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Experimental evaluation of the impact of squirrel-cage material on the performance of induction motors and line-start interior permanent magnet synchronous motors

***Abstract**. The impact of squirrel-cage material on steady-state and dynamic performance of induction motors and line-start interior permanent magnet synchronous motors is evaluated based on experimental data. The performance of motors with equal squirrel-cages manufactured from aluminium and silumin is analyzed and discussed, thus an integral analysis of similarities and differences between both motor types in relation to the squirrel-cage material is performed.*

***Streszczenie.** Analizowano wpływ materiału klatki na właściwości silnika indukcyjnego i startowego wewnętrznego silnika synchronicznego. Badano klatki wykonane z aluminium i siluminu. (**Eksperymentalna ocena wpływu materiału klatki na właściwości silnika indukcyjnego**)*

Keywords: conducting materials, induction motors, squirrel cage, synchronous motors.
Słowa kluczowe: silnik indukcyjny, silnik synchroniczny, silnik klatkowy.

Introduction

Motor designers utilize a squirrel-cage (SC) in induction motors (IMs) and in line-start interior permanent magnet synchronous motors (LSIPMSMs). The SC provides line-starting capability which is the ability to accelerate the rotor from standstill when the motor is fed from a constant frequency and constant amplitude voltage supply. It also enables the damping of dynamic oscillations at fast load changes. The SC is usually made of electrically conducting bars which are embedded in slots of the rotor's iron core and connected on both ends with cage-end rings. In large volume production of small rated power motors the SC is mostly die-casted from aluminium and its alloys. Additionally to the slot design [1, 2], skewing [3, 4], the used manufacturing technology [5] and economic issues [6], the SC material plays a vital role in the electromechanical performance of IMs and LSIPMSMs. Some previous studies on the impacts of different SC materials in IMs were focused on improving the IM efficiency by using expensive cage materials (copper alloys) also in small-sized IMs [7-9]. However, the LSIPMSM offers a substantial higher efficiency improvement by employing permanent magnet material in the rotor of small rated power motors [2, 10-12]. The principal cross-section of an IM and a LSIPMSM rotor is presented in Fig. 1; the stator structure is the same.

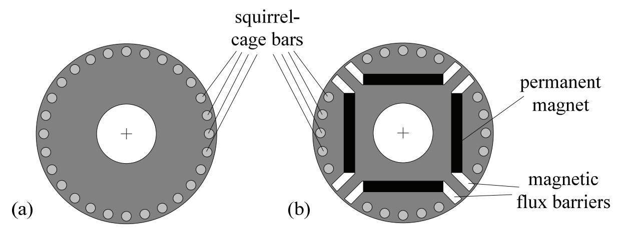

Fig.1. Principal rotor cross-sections of (a) induction motor (IM) and (b) line-start interior permanent magnet synchronous motor (LSIPMSM)

In general, a higher SC resistance of an IM causes that the motor's torque-slip curve exhibits a higher starting torque value, which produces higher initial acceleration of the IM drive. But on the other hand, the torque-slip curve exhibits a higher slip value for the rated motor load because the slope of the torque-slip curve near the synchronous speed is lowered. Thus, losses and motor temperature are increased due to the higher SC resistance and IM efficiency at rated load in steady-state is degraded. The effective SC resistance is a consequence of the material used in the SC die-casting process.

However, the impact of SC material on LSIPMSM performance may be more severe. The LSIPMSM has permanent magnets buried bellow the SC, thus it operates in steady-state as a usual synchronous motor [13] and the SC does not produce any torque. But, when a LSIPMSM is line-started the SC should accelerate the complete LSIPMSM drive up to a certain speed and if the acceleration is sufficient the rotor should be pulled into synchronism. Thus, apart from the mechanical load characteristic, the LSIPMSM's "pull-in" transient into synchronism depends on the slope of the static torque-slip characteristic of the LSIPMSM near the synchronous speed, and consequently the LSIPMSM's starting and synchronization capability depends on the used SC material [12]. Results from different studies which can be related to the SC resistance are available in [2, 14-17].

Analytical [10, 17-26] and numerical methods [1-4, 11, 12, 14, 15, 27-34] are indispensable in the process of electric machine design; however in this work the experimental approach has been utilized. Mainly because the final and effective SC resistance and the consequent SC motor characteristics are significantly influenced by technological factors during the SC manufacturing process, and these are very hard to account for in calculations. The impacts of SC material on performance of LSIPMSMs and with a direct comparison to its IM counterparts have not been reported yet. In this paper the impact of SC material on steady-state and dynamic performance of IMs and LSIPMSMs is evaluated based on experimental data. The results are analyzed and discussed, thus an integral analysis of similarities and differences between both motor types in relation to the SC material related performances is presented.

Description of experimental machines

The experimental LSIPMSMs were designed by using methods described in [11, 12, 32-34] and based on an existing IM design. The three-phase motors used in this study were rated for 7,5 Nm load (1,1 kW for the IM) at 380 V / 50 Hz voltage supply. The used rotors had SCs manufactured from two different materials which are often used in low-cost IM design; these are aluminium and silumin. Aluminium has a lower specific electric resistance (0,0285 (Ωmm^2)/m) when compared to silumin, which is an aluminium alloy with silicon (0,040÷0,065 (Ωmm^2)/m). The actual effective SC resistance [21, 22] may vary because of technological imperfections in manufacturing and die-casting processes of non-insulated SC rotors. Therefore the aluminium and silumin SC rotors were manufactured in the same batch, respectively. Apart from the SC material, the motors had equal: stators, skewing, SC design, iron core, and permanent magnet material, respectively. All the experiments were conducted under equal conditions. The aforementioned enabled a direct comparative analysis of the impacts of SC material on IM and LSIPMSM performances, respectively, and at the same time the direct comparison of IM and LSIPMSM performance with the same SC material. This, as far as the author of this paper is aware, has not been reported yet.

The higher resistance SC made from silumin is denoted as HRSC and the lower resistance SC made from aluminium is denoted as LRSC in the following text and in all successive figures and tables.

Dynamic performance evaluation

One of the important catalogue values and design criterion for general-purpose IMs is their starting torque value or the starting versus rated torque ratio. Fig. 2 presents the measured static torque-slip curves of the analyzed IMs.

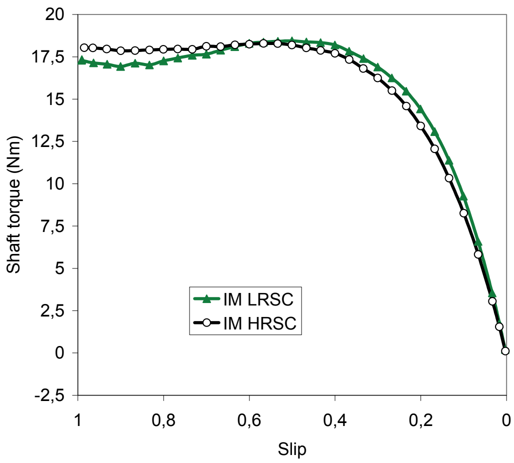

Fig.2. Static torque-slip curves of IMs with different SC materials at 380 V

From Fig. 2 it is evident that the starting torque and the shape of the torque-slip curve depend on the used SC material. The HRSC causes that the motor’s torque-slip curve exhibits a higher starting torque value (at slip = 1), which produces higher initial acceleration of the IM drive. But on the other hand, the torque-slip curve of the motor with the HRSC exhibits higher slip values near the synchronous speed (0,2 ≤ slip ≤ 0); thus the slope of the torque-slip curve near the synchronous speed is lowered. The aforementioned effect manifests in different IM dynamic line-starting performances, which is presented in Fig. 3. The tested motor was line-started from standstill, while coupled to a high inertia drive. The correlation of Fig. 2 with Fig. 3 is more than evident. The IM with the HRSC exhibits a higher speed in the region of low speeds (Fig. 3b) and the IM with the LRSC exhibits a higher speed in the region of high speeds (Fig. 3c), which is a direct consequence of the SC material dependant different torque-slip curves.

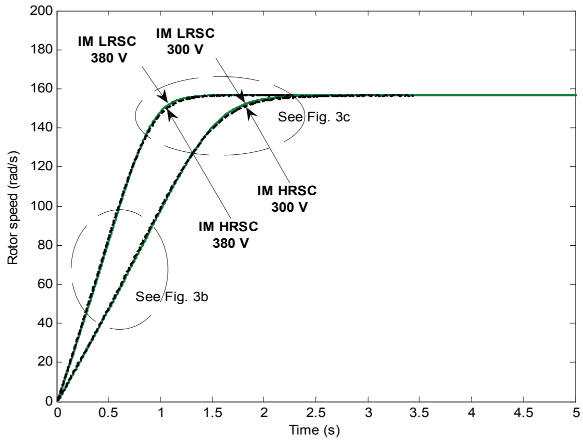

Fig.3a. Line-starting transients when IMs were coupled to the equal high inertia load at different voltages and with different SC materials

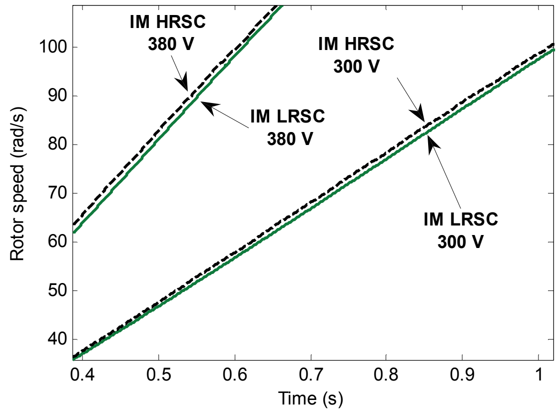

Fig.3b. Detail of Fig.3a at lower speed

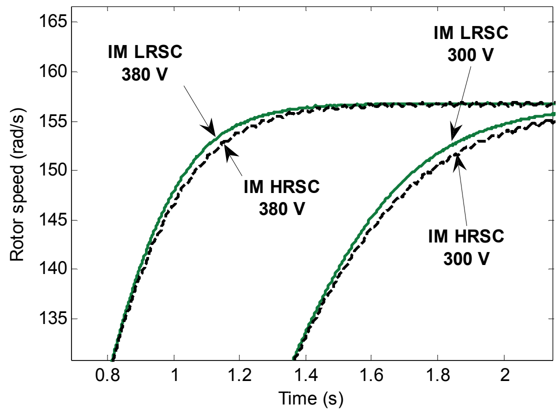

Fig.3c. Detail of Fig.3a at higher speed

In addition, to the starting torque criterion (known from IMs), the LSIPMSMs have to be able to synchronize under load [16]. The total torque (i.e. the cage torque minus the load torque and all other braking torques) should accelerate the complete LSIPMSM drive up to a certain speed and if the acceleration is sufficient the rotor should be pulled into synchronism. Fig. 4 presents the measured static torque-slip curves of the analyzed LSIPMSMs with different SC materials. The difference between LSIPMSM (Fig. 4) and IM (Fig. 2) torque values at certain slip points (slip ≠ 1) is the consequence of different braking torques described in [2, 11, 12, 16, 23, 24]. Fig. 4 shows that the SC material significantly impacts the slope of the LSIPMSM's torque-slip curve near the synchronous speed. The LSIPMSM with the LRSC exhibits significantly higher torque values in that region, which certainly affects the motor's synchronization capability. Fig. 5 presents the line-starting transients of the analyzed LSIPMSM with different SC materials in the high inertia drive. It shows that the LSIPMSM with HRSC at 380 V starts and synchronizes faster than the one with the LRSC. This is a consequence of the higher initial acceleration, because of the higher starting torque value of the LSIPMSM with the HRSC. On the other hand, even though the LSIPMSM with the HRSC starts at a voltage of 330V, it does not synchronize. Contrarily, although it starts slower, the LSIPMSM with the LRSC synchronizes successfully at the same voltage. From the aforementioned, we may conclude, that the LRSC proved to be advantageous in the LSIPMSM's synchronization capability, which is mainly due to the higher slope of the torque-slip curve near the synchronous speed of the LSIPMSM with the LRSC, when it is compared to the one with the HRSC.

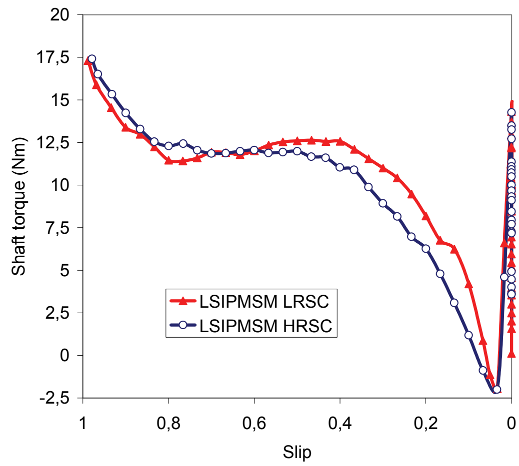

Fig.4. Static torque-slip curves of LSIPMSMs with different SC materials at 380 V

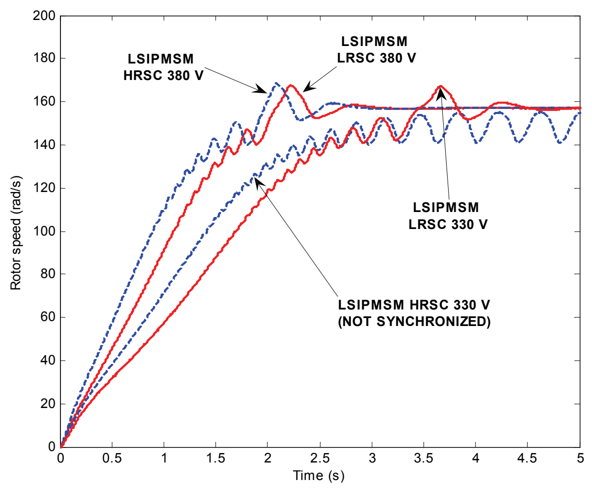

Fig.5. Line-starting transients when LSIPMSMs were coupled to the equal high inertia load at different voltages and with different SC materials

Steady-state performance evaluation

Temperature rise tests were conducted in order to study the impact of SC material on motor operational efficiency, power factor and consequently motor operating temperature. The analysed motors were loaded at rated voltage, frequency and load until thermal equilibrium was reached. Table 1 and Table 2 present the measured values of IMs and LSIPMSMs with different SC materials in thermal equilibrium, respectively. The higher efficiency of the LSIPMSMs, when compared to the respective IMs at the equal load (i.e. the shaft torque), is manifested in substantially lower winding over-temperature of the LSIPMSMs; also the LSIPMSMs power factor values are substantially higher than the ones from the respective IMs. Results in Table 1 show that the IM with the HRSC exhibits lower rotor speed, lower efficiency and higher temperature, which is a direct consequence of the lowered slope of its torque-slip characteristic at rated load (i.e. near synchronism), when compared to the IM with the LRSC. Results in Table 2 also show that the LSIPMSMs with the HRSC exhibits a slightly higher temperature, when compared to the LSIPMSMs with the LRSC, which may indicate that despite that the motor operates in synchronism (small parasitic) currents are flowing through the rotor [25] and cause additional losses [26, 27].

Table 1. Measured values of IMs with different SC materials in thermal equilibrium

Motor	IM LRSC	IM HRSC
Voltage (V)	380,3	380,0
Frequency (Hz)	49,997	49,966
Current (A)	2,78	2,74
Input power (W)	1425	1405
Power factor	0,778	0,778
Shaft torque (Nm)	7,52	7,50
Rotor speed (rpm)	1367,6	1346,8
Output power (W)	1077	1058
Efficiency	0,756	0,753
Power factor * Efficiency	0,588	0,586
Winding over-temperature (°C)	73,8	76,4

Table 2. Measured values of LSIPMSMs with different SC materials in thermal equilibrium

Motor	LSIPMSM LRSC	LSIPMSM HRSC
Voltage (V)	380,2	380,5
Frequency (Hz)	49,991	49,973
Current (A)	2,30	2,34
Input power (W)	1339	1350
Power factor	0,884	0,876
Shaft torque (Nm)	7,49	7,51
Rotor speed (rpm)	1499,5	1499,0
Output power (W)	1176	1179
Efficiency	0,879	0,874
Power factor * Efficiency	0,777	0,766
Winding over-temperature (°C)	40,3	41,6

Conclusion

The impact of SC material on steady-state and dynamic performance of IMs and LSIPMSMs based on experimental data was presented. The presented results show, that the SC material has to be carefully selected in the process of IM and LSIPMSM design; especially in the latter, because its synchronization capability depends on the choice of the SC material.

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