Compact Pushbelt Variator Module to Improve Energy Economy in Electrified Powertrains

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Abstract. A lot has happened since the introduction of the Variomatic with its rubber belts based continuously variable transmission (CVT) in the DAF passenger cars in 1958. The rubber belt evolved into a compact steel belt with a far higher torque capacity, and the transmission is now built into the vehicle instead of a vehicle built around the transmission. Since then, the CVT is known as an excellent system regarding fuel economy and offers outstanding NVH qualities. It is these qualities that EV developers look for, when designing electrified powertrains and reducing the ecological footprint of mobility. CVT is ready for its next evolutionary step. Previously, studies have been published which show that CVT—just as it did for internal combustion engines (ICE) based powertrains—offers the potential to reach better energy economy in electrified powertrains. In this paper these results will be further explained. The CVT will look different from what we know from ICE applications; it is smaller and has a better energy efficiency. The solution consists of a small variator combined with an energy optimal actuation system as the core elements for an electrified powertrain.

Keywords: CVT · Electric vehicles · Motor efficiency · Vehicle performance · Modularity

1 Introduction

Electric vehicles are a fast growing segment in the automotive landscape. Though the first electric driven vehicles were already on the road over 130 years ago, the development went to the background until recently, due to the massive focus on combustion engines. Therefore electric vehicles are still a relative young technology in which still some challenges need to be solved. One of those is the compromise that in some cases has to be made to be able to drive off with maximum payload at a steep hill as well as to reach the desired maximum speed, as in Fig. 1. The majority of electric vehicles on the market at this moment are equipped with a fixed gear ratio between the e-motor and the wheels, by which often a compromise between these two drive conditions must be made.

© Springer-Verlag GmbH Germany, part of Springer Nature 2021
Euroforum Deutschland GmbH (Ed.): *CTI SYMPOSIUM 2019*, pp. 523–535, 2021.
https://doi.org/10.1007/978-3-662-61515-7_46

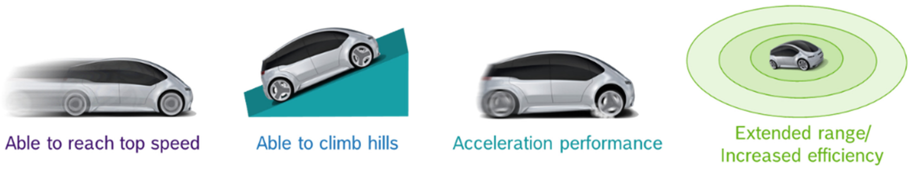


Fig. 1. Base requirements and benefits with CVT

A solution for this issue is to install a multispeed transmission, which brings a ratio spread. With the freedom to choose a ratio, also the choice for more optimal operational conditions of the e-motor becomes available, and with that better overall energy economy.

When for this purpose a stepped transmission is installed, a new challenge needs to be solved: when shifting from one to the other ratio a discontinuity in speed and torque is generated. As with conventional ICE, the solution can be found in powershift solutions, but these introduce additional losses and cost. Such disadvantages can be overcome with another proven technology from ICE powertrains: CVT. With CVT a smooth variation of ratio as well as a wider ratio coverage than e.g. a two speed offers will be obtained. Figure 2 shows an evaluation of different KPIs between CVT, DCT and AMT.

	EM spec.	Comfort	Transm. cost	Efficiency
2-speed AMT	o	–	+	+
2-speed DCT	o	o	o	o
CVT	+	+	o	+

Fig. 2. Evaluation of different multispeed transmissions in electric vehicles

With the wider ratio coverage of CVT—approximately 3,5 compared to 1,8 for two speed—further benefits with respect to single speed can be explored, such as a wider coverage of optimal efficiency operating conditions and keeping the maximum or continuous power operation of the e-motor. With this lower e-motor losses result as well as higher top speed and acceleration elasticity. Figures 3a and 3b offer a graphic explanation thereof.

2 CVT4EV Design Considerations

The process that translates the requirements for a powertrain into the right definition of the components, requires a holistic view. If the powertrain design is part of a product family, an even more extensive and complex challenge has to be fulfilled. A successful outcome demands a careful definition of the priority of the key performance indicators (KPI's), between which in many cases a tradeoff has to be made. In such a complex situation it is very convenient if one of the components offers flexibility which—as an example—enables modularity in component definition or less compromises.

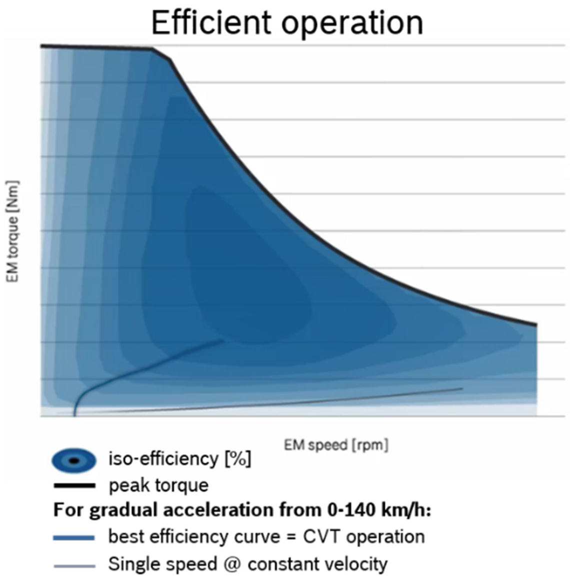


Fig. 3. **a** E-motor operation of single speed and CVT. **b** E-motor operation of acceleration of single speed and CVT

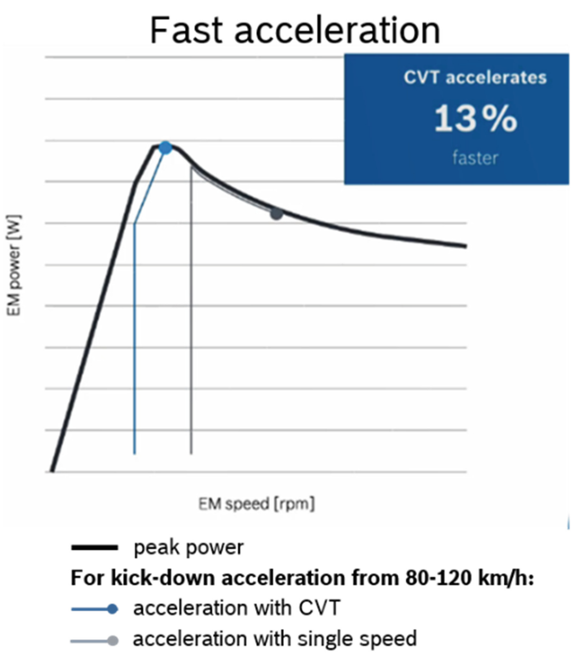


Fig. 3. (*continued*)

In this chapter by a concrete design example some clarification on such a process is given, which also shows the convenient flexibility of a CVT based powertrain.

The use-case is a C-class passenger car with specifications according Table 1. Specifications

Table 1. Vehicle and performance specifications and KPI prioritization

* Curb weight	1550 [kg]
* GVW (loaded weight)	2100 [kg]
* Gradeability	35 [%]
* acceleration 0–100 km/h	9.2 [sec]
* Top speed	170 [km/h]
* Motor power	94 [kW]
* Driving range	400 [km]
KPI priorization	
1. Cost	
2. Efficiency	
3. Packaging	

2.1 Holistic View on System Efficiency

The various components that influence the efficiency of the powertrain are characterized by their specific efficiency mappings. For each operating state of the vehicle the product of the efficiencies of all components determines the overall value. In the case of a direct link between e-motor speed and vehicle speed - fixed ratio transmission - this is a given condition. But when the powertrain contains a (continuously) variable gear ratio, the required wheel speed and torque can be obtained by different combinations of e-motor and transmission operating conditions. Especially in the case of a CVT this gives an almost infinite flexibility for optimization, which can lead to the recognition of e-motor operating conditions that are superfluous. This relates to the low speed - high torque conditions and the high speed - low torque conditions.

Such a change of e-motor operating conditions, towards a limited set within its specification, opens the consideration for a dedicated e-motor for application with a CVT. This offers a cost reducing effect by decreasing mass and volume of active motor parts as well as bearing and balancing related cost.

2.2 Variator Design Parameter Definition

The CVT variator, being a key towards the definition of the other components, has its own design variables. The variator is characterized by its lowest and highest speed ratio, by which also the overall ratio coverage is defined. A further parameter is the center distance between the pulleys, which has an effect on the variator efficiency and it's actuation, and of course the system packaging. Related to the center distance the pushbelt load condition is affected which can lead to the selection of a different belt.

For the specification of this case study, based upon powertrain simulations, the best choice for ratio coverage is 2,1 [-]. Figure 4 shows this relationship. For the concept 3,5 has been chosen to create a unit that is flexible to be applied in a variation of powertrains.

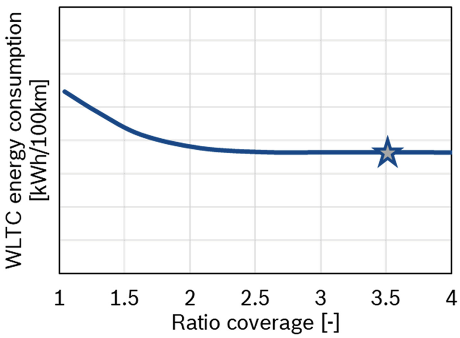


Fig. 4. Efficiency/system losses over ratio coverage

For the definition of the center distance another set of simulations was done, leading to the relationship as shown in Fig. 5.

The decision for this concept was not to go for the minimal possible center distance. The chosen dimensions offer a better overall efficiency and with that cost savings on smaller battery capacity for an equal range prevailed. Together with center distance, the torque capacity of the variator increases, which brings the opportunity to reduce the final drive ratio. The consequence of that again is a reduction of the variator speed, and thereby another reduction of losses.

2.3 Hydraulic Actuation Design

A principle difference between transmissions based on fixed gears and CVT exists in gear versus friction based power transfer. For this friction based transfer a clamping force

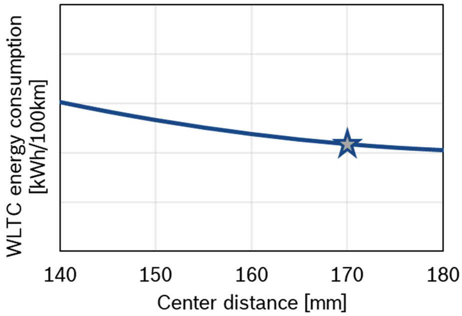


Fig. 5. Efficiency/system losses over center distance

is required, which normally is generated by hydraulic pressure. The system that provides and controls such hydraulic actuation plays a key role in the success of a powertrain. The challenge exists in the minimization of the actuation energy and at the same time to be able to deliver the responses that are required. Figure 6. shows the hydraulic scheme of the proposed control system.

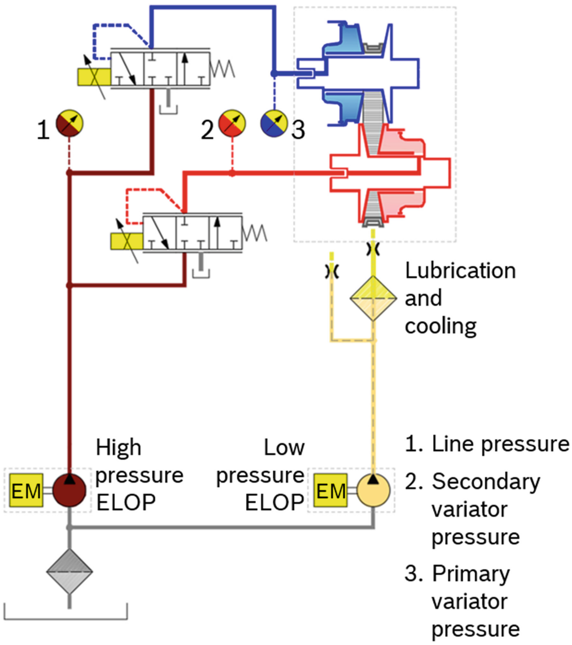


Fig. 6. Scheme of hydraulic actuation system

It is characterized by a minimal number of components, though the choice is made to separate the high and low pressure needs. With this "energy on demand" concept minimal energy consumption is enabled an important consideration in the definition of the component parameters is the responsiveness to throttle commands. As a base for the target setting, the full throttle response, from a steady state condition between ICE and electric powertrains, was compared. Figure 7. shows an example for a given kick-down action. The graph shows a distinctive difference between the two power sources. These could be characterized from comfortable to sportive.

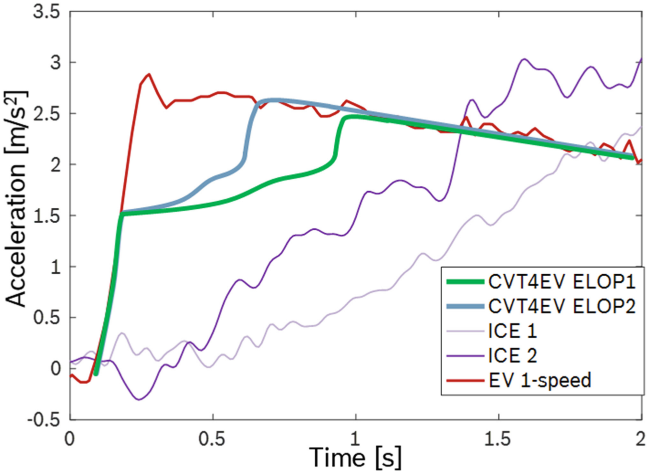


Fig. 7. ICE and EV full throttle response measurements, and simulated CVT4EV response

The response measurements of the electric vehicle are executed with a fixed gear powertrain. For the CVT-hydraulic system the actuation power was taken as a variable in order to evaluate the optimum choice between cost, performance and efficiency. The earlier mentioned KPI priority serves as a guide for this choice. Figure 7 demonstrates that the initial response as well as the maximum acceleration level is equal for a fixed gear and a CVT based powertrain. The difference exists in the transition towards the maximum acceleration which is smoothened in the CVT-case. The magnitude thereof being a function of the available clamping energy. In this case the choice is made for the smaller hydraulic power supply because of the direct relation to lower cost and power consumption. The penalty, like shown in the graph, is a relative small disadvantage which only occurs during full throttle acceleration, but still far more aggressive than the measured ICE responses.

2.4 CVT Control Strategy

The degree of freedom that is offered by the variability of the CVT needs an intelligence to make the right use of this. Therefore a transmission control unit (TCU) is programmed to decide for the right CVT set points. The right set point in this case can be defined for minimal energy consumption, maximum performance or comfort, based upon given priorities (programmed or commanded by a manual or analytic control). For the case of minimal losses the efficiency characteristic of each component is taken into account as well as their interaction. As an example for a given required wheel torque at a certain speed (so power need), various e-motor speed and torque combinations can be chosen by changing the CVT ratio. At the same time the efficiency of the battery, inverter, variator and reduction gears changes: *η-battery* * *η-inverter* * *η-E-motor* * *η-variator* * *η-reduction gears* = *η-system*. Based set upon the consideration of maximum efficiency the best operation can be decided, but if desired also a consideration for readiness for an upcoming request, such as maximum torque reserve for a kick-down, can be taken into account. Figure 8 demonstrates this process.

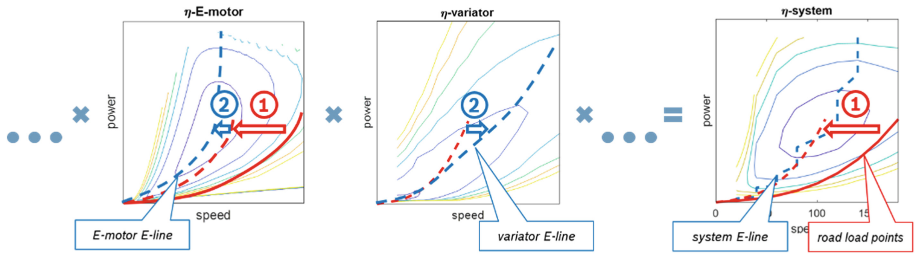


Fig. 8. Determination of system efficiency set-points

With reference to the earlier mentioned development from Variomatic till CVT4EV, Fig. 9 shows the more than 50% reduction of transmission energy losses from the current state of the art ICE CVT to CVT4EV. Figure 10 shows a comparison between the hardware of the ICE and EV application. The clear reduction in number of components and size demonstrates that the expectations about these characteristics for EV can be set to far more flexible integration and a lower cost.

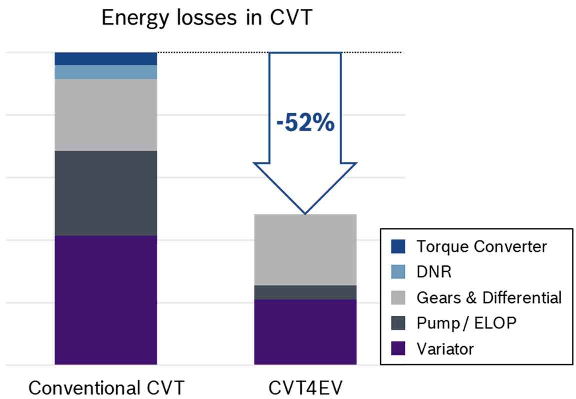


Fig. 9. CVT losses in conventional and CVT4EV powertrain

Besides that, on EV powertrain level, CVT brings a reduction of over 20% on e-motor and inverter losses, as Fig. 10 shows.

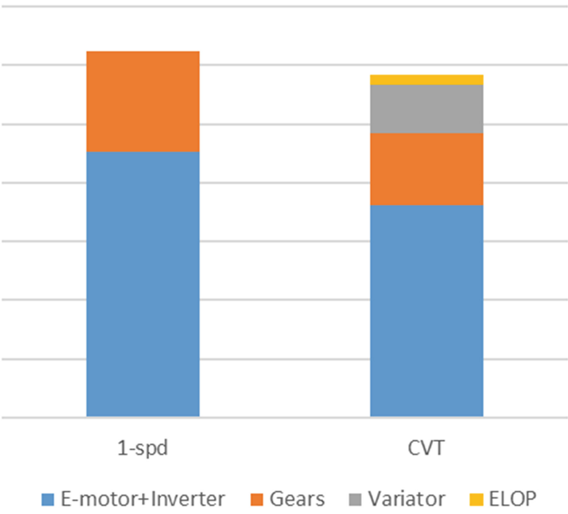


Fig. 10. Powertrain losses 1-speed versus CVT

From this it can be concluded that with the variability of CVT the electric vehicle can become your ‘thinking along’ partner in traffic (Fig. 11).

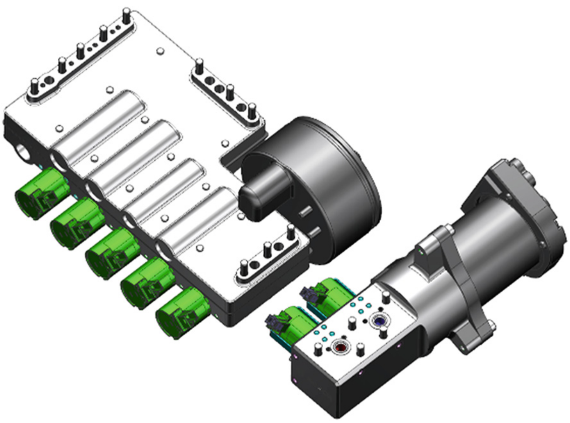


Fig. 11. hydraulic control unit for respectively conventional CVT and CVT4EV

3 CVT4EV in Hardware

The conclusion can be drawn out of the theoretical analysis of CVT in electric powertrains, that there is a potential on different KPI’s. As ever, such an insight only convinces when it can be experienced. Therefore in parallel to this study a first hardware for

CVT4EV has been set up. The motivations for this are, next to demonstrating the performance, comfort and drivability, in the development of skills regarding hardware and controls of such a powertrain.

Within this activity the performance requirements were defined by benchmarking with the base vehicle which is an electric vehicle with a fixed ratio transmission. Concrete target is to prove the ability of a CVT to at least match the drivability of the base vehicle, but with an e-motor that has a lower maximum torque. Further objective is the evaluation of the changes in the operating points with respect to speed (NVH) and responsiveness and to develop the controls based on the findings.

For this first hardware study, as mentioned, an existing fixed gear electric vehicle was selected and rebuilt with a CVT, making use of ready available or slightly adapted components. For this purpose an ICE based CVT has been selected in which the mechanical driven oil pump is substituted by an electric oil pump (ELOP), the torque converter was removed and the drive, reverse function disabled. This means that no optimization with respect to gear ratio—like an input reduction before the variator—was done and a—for the function of an electric vehicle—bulky CVT unit was installed. With respect to the controls of the vehicle, a dedicated e-drive CVT control software was developed, by reverse engineering of the base vehicle's controls. Figure 12. shows the software architecture scheme for that.

3.1 First Results

From the graphs in Fig. 13, which show the results of a wide open throttle acceleration it can be learned that:

* with a reduced maximum motor torque the similar acceleration from standstill can be achieved

* the e-motor speed becomes independent from the vehicle speed

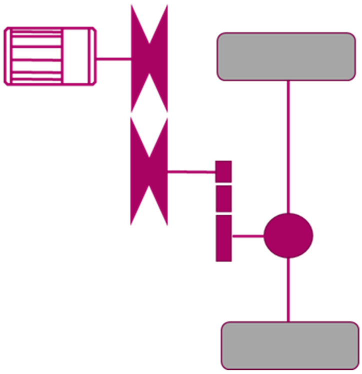
* a higher maximum vehicle speed is possible, without a compromise on launch performance

or the similar maximum vehicle speed is achieved with a lower e-motor speed

These results show that the potential for a dedicated e-motor, designed for lower maximum torque and lower maximum speed can be explored. This opens the option to a design with a reduced size and volume of active parts, saving on magnets and cupper. Reduced speed brings cost reduction potential by a reduced level of bearing and shaft balancing requirements.

4 What CVT4EV Can Bring

As addressed in the previous paragraphs, the flexibility that CVT brings to the powertrain can be exploited in different ways. The choice for that should be motivated from the priority setting between the KPI's as well as the use-case for which the powertrain will be applied. But some of the benefits are inherent. One of these is the reduction of e-motor speed at higher vehicle speeds, by which the vehicle performance is brought on a higher level.



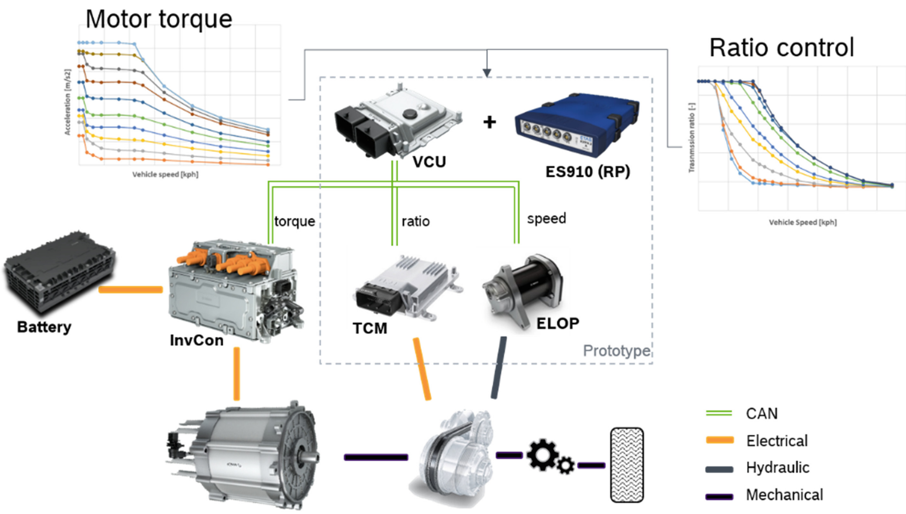


Fig. 12. Software architecture CVT4EV demonstrator

* for intermediate accelerations, like 80–120 km/h a better performance is delivered because the CVT will keep the e-motor in its peak power operation.

* a higher maximum speed results from a similar operation by keeping the e-motor in its peak continuous power operation.

The reasoning that concluded chapter 3.1 can also be valid for the flexibility to match e-drive components to a wider variety of requirements. This can be supportive to a modular line-up approach. Figure 14 shows how CVT can offer both an increased low ratio enabling to drive off with higher loads from standstill and uphill as well as a decreased overdrive gear ratio that prevents limitation of top speed performance.

With this insight the exploration of different use cases with the CVT as the enabling element can be challenged. Bosch is ready to support with its components and system know-how to create successful new solutions.

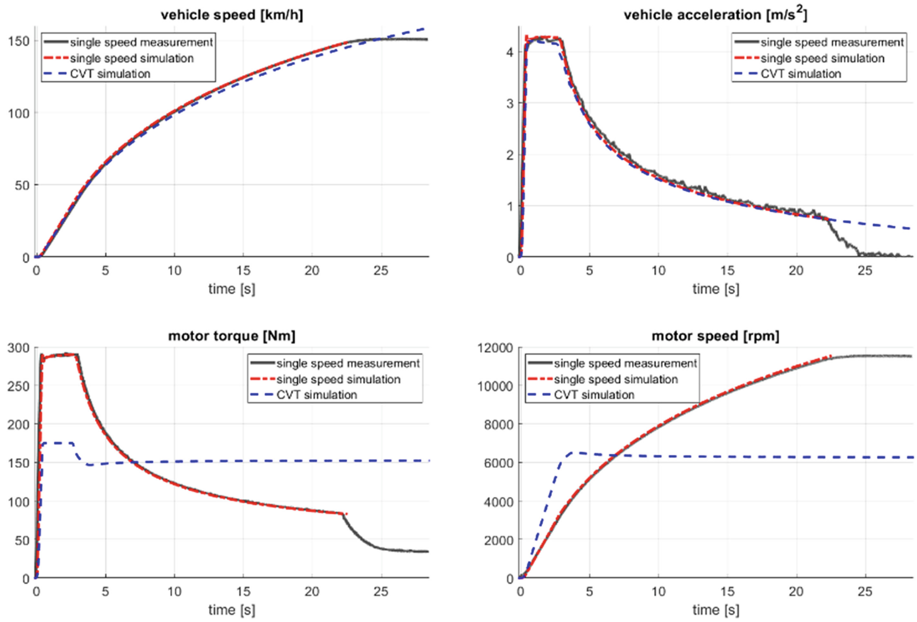


Fig. 13. Acceleration performance evaluation

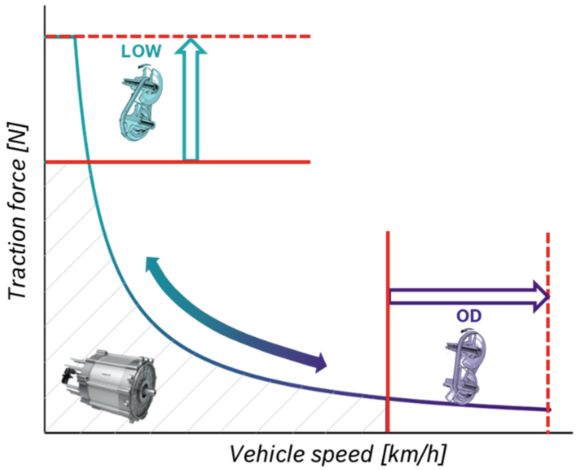


Fig. 14. Potentials for e-motor application with CVT

5 Conclusion

- CVT is ready to be applied in electric powertrains and can be the key for the improvement of different customer values
- A design study is presented that focuses on cost and energy economy

- The design considerations for the variator and the hydraulic control system are explained
- Based upon the understanding of the design parameters the control set points for the desired KPI performance are generated
- The flexibility that is provided by CVT enables downsizing of the e-motor or application of a given e-motor into new use-cases
- The study results have been included into a first hardware development and demonstration platform, with initial results available
- For the future, further optimization of this concept is envisaged that will further enhance the benefit of the CVT equipped electric powertrain.

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