No brushes, no magnets;

The Plusmotor, a new SR-motor has also the simplest electronics.
…. and can get along even without expensive copper!

At the beginning of the new millennium it seems obvious that the brush motors will be increasingly replaced by the brushless ones
Some experts think, the SR-motor is an answer to this question, but its electronics is yet too expensive.

Can the Plusmotor be cheap enough to replace brush motors in a wide range of automotive, cordless power tools and other applications like vacuum cleaners, washing machines and food processors?

The Plusmotor is an electronically switched reluctance (SR) motor with actually the simplest power and speed control electronics.

1) the unique patented features of the Plusmotor:
- the demagnetization energy at the switching of of a phase is directly feed into the next phase without intermediate storage,
-shortest magnetic paths, (minimall losses)
-a new strip winding with the highest space factors, a new winding technology which permits also a replacement of copper with aluminium,
-very small air gaps despite of inexpensive parts, with a newl fixing technology with fluid-rivets,

The Plusmotor is not only simple, but also designed for automated assembly.
It has a very special design with a new, more efficient magnetic circuit which has improved mechanical, acoustical and thermal characteristics and a small, preferably low-profile size. (S. Comparison.pdf)

The Plusmotor has only two phases, their power switches being flip-flop controlled from a single Hallsensor. The electrical 180° phase angle gives the maximum output/weight ratio; the mechanical phase angle is 30°.
We have already tested several sizes of the Plusmotor with a very good power output. Actually we can manufacture small series of a medium motor shape with a rotor diameter of 43mm. (Please ask for more details)

Even at the end of their life the “Plusmotors” have an advantage: having no magnets, they are easy to recycle.

2) Constitution, how it works:
The appellation Plusmotor comes from the special stator arrangement including four U-electromagnets 10 surrounding the rotor 21.

Each of the phases X, Y comprises two electromagnets, see Bild1.gif.

Each of them are made out a “U” lamination stack (yoke 11) with two windings. The stator has also 8 windings and 8 poles. **The four windings of a phase are being wound simultaneously out of two metal strips (current paths) according to a new winding** technology,s. EP 2 251 959A1 (s. Winding.jpg)
Two adjacent coils are being slided on each of the two U-yokes 11 (lamination stacks), so

that a complete phase results. Bobbin cores are not needed.
The four yokes of the phases are fitted on the motor frame, and so emerges the stator with the coils lying outside S. stator.jpg.

The rotor is a non-wound, simple lamination stack 21 with six salient poles pressed on the shaft.
The rotor position control can be given by a 12 pole rotor position magnet and a Hall sensor, 31 or by directly sensing the teeth of the rotor.

A special frame (aluminium die–cast) with integrated bearing shield carries the phase yokes and the electronics. (s.Motor.jpg)

3)Function:
Four active stator poles of the active phase (X) pull the nearest rotor poles. When these poles are almost facing each other, the complementary output (flip-flop) Hall sensor 31 changes over the current to the next phase (Y). (s.Bild1.gif, Circuit.pdf)
If 4 rotor poles are alligned with the 4 “X” stator poles, the “X” windings will be switched off and the “Y” ones will be switched on without a delay (flip-flop). The rotor drives 30° to become alligned with the Y-stator poles. This way the rotor keeps driving.

The bifilar windings (main winding 112, by-pass winding 113) permit a simple and highly efficient recovery of the switch-off energy from the just turned-off main windings 112X, s.Winding.jpg.

When the main current Ip, i.e. the current which passes the main windings 112X and the power switches 21X is switched off, a self induction voltage Ua would arise which can be dangerous for the switches 21.
A by pass current Ib arises from this voltage, i.e from the demagnetisation energy and it flows through the by-pass windings 113Y of the next phase, to the + bar through the diode 221.

This energy recovery enhances the efficiency of the motor, (70-85%), which stays high in a wide speed range. Permanent magnet motors usually have a narrow area of high efficiency.

4)Characteristics:
This motor can work as a generator through shifting of the switching point, i.e. with the Hall sensor shifted.

Advantages: as a Plusmotor has no brushes and magnets, it does not present some disadvantages of a common DC motor, as:
- brush wear
- demagnetisation
- torque/speed ratio shift due to temperature changing magnet properties.

The Plusmotor has basically (whitout speed control) a series motor characteristic with a high starting torque and a very high speed at no load because of the field weakening.
A speed control electronics can adapt the motor characteristic to the load. The speed ratio of the simple motor is about 3:1, with speed control ca. 10:1.

The shape of the Plusmotor can be flat, low profiled; the motor is suitable for high speed applications, the limit being given by the bearings.

A Plusmotor, together with a single stage high speed (ca. 30 000 RPM) impeller can replace an two-stage automotive secondary air pump unit, being just half –sized, s SLP.pdf
SR-motors are known for their fast dynamic. The Plusmotor which has 4 of 6 rotor poles active al any time is outstanding.

For a better understanding, let´s have a closer look at the Plusmotor from several points of vue: The Bild1.jpg, and Circuit.pdf shows the motor constitution with all the windings and electrical components.

5. Magnetic criteria.
The outer edges of the 4 poles belonging to the to the X (horizontal) phase and those belonging to the vertical phase (Y) are spaced by a mm-range gap.
This makes the rotor pole passage from the X to the Y phase almost instantaneous and enables the motor to always start in the right direction.
4 of the 6 rotor poles will be always engaged (active) with the 4 corresponding stator poles.

This enhances the output compared with the classic prior art 8/6 pole SR-motors having a stator with a round O.D. In this case only 2 poles are active, s.Magn.Crit.pdf.
This arrangement gives also a much larger iron area around the air gap; 240° instead of 120° on the stator side, 180° instead of 120° on the rotor side.

The Plusmotor has obviously much shorter flux paths, has also less iron and iron losses. This gives more output & efficiency for a smaller motor.

To create a braking torque, (Generator mode) it is necessary to energise the coils when the circuit reluctance increases.
In other words, a premagnetising current must be shortly built up when the rotor teeth just leave the aligned position of the stator poles of the relevant coil. This operation does not require reversal of the current in the coils. So unidirectional power switches can control motor or generator (braking) operations.

A partial recovery of the braking energy directly to the battery is possible because the voltage produced even at lover speeds exceeds the voltage of the battery which usually drives the motor.

6) Electrical advantages

The above mentioned small distance between the edges of the X and Y poles makes possible that two rotor poles just leaving the aligned position of the X stator poles will pass almost instantly under the attraction of the Y stator poles.

This makes possible the synchronising of the magnetic, mechanic and electrical phaenomena.
This quick magnetic pass-over of the rotor poles from a phase of the other one allows to operate the motor with a very simple electronics.

The motor can be powered by 180° current blocks, so that the **flip-flop control of the two**

power transistors is possible
The self-voltage Ua which arises at phase change at the connexion main winding 112-power switch 21, (demagnetisation energy) can be lead to the by-pass winding 113 of the next phase. The by-pass diode 221 closes the circuit to the + bar. A temporary storage in a capacitor is not necessary.(s. Bild1.jpg, Circuit.pdf)

This switch-off energy will create the by-pass current Ib and flows directly to the by-pass winding 113Y of the Y-yokes. It adds to the effect of the main current Ip and speeds- up the magnetisation of the next phase; this helps so to a steep rise of the torque and the efficiency.
The switch-off energy does not stress the transistors 21 and most of it remains (unlike at prior art motors) inside the magnet circuit.

This energy passes back and forth through shortest paths between the X and Y phases. This also makes the demagnetisation of the switched-off phase less sharp, reducing also the noise; the current graphs are almost trapezoid-shaped.

An interruption of the by-pass current while the motor is running shows clearly that efficiency and noise worsen considerably.

If a PWM start current limitation is not present, the motor will need a high start current, like a DC motor.

The speed control is possible through the power switches 21 with a few inexpensive components.
To control the speed (output), the main current flow will be delayed at the beginning of the phase.
The phase change angle (and thus the switch-off energy recovery) does not change and the attraction by the poles of the next phase immediately after leaving the aligned position will rely only on the field build-up through the by-pass current Ib.

If the delay t of the main current Ip is not depending of the speed, a certain degree of feedback will take place because a speed fall will increase the phase time, i.e. the main current.

To achieve a sufficient RFI level within the middle up to long waves range, a capacitor can be connected parallel to the motor connections.

Only the simplest yet working circuit was described here; in practice we have developed several control circuits in order to optimise the performance of the motor for the specified application.
This happens through the optimisation of the commutation, speed control, soft-start, etc; there is no space here to describe these features.

7) The windings:
The copper or aluminium strip conductor windings for low-voltage ranges with interleaved insulation foil (Mylar) considerably reduce ohmic losses. The space factor of such windings can reach 90% instead of 40-55% for round wire windings, this giving the Plusmotor additional advantages.

At low voltage (automotive), only few turns are necessary.

Due to the superior space factor, an aluminium **strip** winding has the same resistance and volume as a copper **wire** winding, but just 50% of its weight.

A special form of the strip winding enables an “impossible” space factor exceeding 100%; at equal electrical parameters, the legs of the U-yokes can be kept shorter, giving a lighter motor with less iron loss.

The bifilar (main and by-pass winding, 112 and 113) consist of the two leads insulated from each other with Mylar foils, all these being wound together.
The eight ready wound windings 112-113 are slided on the U-stack legs. (S. Winding.jpg)

Unlike conventional stator poles referenced to a round yoke which requires winding of the coils in the interior of an assembled stator, each U-electromagnet can be easily mounted before they are configured into a stator.

By providing for the winding of strip conductor stator coils before assembly, the windings can, if they are produced at large scale, be more economical than enamelled copper wire windings.

This is basically a simpler technology, because instead of the multiple drawing and coating of the wire (enamels and solvants are problematic for the environment), bare metal sheet and Mylar foils are used. We have developed a new, improved technology to coat the metal strips with mylar foils, technology which can be used not only for the Plusmotor.
The strip width results from cutting the metal sheet with simple roll shears and the convenient thickness can be reached by stapling some thinner metal strips.

The edge of these special windings for the mass series produced small motors, is that they can carry much higher currents compared to the wire wound motors, resulting in a considerably higher output and efficiency. Of course, with aluminium strip windings they get lighter and cheaper.

To satisfy practical winding requirements, 2-3 metal sheet of different thickness are sufficient to replace a wide wire gauge range.

It is obviously easier to wind a 0,25x8mm copper strip on a square reel than the corresponding 1,6mm thick wire (e.g.- small automotive motor, -ECF-).The shape of the coil is more precise, and it is shorter.

8).Mechanical design
To build the stator, (s. Stator.pdf) the four U-yokes can be placed and fitted into the motor frame-bearing shield

Other advantages of the new design still enhance the superior properties of the magnetic circuit. The fixture of the U-yokes is done at the pole side edges, near to the air gap, with the windings outside despite of the closed rotor cavity. The bearing shields are placed under the windings. This gives a shorter motor.

For a better cooling, state of the art motors with fixtures at the flux ring have often vented bearing shields. Dirt can reach the air gap blocking the rotor. The Plusmotor with the windings outside, despite of the closed rotor cavity will have superior cooling properties without dirt problems. The back bearing shield is integrated in the frame.

A patented economical adaptive technology (“fluid rivets”, s. FlußNiete.pdf) helps to produce the stator of the Plusmotor with very close air gap tolerances despite of inexpensive, even imprecise single parts.
A rigid and precise positioning of the stator poles with respect to the rotor is the most important requirement.

Let´s follow the force paths from the stator poles through bearing shields, bearings, the motor shaft and the rotor up to the attracted rotor poles of a conventional motor and the Plusmotor and compare their elasticity. (s. Comparison.pdf)
As the Plusmotor does not have a big cylindrical outer flux ring, but has a short shaft and small bearing shields, these force paths are short and stiff, so that noise and vibration can be reduced.

As the rotor is a simple symmetric, precisely punched stack, a balancing is often not necessary.

Slower motors (up to 3000RPM) usually use laminations without special properties and a 0,5mm thickness is OK. Thinner laminations are necessary for high speed motors, e.g. high-speed blowers, depending upon the best ratio costs/efficiency.

9) Heat removal.
After the stator is assembled, the space between adjacent U-yokes (windings) can stay open. The heat exchange between the single turns of the winding is also enhanced, because of the turns being wound without air spaces, separated only by the thin Mylar foil with the thickness of e.g. 23µm.
In this case, the motor exhibits an increased ability to cool which allows a higher horsepower rating than a similar state of the art motor having the windings under the bearing shield.

As the Plusmotor is very powerful being yet small, care should sometimes be taken with the loss heat, this representing 15-35% of the supplied power. The smaller the motor, the more this problem is important.

If a high output /weight ratio of this small motor is continuously needed, a proper cooling must be provided. There are two ways to solve this problem:
- allowing the motor to run at higher temperatures,
(With windings and bearings properly designed, a SR- motor is able to work at temperatures up to 400°C if the control electronics will be kept cool enough.)
-Intensive cooling by ventilation or attachment to a heat sink.

Cooling is also possible through the rotor pole gaps, the rotor teeth acting as a fan, if inlet/outlet vents are present and properly designed.

10).Noise problems:
The actual SR- motors are famed to be noisy.
Noise arises mainly from:
a- the ovalizing of the outer stator ring
b- torque ripple, this prompting other body parts to vibrate.

As a switched reluctance motor (or generator) operates, magnetic flux is continuously increasing and decreasing in different parts of the machine. This changing flux will occur in both the single-pulse mode and the chopping mode.
The changing flux results in fluctuating radial forces which pull the stator into an oval shape.

As the magnetic flux decreases, the stator springs back to it's undistorted shape. This ovalizing and springing back of the stator can cause unwanted vibration and produce audible noise.

As the Plusmotor does not have an outer stator ring, and small, stiff stator-to-rotor positioning paths (s. comparison.pdf) it is less noisy. The magnetostrictive vibrations of the energised opposite yokes will compensate almost completely each-other at the air gap periphery. Here is the low vibrations area where the Plusmotor should be fitted to a frame.

As magnetising (on-switching) is´nt usually very sharp, the demagnetising (switching off) of the windings will have a major effect on the noise. Through its energy recycling circuitry, (by-pass current) the Plusmotor will exhibit a damping of the voltage transitions which renders the decrease in the gradient of the magnetic flux in the machine less abrupt, thus reducing the unwanted vibrations and noise associated with the machine.

11). To think about; A statorless motor?
A unique way to avoid body noise caused by torque ripple instead of damping them by elastic fixtures is to use a twin rotor, counterrotating statorless Plusmotor, where the former stator is used as an outer rotor through supplementary bearings and power supply through slip rings.

Each of these counterrotating rotors drives an axial fan.

The inner rotor will rotate to the left and the outer one to the right, with both fans blowing in the same direction (series flow, i.e. two stage, like the “Kamow” helicopters or the TU95, AN 70 planes)
The relative (air-gap) speed is the added value of the left (-100%) and right (+100%) speed of the rotors, this being twice (200%) the speed of one fan, which has clear limits.
The motor is designed for this higher speed (200%) which is splitted on the two fans, the unit having the same output; but the motor must perform only 50% of the torque of a usual motor with 100% speed.

Compared with the usual motor having the same output,(Speed 100%, torque 100% this new twin-rotor machine with fans driving at half (100) of the motor speed must produce just 50% of the torque at double speed, (200%) being thus lighter (material saving).

If a usual motor drives two parallel flow fans, one directly, (50% of the torque) the second being belt driven (with remaining 50% torque) it will work through torque splitting.
The twin-rotor Plusmotor (motor speed 200%) can drive similar, but counterrotating fans through speed splitting, (+100%, -100% the outer rotor drives directly its fan, the inner rotor drives the contrary rotating fan through a belt).
Application: twin Engine Cooling Fan each at 100% speed.
Additionally to the weight advantage no torque ripple (body noise) will be transmitted to other parts.

Annex: motor characteristics of several Plusmotors