Design of a 2 in 1 Motor to increase the Efficiency of Electric Vehicles

Michael Schier
German Aerospace Center
Pfaffenwaldring 38-40
D-70569 Stuttgart, Germany
Email: michael.schier@dlr.de

N. Satheesh Kumar
Nanyang Technological University
50 Nanyang Avenue
Singapore 639798
Email: ns0001ar@e.ntu.edu.sg

Abstract— **The requirements for the climatisation of electric vehicles largely depend on the vehicles usage location. For example, electric vehicles operated in European countries require heating during the winter season, while those operated in equatorial regions face cooling load throughout the year. To date, the low range for a given battery charge remains the single-most important factor hindering the widespread acceptance of electric vehicles. The principal electrical load of an electric vehicle used in equatorial regions comprises of the traction motor and the air-conditioning compressor motor. These high power loads expedites the battery drain, leading to poor cruise range. The paper proposes a novel design solution geared towards improving the overall operating efficiency of these motors by integrating them into a single housing.**

Keywords—thermal management; air conditioning compressor; swing vane compressor; permanent magnet machines.

I. Introduction

Currently, the commercially available electric vehicles have a cruise range in the region of 100 km to 120 km. The major electrical loads of an electric vehicles battery are the traction and air conditioning compressor motors. These high power loads expedites the battery drain, leading to poor cruise range. The new 2 in 1 motor is jointly developed by the German Aerospace Center DLR and the Nanyang Technological University NTU fulfills the requirements of providing traction and cabin climatisation of electric vehicles in a single package, thus representing an important milestone in the development of highly integrated unit manufactured using fewer components. This configuration eliminates the need for an independent cooling system for each motor type, while reducing the number of required parts while minimizing the overall weight and bulk of the engine. Through the integration, this system is able to increase the space availability within the vehicle. Though the compressor and traction drive are housed within a single casing, the design of the motor enables it to satisfy fluctuating torque-speed requirements of the air conditioning compressor and the vehicle without any interference. A clutch mechanism is included to transfer a fraction of the vehicle's recuperated energy directly to the compressor during braking events. This minimizes energy conversion losses there by increasing the cruise range [1]. In addition, the 2 in 1 motor elegantly integrates a new variant of the swing vane compressor to attain further efficiency gains during compressor operation.

II. Concept of the 2 in 1 Motor

A. Common Aspects

Electric vehicles (EVs) have meanwhile reached a production status. Due to the moderate production quantities, the cost of its acquisition remains relatively high and the attractiveness to purchase is still limited because of the limited range (due to the lower energy density of batteries compared to liquid fuels). For these reasons, it makes sense to aim for a high integration of functions into individual components or to combine separate components in one in order to keep the number of components and the cost and weight as small as possible [2].

The advances in battery technology, the special property of the energy regenerative capability of the electric drive and the high energy conversion efficiency of electrical machines have let the electric vehicle as an alternative to a conventional vehicle and as promising a part of future mobility systems. However, the drive train with its new behavior is not easy comparable to the state of the art of fuel consumption metering. Energy consumption is very sensitive to the operation mode or the usage of the vehicle, as well as on the powering of other electrical loads. The clearest noticeable effect is the drastic reduction of the range when starting the heater or air conditioner. Especially in urban regions, so the particular field of application of electric vehicles, the average value of the required driving power is relatively low. It is in the range of the required power for air conditioning, which is about 6 kW. According to this thermal management has a drastically impact on the range of the vehicles. Regarding the NEDC (new European driving cycle) this leads to halving of range by air conditioning, for heating in European regions or for continuous cooling with high humidity in equatorial regions.

The particularity of electric machines is their ability to transfer energy without contact working with a magnetic field, with a favorable power to weight ratio, high efficiency and also few components. The function of the electric motor in electric vehicles today is limited mostly on a single task, namely for the production of mechanical power for the drive (and in principle also for the electric energy recuperation). This raises the question whether the electric motor can also take over additional functions within the vehicle. Electrical machines are particularly efficient at one operating point, but not over the entire speed range. With a combination of two electric machines, an improvement in the overall efficiency can be expected. The purely electric drive today is supplied by electrical energy which undergoes an extensive conversion chain, as shown in figure 1.

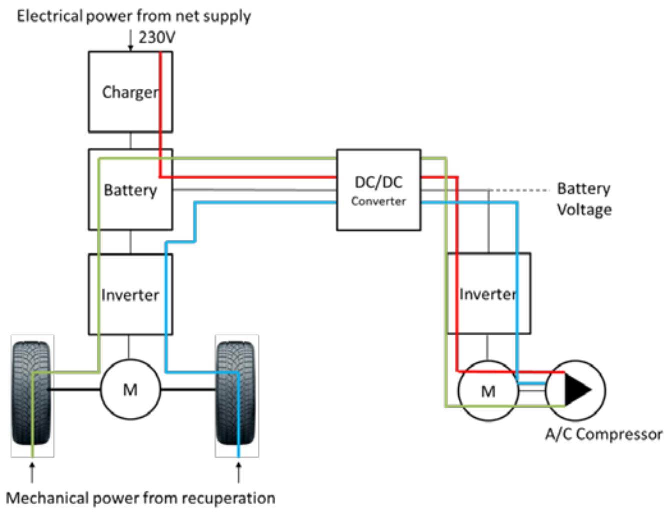

Fig. 1: Electrical power conversion chain (red line: from supply net, green line: from recuperation and stored in battery, blue line: directly from recuperation [1]

Reducing the number of energy conversion stages is an essential step towards more efficient use of high-quality electric power. One path of power supply provides the electrical power from the external power grid via the charger first in the battery, then via a DC/DC converter to the inverter and the compressor motor for the compressor, regardless of whether the vehicle is moving or is braked. When the compressor could be directly coupled to the rotating wheels during the braking events, as shown in figure 2, the overall efficiency must rise.

In addition the number of parts will decrease and so the costs of the total system. The effort to seal the casings, to cool the components, also to handle the electromagnetic compatibility must be easier. These are the aims of the design of the 2 in 1 motor.

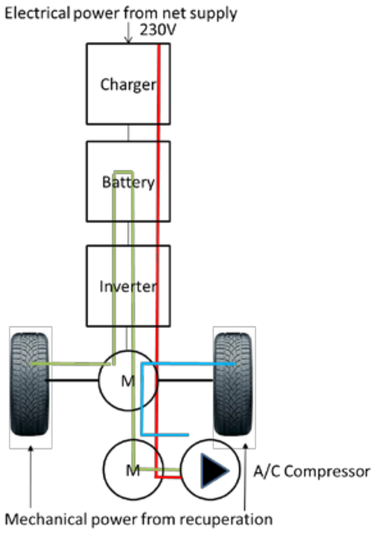

Fig. 2: Feeding the air conditioning compressor directly from the wheels during recuperation (blue line) [1]

A first estimation of efficiency effect was given in [1] by multiplying the individual efficiencies of the components. The conventional system operates with a net efficiency of 62 % during recuperation mode while the proposed configuration attains an efficiency close to 100 % for the same mode if the compressor is directly driven by the wheels, see Table 1.

TABLE 1: EFFICIENCY OF INDIVIDUAL COMPONENTS

type of energy converter	efficiency		
	best case	**worst case**	**average value**
charger	0.95	0.90	0.93
battery	0.95	0.70	0.83
inverter drive motor	0.95	0.85	0.90
drive motor	0.95	0.90	0.93
DC/DC converter	0.95	0.90	0.93
inverter compressor	0.95	0.85	0.90
compressor motor	0.95	0.85	0.90

Since each energy converter in the supply chain has an individual efficiency characteristic, an own control strategy and is also different from component to component, it seems necessary to design a prototype and to investigate the behavior of the system. The following chapters will describe the requirements and the concepts design to develop a demonstrator prototype.

B. *Speed and Torque Requirements*

For a given small city car a power of 20 kW is required to attain a top speed of 120 km/h. To safe costs and weight, electric machines shall operate at high speeds [3]. For reasons of weight savings the drive motor is also supposed to work at the highest possible speed, which is 12000 rpm in this application and depends on the gear ratio of the given test vehicle. Therefore the shaft of the drive motor is connected via a spur gear directly to the wheels. Table 3 shows the motor data of the existing induction machine which has to be replaced by the new 2 in 1 motor.

TABLE 3: DATA OF THE TEST VEHICLE INDUCTION MACHINE WHICH HAS TO BE REPLACED

parameter	**value**
nominal power	12 kW, S6 40 % ED
nominal speed	5920 rpm
nominal frequency	200 Hz
nominal voltage	100 V
nominal current	86 A
number of phasesl	3
number of stator slots	36
number of pole pairs	2
number of holes	3
rotor cant	½ rotor slot pitch
cooling system	air cooled

The mechanical output of the new drive motor can be increased, because the new engine can be cooled with a water jacket. By using a larger diameter for the electromagnetic circuit of the new motor the power can be increased further. Using an electric machine with a small single tooth winding there is some more space within the casing.

The given test vehicle is not equipped with an air conditioning system. So it has to be developed separately. The air conditioning compressor, however, in this case requires a power of about 4 kW at a maximum speed of 2000 rpm. Thus, the air conditioner can be operated independently of the drive motor, the compressor is powered by a separate motor which also needs to work with high speed. As a city vehicle usually operates with max. 60 km/h, the corresponding speed of the drive shaft is then 6000 rpm. During braking, both motors are coupled together. Thus, the maximum speed of the compressor motor is to be interpreted at 6000 rpm. An additional gear reduces the speed of the compressor motor to the speed of the compressor with a ratio of three.

C. *Basic Structure*

Figure 3 shows the basic structure of the 2 in 1 motor concept. The drive motor is connected to the wheels. The gear box between the drive motor and the wheel which is part of the given vehicle is not shown is this figure in principle. The compressor motor can run independently, transmitting its power to the compressor via a planetary gear with high efficiency. Both motors can be coupled by an electromagnetic clutch. All components are located in a common casing.

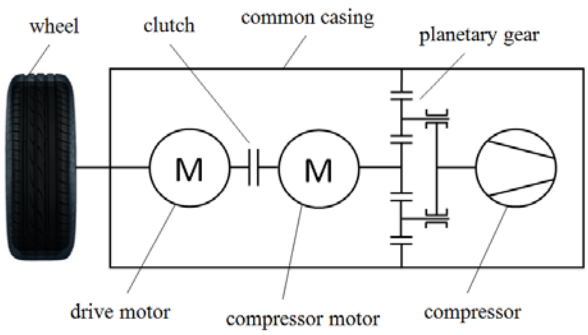

Fig. 3: Basic structure of the 2 in 1 motor concept

D. *Transaxle Structure*

To save space, the large winding interconnections of the drive motor have to be positioned at the opposite side of the shaft outlet. In addition, the shaft is connected to the gear of the vehicle where the flange prevents a large diameter of the electromagnetic circuit for an electric machine and where it prevents the laying of the electric motor cables. This makes it necessary to use a transaxle architecture for the two motors as it is shown in Figure 4.

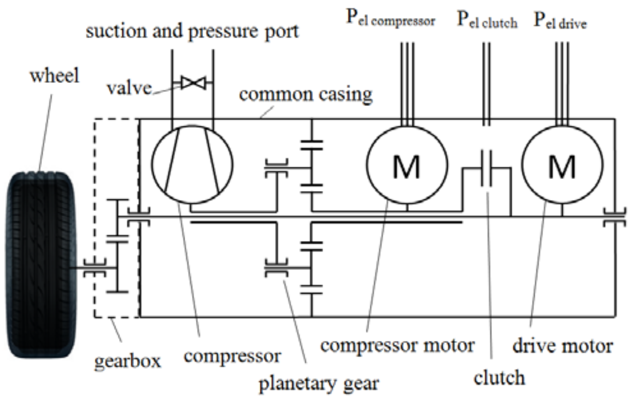

Fig. 4: Concept of the 2 in 1 electrical drive as a transaxle architecture

The compressor motor, the planetary gear and the compressor are located on a second intermediate shaft in transaxle architecture. Figure 4 also shows the electric connections for the motors and the electromagnetic clutch.

Suction and pressure port of the compressor are connected by a bypass valve which will be used for shortcutting the pneumatic circuit in the case of turning off the compressor if it is needed.

III. Parallel Hybrid Mode of the 2 in 1 Motor Concept

The 2 in 1 concept makes it possible to use both motors in a parallel hybrid mode. It allows a large number of operating modes as listed in Table 3. Both motors can operate as a motor or a generator (mot and gen in Table 3), the clutch can be closed or is open, the air conditioning circuit of the compressor can be short-circuited if necessary.

TABLE 3: DRIVE MODES

no	function mode	drive motor mode	compr. motor mode	clutch mode	compr. mode
1	drive only	mot	-	open	-
2	refrigerate alone	-	mot	open	works
3	boost	mot	mot	closed	short cut
4	refrigeration by recuperation	-	-	closed	works
5	refrigeration by recup. and max. charging	gen	gen	closed	works
6	drive and refrigerate independently	mot	mot	open	works
7	drive and refrigerate combined	mot	mot	closed	works
8	drive and refrigerate	mot	-	closed	works
9	charge alone	gen	-	open	-
10	charge max.	gen	gen	closed	short cut

The first function mode 1 in Figure 5 shows simply that the drive motor only drives the wheels while the clutch is open and the compressor is turned off.

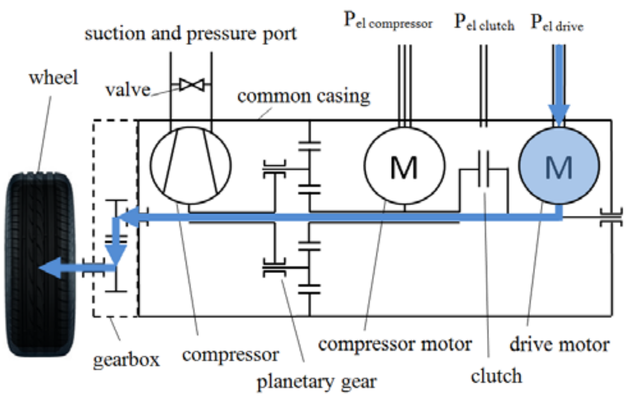

Fig. 5: Function mode 1 where the drive motor only drives the wheels

In the second function mode 2 the air compressor is driven independently by the compressor motor, while the clutch is open, see figure 6. It is to be understood that both of these conditions can be operated independently and at the same time in function mode 6, which is not explicitly shown in the figures.

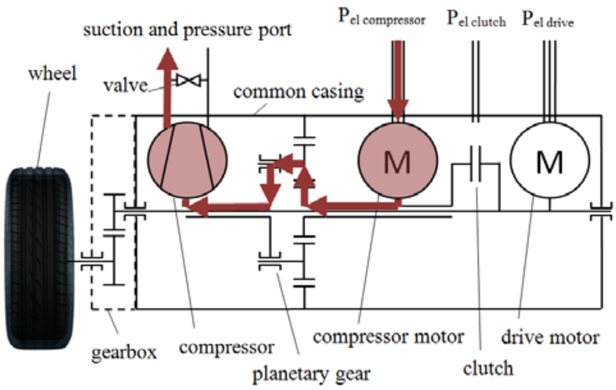

Fig. 6: Function mode 2 where the compressor drive works alone

The system has the ability to use both motors to drive the vehicle (boost function mode 3). Since the compressor is constantly connected with the compressor motor, its pneumatic circuit must be shorted using a valve to prevent power consumption by the compressor, figure 7. In this case, the clutch is closed and must be fed by electric power, also the compressor must be supplied with its friction losses power. The system behavior then belongs to the ability to store thermal energy in the refrigeration circuit.

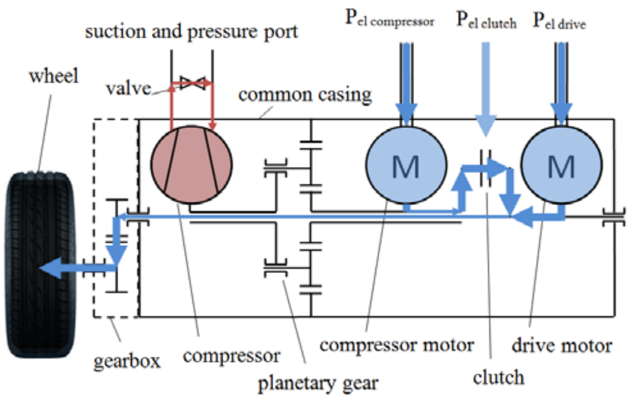

Fig. 7: Function mode 3 as a boost function

Function mode 4 describes the main application of the 2 in 1 motor system, where the refrigeration task is solved by recuperation of kinetic energy, see figure 8. During a braking event, the compressor is coupled to the drive shaft without being driven by the compressor motor or drive motor. A part of the kinetic energy of the vehicle is forwarded directly to the compressor without taking the detour via the battery or some more electronic converters. The clutch is closed in this case.

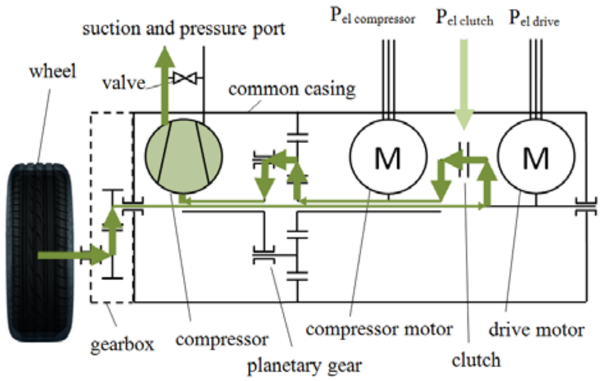

Fig. 8: Function mode 4 with refrigeration by recuperation

Figure 7 is also guilty for a possible application in which both motors drive the vehicle as well as the compressor, function mode 7. The power distribution between the two motors occurs here individually or through a selective control valve in the refrigeration circuit. With this arrangement, the motors can be operated close to their best efficiency regions.

It will be appreciated that the different possible combinations are also applicable to regenerative operation of the electric machines, which is listed in Table 3 with function mode 5 (see figure 9), 9 and 10.

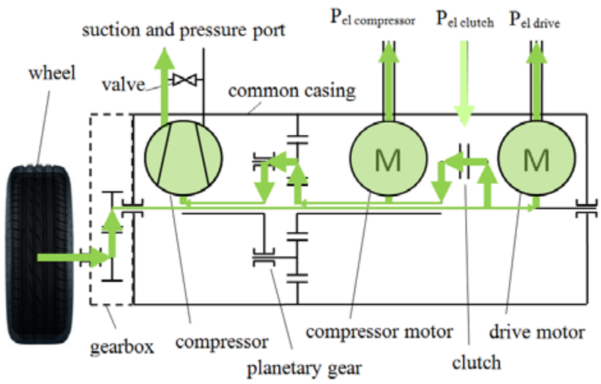

Fig. 9: Function mode 5 with refrigeration by recuperation and max. charging

IV. Design of the 2 in 1 Electric Drive

Figure 10 shows the design of the 2 in 1 electric drive. The drive motor is mounted on the main shaft and can be directly connected to the wheels of the vehicle. The second motor to drive the compressor is located on a concentric shaft and can be coupled to the drive motor over the electromagnetic clutch. The planetary gear is located between the compressor motor and the compressor. On the one hand it is possible to drive the compressor separately when the vehicle stands still and on the other hand the compressor can be driven by the wheels in recuperation mode.

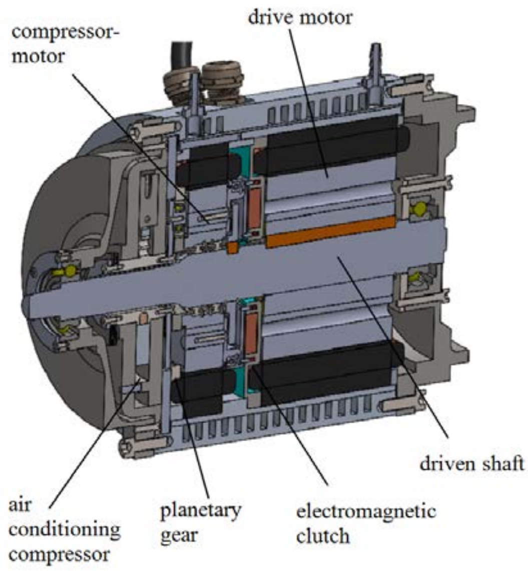

Fig. 10: Design of the 2 in 1 electrical drive

The stators, which are lined up in one single housing, is cooled using a common water jacket. The torques generated by the stators are transferred to the housing through axially inserted pins located at the inner periphery of the stator housing. The system is designed so that it can be easily unassembled.

A. *Compressor Drive*

Since the two motors operate for reasons of weight savings with the highest possible speeds, the air conditioning compressor on the other hand advantageous manages with a smaller speed range, it is helpful to use an additional planetary gear between compressor motor and compressor, as shown in figure 11.

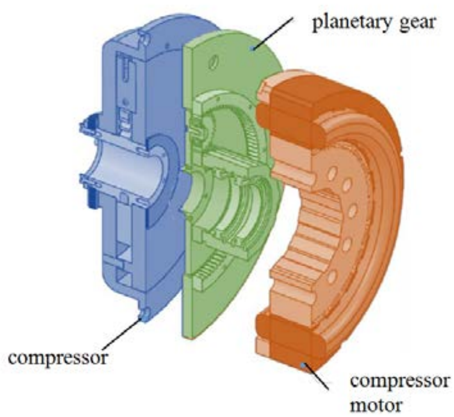

Fig. 11: Design of the compressor drive

The rotor of the compressor motor drives the sun gear of the transmission while the planetary carrier drives the compressor.

B. Swing Vane Compressor

A rolling piston compressor employs a piston eccentrically mounted to the crankshaft. During operation, the two volumes confined by the cylinder inner surface, roller contact point and the vane changes in size, leading to the compression of the refrigerant. With a swing vane compressor the round piston is driven by an eccentric shaft, but does not roll on its periphery, as shown in figure 12. The piston inside the cylinder and the outlet valve vane both have an oscillating movement.

A conventional swing vane compressor (figure 12, left side) has an oscillating vane while the new variant (right side of figure 12) has its vane rigidity held against cylinder wall. This reduces the frictional losses between the vane bush and the vane as the contact force between these components are no longer a function of pressure difference acting on the exposed vane surfaces.

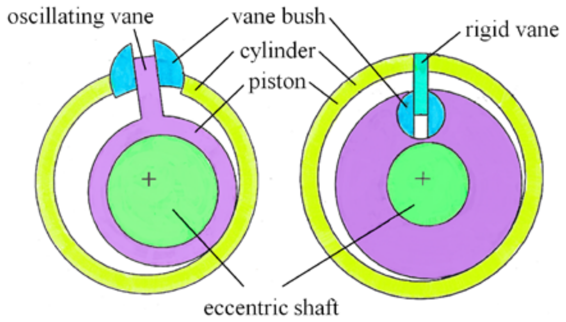

Fig. 12: Conventional swing vane compressor (left) and new variant (right)

Figure 13 shows the internal structure of the air conditioning compressor.

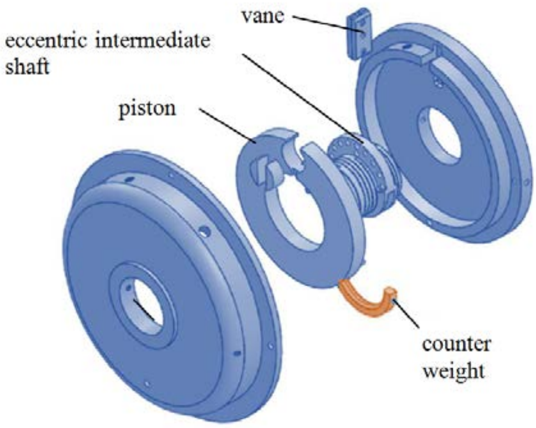

Fig. 13: Design of the compressor

It is a new variant of the swing vane compressor type.

The piston is driven by an eccentric intermediate shaft which is balanced with a counterweight and with additional holes in the same plane than the piston to avoid vibrations. In this particular design, the valve is fixed inside the vane housing, the piston is movably on the valve vane with two cylindrical half-shells as the vane bush.

C. Planetary Gear

The compressor motor is working on the sun gear of a one stage planetary gear, as shown in figure 14. The ring gear is fixed to the housing, the planetary carrier drives the compressor. The sun gear has z_1 = 60 teeth while the planet gears have z_2 = 25 teeth and the ring gear has z_3 = 110 teeth. The gear ratio i is

$$i = 1 + \frac{z_3}{z_1} = 2.8 \qquad (1)$$

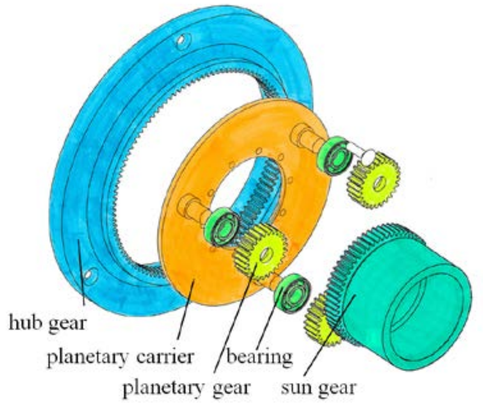

Fig. 14: Design of the planetary gear

The sun gear is supported by two ball bearings on the main shaft, thus forming the coaxial intermediate shaft for the compressor drive, also seen in figure 10.

D. Electromagnetic Clutch

The electromagnetic clutch is located between the drive motor and the compressor motor and consists of a fixed clutch casing in which the coil is wound, a clutch disc mounted on the shaft and a two-part clutch plate (see figure 15). One part of the clutch plate serves as a magnetic yoke and also stands still, the second part is mounted on a ball bearing on the fixed part and dives on axial pins into the rotor of the compressor motor. This pins transmit the tangential forces. The restoring force is generated by small springs which are located in the fixed part.

The coupling requires a minimum magnetic flux density of $B = 1$ T, for which purpose it is necessary to provide a magnetic voltage θ of

$$\theta = \frac{B}{\mu_0} \cdot \delta = 800 \text{ A} \qquad (2)$$

with an air gap width of $\delta = 1$ mm. μ_0 in equation (2) is the permeability constant.

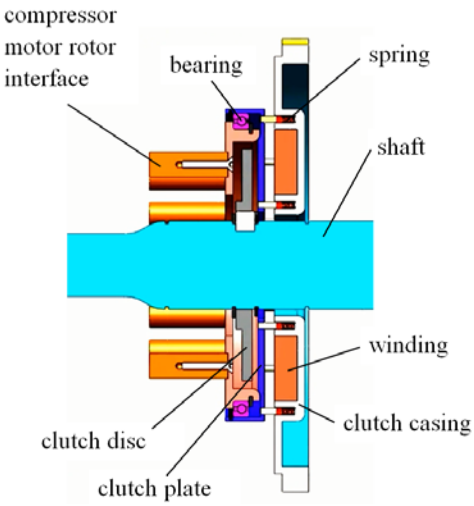

Fig. 15: Design of the electromagnetic clutch

E. Electrical Machines

The compressor, the planetary gear, the compressor motor and the clutch plate form a unit, which is mounted coaxially on the shaft of the drive motor. The drive shaft carries the rotor of the drive motor, as shown in figure 16. It also carries the clutch disc with a solid connection.

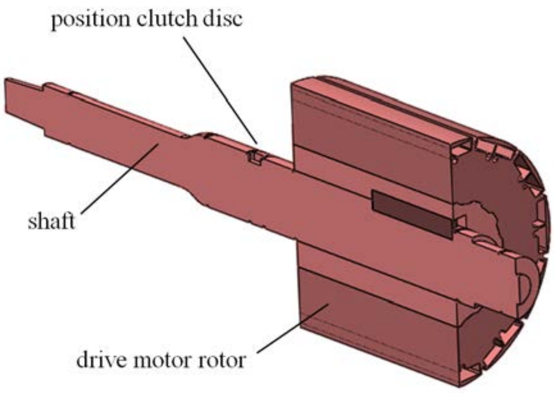

Fig. 16: Shaft and rotor of the drive motor

Both electrical machines are permanent-magnet excited synchronous machines and have the same topology in the electromagnetic circuit. They have a single tooth winding architecture with 18 teeth fed by 3 phases, the number of pole pairs is 6, see Figure 17. The rotor of the compressor motor has holes in which the rotating member of the clutch plate gears into and thus transfers the force in the tangential direction. At the same time it allows the movement of the clutch in the axial direction. The magnets made of iron-neodymium boron are housed in rectangular pockets. They have a residual magnetism of 1.3 T and produce a magnetic flux density of 1 T in the air gap.

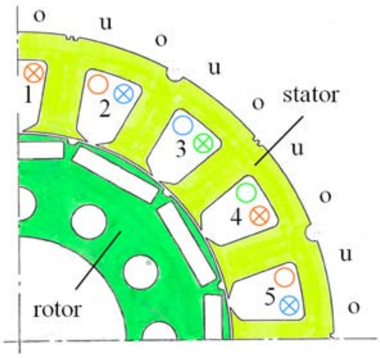

Fig. 17: Motor electromagnetic circuit architecture with N = 18 and p = 6, m = 3

In figure 17 N is the number of slots or stator teeth, p the number of pole pairs and m the number of phases.

Figure 18 shows the interconnection of the individual coil sides for the 3-phase winding of the stator of the compressor motor. The numbers in figure 17 and figure 18 are the numbers of the slots, a, b and c in different colors mean the three phases, and o and u stand for the two layer sides of the winding in a slot. One phase consists of 6 coils which are connected in serial.

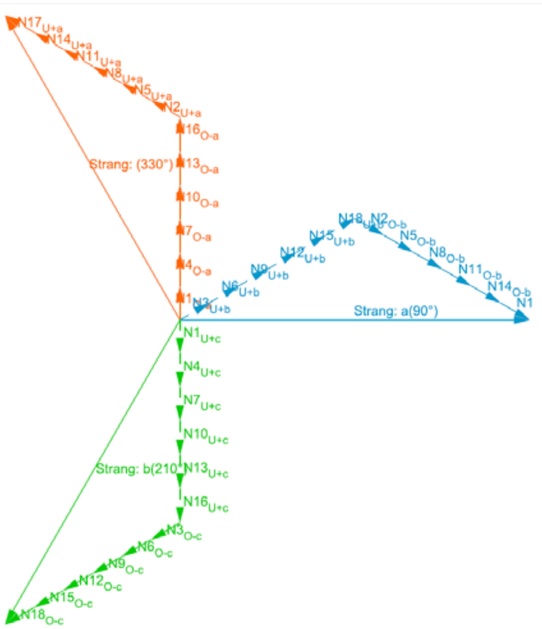

Fig. 18: Connecting the wires in the slots to coils

The figure also describes the location of the electromagnetic forces of the wires in the slots, which have a mechanical angle of 20 ° between the N = 18 positions of the slots, with an electrical angle of 120 ° between the electromagnetic forces of the wires in two neighbored slots. The electrical angle α between the voltages of two neighbored slots

$$\alpha = \frac{p}{N} \cdot 360° \quad (3)$$

is 120°. The winding factor of this two layer topology is

$$\xi = 0{,}866 \quad (4)$$

This is not the maximal possible one, but this topology has another advantage. With this topology it is easy to wind the neighbored stator tooth with a coil of the following phase. If both coils are connected together and by replying this scheme with the coils of all following teeth, this results automatically in a triangle phase connection scheme. The drive motor is of this scheme. Here all the coils of one phase are connected in parallel.

Both winding systems – drive motor and compressor motor - make it possible to use the same number of turns and the same wire diameter.

V. RESULTS

The paper describes the concept and the design of a new 2 in 1 motor system for usage in electric vehicles. The integrated unit is expected to operate the air conditioning compressor inlet shaft close to 100 % efficiency during recuperation mode. The improvement in efficiency is achieved through direct mechanical coupling of the traction motor with the air conditioning compressor during breaking events. The mechanical configuration of the unit is such that the torque and speed characteristics of drive and compressor motors can be also independently controlled during drive mode. In addition to improved efficiency, the integrated unit has numerous other advantages such as increased reliability, compact design and weight saving.

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