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저전력 하이브리드 SRM의 운전 효율 특성

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Efficiency Characteristics of Low Power Hybrid Switched Reluctance Motor

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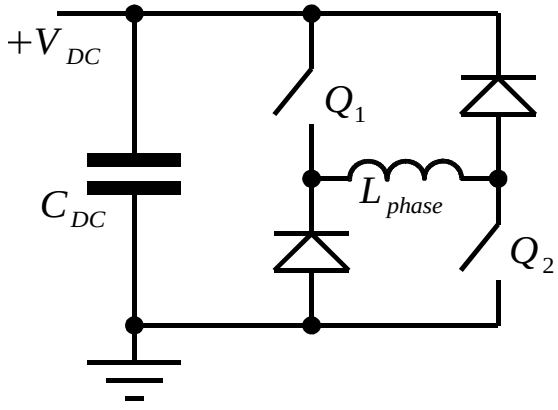
Abstract - Switched reluctance motors (SRM) are usually considered inferior in terms of efficiency as compared to permanent magnet synchronous motors (PMSM) and brushless DC-motors(BLDC), but less costly. This article presents a test of a 70W hybrid switched reluctance motor (HSRM), that achieves a peak efficiency for the motor drive of more than 74%, and an efficiency for the motor of almost 80%.

1. Introduction

Drive efficiency is increasingly becoming an issue in development of motor drives. For high efficiency drives it is common to consider permanent magnet motors as replacement for existing induction motor drives. The most common type of permanent magnet motor is the permanent magnet synchronous motor (PMSM) and the brushless DC-motor (BLDC).

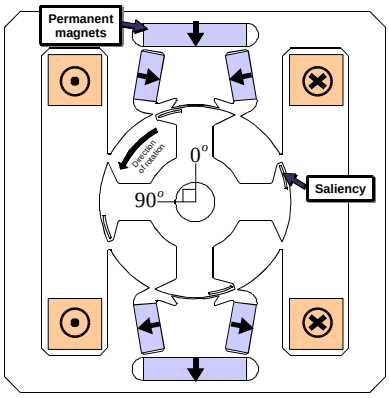
This article tests a single phase hybrid switched reluctance machine (HSRM) regarding efficiency. Though the motor type has previously been presented, the previously reported motor efficiency was 70%[1]. The target for this efficiency test is to verify wether the relatively new technology of HSRM can compare to the more mature motor types: IM, PMSM, and BLDC.

2. Motor Drive Used for the Test



<Fig .1> The converter for the hybrid switched reluctance motor. The MOSFET are Fairchild FCH20N60 and the diodes are IR 15ETH06 switching diodes.

The motor uses an asymmetrical halfbridge to drive the single phase HSRM. The motor structure is shown in Fig .2 The machine has six poles on the stator side, two permanent magnet poles (PM-poles) and four reluctance poles. The rotor has four poles with a saturable saliency. This ensures that the rotor is parked by the permanent magnets at a known rotor angle when there is no phase current. Refer to Fig .2 for details on parking.



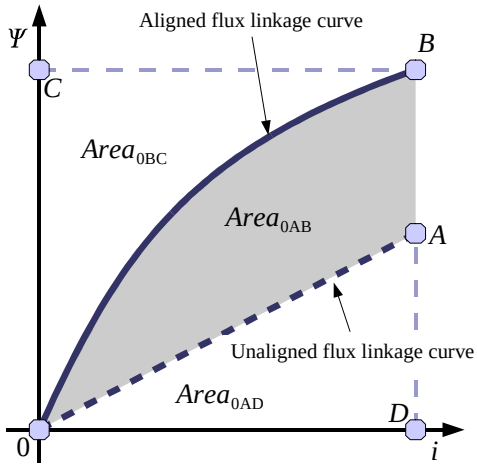
<Fig .2> The structure of the hybrid switched reluctance motor (HSRM). Six permanent magnets increase the flux density in the airgap.

<Table .1> Motor dimensions

Outer diameter	Rotor diameter	Airgap length	Stack length
96.4 mm	48.4 mm	0.4 mm	30 mm

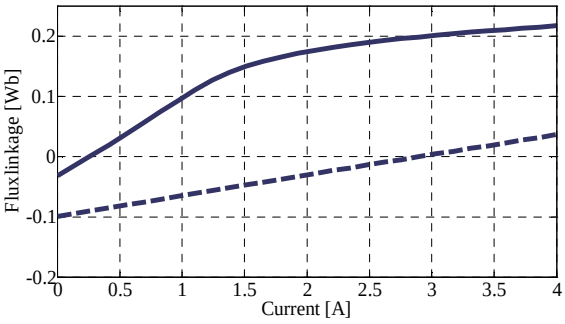
When the two series connected coils are energized, a flux is generated that opposes the flux from the permanent magnets and thus attracts the rotor poles to the reluctance poles. When the coil is defluxed, the process repeats as the permanent magnet poles attract the rotor.

2.1 Energy Conversion in HSRM



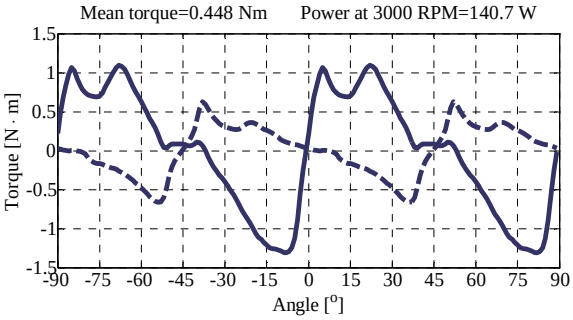
<Fig .3> The flux linkage profile for a switched reluctance motor. The area ($Area_{0AB}$) is equivalent to the energy converted from electrical to mechanical form.

The primary task of any rotating electrical motor is to convert electrical energy to mechanical energy. In switched reluctance motors this energy conversion can be found by looking at the area between the aligned and unaligned flux linkage, This is shown in Fig .3.



<Fig .4> The flux linkage profile for the hybrid switched reluctance motor. The full line shows the phase flux linkage when the rotor is aligned with the two reluctance poles. The dotted line shows the unaligned flux linkage. Notice that both curves start with a negative flux linkage

However the hybrid switched reluctance motor uses permanent magnets which provides a magnetic bias in the motor. This increases the torque density as it is shown in Fig .4. More importantly since the flux linkage goes from negative to positive during one work cycle, the core is experiencing both positive and negative flux. For a normal SRM, the flux is only positive and to produce the same amont of torque the flux has to be higher. This may cause extra iron losses for the normal SRM as compared to the HSRM.

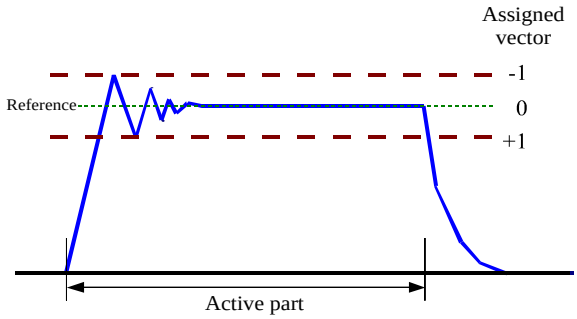


The torque profile from finite element simulation is shown in Fig .5.

<Fig .5> The torque profile for the hybrid switched reluctance motor. The full line shows the combined torque with current in the phase at 4A. The dotted line shows the cogging torque with a phase current of 0A.

2.3 Control method

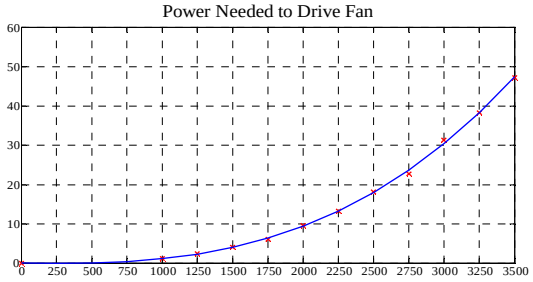
To achieve efficiency in the HSRM, the choice of current control method is important.
The HSRM is controlled using hard chopping at 50 kHz using a modified proportional controller. When the current is outside an hysteresis band of 0.4A compared to the reference current, the controller acts as a hysteresis controller. Inside the hysteresis band the controller acts a proportional controller. See Fig .6 for details on the current control method.
Since the pdate frequency for the current control is 50 kHz, this gives an accuracy of angle control of +/-0.36 degrees. Due to the high switching frequency, currently 37% of the CPU-time is interrupt overhead on a 32 bit 150 MHz fixed point DSP
Since the speed controller has lowest priority, it can not update faster than approx 300 times/sec, which limits the drive speed to 4500 RPM.



<Fig .6> The proportional controller has a saturation that limits the output to the range between -1 and 1. An ouput voltage of -1, means that both transistors are off for a full switching period. An ouput voltage of 1, means that both transistors are on for a full switching period.

2.3 Efficiency test method

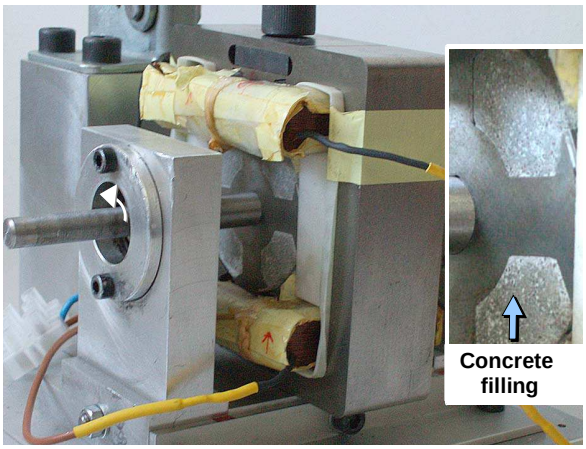
To test the efficiency of a given motor the input power and the output power has to be known. For low power drives torque transducers are not always reliable and an alternative is used. The power losses are determined using the measured losses of a fixed fan. And since fan losses change due to atmospheric pressure and humidty the tests are performed the same day as the HSRM is tested. See Fig .7 for details.



<Fig .7> The power loss due to a fan is measured using a 500W DC-motor. The DC-motor input power is measured both loaded with the fan and unloaded.. Compensating for the extra copper losses, the output power to the fan is calculated. The extra core losses due to the fan is not considered since the n oload power loss at 3000 RPM is higher than 100W.

2.4 Results

The HSRM is supposed to replace an existing induction motor with the HSRM. Therefore the existing IM is tested for efficiency and the HSRM is tested for its peak efficiency. The tested prototype HSRM is shown in Fig .8.



<Fig 8> The prototype motor used in the tests.

2.4.1 Induction motor test

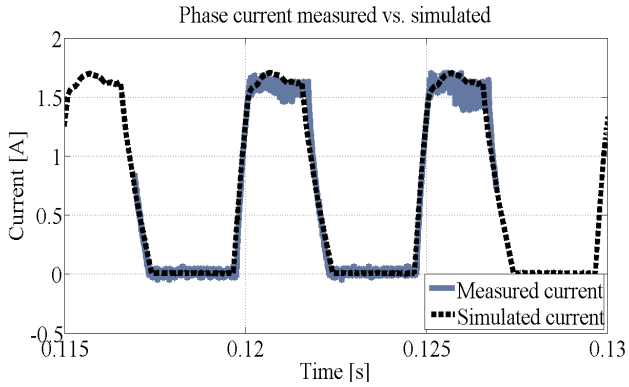
The induction motor is a single phase split capacitor motor with thyristor control. The motor is normally used in a wet runner pump, where the airgap is flooded with water. To protect the windings a steel can is inserted in the airgap. The steel can will incur some extra eddy current losses, and therefore four measurements are done with and without the steel can. The efficiency measurement results are shown in Table .2.

<Table .2> Efficiency of induction motor (IM) combined with thyristor based controller. The speed of the motor is 2600 RPM, when supplied with 50 Hz, 230V. The input power measurement is done using a Yokogawa WT3000.

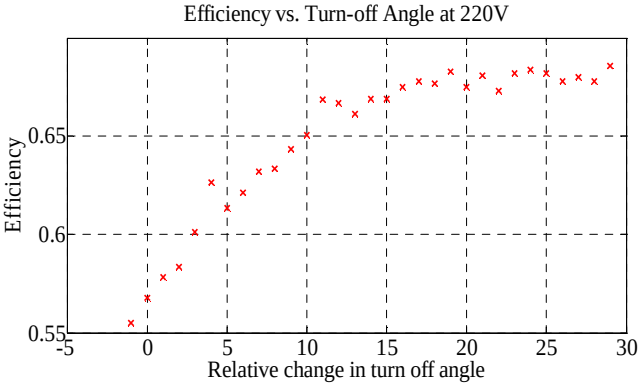
Type of test	η
IM without can	0,39
IM with can	0,38

2.4.2 HSRM efficiency test

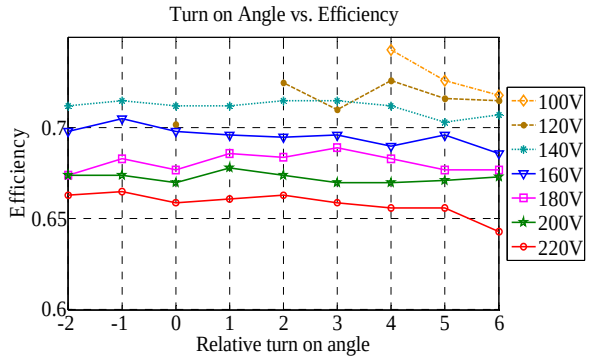
The motor efficiency is measured with a Yokogawa WT3000, measuring the input power to the inverter. The speed through all tests is kept constant at 3000 RPM using a non-linear, time variant speed controller that handles the speed ripple caused by the torque ripple. The speed control method is described in [3].



<Fig .9> The phase current for the HSRM, with the turn-off angle advanced 15 degrees.



<Fig .10> The turn off angle at 3000 RPM is moved relatve to the zero speed optimal turn and turn off angles found from Fig .5. The DC-link voltage is kept at 220V. The angle advance has nearly a plateau from 15 degrees and onwards.



<Fig .11> To evaluate the peak efficiency, the turn off angle is kept advanced at +14 degrees. The turn on angle is advanced up to 6 degrees and delayed up to 2 degrees. The motor was also measured with 80V, but the motor could not achieve 3000 RPM with any angle. Similarly some points are missing from the graph, since the motor could not achieve 3000 RPM.

2.4.3 Inverter efficiency test

Since the motor is tested with an inverter it is interesting to see the efficiency of the inverter at different switching frequencies. The losses are measured with a turn-off angle advance at 3000 RPM of 14 degrees, the turn on angle is not advanced. Measuremt results are shown in Table 3. The DC-link voltage is kept at 220V.

<Table .3> Inverter efficiency

P_{IN}	P_{OUT}	f_{sw}	η
48.5 W	45.3	25kHz	93.5%
48.7 W	45.3	50 kHz	93%

3. Conclusion

This paper presents a test of a low power HSRM, that achieves efficiency comparable to that of reported numbers for optimized mature permanent magnet motors, such as BLDC and PMSM. The peak efficiency for the HSRM compares well with a peak efficiency of 80% in [2] for BLDC and PMSM of a similar size. This means that for low power, low performance single quadrant variable speed drives the HSRM is a useful alternative to other permanent magnet motors.

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