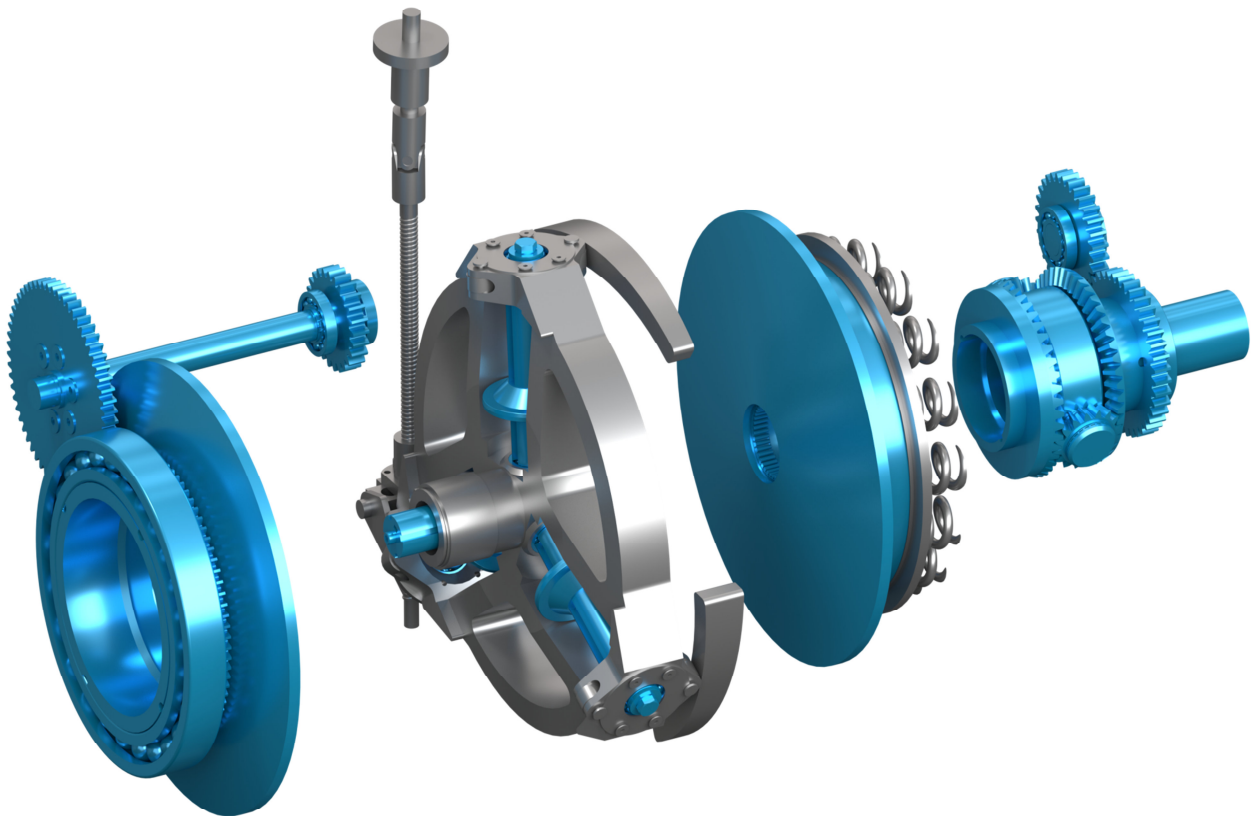# RADIALcvt as an electric vehicle transmission

Dr. J. J. Naude   **19 July 2017**

Version 1.4

Table of contents

List of Figures

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
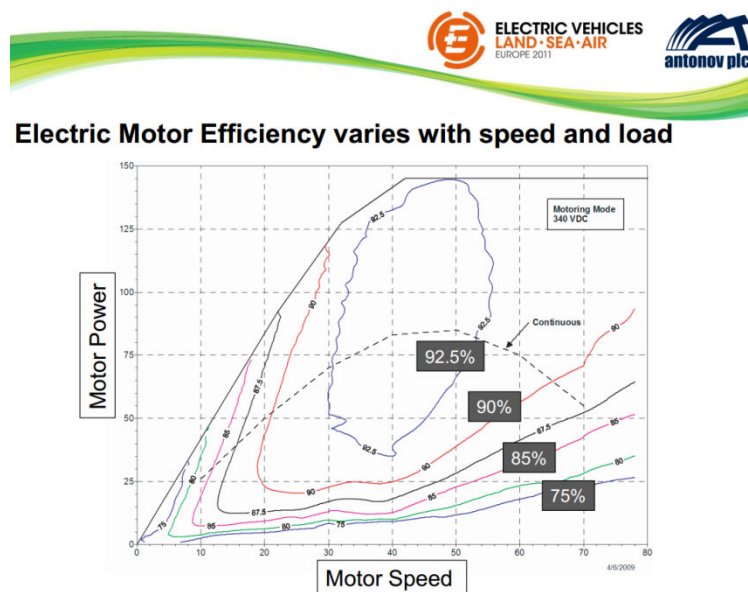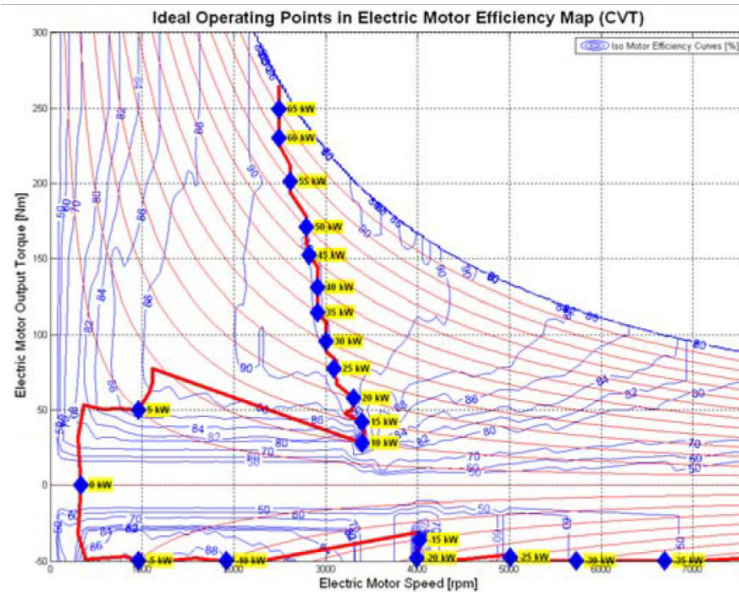

Figure 1 Electric motor speed vs motor power efficiency (David, 2011)

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

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

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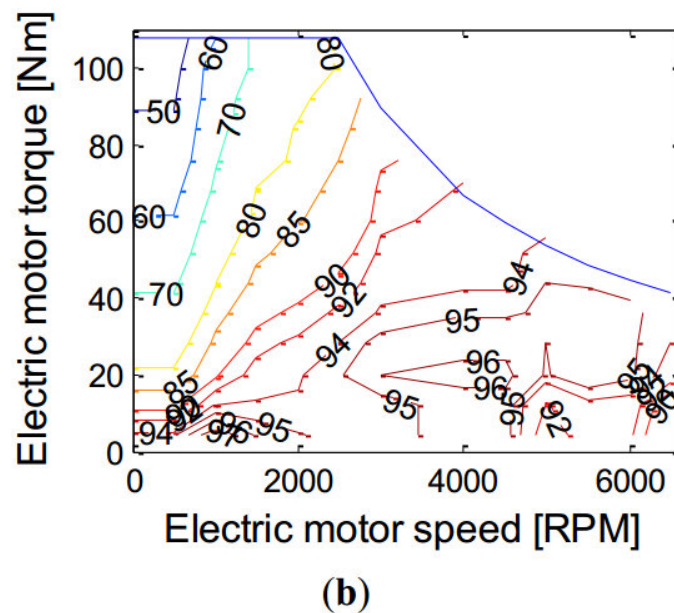
Figure 3 (Bottiglione, De Pinto, Mantriota, & Sorniotti, 2014)

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)

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:

➢ 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, 2017) can be obtained from http://www.varibox.com/media/1177/radialcvtdesignver16.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, 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, 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, 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.

Above RADIALcvt 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.

3 References

Beissmann, T. (2014, July 18). *Electric cars to get automatic transmissions with multiple gears, says Bosch*. Retrieved May 19, 2017, from CARADVICE: http://www.caradvice.com.au/297602/electric-cars-to-get-automatic-transmissions-with-multiple-gears-says-bosch/

Bottiglione, F., De Pinto, S., Mantriota, G., & Sorniotti, A. (2014). Energy Consumption of a Battery Electric Vehicle with Infinitely Variable Transmission. *Energies 2014*.

Case Study:Limo Green - eco-friendly Luxury Limousine. (n.d.). Retrieved May 18, 2017, from HORIBA MIRA: https://www.horiba-mira.com/research/limo-green-collaboration

David, P. (2011). 3-Speed High Efficiency Transmission for Electric Vehicles. *Electric Vehicles Land-Sea-Air, Europe 2011.* Stuttgart, Germany: Antonov plc.

Loewenthal, S. H., & Zaretsky, E. V. (1985). *Design of Traction Drives.* Ohio: NASA Reference Publication 1154.

Naude, J. (2017, May 19). *RADIALcvt prototype design and simulation.* Retrieved from Varibox CVT Technologies: http://www.varibox.com/media/1177/radialcvtdesignver16.pdf

Tom, M. (2014, December 2). *Coming to an EV Near You: Multi-Speed Transmissions*. Retrieved May 19, 2017, from WARDS AUTO: http://wardsauto.com/blog/coming-ev-near-you-multi-speed-transmissions

Torrelli, C. (2012, February 14). *Clutchless four-speed EV transmission debuts*. Retrieved May 19, 2017, from SAE International: http://articles.sae.org/10669/

Turner, A., Cavallino, C., & Viotto, F. (2011). Selection of the Optimal Gearbox Layout for an Electric Vehicle. *SAE International Journal Engines, Volume 4, Issue1* (pp. 1267-1280). SAE International.

Wang, J., Liu, Y., Liu, Q., & Xu, X. (2016). Power-based Shift Schedule for Pure Electric Vehicle with a Two-speed Automatic. *2016 Second International Conference on Mechanical Engineering and Automation Science.* IOP Publishing.

4 Appendix A

RADIALcvt prototype design and simulation: Executive summary (Naude, 2017)

This document provides a design and traction drive contact analysis and simulation of the first RADIALcvt prototype. The simulation results are discussed and improvements to the current design recommended. It presents a high mechanical efficiency and eliminates the use of a hydraulic control system. The RADIALcvt has a number of fundamental advantages that sets it apart from all other developmental and commercial CVT's and are listed below:

➢ **One friction interface:** Only one friction drive interface in series in a parallel power path. All other CVT's, developmental and commercial have 2 friction drive interfaces in series thus resulting in a compound friction loss. Thus if the friction contacts have the same efficiency then the RADIALcvt will have 50% of the friction drive losses of other CVT's.

➢ **Line contact:** The friction drive contact in the RADIALcvt friction drive can be a line contact, which is only possible in belt/chain CVT and cone ring CVT and not possible in toroidal and planet ball CVT's. Line contact reduces the maximum contact stress.

➢ **Constant input radius:** The RADIALcvt has a constant friction drive input radius. All other CVT have a variable input radius which results in high surface rolling speeds and lower coefficient of friction which require higher clamping forces.

➢ **Six parallel power paths:** The RADIALcvt has at least 6 parallel power paths. Such a large number of parallel paths is only possible in planet ball CVT's.

- **Large output friction disk:** The output friction drive disk of the RADIALcvt can be positioned concentric and close to the engine flywheel and can approximate flywheel size. Thus the diameter of this output friction drive can be much larger than any of the belt/chain or toroidal or cone ring CVT output friction drive components. Due to this fact the RADIALcvt provides its highest efficiency in low ratios associated with city driving.

- **High power efficiency:** Above results in a RADIALcvt with a friction drive contact power efficiency in all ratios, under maximum engine torque, of about 95% in high ratio to about 98% in low ratio including in use without a 2 speed AMT, with a ratio range up to 4.7, or with ratio range up to 10 and beyond with AMT integration. A ratio range of 10 is currently the maximum in the industry.

- **No hydraulic control:** The RADIALcvt can be realised without any hydraulic control. All current developmental and commercial CVT require a hydraulic control system.

- **Clamping force utilization:** In the RADIALcvt configuration, a unit of clamping force supports two parallel friction drive interfaces, while in all other developmental and commercial CVT's only one friction drive interface is supported. Losses due to clamping forces should thus be 50% lower in the RADIALcvt.

- **Clamping force location:** The RADIALcvt clamping force, bearing losses are only associated with the RADIALcvt output, namely the Convex and Concave disks, while the RADIALcvt input, the radial drivers, are in equilibrium. Thus these bearing losses, for a given clamping force, are only a function of the RADIALcvt output speed. This has the obvious low loss advantages in low output speed ratios. In contrast in all other CVT's, the clamping force is associated with both the input and output speeds of the respective CVT, thus for a given clamping force the applicable speed for bearing loss calculation would be the average of the input and output speeds.

- **Low bearing losses:** Disk bearing (clamping) losses, which are a well-known source of traction drive losses (Loewenthal & Zaretsky, 1985), is a maximum of 2.5% in high ratio to about 1.5% in low ratio of transmitted power.

Since the RADIALcvt use existing very well developed traction/ friction drive technology, any potential licensee of our technology can very easily evaluate and verify the

advantages of the RADIALcvt. The advantages of the RADIALcvt is realised by its unique patented configuration of components which realise its fundamental advantages.