Design of a Wheelset Drive

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Abstract — **The paper describes trends in individual wheelset drive and drives of the independently rotating wheels of modern low-floor trams and railway vehicles. It documents the way of a constructive design of the individual wheelset drive (without gearbox) and wheelset drive with gearboxes.**

Keywords — Railway vehicle, modern AC drives, design of mechanical parts of traction drive, low-floor trams, electric locomotive, electric train units.

I. Introduction

From 90 years of the 20th century, the wheelset drive of rail vehicles uses modern AC drives. The basic powertrain consists of an induction motor (IM) or a synchronous motor with permanent magnets (PSMS). The driving torque of an electric motor is transmitted across the components (mechanical parts) of the drive on the wheelset or on wheels drive portal axles of low-floor trams [1, 2].

II. Design of Traction Drives for Low-Floor Trams

Use of a low floor in the throughout length of the passenger compartment in low-floor trams required to locate wheelset drive or drive of independently rotating wheels on the outside of the tram-wheels. The design (dimensions) of mechanical parts of the independently rotating wheel drive (IRW) or wheelset drive (CW) is dependent on the free space which is available in the bogie for installation of the drive. The lower and lateral part cross-sections are limited by the kinematic gauge for the bogie vehicle. The upper parts are limited by height of the floor above the bogie. In the 25 years of the low-floor tram development a large number of the mechanical drive design variants were developed. Some remained at the prototype stage, others have been successfully implemented. The successful designs can be divided into four basic groups.

A. Drives with Transverse Mechanical Coupling of the Independently Rotating Tram Wheels

This drive concept has been motivated by a desire to maintain (during driving vehicle) sinusoidal movement of the wheelset. The design of these traction drives is successfully resolved in two basic versions. The first variant represents a solution of fully sprung traction motor with a disc brake, connected rigidly to the frame car body. The two-axle bogie has one driving axle and is powered by traction induction motor with power of about 85-100 kW, see Figure 1.

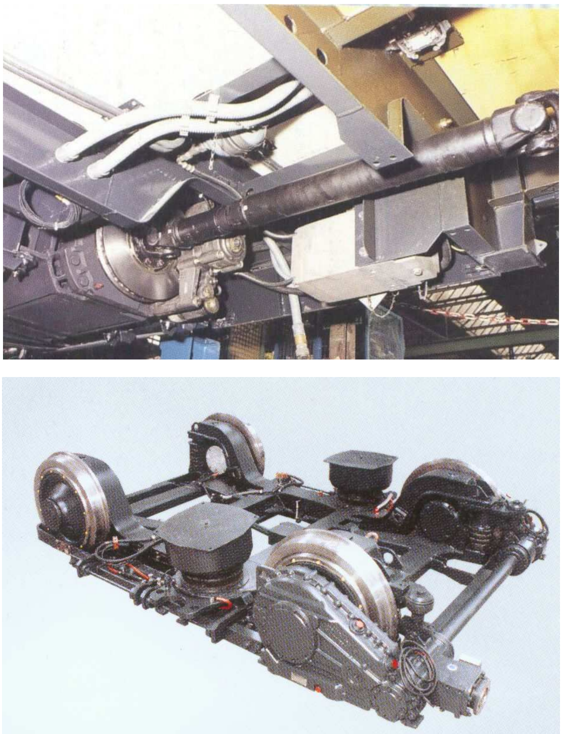

Fig.1. Concept of traction drive in not pivoting bogie low–floor trams “Brems-tram” [*AEG, MAM, Voith*].

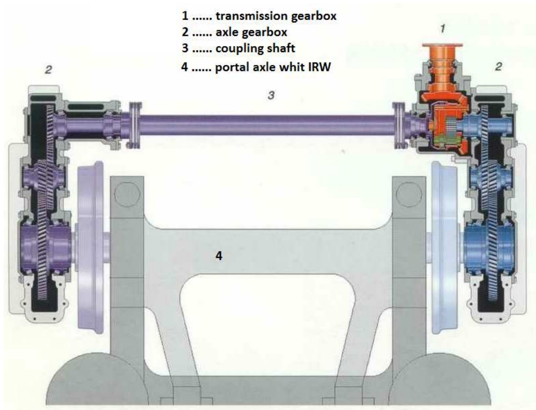

Fig.2. Concept of gearboxes in not pivoting bogie low–floor trams “Brems-tram” [*AEG, MAM, Voith*].

The long cardan shaft is driving torque transferred into the transmission gearbox. That consists of bevel gears and self-locking differential, see Figure 2. Transmission gearbox is positioned in front of one of the axle gearboxes. Four wheeled axle gearboxes represent the concept of the partly sprung traction drive. This design of the drive can be used only in city with a flat level urban tram track. The efficiency of the traction drive mechanical part is about 90 %.

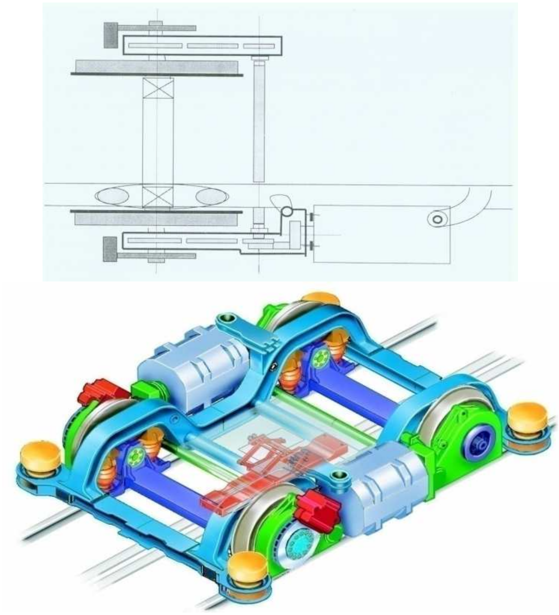

Fig.3. Concept of traction drive in not pivoting bogie low–floor trams Sirio 7C4 [*Ansaldo Breda*].

The second variant of the traction drive, see Figure 3, has an analogous structural design. The difference is that the longitudinally oriented traction motor (IM with power of about 100 kW) is fixed to the bogie frame and the torque is transmitted through the cardan shaft into the transmission gearbox. That consists of bevel gears and self-locking differential. The transmission gearbox is positioned in front of one of the axle gearboxes. The output shaft of the transmission gearbox drives the opposite axle gearbox. Three wheeled axle gearboxes represent the concept of the partly sprung traction drive. Unsprung traction bogie mass weight is about 1650 kg. This drive concept is quite complex, with the efficiency of the traction drive mechanical part of about 85 %.

B. Drives with Longitudinal Mechanical Coupling of the Independently Rotating Tram Wheels

This concept does not guarantee sinusoidal movement of the wheelset. The design of these traction drives is successfully resolved in two basic versions. The first variant, Figure 4, represents a solution of fully sprung traction drive, wherein the longitudinally oriented driving motor (IM or PMSM with power of about 110 kW), together with the bevel or hypoid gear boxes constitute an integrated unit, which is attached to the bogie frame. The hollow output shaft of the hypoid gear box is connected to the PTO driving shaft of the tram wheel. This concept has minimum unsprung mass of the traction drive and the efficiency of the traction drive mechanical part is about 95 %. The weigh of one integrated unit is about 870 kg. The traction bogie SF 30 TF weigh is about 4500 kg, unsprung mass is only 1300 kg.

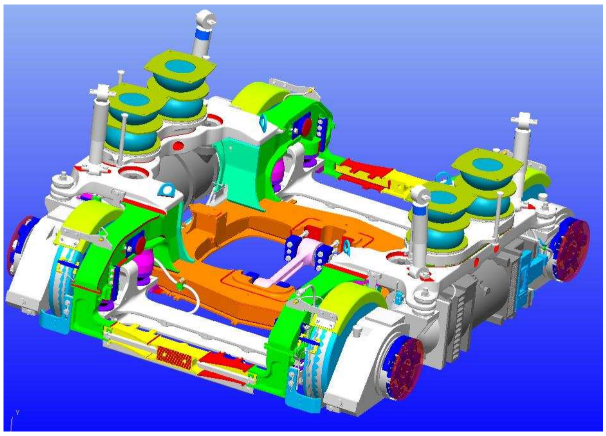

Fig.4. Concept of traction drive in partly pivoting bogie SF 30 TFW low–floor trams Avenio [*Siemens*].

A second variant of the drive is shown in Figure 5 and represents the concept of the partly sprung traction drive. There is the longitudinally oriented traction motor which is mounted on the bogie frame; via two articulated joint shafts the torque of the axle-hypoid gearbox is transmitted. Their output shafts drive the front and rear tram wheels on one side of the two-axle bogie. Induction motors work with the nominal power of about 120 kW. The efficiency of the traction drive mechanical part is about 94 %.

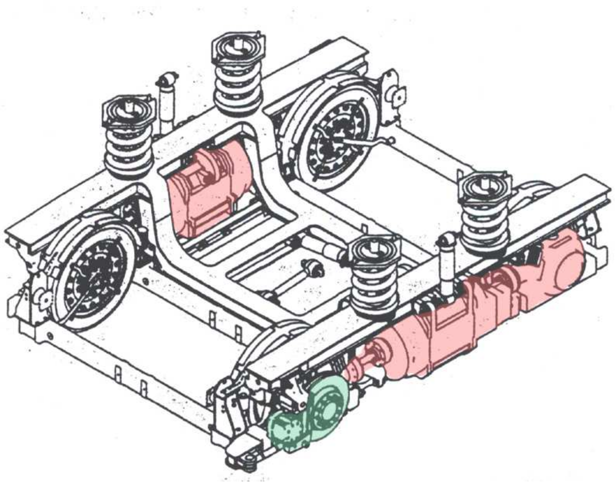

Fig.5. Concept of traction drive in not pivoting bogie Corege low–floor trams Citadis 302 B [*Alstom*].

C. Drives without Mechanical Coupling of the Independently Rotating Tram Wheels

This concept does not guarantee sinusoidal movement of the wheelset. This group of traction drives is represented by two concepts, see Figure 6. The first variant of the solution is represented by a completely unsprung wheel-traction motor. In application of the synchronous permanent magnet motor (PMSM), the motor is implemented as a direct drive. The weight of the synchronous motor with power of 45 kW, which is water-cooled, is about 500 kg. The efficiency of the traction drive mechanical part is about 99 %. In application of an induction motor (IM) the planetary gearbox is used. The weight of the water-cooled induction motor with power of 55 kW is about 425 kg. The efficiency of the transmission mechanical part is about 98 %. This concept is more economical way of solutions of the drive with respect to the spatial installation in the bogie however on the other hand, the wheel-motors are becoming unsprung mass. The tramcars with this drive require a high quality and geometrically stable tram track.

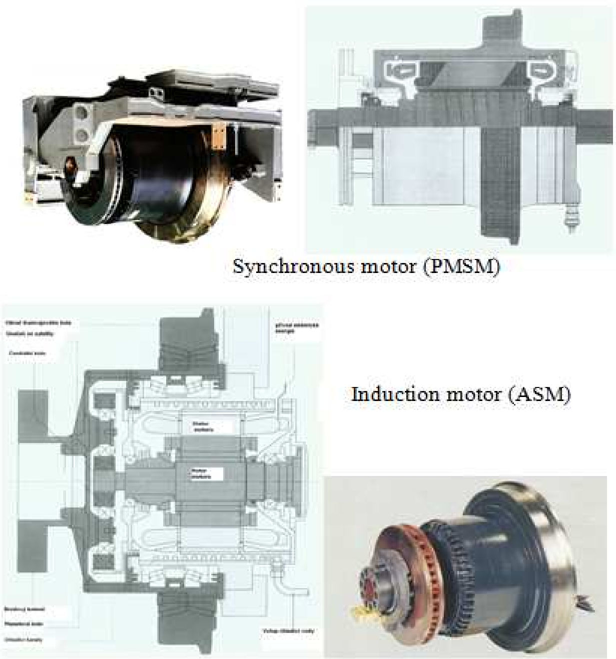

Fig.6. Concept of traction wheel motors.

A modern version of a fully sprung direct traction drive in two-axle bogie is the application of the synchronous motor with power of 55 kW. The traction motor with the hollow shaft of the rotor is mounted on the bogie frame. In the hollow rotor of the motor the PTO shaft is mounted and it drives a tram-wheel, see Figure 7.

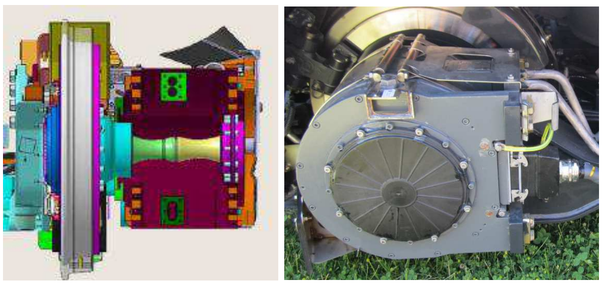

Fig.7. Concept of drive wheel of tram Skoda 15 T.

The second conceptual solution of the traction drive is represented by an integrated driving unit, consisting of the traction motor and wheel gearbox with the hollow output shafts. The output drive torque is transmitted through the coupling type “Alstom” on the tram-wheel. The efficiency of the traction drive mechanical part is about 95 % (for three helical gears) or 97 % (for two helical gears). Example of this completely sprung drive design is shown in Figure 8. On the gearbox output shaft a disc brake is mounted. The brake unit, which is not shown in Figure 8, is mounted on the gearbox.

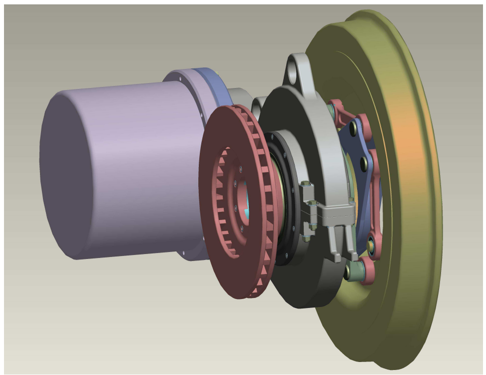

Fig.8. Concept of integrated driving unit - induction motor with gearbox with hollow output shaft.

Into this design group the full sprung driving unit tram wheel of tram ULF 197 belongs. The driving unit consists of a traction motor, hypoid gear and disc brake, which are placed on the opposite side of the traction motor, see Figure 9.

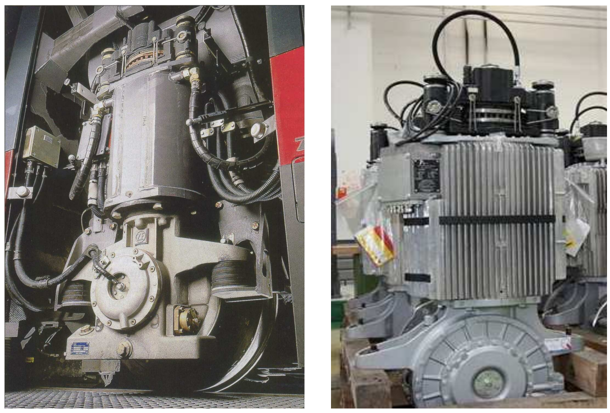

Fig.9. Concept of the traction drive in not pivoting one-axle bogie Tram ULF 197 [*Siemens*].

The first generation of one-axle bogies uses traction induction motors of power 60 kW, which are cooled by water.

The second generation of the one-axle traction bogies uses motors of power 80 kW with own air-cooling ventilation.

The output drive torque is transmitted through the sprung coupling to the tram-wheel. The efficiency of the traction drive mechanical part is about 95 %.

D. Drives of the Tram Wheelset with Smaller Diameter Wheel ($D_K \leq$ 570 mm)

The development engineers of the low-floor trams agreed with compromise of floor height above the traction bogie to value of about 450 mm in recent years. This allows the use of a wheelset with smaller diameter wheels, which exhibit sinusoidal motion during drive. In the bogie FLEXX Urban 1000 the wheelset is driven by integrated drive unit with power of about 120 kW, consisting of the traction motor and two-section gear box (with one spur gearing and one bevel gearing) or hypoid gear.

From the hollow output shaft the drive torque is transmitted through the special joint shaft on the wheelset. The disc brake is positioned on the opposite end of the wheelset, Figure 10. The efficiency of the traction drive mechanical part is about 94 %.

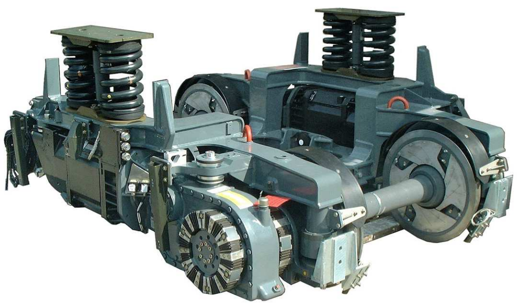

Fig.10. Concept of the traction drive in not pivoting bogie Flexx Urban 1000 [*Bombardier*].

The FLEXX Urban 3000 bogie is used for FLEXITY 2 trams. The axle gearbox (two-section) with vertical sprung support creates partly sprung mass of the traction drive, see Figure 11. The efficiency of the traction drive mechanical part is about 94 %.

Fig.11. Concept of the traction drive in partly pivoting bogie Flexx Urban 3000 [*Bombardier*].

An interesting design of the drive axle in the Ixege bogie it documented in Figure 12. Two traction synchronous motors (PSMS) are mounted on the bogie frame. The driving torque is transmitted by the short joint shaft (coupling) to the pinion of bevel gearing. The bevel axle gearbox is mounted on the wheelset and thus it is an traction drive unsprung mass.

The axle gearbox is held in position by a horizontal sprung support. The efficiency of the traction drive mechanical part is about 95 %.

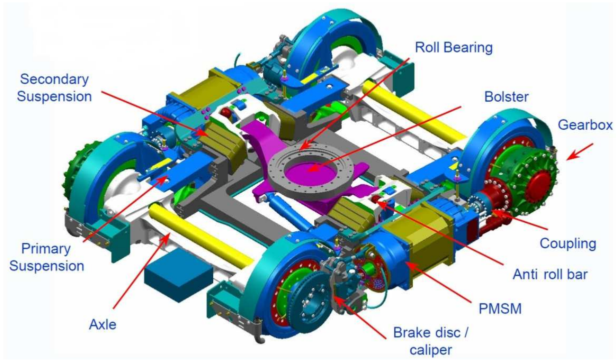

Fig.12. Concept of the traction drive in pivoting Ixege bogie [*Alstom*].

The concept of partially sprung drive of the wheelset with small tram-wheels of low-floor trams, company Skoda is documented in Figure 13. The induction motor with the disk brake is rigidly mounted in the frame of the two-axle bogie. The axle gearbox is embedded at the wheelset and opposite side of the axle gearbox is attached with the vertical flexible support to the bogie frame. The axle gearbox constant drive is divided into two groups, the bevel gearing and spur gearing.

Fig.13. Concept of the traction drive in not pivoting trams bogie SKODA.

For low-floor trams the concept of traction drives with longitudinally oriented traction motors is dominating. These designs have better efficiency of the traction drive mechanical part, smaller number of traction motors and simpler procedure to install larger vehicle traction power. With respect to the dynamic effects and noise, it is preferable to apply fully sprung drives i.e. drives with an integrated traction motor and gearbox in a single-block which is fixed to the bogie frame.

III. Design of the Traction Drives for Electric Locomotive and Electric Train Units

Electric locomotive and train units are used for driving the wheelset traction drive with a transverse axis traction motor. Design of this drive wheelset can be solved in three variants:

- direct traction drive of wheelset
- partly unsprung drive of wheelset
- fully sprung drive

A. Wheelset Direct Traction Drive

An idea of the wheelset direct drive is nothing new. The wheelset direct drive in design with the hollow shaft has already been used in the early 20th century (company AEG).

The wheelset direct drive in design with the hollow shafts was tested in the year 1987 in the company ŠKODA in a prototype locomotive, series 169 (449.5), company mark 85 E0-ATM, see Figure 14. In this design the low-speed induction motor MD 4859 K/12 with nominal power 650 kW was used. The locomotive had a maximum speed of 120 km/h at maximum speed of the traction motor 54 rpm. The couplings at wheels of the wheelset in bogies were different embodiment. In the first bogie it was tested the wheel-clutch (connecting rod type Alstom), then in the second bogie it was tested the wheels-clutch composed of spring strips, see Figure 14.

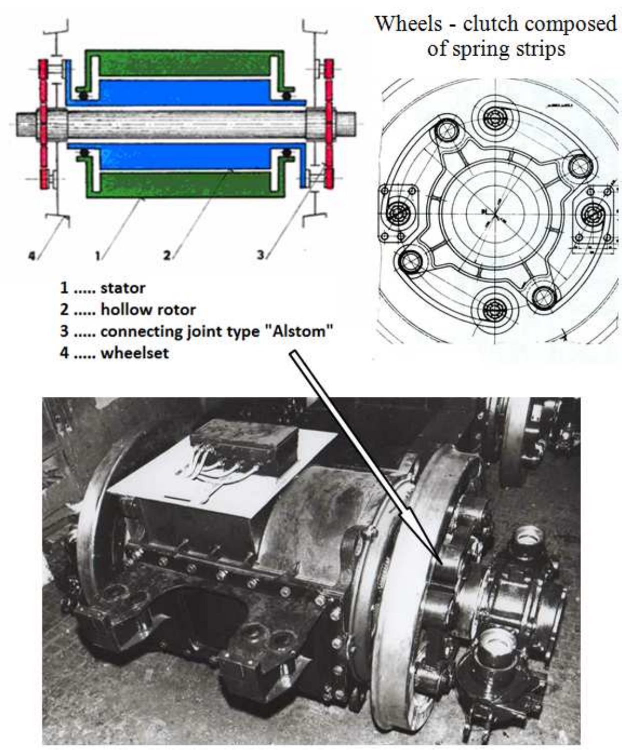

Fig.14. Direct traction wheelset drive of the locomotive 85E [*Škoda*].

In the year 1990 the traction output of the locomotive increased and a new bogie with a partly sprung wheelset drive was used. It was designed with a high-speed induction motor ML 4447 K / 4 with the hollow rotor. The joint shaft, which is located in the hollow rotor of the motor, propelled the axle gearbox.

The second example of the direct drive is represented by the synchronous motor with the hollow shaft rotor and with the special hollow joint shaft which surround an axle of the wheelset, see Figure 15. This gearless direct wheelset drive in variant with the synchronous motor with permanent magnets was designed as an alternative solution of the drive for the high-speed electric-units of ICE 3 [3]. The motor of power 500 kW is cooled by water. This design of the wheelset drive was not finally used in the train ICE 3, however, the efficiency was 99 %.

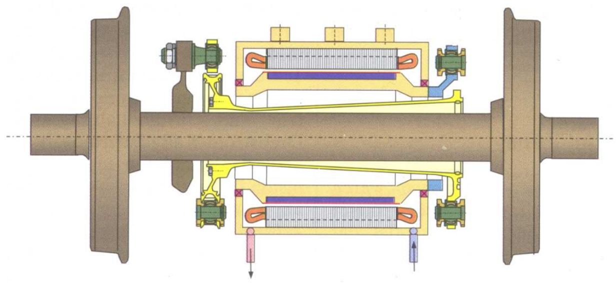

Fig.15. Study of the direct wheelset traction drive – top view [3].

Fig.16 represents an example of the unsprung direct traction drive design in the bogie Syntegra for Metro unit. This gearless single-axle direct wheelset drive has a completely encapsulated permanent magnet synchronous motor. Two-axle bogie has an inner frame which is formed of a robust cross beam and two flexibly connected longitudinal beams. The axles are guided in the bogie frame by means of a three-point wheelset guide with elastic points for each wheelset bearing. This allows passive radial adjustment of the wheelset, which has a positive effect on running of the wheelset behaviour. The bogie frame design offers higher safety in derailment protection of the vehicle.

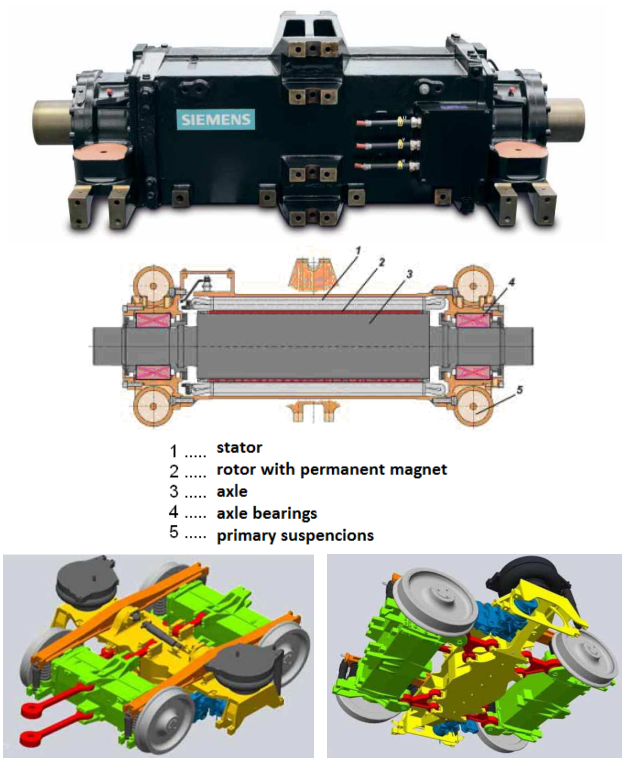

Fig.16. Concept of the direct drive in traction bogie Syntegra [*Siemens AG*].

This concept is an economical way of drive solutions with respect to the spatial installation in the bogie, however on the other hand, the motors are becoming unsprung mass. A vehicle with this drive requires a high quality and geometrically stable track. The efficiency of the traction drive mechanical part is theoretically 100 %.

B. Traction Drive of Electric Locomotives

Design of the individual drive of wheelset of the electric locomotives is dependent on the maximum speed. A traction motor of electric locomotives works with the continuous power of 1600 kW. Maximum tractive force per wheelset is about 75 kN. The nominal diameter of wheel of the locomotive wheelset is from 1100 mm to 1250 mm. Modern cargo locomotives for the maximum speed of 140 km/h have to use the compact integrated block of the induction motor with a gearbox, which is embedded in the roller bearings on the wheelset. The traction motor is fixed on the motor opposite side with flexible vertical support to the bogie frame. The pinion of spur gearing is embedded in a gearbox, see Figure 17, i.e. the pinion is not overhanging as in older designs of the drive with “paw motor”. The motor has forced air-cooled ventilation.

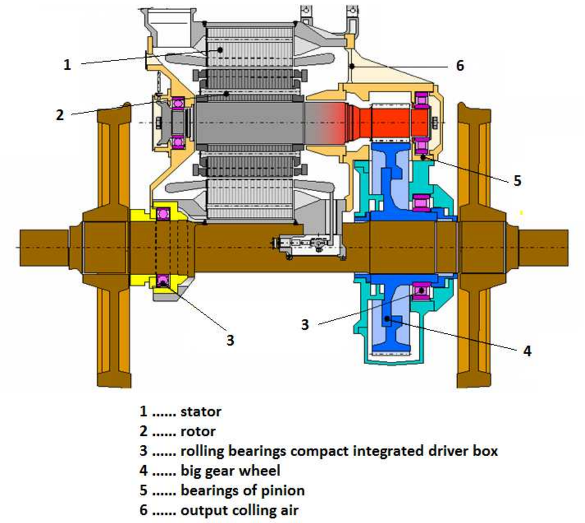

Diagram of a modern solution of the wheelset drive with “paw motor”.

Fig.17. Design study of a modern wheelset drive concept with “paw motor” [*AEG*].

This wheelset drive concept has a high percentage of unsprung mass.

The modern electric locomotives for maximum speeds up to 200 km/h used the design of a partly sprung wheelset drive. This is documented in Figure 18.

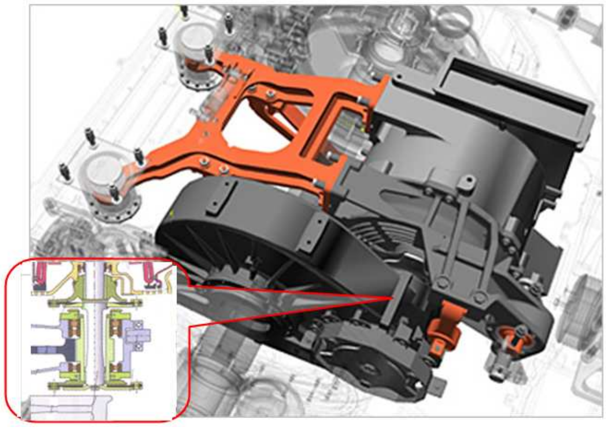

Fig.18. Design of the modern wheelset drive for locomotive Vectron for speed up to 200 km/h [*http://www.mobility.siemens.com/mobility*].

The axle gearbox has the hollow pinion. Torque of the traction motor is transmitted by a special joint shaft inside the hollow pinion, which has a flexible disk-joint, see Figure 18.

In this solution of the drive the unsprung masses are significantly smaller than in case of the drives with "paw motor" and only slightly higher than in case of a fully suspended quill drive. The pinion hollow shaft drive thus represents the optimum technical solution.

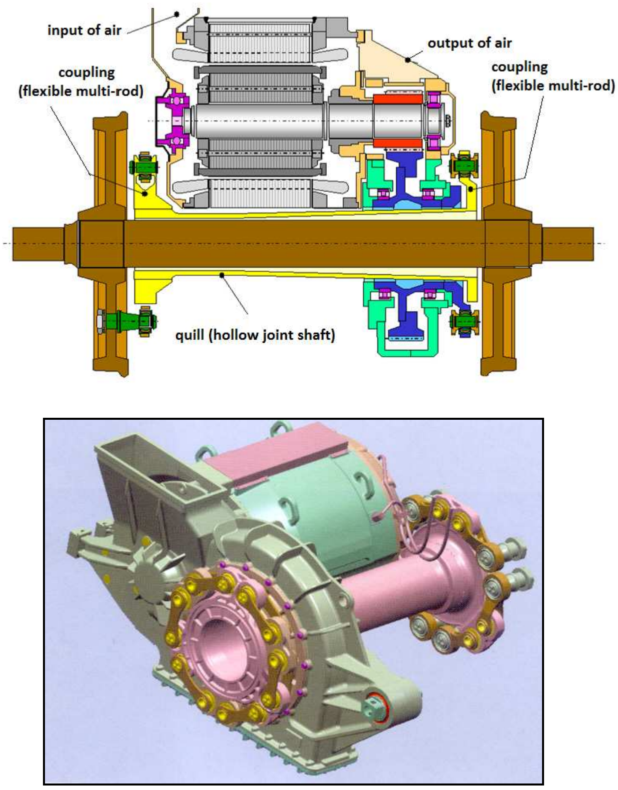

Fig.19. Principle of full sprung wheelset drive for high-speed locomotive.

The modern electric locomotives for maximum speeds up to 230 km/h used the design of fully sprung wheelset drive. Example of the fully sprung wheelset drive of high-speed locomotives is documented in Figure 19.

The transmission of driving force is as follows. The there-phase induction traction motor with a gearbox creates an integrated drive unit, which is connected via a flexible vertical supports attached at three points to the chassis frame.

The gearbox has a hollow output shaft. The output driving torque is transmitted via coupling (flexible multi-rod) to the hollow shaft, which surrounds the wheelset axle. On the opposite end of the hollow shaft the torque is transmitted by means of a coupling (flexible multi-rod or flexible claw coupling) to the disc-wheel.

The gearbox design depends on value of the gear ratio, on the outer diameter of the traction motor and on outer diameter of the couplings (flexible multi-rod) and also on the location of the disc brakes. If disc brakes are placed in the wheels of the wheelset, it is possible to use the gearbox with one helical gearing. This design solution is used for the wheelset drive of a high-speed locomotive series 380, company mark Skoda 109 E. This concept has a minimum unsprung mass, and efficiency of the traction drive mechanical part is about 98 %.

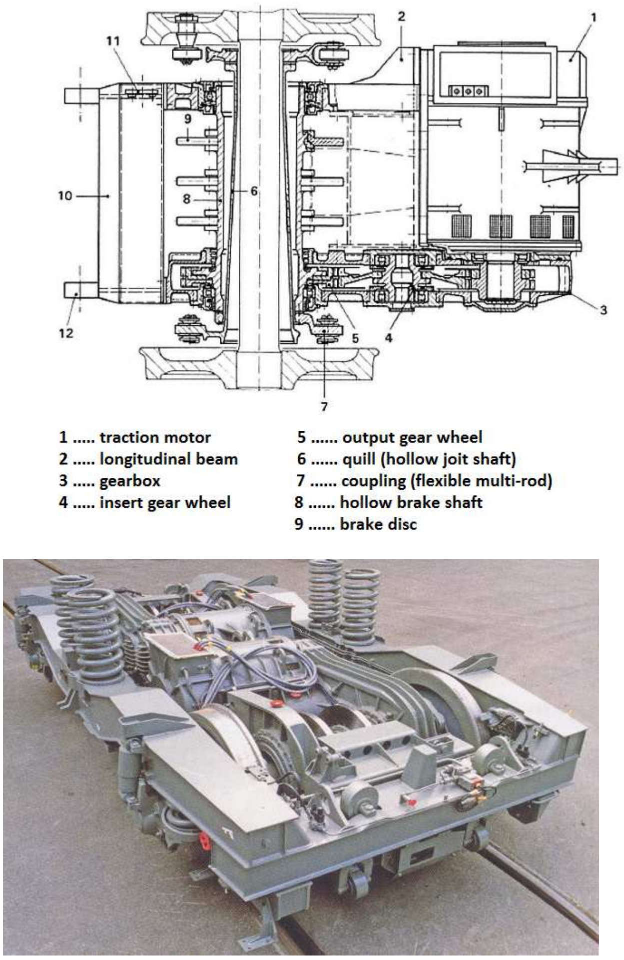

Fig.20. Full sprung wheelset drive in bogie ICE 1 [*Siemens*].

If case of the disc brakes mounting in to the wheels of a wheelset is not possible, then the design with a shaft with disc brakes must be used. In a practice there are two alternatives of the design solution:

- The first variant is a hollow brake shaft, which surrounds the quill (hollow joint shaft). This variant with three-wheel gearbox is using for the wheelset drive of a head motor vehicles of the high-speed train ICE 1 and ICE 2, see Figure 20.
  Motor of power 1200 kW is cooled by air. This concept has a minimum unsprung mass, and efficiency of the traction drive mechanical part is about. 95 %.

- The second variant uses a high-power brake shaft, whose pinion meshes with a large gear wheel of the gearbox. It is called HBA drive. This variant is used for the wheelset drive of the high-speed locomotive ES64U4 Taurus, see Figure 21.

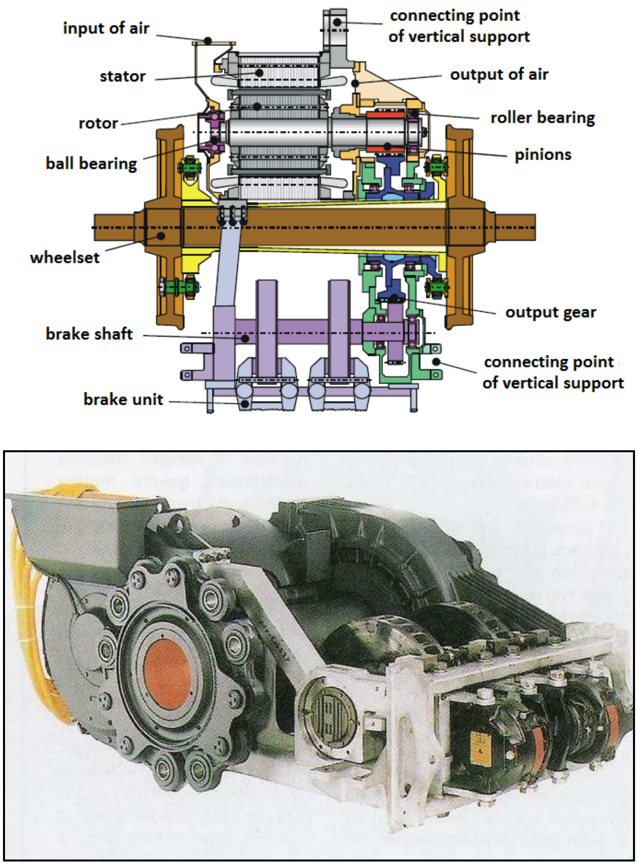

Fig.21.
Full sprung whellset drive HBA of the locomotive Taurus [*Siemens*].

The induction traction motor works with the continuous power of 1500 kW and with hour-power of 1600 kW. The motor is cooled by air. This concept of the wheelset drive has a minimum unsprung mass, and efficiency of the traction drive mechanical part is about 97 %.

C. Traction Drive of Electric Units

The high-speed electric rail units use the partially sprung traction drive. The bogie frame is designed as flexible, open H-Frame. The nominal wheel diameter of the high-speed rail unit wheelset is 920 mm. The traction motor (IM or PMSM) is sprung affixed to the bogie frame and axle gearboxes, (two-wheel or three-wheel), are affixed on the wheelset. The axle gearbox is embedded at the wheelset and the opposite side of the axle gearbox is attached by a flexible support into the bogie frame. The reaction torque of the axle gearbox is absorbed via a sprung support (vertical, diagonal or horizontal) affixed to the bogie frame [4].

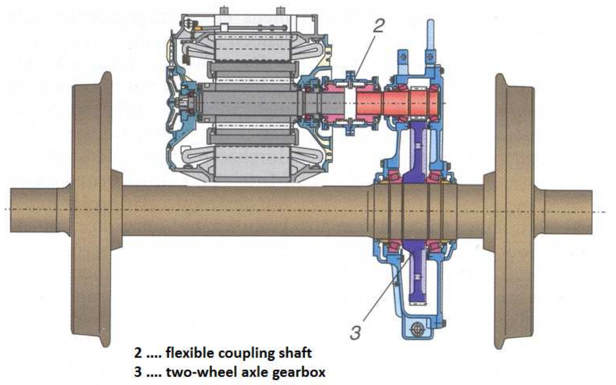

Fig.22. Top detail view of the axle gearbox of the traction drive ICE 3 [3].

Between the traction motor driving shaft and pinion of the axle gearbox there is inserted flexible coupling shaft with two-claw couplings, see Figure 22 and Figure 23. The wheelset drive of the ICE 3 train is driven an the induction traction motor with the continuous power of 500 kW. The motor has forced air-cooled ventilation.

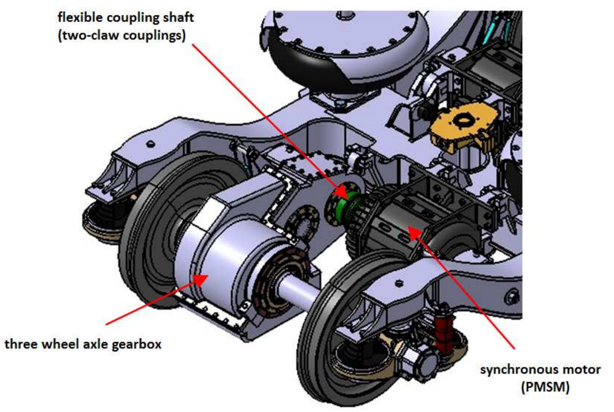

Fig.23. Design study of the traction drive AGV.

The wheelset drive of the AGV-train is driven by the synchronous traction motor with the continuous power of 800 kW and the weight 785 kg. The motor has own air-cooled ventilation. The efficiency of the traction drive mechanical part is about 97 % or 95 %.

For the wheelset drive the regional electric units and a Metro transverse oriented traction motor with a single- or two-stage gearbox is used. The design of the gearbox is dependent on the drive torque and power of a traction motor (limits are the diameter and length of the motor), on gear ratio, on wheel diameter and the desired height of the floor above a bogie. Using a partly sprung wheelset drive with the axle gearbox (design is similar to Figure 22 or Figure 23) is a simpler, cheaper, but dynamically less favourable because a ride on a track vertical inequality is causing swinging of the gearbox and in consequence a pinion of gearing is rolling after a large gear wheel (at two-wheel gearbox), or intermediate gear or pinion of lay-shaft (in three- or four-wheel gearbox) is rolling after the gear wheel of the output gearing. This satellite motion causes dynamic torque, which cause an increase of forces in gearing and of torsional vibrations in the wheelset drive. The large diameter of the disk large gear wheel in two or three-wheel axle gearbox increases its noise.

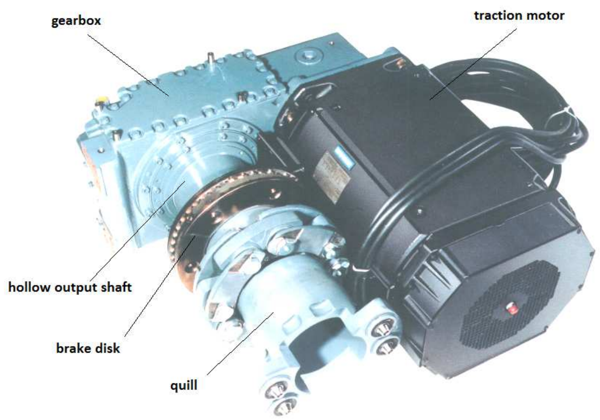

Fig.24. Design of the integrated traction-unit.

The regional electric units are often used to drive wheelset system of the full sprung traction drive, designed as an integrated traction-unit. This layout has a beneficial effect on dynamics of the drive, but it is more expensive.

The drive unit is integrated in one block of the traction motor and gearbox. This block is mounted in flexible supports (three or four) to the bogie frame. The gearbox is ordinarily designed with an intermediate gear (three-wheel gearbox) or lay-shaft (four-wheel gearbox) and with a hollow output shaft. Out of the output shaft the driving torque is transmitted via the quill, (hollow propeller shaft which surrounds the wheelset), to the wheelset axle. Disc brake of the mechanical brake is usually mounted on the hollow output shaft of the gearbox, see Figure 24, or on the wheelset.

This concept has a minimum unsprung mass, and efficiency of the traction drive mechanical part is about 95 %.

IV. CONCLUSION

A rail vehicle drive works with variable operating conditions (changing of a drive mode with braking mode, bidirectional traffic, variable load) and climatic conditions (temperature changes, snow, dust, humidity). Design of the drive should be based on a detailed analysis of the vehicle driving cycle. Therefore it is necessary to define correctly a requirement on the vehicle acceleration and maximum vehicle speed. It is necessary to analyse the variability of traction forces with respect to the speed and their influence on the torsional oscillation natural frequency of the drive system [5], see Figure 25.

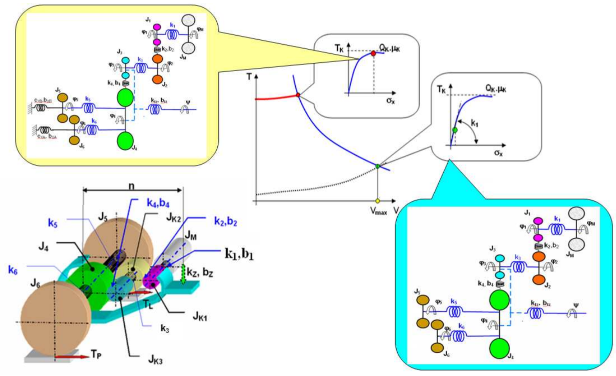

Fig.25. Model of the torque system partly sprung wheelset drive.

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