MOŽNOSTI HYBRIDIZACE VOZIDLA S MANUÁLNÍ PŘEVODOVKOU

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POSSIBLE HYBRIDIZATION OF A VEHICLE WITH A MANUAL GEARBOX

Abstract: *Driver operated manual transmission holds more than 70 % market share in Europe. In certain vehicle segments, this share is even bigger. On the one hand this type of mechanism brings outstanding efficiency but on the other hand cannot provide shifting under torque load, thus limiting driving comfort. Implementing advanced features like self-driving capability or hybridization are also difficult. Because of the inconsistency caused by the human driver, complex control of these functions is impossible. This paper is focused on a way of electrifying a manual transmission so it could provide advanced functions, improve efficiency and maintain low price.*

Key words: *HEV, Hybridization, Hybrid Automated Manual Transmission*

INTRO

From certain point of view, motor vehicles can be sorted into two main groups: those with driver operated transmission and those with automated/automatic transmission. From an automotive engineer's perspective, this means using different transmission mechanisms with different advantages and disadvantages.

Conventional ATs (Automatic Transmissions) and DCTs (Dual Clutch Transmissions) suffer from mechanical complexity (negatively influencing especially price). These mechanisms usually work with hydraulically actuated shifting elements. Thus, overall transmission efficiency is affected by parasitic friction losses in open shift elements. Oil pumps are required, representing another source of losses, as well as slipping torque converter in conventional ATs. But there's a significant advantage: Friction multi-plate shift elements allow shifting under torque load, which is very comfortable for driver and passengers. Automated systems can also perform certain maneuvers automatically. Remote Parking Assist or Adaptive Cruise Control with Stop&Go cannot be performed with the need to operate a clutch manually.

Manual transmission on the other hand, offers low price and very good efficiency. Conventional synchronizers are widely used as shift elements. They have very small friction losses and can be easily actuated (even electrically, which further lowers power demands in comparison with hydraulic control). Main disadvantage: Shifting under torque load is impossible. Shifting without torque load leads to a so called "torque gap" which is recognized to be very unpleasant, especially by the driver, who isn't aware when will the shifting occur. This contributes to a very low success on a market.

Improvement of a manual transmission can be a solution. It should be upgraded (automated) in order to implement modern ways of engine control (engine sweet spot tracking) but also to fulfill future ADAS (Advanced Driving Assistance Systems) requirements. Automation, together with hybridization then allows us to implement more sophisticated shifting control strategies. This should contribute to further reduction of CO_2 emissions, but also improve behavior of the mechanism significantly, so it would be attractive for the customers [1]. This article proposes implementation of an electric motor into a modular VW MQ200 manual gearbox, but the principle can be transferred to many other transmissions with suitable layout. Development in this field would make a big overall impact as there is a substantial number of vehicles equipped with manual transmission, especially in Europe [3].

CHOSEN VEHICLE PARAMETERS

Article will be focused on VW modular MQ200 transmission with 200 Nm maximum torque capacity. Because we want to keep the price as low as possible, 1.0 TSI (70 kW) three-cylinder engine is chosen, which is exclusively available with 5speed variant of the MQ200. This gearbox offers very good modularity. Fifth gear is closed in a removable housing cover in the rear part of the gearbox casing (left yellow part in Fig. 1). It is possible to take the cover off and modify this

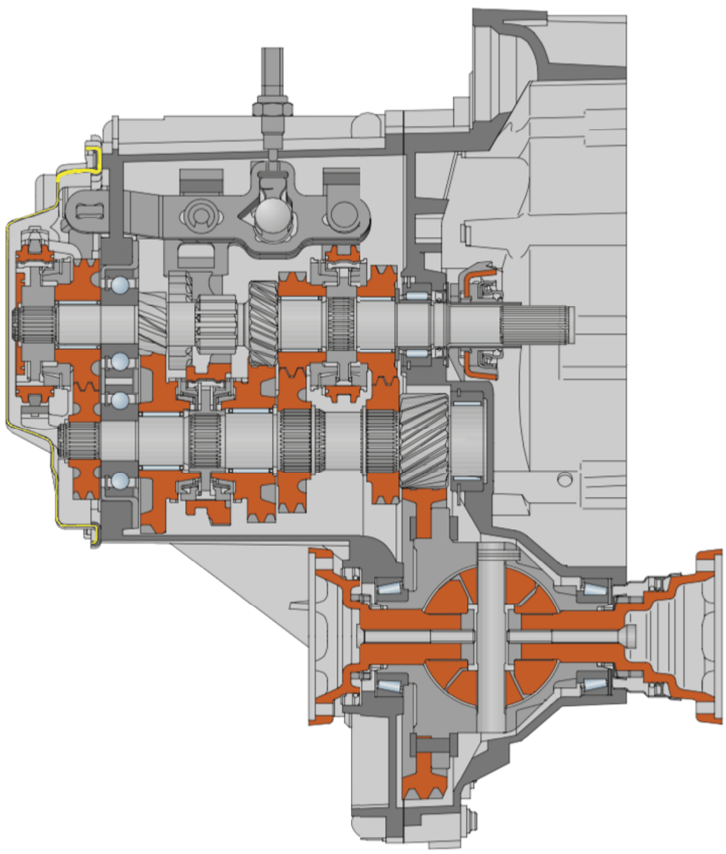

Fig. 1 *VW MQ200 gearbox, 5 forward gears [4]*

end of the transmission with no need to replace any other casing components. This makes MQ200 very suitable for intended application. Vehicle parameters and transmission gear ratios are to be found in Tab. 1:

Tab. 1 *Škoda Fabia 1.0 L TSI (70 kW) parameters*

Vehicle parameters		Transmission ratios	
Curb weight [kg]	1130	i_1	3,77
Frontal area [m^2]	2	i_2	1,96
Drag coefficient	0,326	i_3	1,28
Tire size	185/60 R15	i_4	0,93
Tire dyn. rad. [m]	0,299	i_5	0,74
Final drive ratio	3,625	i_R	3,18

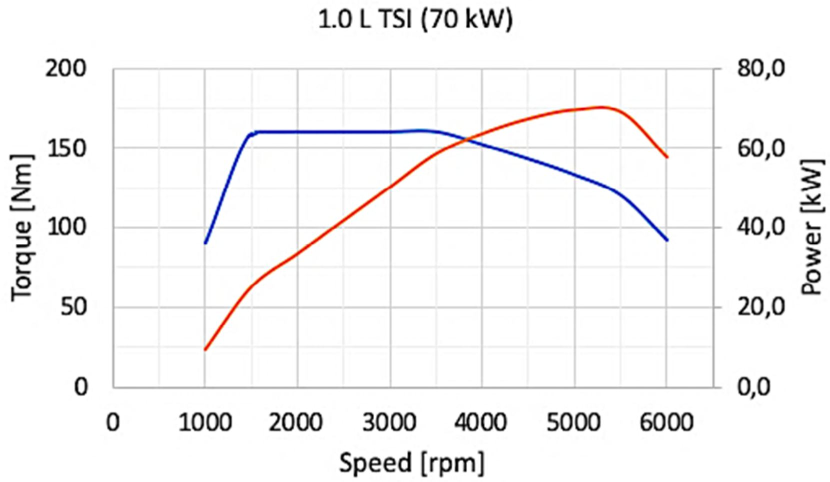

Fig. 2 *1.0 L TSI (70 kW) Performance*

With the help of the electric machine, system performance will be improved. There is a question if this improvement will meet or even exceed 85 kW 1.0 TSI (with 7 speed dual clutch transmission) performance and whether the price will be competitive.

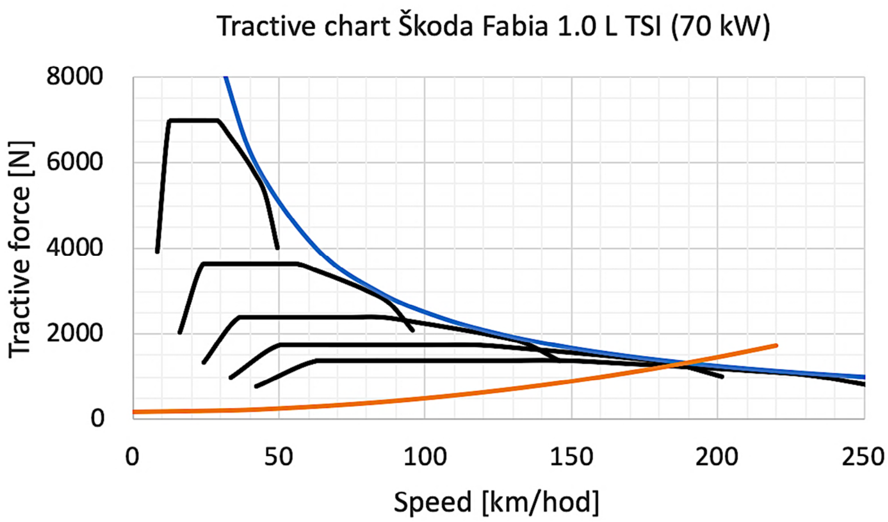

Fig. 3 *Škoda Fabia Tractive chart (1.0 L TSI 70 kW) with 5speed MQ200*

EXISTING ADD-ON HYBRID POSSIBILITIES

Hybridization of a manual gearbox involves installing an electric machine into an existing drivetrain. As we want to keep the transmission as similar to a production one as possible, the electric motor will be installed as “add-on” part. Some of the existing possibilities are described with so-called PX-position system.

P0 Position (“Starter/Generator”)

Very simple way of hybridization of a conventional vehicle. In this layout, conventional alternator is replaced by a more powerful starter/generator. Extended stop-start operation is permitted. The e-boost is possible too. The biggest disadvantage is that pure electric drive isn’t possible, even using a more powerful electric motor and battery. This architecture only allows a mild hybrid, not full hybrid capability.

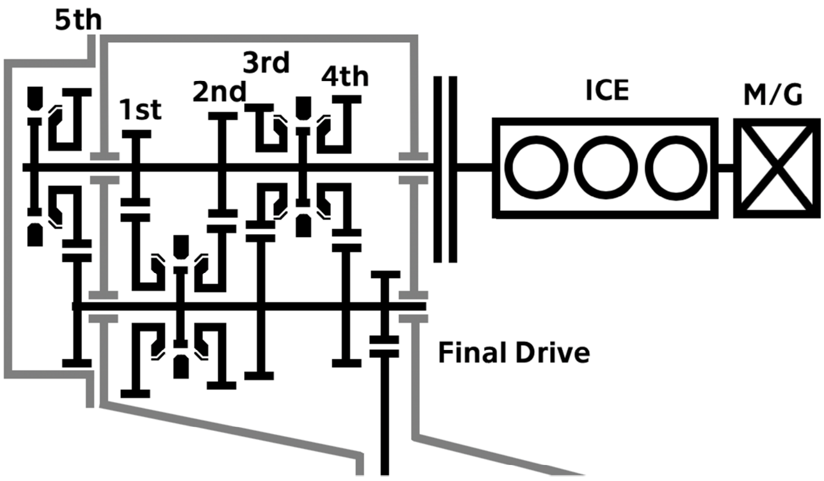

Fig. 4 *P0 Hybrid Layout*

In Axis P2 Position

Electric motor mounted on a transmission’s input shaft allows electric machine to profit from benefits of a stepped gearbox: Torque multiplication allows using smaller M/G, but gear losses are

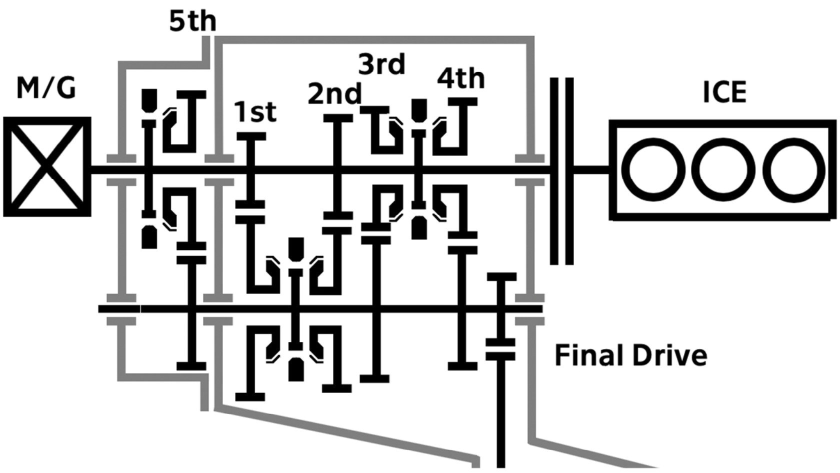

Fig. 5 *P2 Hybrid Layout*

higher. Engine cranking or external synchronization during shifting is also possible. This placement is very favorite in automatic transmissions. In case of manual transmission, P2 is not so promising, because it doesn't prevent torque interruption during shifting. Integration of an axially mounted M/G is shown in Fig. 5. Coaxial installation is also possible. High speed M/G with reduction gear can be smaller, but there will be additional losses in gearing.

P3 Position

Electric motor mounted to a differential gear or to a transmission output shaft. In this arrangement, the M/G can provide smooth pulling force in low-speed, driver-independent maneuvers and serve as TGF (Torque Gap Filler) during shifting. Getrag claims that shift quality with electric TGF can be comparable to a good automatic transmission, except 1-2 WOT (Wide Open Throttle) upshift, even if the electric motor performance reaches only 20-40 % of the ICE (Internal Combustion Engine) performance [1]. According to Schaeffler, this can be done with a 48-V hybrid system (covering electric motors up to 20 kW of power), further reducing overall price [2]. Full potential of recuperation is unleashed with motors over 20 kW, because during usual braking, no bigger power flows in the system. Using low-speed M/G with high torque allows only one gear pair (low gearing losses) but only one speed for the electric machine isn't much favorable. Using at least two M/G gears would be better but it would bring another complication, as it needs additional shifting system. In P3 arrangement, it is not possible to charge battery via ICE at vehicle standstill, which can be a useful feature sometimes (battery depleted).

Intended PMSM (Permanent Magnet Synchronous Motor) is permanently excited (permanent magnets), so it can't cease its operation when unnecessary (high speed highway driving). Transmission mechanism should be able to disconnect motor from wheels during these unfavorable conditions. An extra clutch (not depicted in the on Fig. 6 or Fig. 7) has to be implemented into the gearbox.

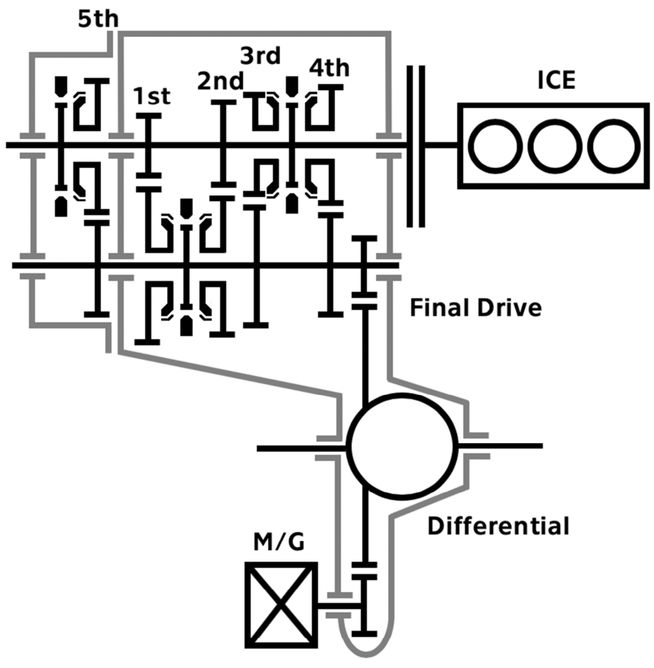

Fig. 6 *P3 Hybrid layout (type 1)*

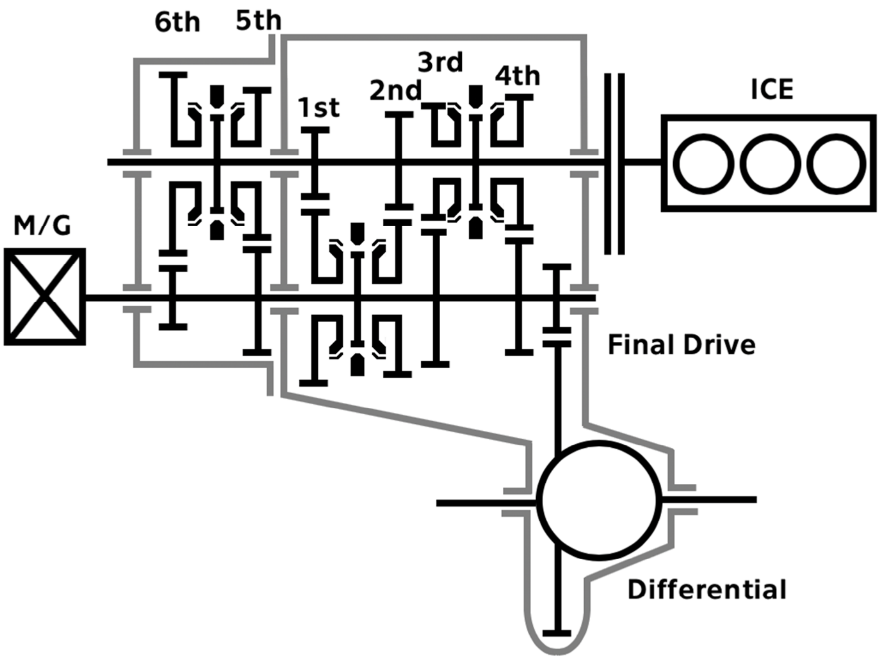

Fig. 7 *P3 Hybrid layout (type 2)*

P2-P3 POSITION

General Overview

The aim of this article is to present an arrangement combining advantages of all of the above-mentioned full-hybrid layouts.

If motor-generator can be connected to both transmission shafts via shiftable device (in place of 5th and 6th gear pair). This allows operation in both P2 and P3 modes. Tab. 2 describes main features of these widely used designs. Proposed shiftable P2-P3 arrangement offers all of the important hybrid vehicle features. The only drawback is slightly increased mechanical complexity (additional shift element required) in comparison with other add-on variants. However, it doesn't require conventional synchronizers, the simple dog clutch would be sufficient, as the synchro-nization can be performed with the electric motor power.

Tab. 2 *PX hybrid layouts comparison*

<table>
<tr><th></th><th>P0</th><th>In Axis P2</th><th>P3 (type 1)</th><th>P3 (type 2)</th><th>P2-P3</th></tr>
<tr><td>Pure EV drive</td><td>NO</td><td colspan="4" rowspan="2">YES</td></tr>
<tr><td>E-Boost</td><td>YES</td></tr>
<tr><td>Efficient power flow</td><td>-</td><td>-</td><td>+</td><td>-</td><td>0</td></tr>
<tr><td>Multiple EV gears</td><td>NO</td><td>+</td><td>-</td><td>-</td><td>+</td></tr>
<tr><td>Mechanical simplicity</td><td>+</td><td>+</td><td>+</td><td>+</td><td>0</td></tr>
<tr><td>ICE runs M/G at standstill</td><td>YES</td><td>YES</td><td>NO</td><td>NO</td><td>YES</td></tr>
<tr><td>Low speed TGF</td><td>NO</td><td>NO</td><td>YES</td><td>YES</td><td>YES</td></tr>
<tr><td>External synchronization</td><td>NO</td><td>YES</td><td>NO</td><td>NO</td><td>YES</td></tr>
</table>

Layout and Shifting Table

Layout was designed for a 5speed MQ200 variant. This should compensate packaging demands of an electric motor, which can be placed partially in the place where 6th gearwheel was. To keep as many carry-over parts as possible, the only modified parts will be the housing cover and 5th driven wheel, which can be released from the output shaft via a dog clutch. Synchronization is ensured with the help of the electric motor.

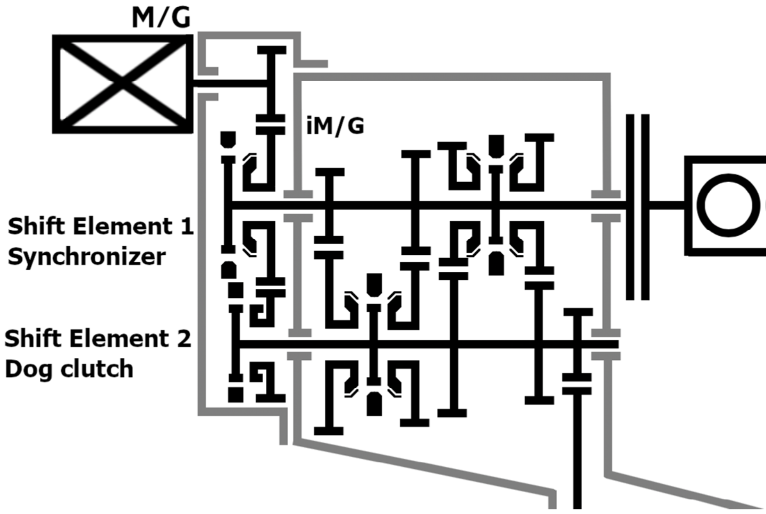

Fig. 8 *P2-P3 Hybrid layout*

Tab. 3 *Hybrid transmission shifting table*

	SE 1	SE2
P2 Mode	X	
P3 Mode		X
5th gear E-Boost	X	X
M/G Disconnected		

Number of Gears

Škoda Auto doesn't offer 1.0 TSI (70 kW) with 6 gear transmission. "Missing" 6th gear can be substituted with a longer (numerically lower) final drive ratio. This changes the total gear ratio of all of the other gears, lowering tractive force respectively. Especially in the lower gears, this can be a problem. But with the help of the electric motor (e-boost in low gears) it's possible to overcome this disadvantage. This is another hybridization benefit.

Unfortunately, this layout doesn't allow electric machine to be disconnected in 5th gear. Using a one-way clutch isn't preferable, because it would make recuperation impossible. Additional dog clutch can be placed to a M/G shaft, disconnecting it from the rest of the powertrain.

CHOOSING THE MOTOR/GENERATOR

The first condition for choosing the correct M/G is the speed range. In P2 mode, electric machine has to work in the entire ICE speed range (0-6000 rpm). Because M/G is mounted to a transmission input shaft via a reduction gear, it's possible to adjust its speed up to a certain extent.

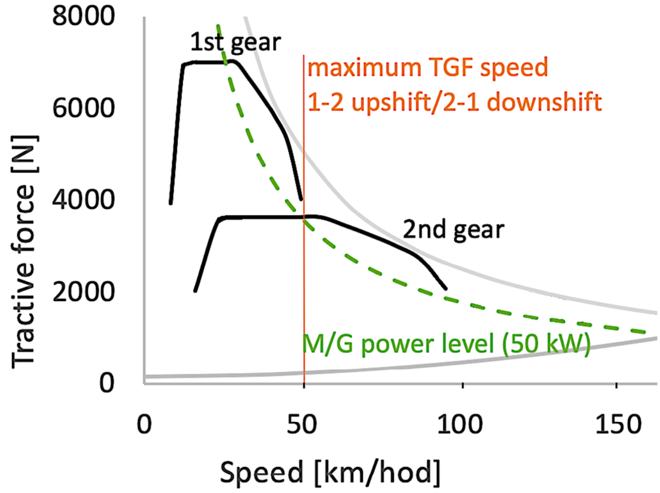

Fig. 9 *Wide Open Throttle (WOT) upshift with electric TGF (50 kW)*

According to the tractive chart (see Fig. 9), we will determine power of the electric motor. The maximal tractive force during WOT acceleration in 2nd gear is slightly over 3600 N. That's what M/G should provide in order to make acceleration during 1-2 upshift perfectly smooth. In maximum speed where 1-2 upshift/2-1 downshift is possible (50 km/hod), this requires about 50 kW of power (Fig. 9). This power level would roughly satisfy demands for any gear change with desired TGF capability, but it's too much for 48 V architecture, which is able to deliver 30 kW in the most powerful applications [6]. If we want to keep this power level, we have to go for a high voltage.

Following calculations are performed for YASA P400 R Series engine. Delivering peak 58 kW in very wide speed range, it can provide the TGF capability smoothly. Motor performance is shown in Fig. 10. Continuous performance is approximately half of the peak performance (which lasts for 30 seconds).

Tab. 4 *YASA P400 R Series [7]*

Motor Parameters		Dimensions	
Speed	0-8000 rpm	Outer Diameter	305 mm
Peak Power (250 V)	58 kW	Axial Length	107 mm
Peak Torque (30sec)	375 Nm	Dry Mass	28.2 kg
Continuous Power	20 kW	Stator Cooling	Oil

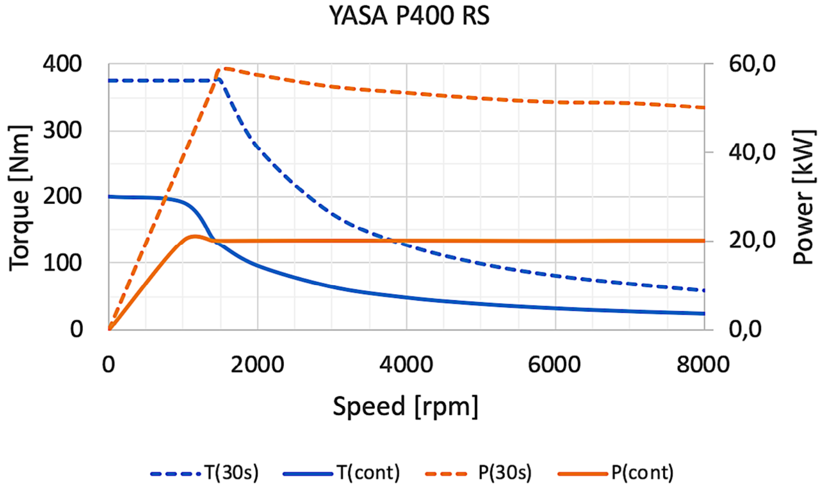

Fig. 10 *Yasa P400 RS Performance [7]*

RESULTING CHARACTERISTICS

Motor/Generator Gear Ratio Calculation

Total gear ratio from M/G to wheels will be calculated from $i_{M/G}$, i_5 and i_{FD}. There are many possibilities of gearwheel combinations in MQ200, but we will be calculating with standard Škoda Fabia 1.0 TSI (70 kW) gear ratios. Thus, we can only optimize the $i_{M/G}$ parameter (size of the M/G pinion). If we want to match speed range of the ICE (0 - 6000 rpm) to the M/G (0 - 8000 rpm), even this parameter is already determined as:

$$i_{M/G} = \frac{n_{M/G\,max}}{n_{ICE\,max}} = \frac{8000}{6000} = 1,25 \tag{1}$$

$$i_{M/G\,total} = i_{M/G} \cdot i_5 \cdot i_{FD} = 1,25 \cdot 0,74 \cdot 3,625 = 3,353 \tag{2}$$

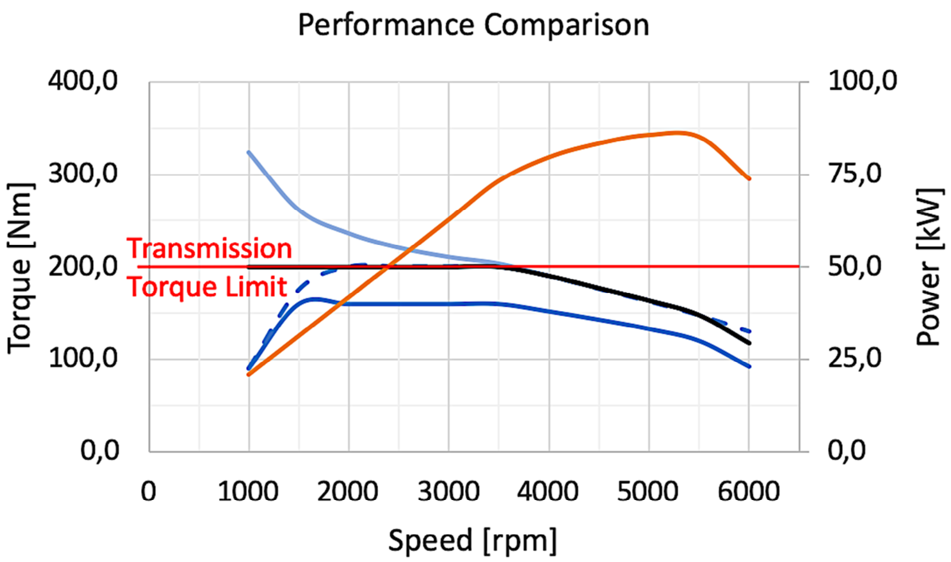

Fig. 11 *System Performance Comparison (P2 Mode)*

To see if the calculated ratio is suitable for both P2 modes of the transmission, overall system performance comparison was made (Fig. 11). Chart shows (continuous) system torque (light blue line) is much higher than transmission torque limit under 3500 rpm. We cannot use full potential of the P2 arrangement. Maximum torque must be electronically limited at 200 Nm (red line) which makes the power line (orange) linear from 1000 rpm to 3500 rpm. In P2 hybrid mode, although very limited by the transmission, system produces 85 kW, which is comparable to stronger 1.0 L TSI engine variant.

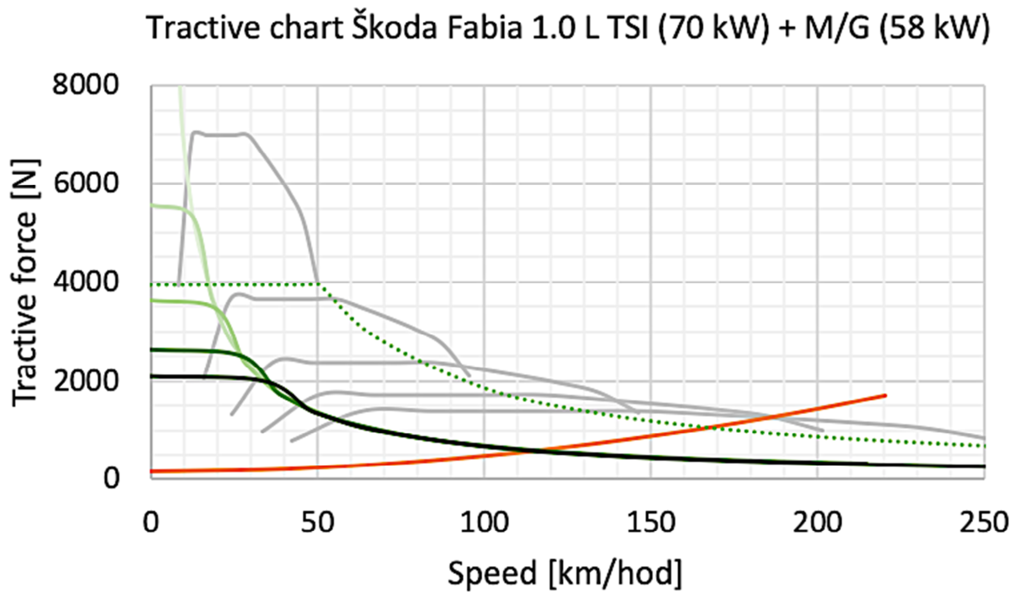

Fig. 12 *Tractive chart Škoda Fabia 1.0 L TSI (70 kW) + M/G YASA (58 kW)*

Tractive force in P2/P3 pure EV mode is also very promising (Fig. 12). Green dotted line signs that desired TGF functionality (M/G peak power) can bypass the torque gap even during WOT acceleration in almost entire vehicle speed range.

Green lines going from the lightest (first gear) to the darkest (last gear) show continuous tractive force of the electric motor. Driving in second gear, vehicle would be able to hold a speed over 110 km/hod and because electric motor can be overloaded for 30 seconds, there will not be a substantial lack of power.

Modular Possibilities

Described hybrid architecture offers potential for a plug-in hybrid vehicles too. Mechanical side of the design is “plug-in ready”. Chosen electric motor has a possibility of a voltage scalability. Appropriate battery pack would be necessary, this equipment would have to be upgraded. Pure electric drive is ensured in TGF (P3 hybrid) mode and in every gear of the stepped transmission (P2 hybrid). This is what P0 arrangement cannot provide.

Future Development

Although the mechanism can work with a manually operated clutch and gear shift lever, automated operation is favored. Application and control of the entire transmission have to be a subject of a future development. The most important function is the torque gap filling during shifting, hybridization of vehicle is a complementary function (but very favorable in terms of CO_2 reduction).

In case of series production, some other improvements can also be implemented. As the electric motor can serve as an external synchronization, higher transmission gears don't require synchronizers. Torque gap isn't so unpleasant in higher speeds.

CONCLUSION

Idea of an upgrade of the VW MQ200 transmission was presented. Electric motor installed to a conventional manual transmission can serve as a torque gap filler (P3 hybrid). One actuated dog clutch is required to provide shifting from P3 to P2 hybrid mode and vice versa, so the vehicle is able to operate in multiple transmission gears.

Mating YASA P400R electric motor (58 kW peak, 20 kW continuous) with a 1.0 L TSI (70 kW) and MQ200 transmission makes 85 kW of total system power, which is comparable to a more potent 1.0 L TSI (85 kW), gaining hybrid capability and automated shifting (under torque load). If the transmission was more durable, total continuous power of this hybrid powertrain could reach up to 96 kW.

REFERENCES

[1] GETRAG Ford Transmissions GmbH, Magna Powertrain. *P3 Hybridization of Manual Transmissions. CTI Mag* [online]. 2017, July 31, 2017 [cit. 2019-08-05]. Available at: https://drivetrain-symposium.world/de/cti-mag-p3-hybridization-of-manual-transmissions/

[2] SCHAEFFLER. *Fact Sheet XXL: 48 Volt: New dynamism in the car [online]. [cit. 2019-08-05]. Available at:* https://www.schaeffler.de/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/brochure/downloads_1/48_Volt_fact_sheet_xxl_de_en.pdf

[3] *Global light vehicle production by transmission type in 2012 and 2017. Statista.com* [online]. October 10, 2013 [cit. 2019-08-05]. Available at: https://www.statista.com/statistics/204123/transmission-type-market-share-in-automobile-production-worldwide/

[4] VOLKSWAGEN AG, *Manual gearbox 02 T: Design and function* [online]. [cit. 2019-08-05]. Available at: http://www.volkspage.net/technik/ssp/ssp/SSP_237_d1.pdf

[5] ŠKODA AUTO. *Vnější výkonová a momentová charakteristika motoru 1,0 TSI (85 kW). In: ŠKODA Storyboard* [online]. June 9, 2016 [cit. 2019-08-05]. Available at: https://www.skoda-storyboard.com/cs/engine-charakteristics-2/

[6] CONTINENTAL AG. Low Voltage, High Performance: Full-Hybrid Vehicle with 48-Volt High-Power Technology [online]. July 2, 2019 [cit. 2019-08-05]. Available at: https://www.continental.com/en/press/press-releases/2019-07-02-48v-high-power-176814

[7] YASA LIMITED. YASA P400 R Series Datasheet [online]. 2018 [cit. 2019-08-05]. Available at: https://www.yasa.com/yasa-p400/

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