The PLANETARY MOTOR –
A Novel, Unconventional Combination of Electric
Motor and Planetary Gear for Driving Vehicle Axes

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1. Introduction

Electric machines are frequently combined with gear boxes in order to reduce angular velocity and to increase torque of the shaft. The classical solution is to use the electric motor shaft as input into a spur gear or planetary gear box. Hence, electric motor and gear box are separate functional units.

The presented paper shows a novel approach of a combined motor/gear unit, at which the electric motor is realized as a distributed system with several rotors combined with a planetary gear box function [1].

In the following chapter, the idea is described step by step.

2. Descripition of the novel motor structure

The description starts with a simple two-pole electric motor with a three-phase winding, consisting of one tooth per winding phase (fractional pitch winding, q=1/2). Without loss of generality, we assume a permanent magnet rotor. The geometrical arrangement of the phases can be seen in Fig. 1.
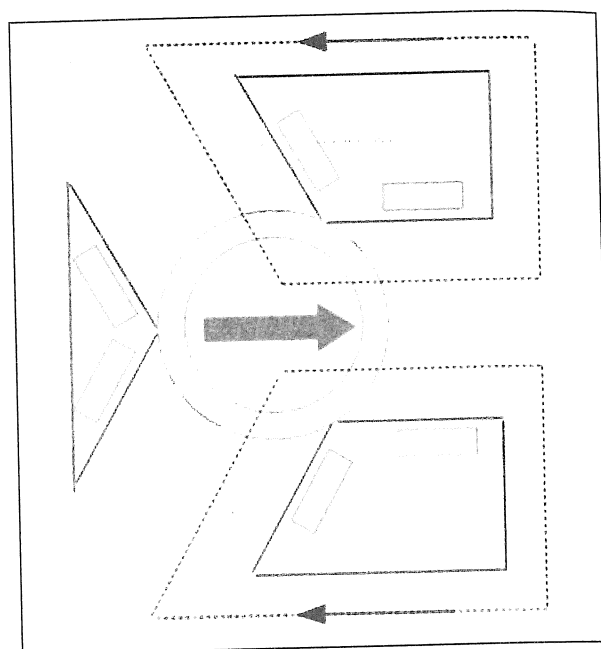

Fig. 1: Starting point: A three-phase two pole AC motor (e.g. with permanent magnets in the rotor)

Assume a symmetric arrangement of four motors according to Fig. 2. The direction of magnetisation is chosen horizontally, at which the direction of the lower magnets is left to right and the direction of the upper magnets is right to left:
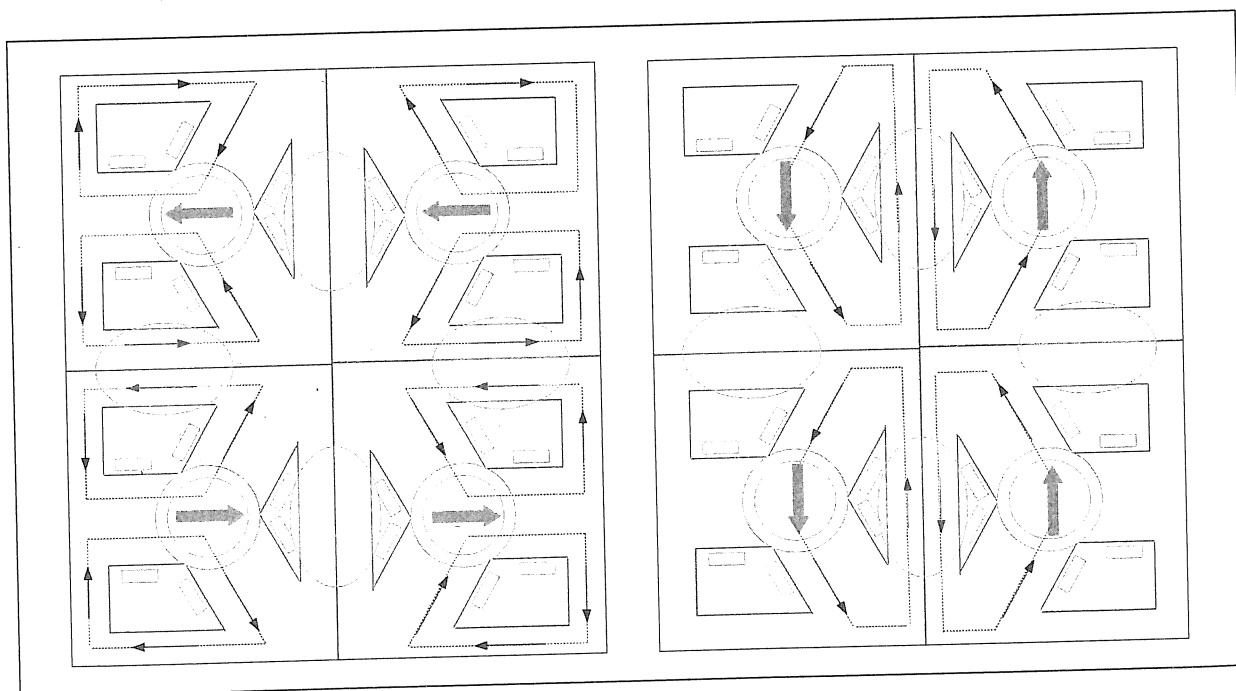

Fig. 2: Symmetrical arrangement of four motors (Brown regions: Magnetic field is compensated, green regions: Magnetic field is zero)
a) Horizontal rotor positions
b) Vertical rotor positions, achieved by proper +/- 90 degrees rotations compared to a)
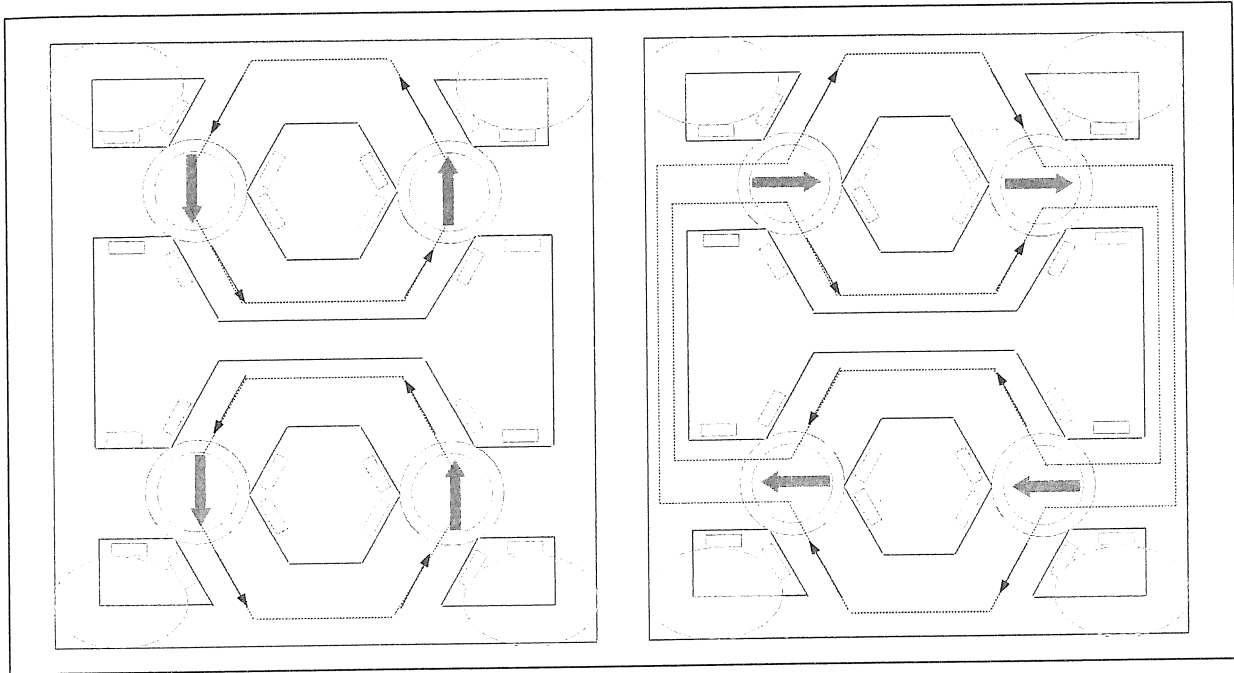
Fig. 3: Reduction of active mass by elimination of magnetically inactive regions (green and brown parts in Fig. 2)

Moving the motors together, some regions are not necessary from magnetic point of view. (Fig. 2a). Now the rotors are rotated by ±90°, at which neighboured rotors are moved in opposite directions (Fig. 2b). After rotation, the rotors produce a magnetic field distribution, in which the same regions are again not necessary. Hence, a simplification of the whole structure is possible, thus reducing active mass and iron losses compared to the starting situation with separated four motors (Fig. 3 a,b). Since the corner parts of the structure are magnetically not used, a further reduction of complexity and mass is achieved (Fig. 4).

In Fig. 3, the resulting (symbolic) magnetic field lines in horizontal (a) and vertical (b) rotor positions are shown. It can be seen that the corner parts are not used by the magnetic field. By elimination of
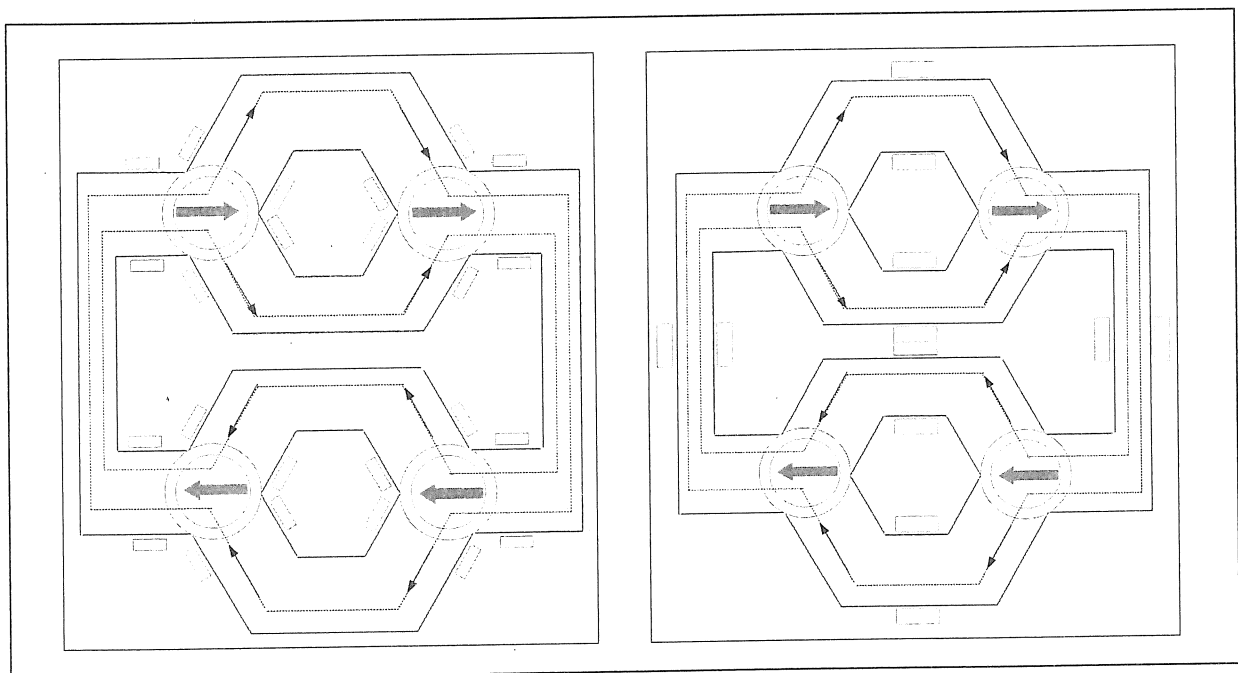

Fig. 4: a) Elimination of the corner regions (green parts in Fig. 3)
b) Shifting together adjacent coils and reducing the number of coils from 12 to 6.

the corner parts (green regions in Fig. 3), adjacent coils (which are linked with the same flux) can be shifted together along the iron parts. Thus reducing the number of coils from 12 to 6. The four motors share hence 6 coils, where two coils are assigned to one phase.

Performing the above mentioned reduction steps in geometry, a four-rotor-motor with only six concentrated coils is obtained. In the next step, the rotors are coupled mechanically, where adjacent rotors have to rotate in opposite directions. This mechanical coupling is achieved by using a certain kind of planetary gear box. Opposite „planetary rotors" interact with a central sun wheel with a gear ratio (Fig. 5). This gear ratio can vary in a wide range (≤1 .. ≥1). Typically, in electrical drives a reduction gear is used, since normally higher torque and lower angular velocity at the gear output is needed. (Fig. 5a). Drives with a gear ratio to higher speeds can also be realized but are less frequently used. The inverse direction of rotation of the remaining planets can be realized by a sun wheel with internal teeth (Fig. 5b).

By using a gear ratio of R1:r1 = R2:r2, both sun wheel parts (with outer and inner teeth) rotate at the same angular velocity. The planets rotate at the same magnitude of angular velocity, but

adjacent planets have opposite directions. In order to prevent collisions of the cog wheels, planets with opposite directions have to be geometrically decoupled. This can be achieved by axial shifting of both planet groups (and the respective sun wheel parts). Another possibility is radial decoupling by increasing R2 and r2 by the same factor. In this case, the axes of the four rotors do not build the corners of a square but corners of a rhombus or a rhomboid. This latter variant was built up and tested (Fig. 8).

3. Electrical interconnection of the planetary motor

Starting from the four-motor topology with 12 coils, the single motors can e.g. be connected in star connection. (Fig. 6a). The simplified coil arrangement of the planetary motor can be connected e.g. in star or delta connection or in an open H-bridge. Furthermore, the two coils of each phase can be connected in parallel or in series. In Fig. 6b an example with two parallel coils per phase and star connection of the phases u, v, w is shown.
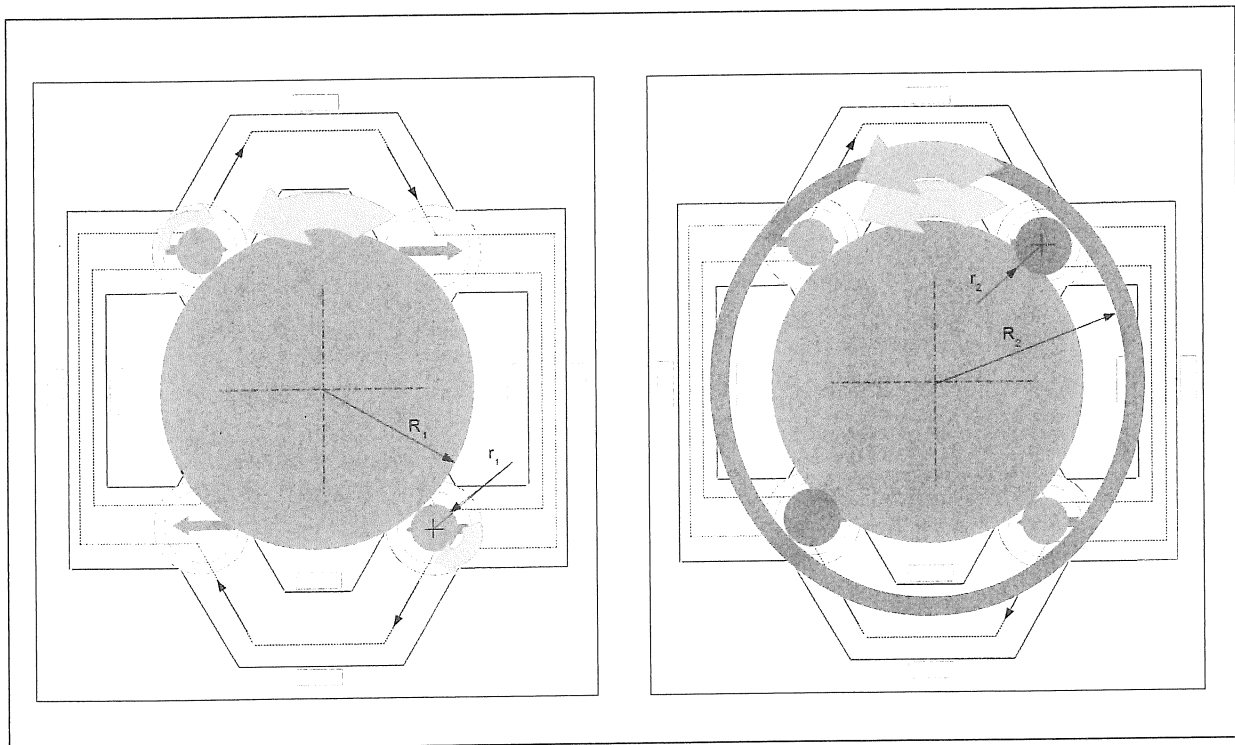

Fig. 5: Coupling of opposite planetary rotors using a sun wheel with outer teeth (a) and inner teeth (b), respectivlely.
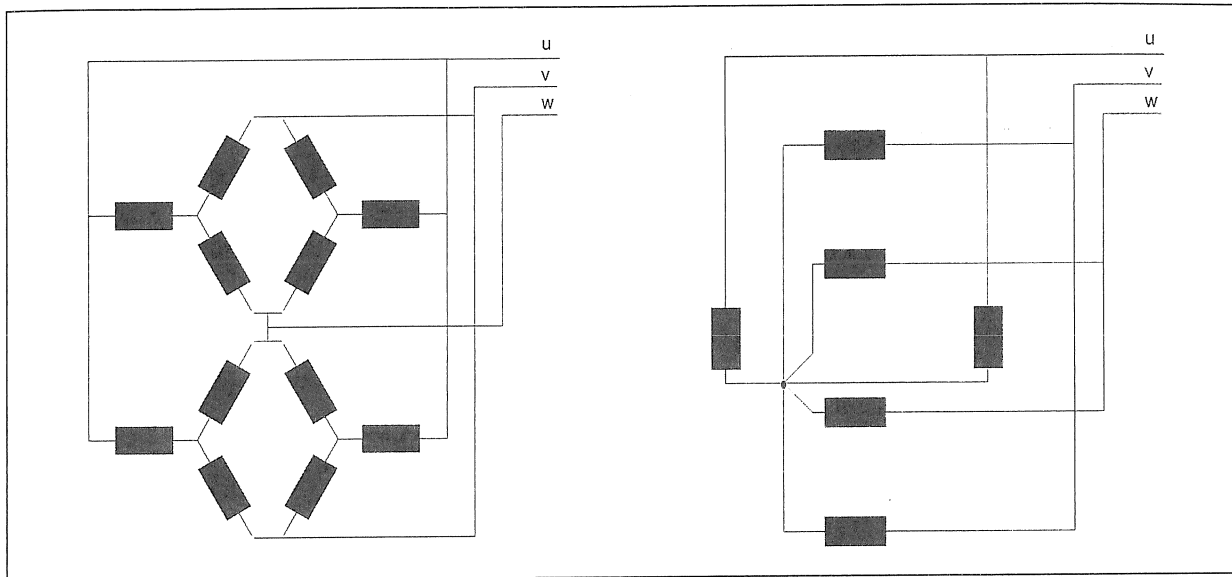
Fig. 6: a) Original quadruple star connection of the partial motors.
b) Planetary motor with star connection of the phases and parallel connection of the phase coils (Alternatively, series connection is possible)

4. Control of the planetary motor

As shown in Fig. 6, the planetary motor behaves like a classical three-phase system at the motor terminals. Although the geometry of the electrical active parts is not cylindrical, the motor behaves like a symmetrical three-phase machine. Hence, a normal three-phase inverter with conventional control (e.g. field-oriented control) can be used (Fig. 7).

As shown in Fig. 7, an economic realisation of the planetary motor is achieved by using speed-sensorless control methods [2]. Sensorless methods (without mechanical encoders) have been important topics of research for many years and have been already used in practical series applications [3], [4], [5].
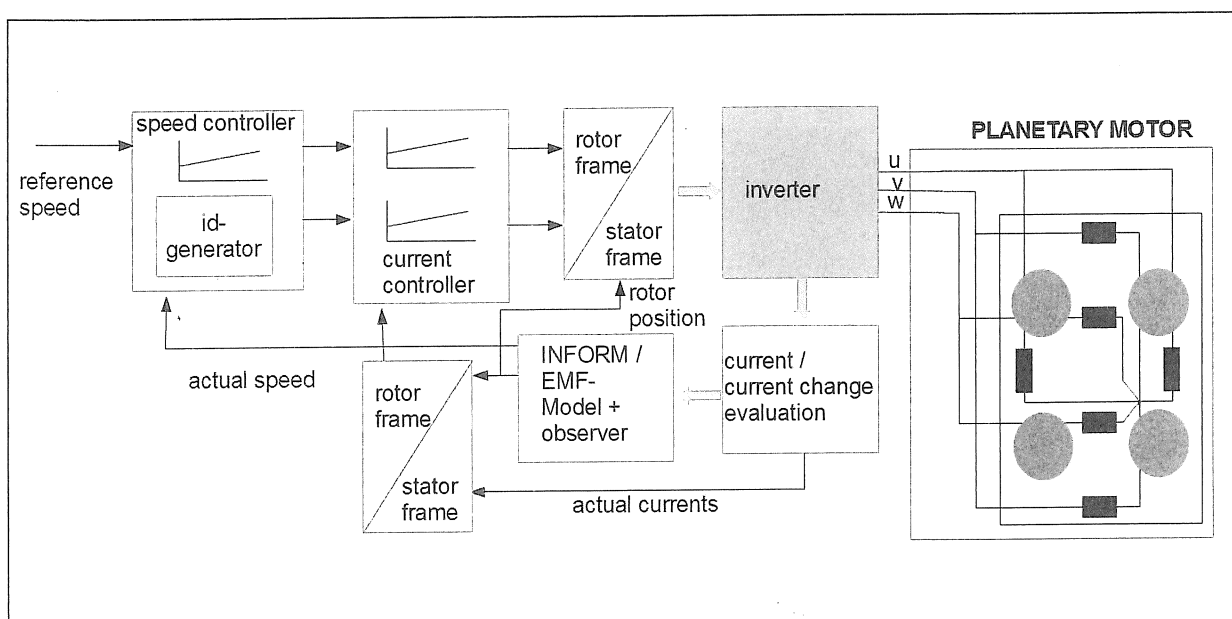

Fig. 7: Sensorless field-oriented INFORM® / EMF control of the planetary motor

5. Advantages of the planetary motor

Reduced weight of the active parts

As was shown, the novel configuration enables considerable reduction of the magnetically active parts compared to four single motors.

Reduced amount of coils and simple production

The original 12 coils were simplified to six coils with rectangular cross section. All coil terminals can be performed in the same plane. This enables a simple (fully automatic) assembly of motor and electronic part. The two coils of a phase can be connected in parallel or in series. Furthermore, the phases can be realised in star or delta connection.

Remarkable increase of installable power in high-speed rotors

Considering a compact drive consisting of high-speed motor and reduction gear box, e.g. in an electric vehicle (EV) drive (Fig. 9)
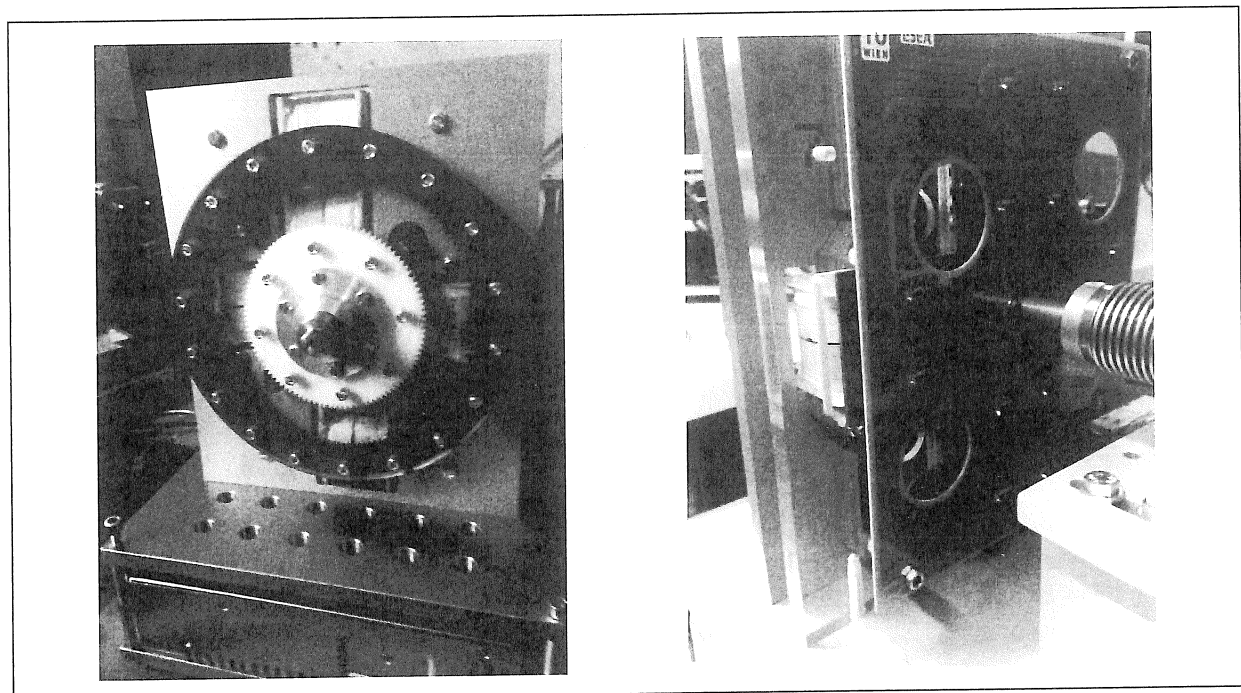

Fig. 8: a) Planetary motor with rhombus arrangement of the planet axes and gear reducion of 1:10.
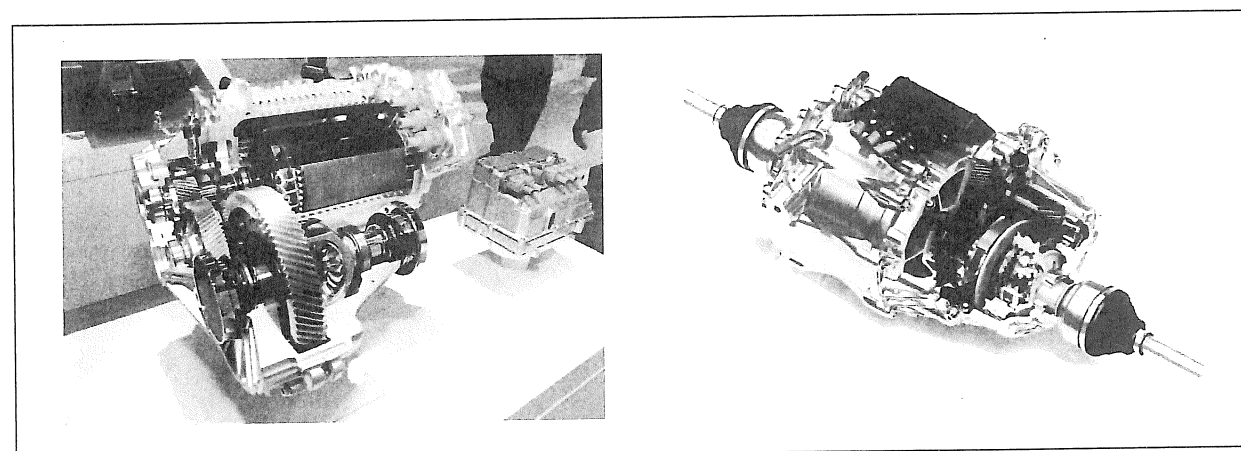b) Simple connection of electronics and coils at the rear side of the planetary motor

Fig. 9: a) Classical drive unit of an EV drive consisting of electric motor, spur gear and differential gear (photo by VW).
b) Electrical drive unit with coaxial output of half-axes using a hollow shaft of the electric motor (Figure by GKN).

At given rotor diameter, the circumferential speed is limited by the strength of the rotor material. Typically, circumferential speeds of about 100-200 m/s can be realized economically [6]. Assuming the same specific circumferential force (N/cm2) of original motor and planetary motor (same flux density fundamental wave and same current sheet), we can replace the original rotor (diameter D) by four rotors with the same resulting cross-section area (diameter D/2). Each planetary rotor yields then ¼ of the original torque (half circumferential force due to half circumferential area; half rotor radius), hence, four rotors provide the same torque compared to the original rotor. Assuming same output power of the original rotor and the planetary rotors, this means the same angular velocity of the original and the planetary system. Because of the halved diameter, only half the circumferential speed occurs at the planetary rotors, compared to the original rotor. In cases where the power limitation is caused by the circumferential speed, the planetary motor offers the possibility of doubling the power by doubling the angular velocity until the same circumferential speed occurs at the planetary rotors.

Simplified planetary gear box stage

Compared to a normal planetary gear box, the planetary gear of the planetary motor offers some advantages. All four rotors produce practically the same torque – hence, an equal sharing of the tooth forces is guaranteed. There is hence no special precision of the teeth production necessary from this point of view. Furthermore, the force transmission is performed only in one point per planetary wheel (classical planetary wheels have two force contact points). This increases the efficiency of the planetary motor gear box compared to a normal planetary gear.

6. Measurements on a prototype

In order to verify the principle of the planetary motor, a 1 kW-prototype was built up and tested (Fig. 10 a). The sun wheel was produced using a transparent material, in order to show good optical inspection of the functional principle. The magnetic circuit was designed by numerical simulation. Because of the small amounts of teeth, the induced voltage shows a certain content of harmonics (Fig. 10 b). This can be optimised by an imporved geometry.

7. Advantageous applications

The structure of the planetary motor offers many advantageous applications. Especially in drive tasks with reduction gears, very compact solutions with high level of automation in production are possible.
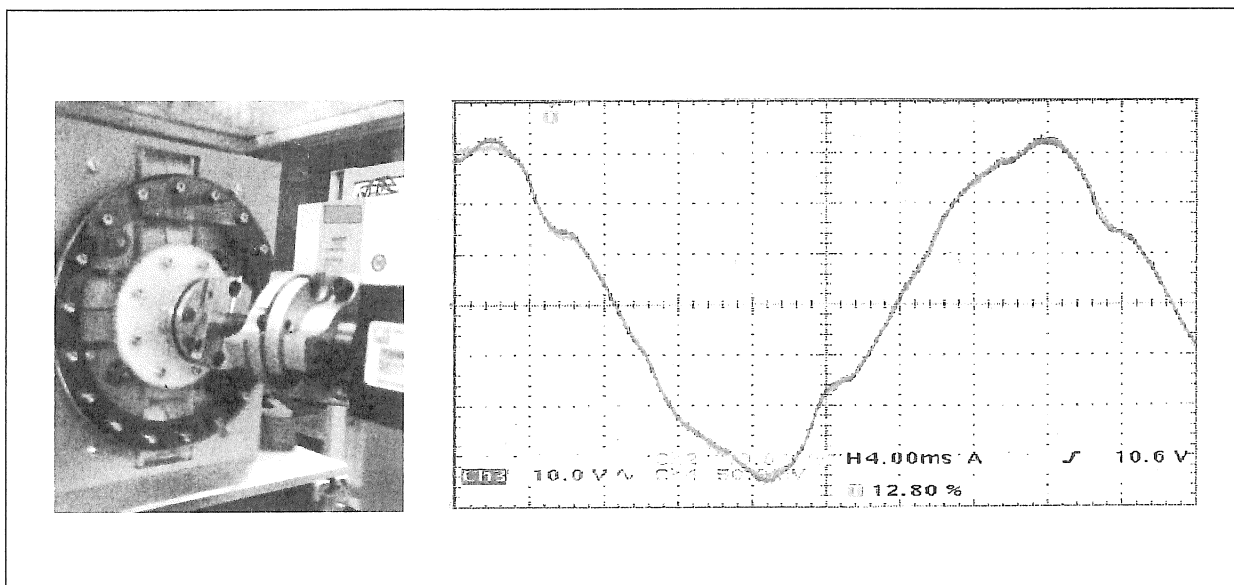

Fig. 10: a) 1 kW planetary motor at the test stand.
b) Course of the terminal phase voltages over time at no load

Wind power drives

As an example of high power applications, wind power drives are mentioned. The main shaft carrying the rotor blades can be coupled to the sun wheel of a planetary motor/generator, thus enabling an electrical machine with higher speed and lower weight. Hence, frequently used gear boxes can be replaced by this new concept with considerable simplification.

External rotor applications

In external rotor applications (e.g. drum motors, wheel hub motors, tube motors) the sun wheel of the planetary motor can be directly connected to the rotating outer part of the drive. Thus enabling very compact solutions.

Electric vehicle drives

Electric vehicles use drive units consisting of a classical electric motor and a gear box. In Fig. 9a), the drive unit of a VW E-Golf is shown. The electric machine is coupled to the two semi-axes via a two-stage spur gear and a differential gear. Alternatively, the drive can be built coaxially (e.g. the solution of GKN, Fig. 10b), where the motor shaft is built up as a hollow shaft. The electric

motor is connected to a planetary gear and a following differential gear box. This differential gear is coupled to the two semi-axes, one of them rotating inside the mentioned hollow shaft of the electric motor.

Building up this basic structure as a planetary motor, a very compact unit is obtained (Fig. 11). The sun wheel of the planetary motor has a hollow shaft and is directly connected to a planetary gear. Hence, several mechanical components can be saved. As a further important advantage, the reduced circumferential speed of the planet rotors shall be taken into account. As an obvious benefit, the possible compact combination of motor and electronic unit is mentioned.

8. Outlook: Planetary motor structures with other numbers of planets and pole pairs

The derived basic structure can be adapted to other numbers of planets and pole pairs. As an example, motors with four pole rotors or with six planets can be realised. Fig. 12 shows the basic motor structure of an arrangement with four 4-pole rotors (coils are not depicted). Adjacent rotors move again in opposite directions and same magnitude of angular speed. The arrows in Fig. 12 indicate the magnetic field lines in the given rotor position.
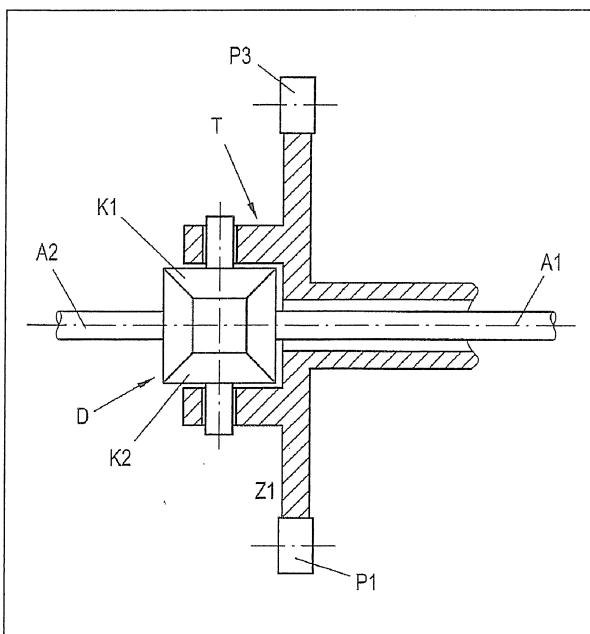

Fig. 11: Planetary motor with differential gear box D (housing T, bevel wheels K1, K2), functionally combined with sun wheel Z1. Planets P1, P3 (shown without connected rotors of the electrical part). Semi-axes A1, A2, connected to the drive wheels.
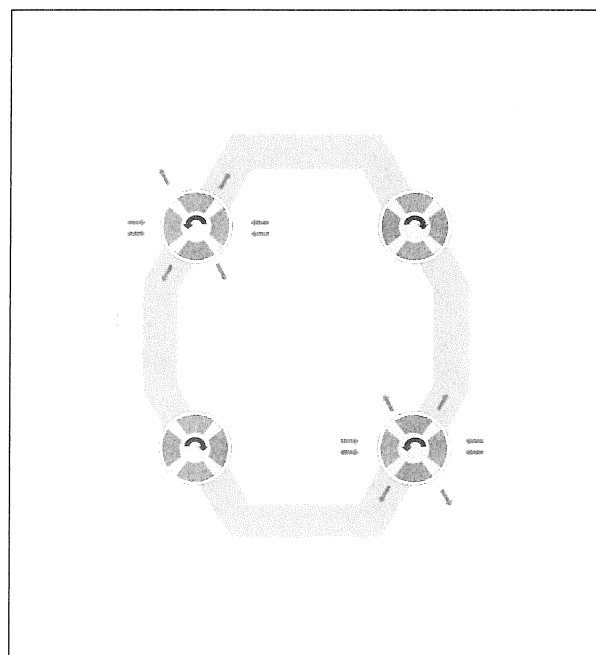

Fig. 12: Planetary motor with four-pole rotors (phases u, v, w in different colours)

Interpreting the structure of Fig. 4b as a series connection of two similar structure modules, different planetary motors can be constructed. As an example, Fig. 13 shows a planetary motor with 6 planets. This is achieved by connecting three structure modules together. Adjacent plantets rotate in different directions.
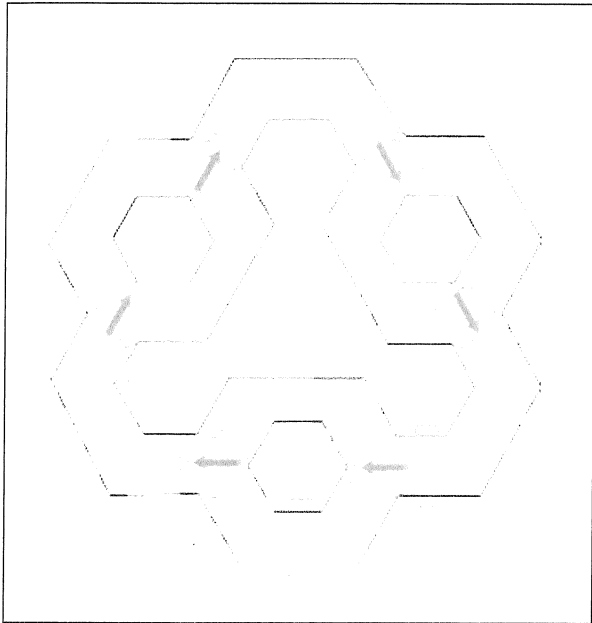

Fig. 13: Structure with 6 two-pole planets

9. Conclusion

In the presented paper, the (electric) planetary motor was introduced – a novel concept of an integrated multi-electric motor with a planetary gear box. After deriving the new structure, a prototype was built up, the control scheme was explained and the properties of the drive were verified. The implemented field-oriented control used the speed-sensorless INFORM/EMF rotor position detection method and was tested in the whole speed range including standstill. Extensions of the structure to different numbers of pole-pairs and planets were explained.

10. References

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