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ASSOCIAÇÃO PORTUGUESA DO VEÍCULO ELÉCTRICO

PORTUGUESE ELECTRIC VEHICLE ASSOCIATION

Electrical Motorized Wheel

The future of the greatest invention of mankind

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Summary

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- Evolution of the wheel into a motorized one, focusing in the Electrical Motorized wheel.
- Overview of all Electrical Motorized wheels available.
- Definition of the desired electrical motor characteristics for an Electrical Motorized Wheel.
- Presentation of a new special purpose electric motor for the Electrical Motorized wheel and its major design characteristics.
- Proposed motor applicability into several EV platforms.
- Conclusions and final questions.

Introduction
Invention of the wheel

Steps and developments to invent a functioning wheel:

1. Humans realized that heavy objects could be moved easier if something **round** (e.g. a tree log) was placed under it and the object rolled over it.
2. Humans realized a way to move heavy objects, with an invention archaeologists call the **sledge**. Logs or sticks were placed under an object and used to drag the heavy object, like a sled and a wedge put together.
3. Humans thought to use the round logs and a sledge **together**, by using several logs or rollers in a **row**, dragging the sledge over one roller to the next.
   With time the sledges started to wear **grooves** into the rollers and humans noticed that the grooved rollers actually worked better, carrying the object further.

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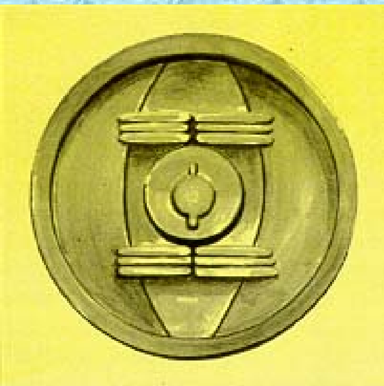
Introduction

Invention of the wheel (2)

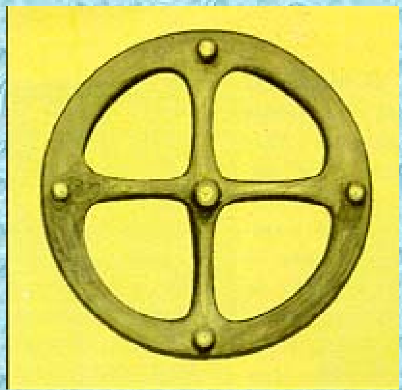
4. The log roller was becoming a **wheel**, humans cut away the wood between the two inner grooves to create what is called an **axle**.
   Wooden pegs were used to fix the sledge, so that when it rested on the rollers it did not move, but allowed the axle to turn in-between the pegs, the axle and wheels now created all the movement. These were the **first carts**.
5. **Improvements** to the cart were made. The pegs were replaced with holes carved into the cart frame, the axle was placed through the hole.
   This made it necessary for the larger wheels and thinner axle to be separate pieces. The wheels were attached to both sides of the axle.
6. The **fixed axle** was invented, where the axle does not turn but is solidly connected to the cart frame.
   Only the wheels did the revolving by being fitted onto the axle in a way that allowed the wheels to rotate. Fixed axles made for stable carts that could turn corners better. By this time the wheel was a **complete invention**.

Introduction
Development of the wheel

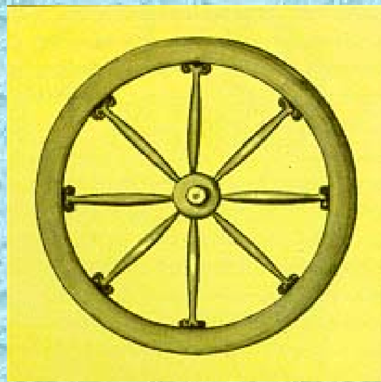
- The oldest wheel found in archaeological excavations was discovered in what was Mesopotamia and is believed to be over fifty-five hundred years old.



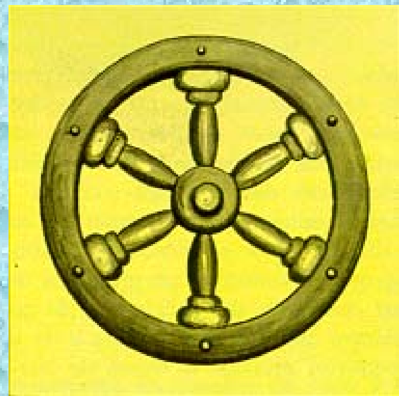
Wheel used in Ur,
~4.000 BC



Greek wheel,
VII BC



IV BC



III BC

Introduction
To roll and steer the wheel

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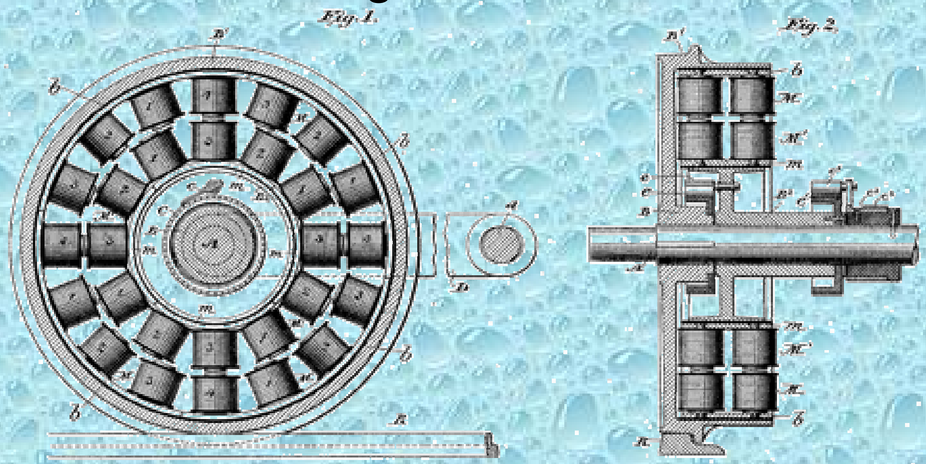
- When prehistoric man first invented the wheel, it required the use of manpower to roll and steer a load.
- For millennia, the only improvement was the usage of horsepower, to roll and steer a load.
- The industrial revolution replaced the animal by mechanical engines (steam, petrol, diesel), still outside the wheel.
- Nevertheless, the usage of electrical motorized wheels (EM wheels) in ground vehicles has now a long tradition.

The first technical reference in literature to this type of wheels, also for non railway vehicles, was made in 1890 by A. Parcelle.



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Motorized Wheel

Concept

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- The motorized wheels concept is associated with the combination of a motor from which the torque is mechanically transmitted through a reduction gear or a shaft to a wheel. Other approaches were made without mechanical transmission, e.g., hydraulic motorized wheels or air-powered motorized wheels (Skondin).

- Motorized wheels can, theoretically, also use as a prime mover an internal combustion engine. However, it is ineffective since it uses fuel, needs auxiliary lubrication and cooling systems, has a large size, and undesirable environmental impacts.

- In the EM wheels the rotation is conveyed to a wheel by means of an electromagnetic gearless cooperation of magnetic systems of a fixed part (stator) and a rotating one (rotor).

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Electrical Motorized Wheel Characteristics

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- Incorporation of an electric motor inside the wheel.
- Capable of generating traction by itself.
- Capable of performing electromagnetic breaking.
- Diversified approaches to design EM wheels can be used.

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Evolution of the EM Wheels

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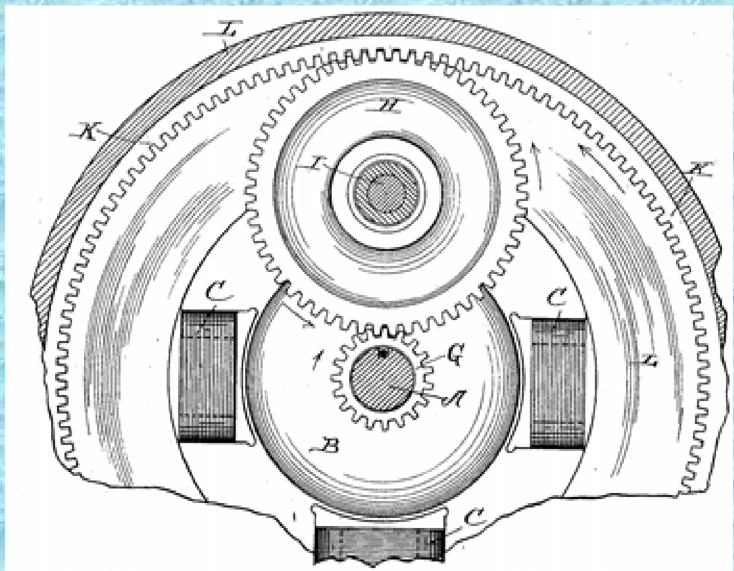
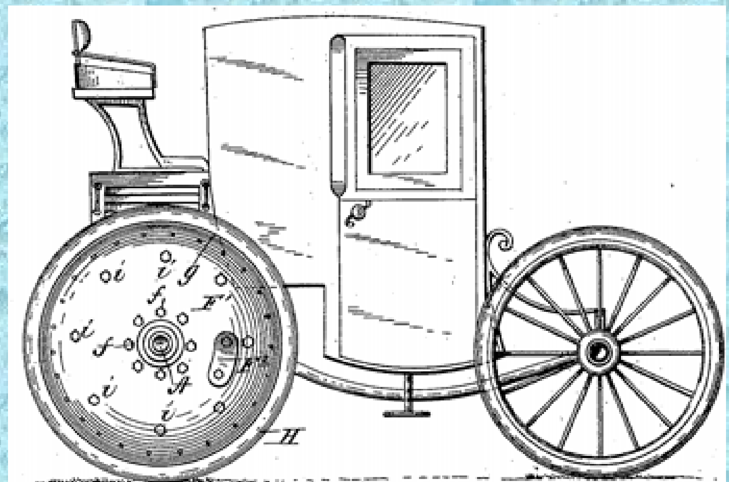
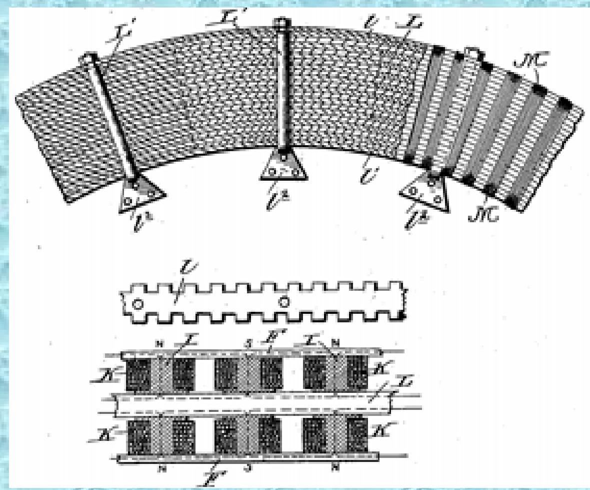


Newman, 1899





Whittlesey, 1900

Evolution of the EM Wheels (2)

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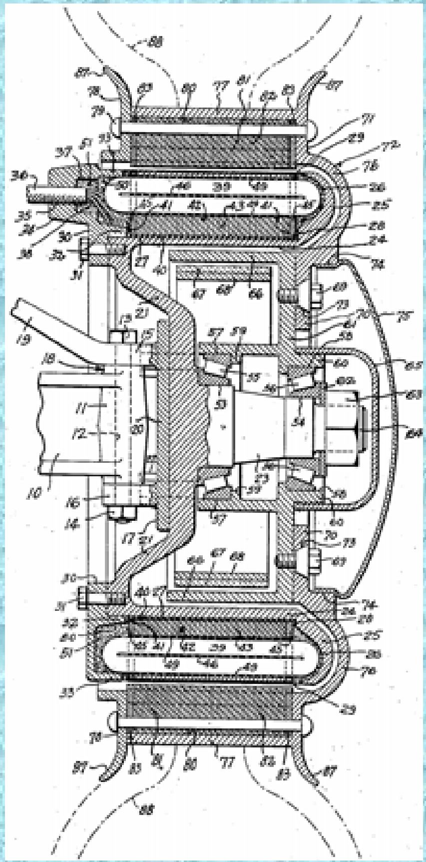
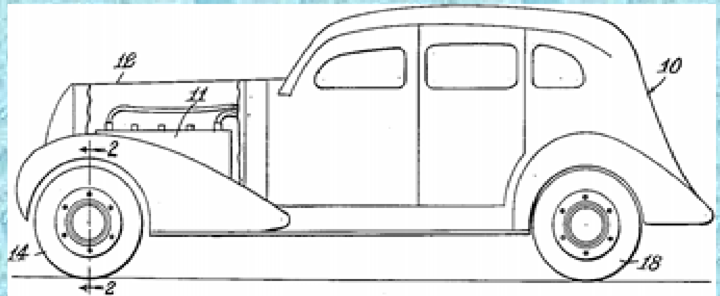
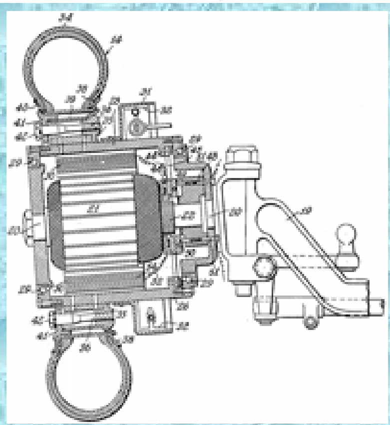
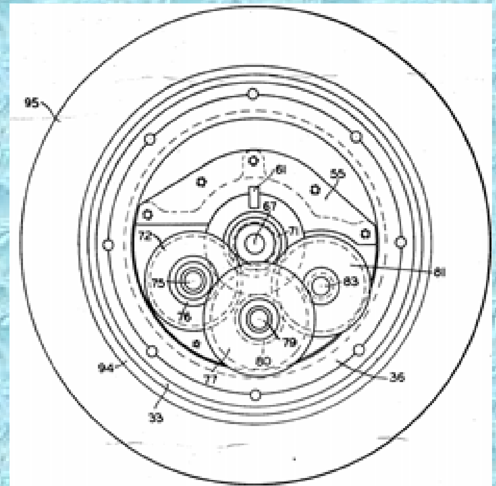


Gladish, 1947





Myrmirides, 1950



Hawkings, 1952

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Evolution of the EM Wheels (3)

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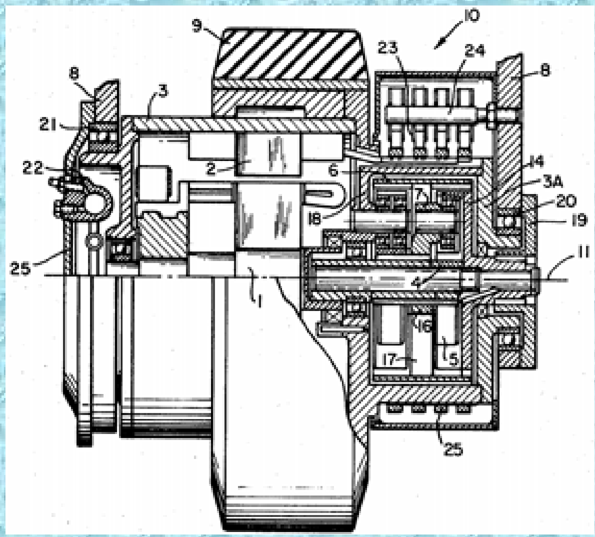
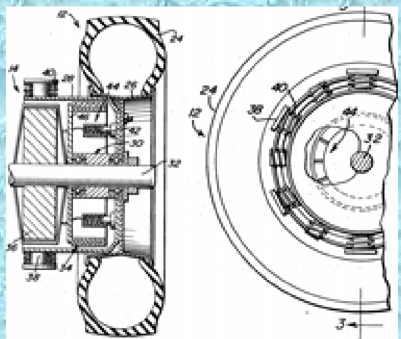
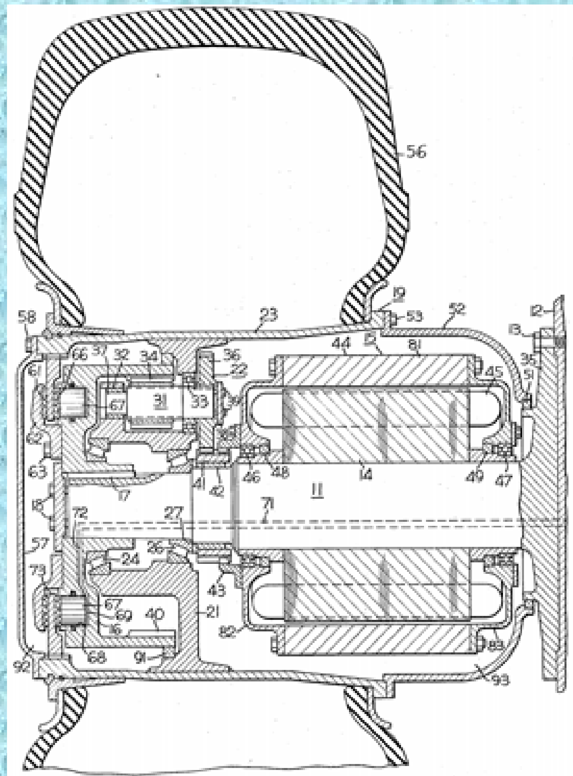


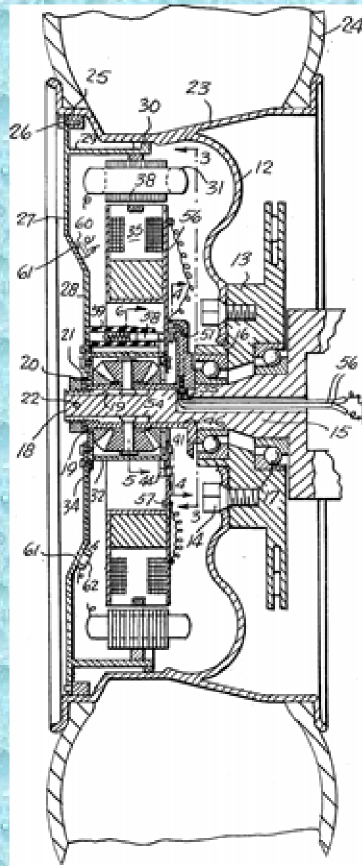
Vitkov, 1972



Mager, 1974



Rockwell, 1974



Burton, 1974

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Evolution of the EM Wheels (4)

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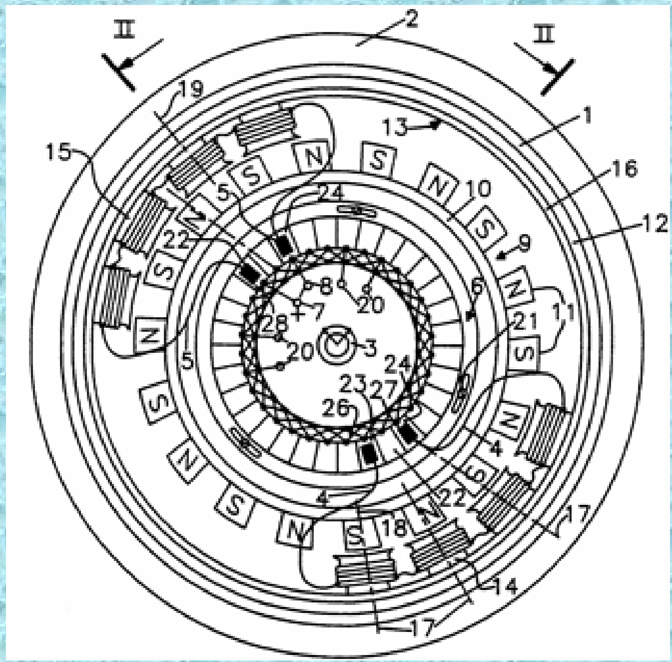
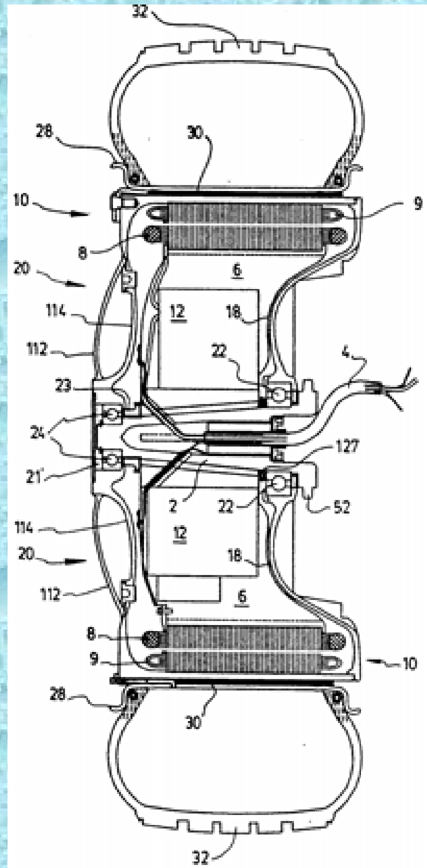
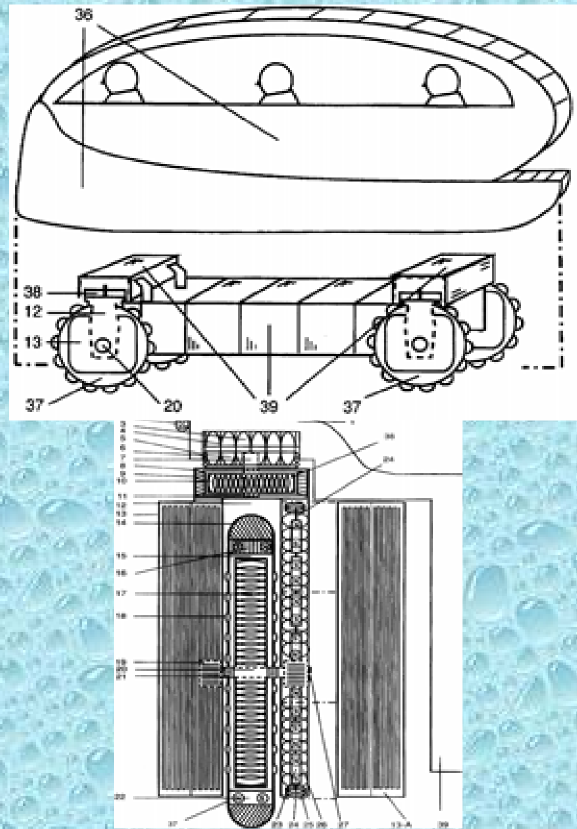


Skondin, 1992



Couture, 1994



Devries, 1998

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Evolution of the EM Wheels in Bicycles

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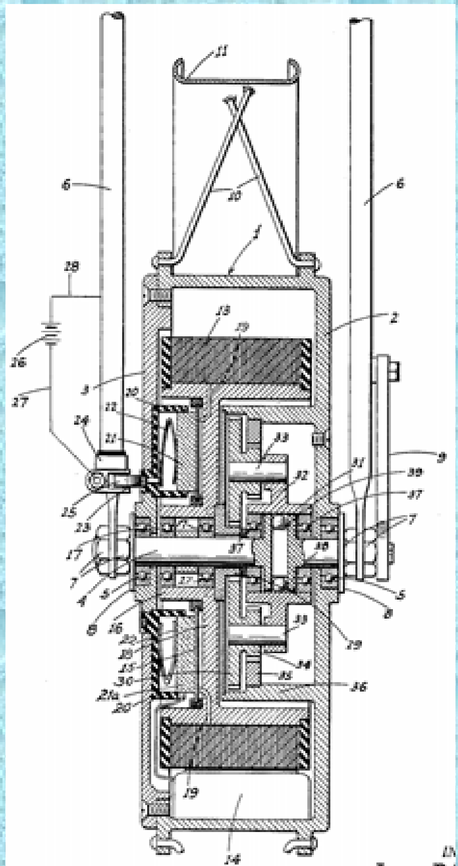
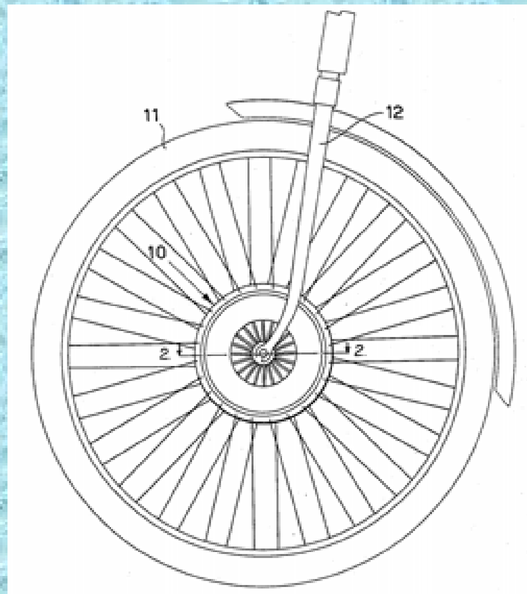
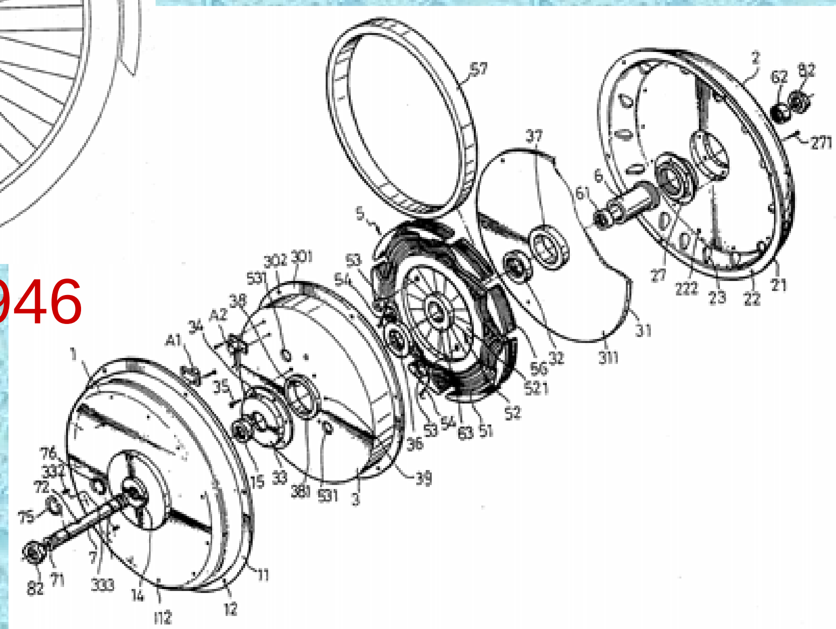


Tucker, 1946



Restelli, 1946

Li, 1995



Evolution of the EM Wheels in Trucks

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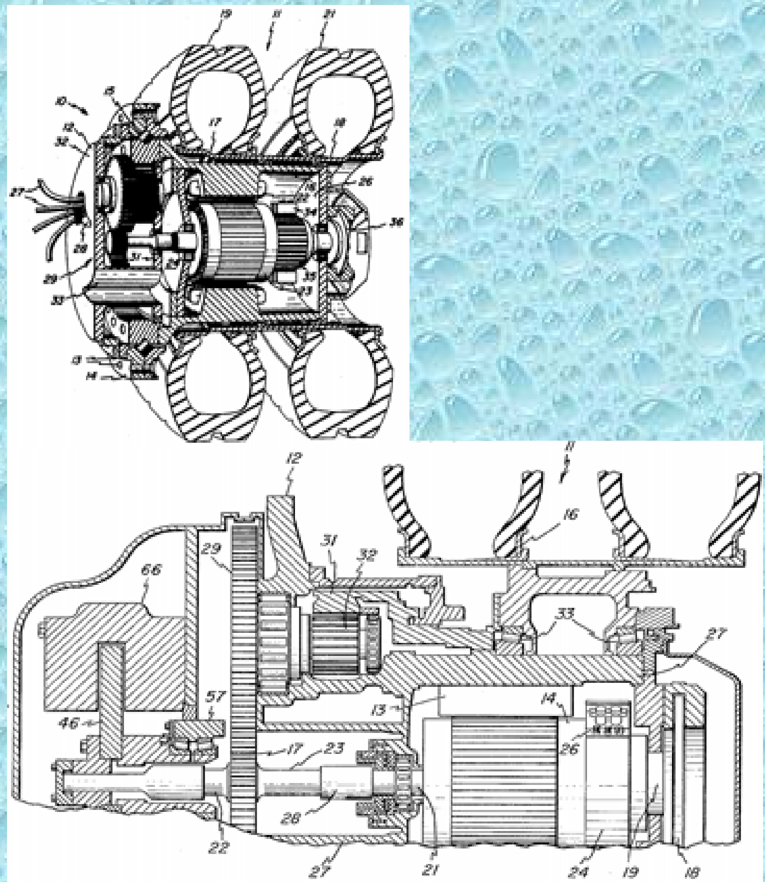
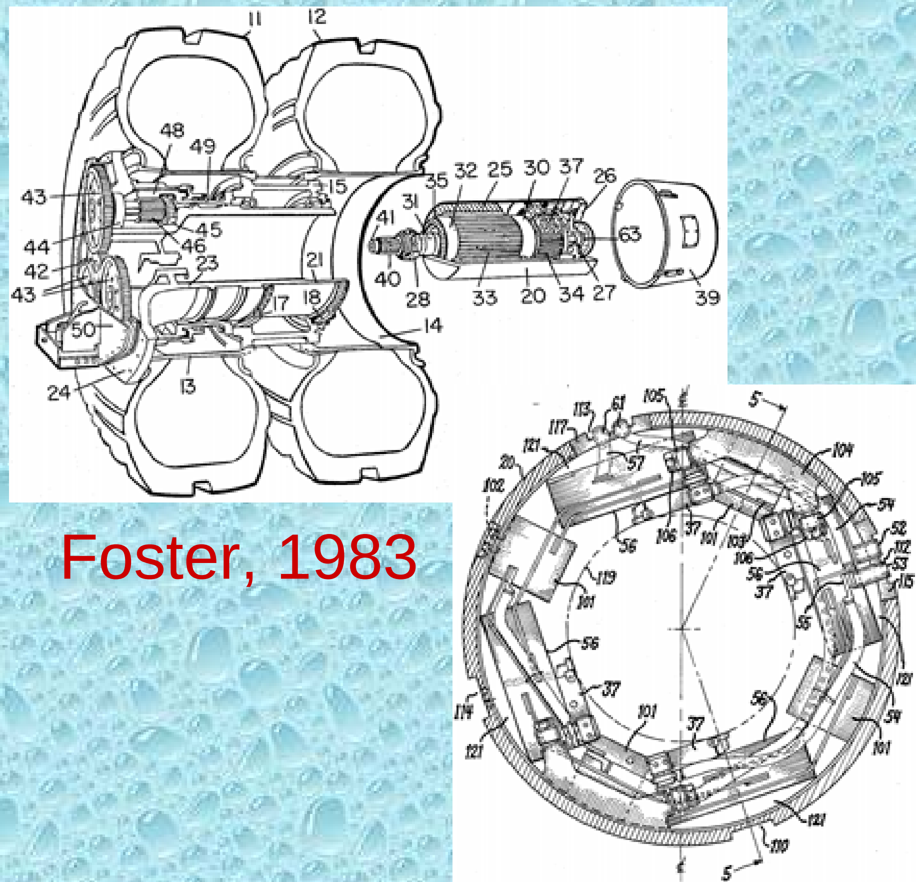


Hapeman, 1975



Foster, 1983

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Major breakthroughs in EM Wheels

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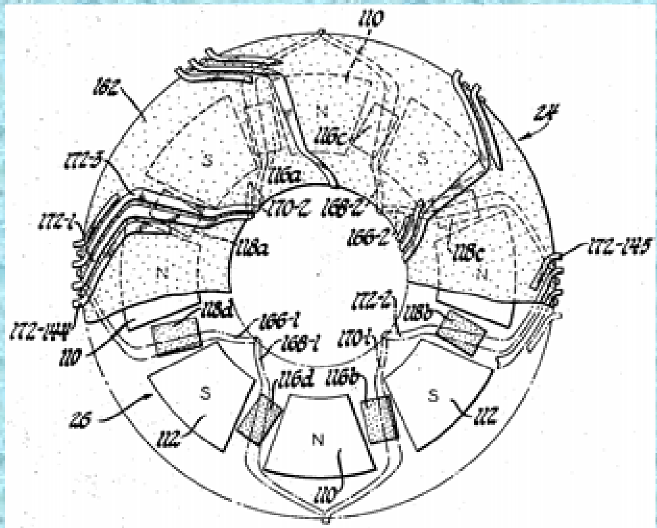
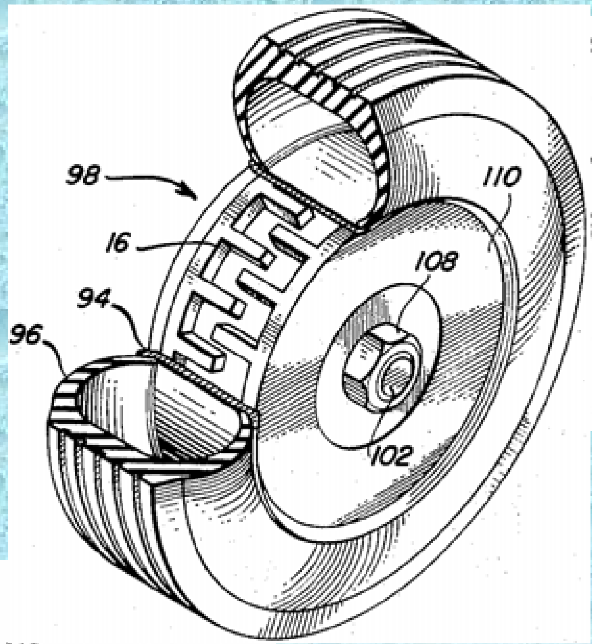
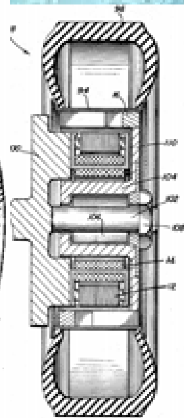


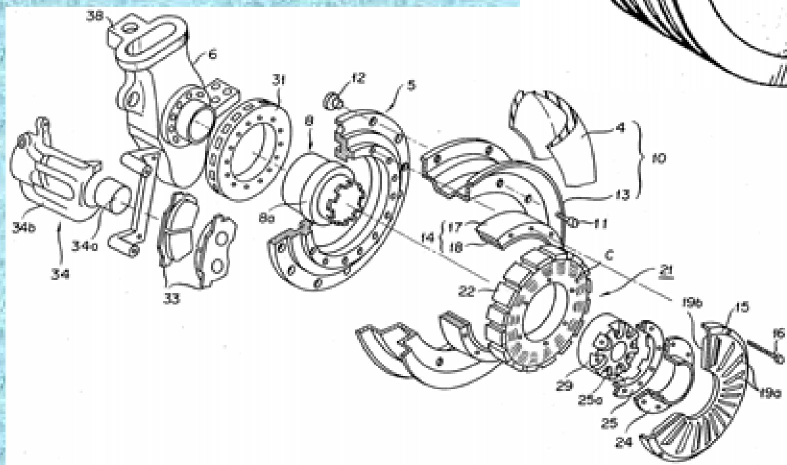
Pierro, 1970
First gearless drive with a linear synchronous motor and a interdigitated Rotor.





Lohr, 1969
Serious usage of permanent magnets.

Bruyant, 1975
First brushless motor with field fixed to axle to drive a road wheel.



Hiroshi, 1988
Wheel disc motor fastened to the outside structure of the wheel.

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Features of the EM Wheels

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- Absence of gears.
- Possibility to have direct acceleration control.
- Internal capability to regenerate and sometimes store energy:
  - Regenerative breaking with capacitor based storage inside the wheel (Devries).
- The incorporation of an additional steering mechanism allows:
  - Even self-steering by resorting to photo cells or cameras focused on a guide line on the pathway.
  - Automatic impact evasion reaction (that can be, on wheel, automatically triggered by an obstacle approach).
- As a consequence of the auto-steering capabilities of these wheels:
  - Simplified parallel parking procedure (Devries).
- Motorized wheel incorporation into commercial available vehicles:
  - Providing a reduced weight while being compatible with standard braking systems, suspension systems and steering systems (Couture).

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Industrial EM Wheels

State of the Art and Concepts

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Manuf.	Model	Motor Type	Quantity	Power	Torque
Aurora	RMT - 101	Brushless DC	1	-	3,24 Nm
Ford	ESCAPE	PM	4	65 kW	-
TM4	TM4 Transport's	Brushless AC PM	-	18,5 kW	180 Nm
PML FlightLink	PML	Brushless	-	<6kW	-
ICAZ	KAZ	Synchronous PM	8	55 kW	100 Nm
CEM – UT	ATTB	PM	-	100 kW	-
GM	AUTOnomy	-	-	-	-
WaveCrest	M35-1000	PM	-	37kW	1000Nm

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Industrial EV
2003/2004

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Toyota Prius | DeLorean TEV | Chevy S10 Fuel Cell Vehicle (FCV) | Honda Civic Sedan Hybrid | Ford Escape HEV | Toyota Estima Hybrid | Suzuki Covie Concept Car | Toyota FCHV-4 Fuel Cell Hybrid SUV | Chrysler Natrium Fuel Cell Van | Chrysler EPIC Electric Delivery Van | BMW 750hL Hydrogen/Fuel Sedan | GM Autonomy Fuel Cell Concept Car | ZEbus Fuel Cell Bus | Smart EV electric commuter car | Hyundai Santa Fe Fuel Cell SUV | Renault Kangoo Hybrid Electric Van | Lexus 2054 EV | Yugo EV | Reva | Betti Electric Motorcycles | Toyota POD | Honda FCX-V4 FCV | Toyota RAV4 EV | Nissan Xterra FCV | Tango | KAZ EV Limo | GM's Parallel Hybrid Truck | SDSU Enigma Hybrid | GEM NEV's | NECAR 5 | Allison Electric Drive | Vikram EV | Lido NEV | Honda Dual Note |

EM Wheel

Solutions available on the market

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- The majority of EM wheels have a reduction gear and an induction motor since they are ecologically safe, reliable and economical.
- The use of a reduction gear has an increased risk during its operation.
- The use of an induction motor turns needs to use an electronic power converter, and an auxiliary lubrication and cooling systems.
  It is difficult to ensure energy recovery during the breaking, it can lead to a shorter storage battery life, and usually higher voltage power supplies have to be used.
- The use induction motors *per se* originates high heat emission.
  (result of a residual field in the magnetic system of the motor).
- Also difficulties in maintenance and inspection are foreseen for this kind of solution.

These characteristics do not allow geared EM Wheels powered by an induction motor to be regarded as promising for the future.

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EM Wheel

Solutions available on the market (2)

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- An EM wheel solution using a DC motor and a torque transmission gear that has a hollow flexible cylindrical rotor with a ring gear connected with a gear attached to the axle was proposed. (Shkondin)
  The main disadvantage is the need for a large energy consumption (especially during the starting of the vehicle), as well as its large size and heavy weight.
- Other type of EM wheel comprises of a wheel having a rim and a shaft incorporating an disk type induction motor. Has its stator with a magnetic circuit, windings and current leads secured to a fixed axle of the wheel and a squirrel-cage rotor having a winding and magnetic circuits positioned on either side of the stator.
- The disk type induction solutions of the EM wheels are more reliable due to the absence of a mechanical gear and enhances stator and rotor cooling through radial passages of the stator.

These solutions are effective but have an high technical complexity, and therefore are not in most cases economically viable.

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EM Wheel

State of the art (3)

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Other new approaches are:

- The reluctance motor with magnetic poles formed by laminating steel plates in circumferential direction, (Kawabata, Toyota).
- The multiple magnetic path electrical motor, (Pyntikov, Wavecrest Laboratories).
- The rotary electric motor having magnetically isolated stator and rotor groups, (Maslov, Wavecrest Laboratories).

These solutions are promising and may result in viable mass industrial implementations.

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EM Wheel

Electrical Machine Basic Requirements

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The EM wheel should incorporate a special electric machine which is to comply with the following basic requirements:

- Possibility of incorporation in a vehicle wheel without using a gear;
- Use of low voltage electrical power supplies;
- Maximum simplicity, low weight and compactness;
- Enhanced reliability and long service life;
- Maximum torque at starting of a vehicle and torque reduction with an increase in the wheel speed;
- Absence of auxiliary cooling and lubrication systems;
- Good thermal conditions;
- Energy recuperation;
- Facilitated control of electrical motorized wheels and possibility of manoeuvring them within restricted areas.

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Special Purpose Electric Motor

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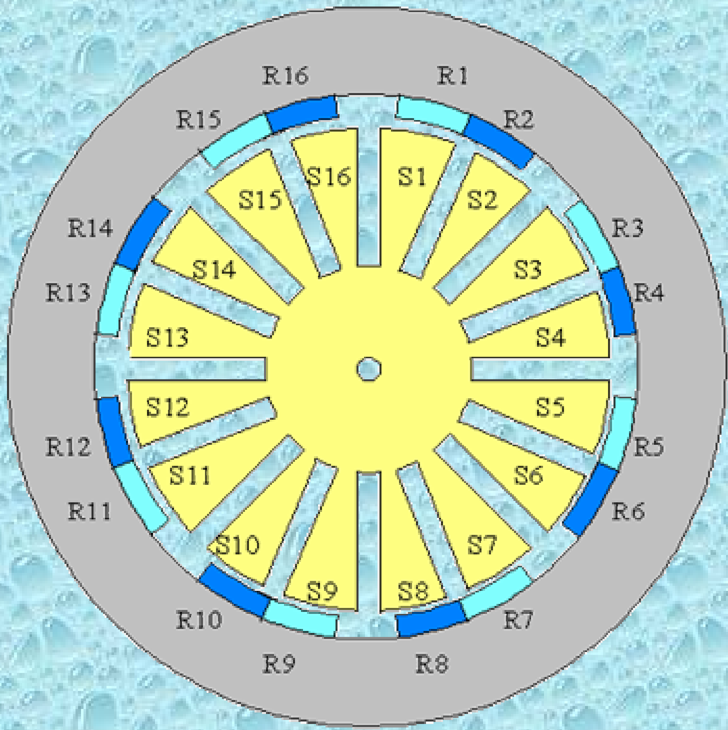
Permanent Magnet Motor

- It is embodied as a sleeve-shaped external rotor.
- It has sixteen electromagnetic poles, on the electrically commutated stator (S1 to S16) and sixteen permanent magnet poles in the rotor (R1 to R16).
- The air gap surfaces in the region between the stator and rotor are provided with fine gearings in order to reduce the torque between them.



Special Purpose Electric Motor

Characteristics

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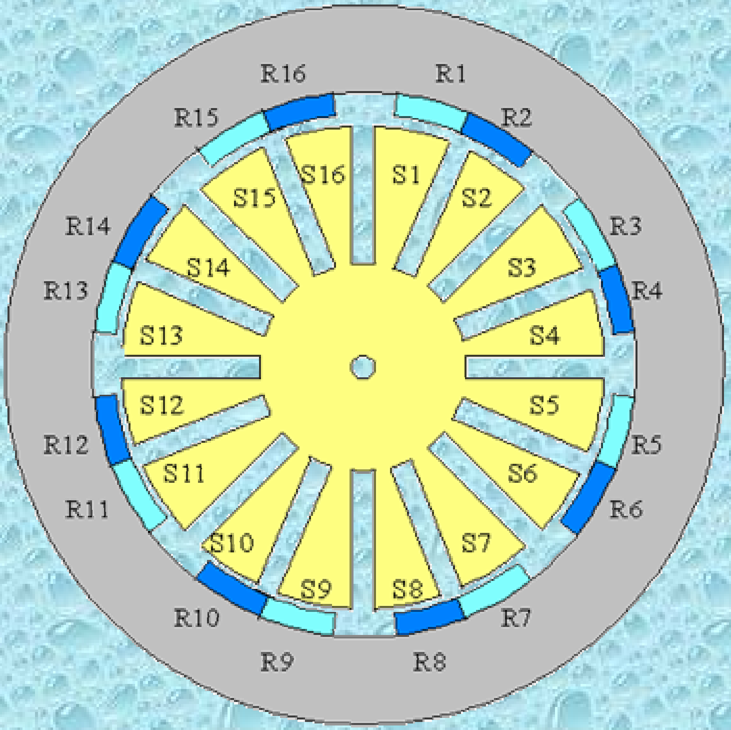
- Very simple and reliable EM wheel motor.
- New design and new relative position of the components ensuring an electromagnetic linkage between rotor and stator.
- Usage of low-voltage power supplies (48V).
- Maximum torque during the start of the motor without using auxiliary cooling systems.



Special Purpose Electric Motor
Deviation Angle

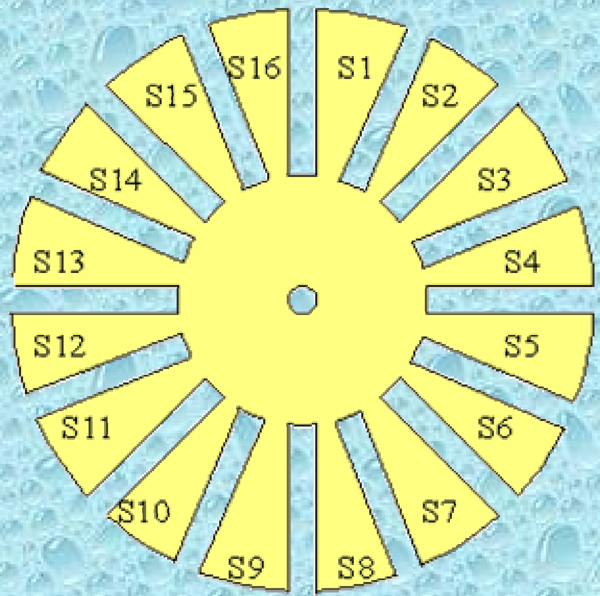
- The poles of the stator were not disposed uniformly since they alternating assume a deviation angle (α) of less than and greater than the quotient between the perimeter of the machine and the number of poles considered, i.e

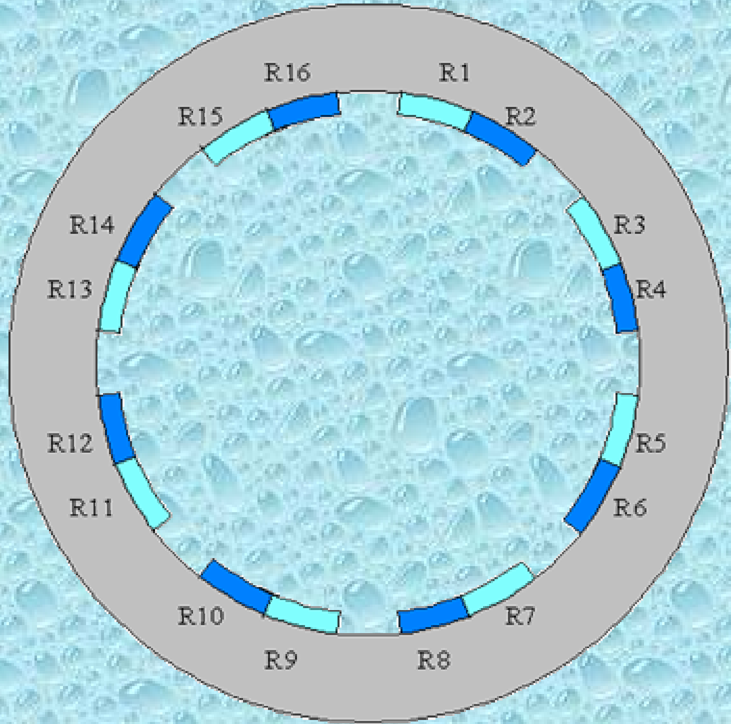
$$\begin{cases} \alpha > \dfrac{\pi}{p}, & \text{even} \quad p \\ \alpha < \dfrac{\pi}{p}, & \text{odd} \quad p \end{cases}$$

- The deviation angle allows a more uniform magnetic field distribution.
- This leads to the reduction of the torque between the rotor and stator.
  Without this offset of the permanent magnets, the numbers of poles would cause a number of non symmetric behaviors to be produced between the rotor and stator, which could result in an unsteady and noise encumbered operation of the motor.
- It requires a complex design of the stator which depends on the precise installation of the permanent magnets.

Special Purpose Electric Motor
Machine Elements

- Its design was done considering also an improved potential for torque compensation.
- The stator and rotor of the proposed motor as separate elements can be observed:





Special Purpose Electric Motor

Fine Gearing Teeth

- The offsetting of the fine gearing teeth in the vicinity of the air gap surfaces of the stator allows a symmetrically designed permanent magnet rotor which is simple to manufacture.
- Also produces definite magnetic field ratios in the circumference direction that can be influenced in a number of ways via the fine gearing teeth disposed on the stator. The stator is still essentially symmetrical.
- The compensation of the torque remains limited to the design of the fine gearing teeth (produced by simple armature stamping).
- Moreover, a power supply by means of sliding contacts is no longer necessary and a simple electronic control circuit can be used.

Special Purpose Electric Motor

Torque Compensation

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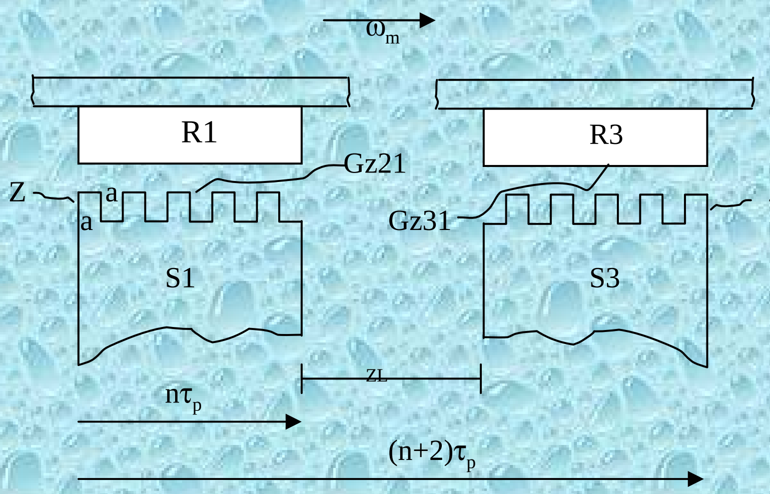
- The effective compensation of the torque is produced since the offset of the fine gearing of the pole pairs is identical and corresponds to half a spacing of the fine gearing teeth.
- Planar representation of the formation of pole pairs from diametrically opposed poles:



a - offset between the fine gearings;
Gz21, Gz31 – fine gearings;
R1, R3 – Permanent magnet poles;
Z – Tooth;
ZL - Tooth space;
τp - Pole spacing;
n = 1 or 2.

- The electromagnetic poles S1 and S3 are at a distance d:

$$d = (n+2)\tau_p$$

Special Purpose Electric Motor

Mathematical model

The mathematical model of the motor used to simulate its dynamic behavior:

$$\begin{cases} \frac{d}{dt}\lambda_d = \omega_m \cdot \lambda_q - R_s \cdot i_{ds} + u_{ds} \\ \frac{d}{dt}\lambda_q = -\omega_m \cdot \lambda_d - R_s \cdot i_{qs} + u_{qs} \\ \frac{d}{dt}\lambda_o = -R_s \cdot i_{os} + u_{os} \\ \frac{d}{dt}\omega_m = \frac{1}{J} \cdot \left[8 \cdot \left(\lambda_d \cdot i_{qs} - \lambda_q \cdot i_{ds} \right) \right] - \frac{8}{J} \cdot T_{Load} \end{cases}$$

λ - the machine linkage fluxes;
i - electric currents;
u - voltage applied to the machine;
ω_m – mechanical velocity.

Motor Applicability

Wheel Chair & Bicycle

Configuration: Wheel Chair with two EM wheels.
Voltage: 24 V (two storage batteries of 12 V).
Average working current: 6 A.
Power: 60 W (per wheel).
Speed: 8 km/h.
Load carrying capacity: 100 kg;
Range: 80-140 km (estimated).

Configuration: Bicycle with a single EM wheel.
Voltage: 48 V (four storage batteries of 12 V).
Average working current: 5 A.
Power: 220 W.
Speed: 50 km/h.
Load carrying capacity: 100 kg.
Range: 90-150 km (estimated).
Note: Performance compared to the Li proposed solution and better than Restelli.

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Motor Applicability

Mini Agricultural Tractor & Forklift

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Configuration: Mini agricultural tractor with four EM wheels.

Voltage: 24 V (two storage batteries of 12 V).

Average working current: 28 A.

Power: 670 W.

Speed: 20 km/h.

Range: 60-80 km (estimated).

Note: Heavily dependent on the storage battery type.

Configuration: Electric forklift with two EM wheels.

Voltage: 24 V (two storage batteries of 12 V).

Average working current: 22 A.

Power: 250 W (per wheel).

Speed: 25 km/h.

Load carrying capacity: 300 kg.

Range: 30-50 km.

Note: Depending on the storage battery type.

Motor Applicability
Urban & Other Vehicles

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Configuration: Small urban vehicle with two EM wheels.
Voltage: 48 V (four storage batteries of 12 V).
Average working current: 16 A.
Power: 380 W (per wheel).
Speed: 90 km/h.
Load carrying capacity: 250 kg.
Range: 10-30 km.

- The proposed motor can not be used with efficiency in heavier vehicles.
- The usage of these motor on toys, roller skates, among other very low power applications without demanding performances, is only limited by economical factors.

Conclusions

- The proposed special purpose motor has the following characteristics:
  - Allows its incorporation into an EM wheel without gears;
  - Designed for low voltage electrical power supplies;
  - Maximum simplicity, low weight and compactness;
  - Maximum torque at starting of a vehicle;
  - Absence of auxiliary cooling systems;
  - It has good thermal conditions and allows energy recuperation;
  - Facilitates the control of electrical motorized wheels and the possibility of maneuvering within restricted areas.
  - It requires a complex design of the stator (easy to produce).
  - Depends on the precise installation of the permanent magnets.
  - The reliability and service life depend on the magnets mechanical specifications;

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Future Work

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- Further developments can be achieved with this motor by placing the rotor magnets in different positions.
(Achieving other embodiments and consequently other dynamic performances).
- It needs to extend its application range, since the results achieved so far are promising for low power applications, but ineffective for higher power applications.
- Technically and economically prove to the manufacturers that the EM wheels is a good solution for all types of EV's.

Electrical Motorized Wheel

Final Questions

Why after more than one century the Electrical Motorized Wheel is not industrially solid implemented?

There were technological limitations. The emerging technologies for EM wheels will boost its implementation.

Why does it still appears in the majority of the revolutionary concept EV vehicles?

The manufacturers are betting in the EM wheels as a middle-term solution.

What is its future?

The future is strongly linked with the EV vehicles future, i.e. will be a bright one.