line with mechanical efficiencies of current commercial CVT's. Note that these tests present the result of the first tests on the first RADIALcvt prototype compared to CVT's that are in production and have been developed over many year.

The RADIALcvt potential mechanical efficiency is at most within an estimate of about 3% less than the stepped transmissions while it is much more compact lengthwise than the stepped transmission with a clutch or dual clutch.

The various cited CVT simulations proved the advantages of a CVT transmission in pure electric vehicles, but the low overall efficiencies of current commercial CVT's in some cases eroded all the advantages away.

The RADIALcvt thus provides an excellent solution to pure electric vehicles, because of its simplicity and fundamental advantages with very high mechanical efficiency.

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