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Experimental Results of Synchronous Reluctance Motors to Meet the IE4 Efficiency Standards in Variable Speed Applications

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Regulation of the efficiency of electric motors worldwide has recently been tightened further because the contribution of electric motors to overall energy consumption cannot be denied. For many years, induction motors have fulfilled tasks in various fields of industry; however, alternative motors have also been gaining attention to realize more cost-effective motors over the long term. It is foreseen that induction motors (IMs) may not be replace-able in single-speed applications, excluding a few special applications; however, applications for which the variation of speed is required offers opportunities for the entry of other motor technologies. Synchronous reluctance motors (SynRMs) are one option that could provide such benefits. This paper provides the experimental results of SynRMs which, under the rated condition, aim to satisfy the IE4 efficiency class. Five SynRMs ranging in power through 5.5, 15, 37, 75 to 132 kW have been manufactured and tested for experimental comparison with IMs of equivalent output power.

Keywords : Synchronous reluctance motor (SynRM), high efficiency, Super-premium class, inverter drive

1. Introduction

Growing concern about the environmental impacts of energy consumption has forced a worldwide push to increase energy efficiency. Electric motors, which are widely applied in industrial applications such as fans, pumps, mills, presses, elevators, and grinders, are the most energy demanding loads and consume about 50 % of all the electric energy generated [1]. Improved efficiency of electric motors is particularly attractive owing to their wide applications in industrial fields. This fact has encouraged those in industry to install higher efficiency motors. New regulations on the efficiency of electric motors have been introduced. Electric motors are now classified by the international electrotechnical commission (IEC), which has specified a set of international efficiency (IE) classes, and the nominal efficiency of a tested motor should be determined according to IEC 60034-30 [2]. Recently, these efficiency regulations are being strictly applied around the world to reduce energy consumption worldwide.

Induction motors (IMs), have by far, the vast majority of the market share of electric motors, and this may be owing to their feasibility for line-start single-speed applications. The estimated domestic energy consumption of the IMs is about 19.4 T KRW, corresponding to 42 % of the total amount of energy consumed in South Korea. An IE2 standard was first regulated for three-phase IMs for single-speed application in 2008, but the current efficiency standard is now being replaced by the IE3 standard for large to medium-small power motors for further reduction of energy consumption. The national regulations will be further tightened to meet the demands of the IE4 standard. The IMs that can offer IE4 performance for line-start single-speed motor applications may be the most cost effective IE4 motors available in the market at the moment. One potential motor technology that could be introduced to the market in the near future is that of synchronous reluctance motors (SynRMs) with embedded rotor cages [3]. However, these motors still need further research and development to enter the market broadly.

Apart from single speed applications, IMs lose their

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advantages as high efficiency motors in variable-speed applications. Generally, the power density becomes lower to achieve higher efficiency, which calls for the use of more active materials. The perception of this fact leads to employment of other motor technology for variable speed applications. The inverter-fed SynRMs are capable of offering potential cost reduction when compared to the IMs driven by a vector controller owing to elimination of the rotor cages. The advantages of the SynRMs over the IMs are related to the elimination of copper rotor losses owing to the absence of the rotor bar, which is the cause of around 25 % of the total loss in IMs [4]. Therefore, it would not be an irrational expectation that the SynRMs could significantly improve the efficiency of motors in variable speed applications for a specific power range. Although IMs are currently the major electric motor in the market for single-speed applications, demand for variable speed applications will arise in the future. Still, many energy demanding applications have not utilized motor drivers, for example, in such as heating, ventilation, and air conditioning. Furthermore, large growth prospects in integrated motor drive components of a system owing to the technical innovation relative to the industrial internet of things will encourage manufacturers of machinery components to supply digital and automatic machines for the system approach [5]. As market demands change, motor equipment providers will use this opportunity to begin a system approach that involves higher-efficiency motors and drivers. This will demand continuous research investment to make sustainable and reliable high efficiency motors. For now, at least, to satisfy the upcoming demand for variable speed applications, the SynRM is expected to be the most viable alternative in terms of cost effectiveness, compared to IMs.

In this paper, the prototypes of five SynRMs are investigated for their ability to meet the IE4 standard for inverter-fed motors and to compare them with direct drive IMs of equivalent output power. The specifications and results are discussed throughout the rest of this paper.

2. Efficiency Determination

In this study, the IEC standard used for single speed induction motors powered by a sinusoidal power supply is IEC 60034-2-1 [6]. In the SynRMs fed by inverters, the total losses are increased owing to pulse width modulation (PWM) harmonics. The separation of the additional losses could be determined by IEC 60034-2-3; however, for this paper we did not follow it. To meet IEC 60034-2-3, the test motor has to be operated by a sinusoidal power supply, which is difficult to perform with a synchronous motor. The test procedure performed in this paper is outlined hereafter. The experimental setup is illustrated in Fig. 1.

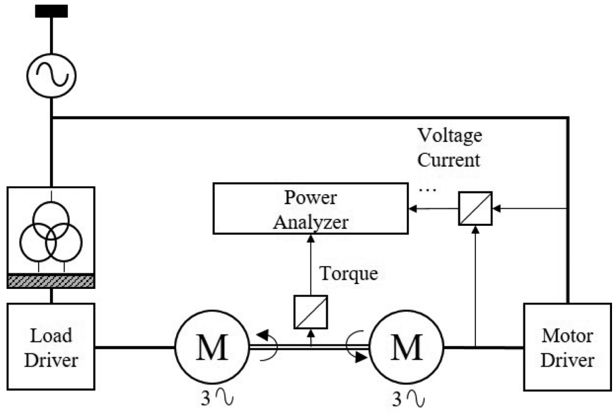


Fig. 1. Measurement setup.

2.1. IEC 60034-2-1 Standard

The standard for the efficiency determination of low voltage induction motors is IEC 60034-2-1. The total losses of the test motor are obtained by adding the load losses, the stray losses, and the constant losses. The separation of the losses reveals the load losses and the constant losses. The remains of the losses differed from the calculation with direct measure of the input, and the output power was regarded as the stray loss, which refers to unclear losses that need to be evaluated.

The stator and rotor joule losses are evaluated at the rated load temperature, of which the gradient should be 2 °C per hour. The stator joule losses are then given by:

$$P_s = 1.5I^2 R_s(\theta), \tag{1}$$

where $R_s(\theta)$ is the corrected stator resistance inferred from the winding temperature, and I is the stator current. The stator resistance has to be corrected to the value with the ambient temperature of 25 °C in the calculation of the nominal efficiency.

The rotor joule losses are given by:

$$P_r = (P_1 - P_s - P_{ir}(U_{ir}^2)) \cdot s, \tag{2}$$

where $P_1, P_s, P_{ir}(U_{ir}^2)$ and s are the input power, iron losses, and slip.

The load test is carried out at six points between 25-125 % of the rated condition as soon as possible after the rated load test to minimize temperature related effects of the test motor during the test. The constant loss is determined immediately after the load test. It can be measured with a no-load test. The contributions of the mechanical losses, including the friction, windage losses, and iron losses are determined by subtracting the no-load stator joule losses from the no-load input power:

$$P_0 - P_{s0} = P_{fw} + P_{ir}(U_{ir}^2), \tag{3}$$

where P_{fw}, U_{ir} are the mechanical losses and the no-load input power. The no-load input voltage which varied from 20 to 125 % of the rated voltage is fed to the test motor. The mechanical losses are measured from the portrayal of the no-load losses with the varied power supply voltage. The intercept of the no-load losses where the square of the supply voltage becomes zero, is regarded as the mechanical losses. It may be dependent on the rotating speed and the temperature, however, it is assumed to remain constant because the analyzed points are close together.

The iron losses in the full load condition can be calculated in consideration of only the resistive voltage drop in the stator winding, neglecting the leakage inductance:

$$U_{ir} = \sqrt{\left(U - \frac{\sqrt{3}}{2} I \cdot R_s(\theta)\cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} I \cdot R_s(\theta)\sin\varphi\right)^2}, \tag{4}$$

where $\cos\varphi$ is the power factor and U is the supply voltage. From the obtained relationship between the iron losses (equivalent to the no-load losses minus the intercept) and the square of the supply voltage down to only 60 %, the iron losses under load are determined by interpolation. The residual losses P_{Lr} are determined by the varied load test:

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fw} - P_{ir}, \tag{5}$$

where P_2 is the output power. The residual losses are smoothed using linear regression as a function of the torque T given by:

$$P_{Lr} \approx AT^2 + B, \tag{6}$$

where A, B is, respectively, the slope and the intercept of the regression model. The load stray losses should not appear under the ideal no-load operation (zero torque); therefore, the load stray losses are determined by subtracting the corresponding intercept. The intercept has to be less than half of the residual losses at the rated torque; otherwise the measurement error needs to be checked. A summary of the standard procedure is shown in Fig. 2.

It should be noted that the iron losses measured by the IEC 60034-2-1 standard are convectional iron losses not the actual ones [7]. The calculated iron losses in no-load operation of an IM, in fact, include the no-load stray losses; however, it is not separated according to the standard. The major portion of the load stray losses

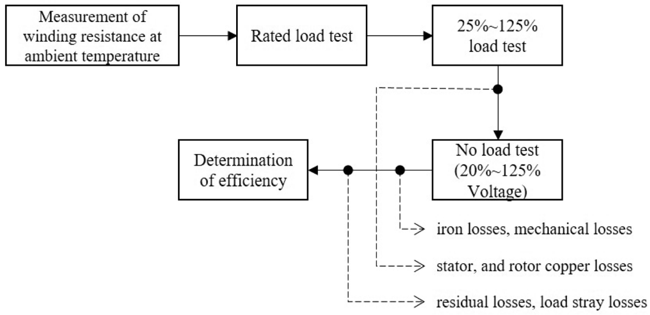


Fig. 2. Testing flow chart.

measured by the standard would be the joule losses of the rotor cage owing to the air gap spatial harmonics [8], and some part of such losses may potentially be contained in the calculated iron losses. However, exact separation of the copper losses and the iron losses is outside the scope of this paper.

2.2. Test Procedure Considerations for Synchronous Reluctance Motors

The inverter feeding the SynRM contributes to additional losses generally owing to the harmonics of the PWM voltage and current. The non-sinusoidal voltage and the current produce the harmonic losses of the motor, which greatly depend on the PWM frequency [9]. The increased frequency may reduce the harmonic losses; however, they also increase the switching losses of the driver. Therefore, the frequency should be chosen to balance the system efficiency.

The additional losses of the test motor introduced by the inverter switching, are identified as additional harmonic losses. The determination method for this is quite similar to that for the load stray losses when the test motor is supplied with sinusoidal voltage. The calculation of the additional harmonic losses can be followed by measuring the difference in the overall losses between operation fed by sinusoidal voltage and by the inverter according to IEC 60034-2-3. However, it is difficult to operate a SynRM without the driver due to starting and operation-related problems. Alternatively, the additional harmonic losses may be measured by subtracting the overall active power fed to a test motor from the active power calculated with only the fundamental voltage, the current, and the associated power factor, as suggested in [10]. The constant losses are determined as follows:

$$P_0^{(1)} - P_{s0}^{(1)} = P_{fw} + P_{ir}^{(1)}(U_{ir}^2). \tag{7}$$

It is a similar procedure as given in (3), however, the no-load input power $P_0^{(1)}$ is the fundamental power fed to a SynRM. The no-load voltage in (7) is calculated by the

Table 1. No-load experimental results.

	Varying supply voltage referred by the rated supply voltage								
	110 %	103 %	100 %	97 %	80 %	60 %	50 %	35 %	20 %
Fundamental line voltage [V]	346.5	324.5	315.0	305.6	253.4	189.2	158.0	110.7	63.2
Fundamental current [A]	102.4	88.4	84.4	80.2	63.9	47.1	39.3	28.0	19.2
Fundamental input power [kW]	17.1	1.96	1.69	1.70	1.38	1.14	1.03	0.92	0.84
Constant losses [W] (Mechanical losses + Iron losses)	2081	1881	1621	1631	1335	1117	1010	907.1	835.1

fundamental supply voltage which can be measured with a power analyzer. The equivalent procedure described in the previous section is applied to determine the mechanical losses. The iron losses estimation method equivalent to that of the induction motor is also applied. At the rated operation, the remains of the losses from the differences between the summation of the measured output power and the approximated fundamental losses, and the output power of the inverter, are assumed to be the additional harmonic losses of the SynRM:

$$P_{\text{add}} = P_1 - P_{\text{fw}} - P_{\text{ir}}^{(1)}(U_{\text{ir}}^2) - P_{\text{s}}^{(1)} . \tag{8}$$

2.2.1. Experimental Results of the Loss separation

The full experimental results of the 132 kW SynRM are provided in this section. The results measured at the no-load operation are given in Table 1. The inverter was supplied with 380 V, however, the measured fundamental voltage fed to the tested motor is only 315 V.

From the measured results, the mechanical losses can be determined according to (7). The linear regression resulted in the mechanical losses of 803 W is shown in Fig. 3(a). After that, the relationship of the calculated iron loss voltage with the iron losses can be obtained. The iron losses at the rated operation is calculated over the linear regression of the constant losses with the no-load supply voltage between 97 % to 103 %. The calculated iron loss voltage at the rated operation was 313.3 V which is slightly less than the fundamental supply voltage of 315 V. The linear regression model shown in Fig. 3(b) leads to the iron losses of 884.9 W at the rated operation. It is evidence that the iron losses of SynRMs are not in a linear relationship with the square of the supply voltage even in very close range. Finally, the resulted residual losses which are treated as the additional harmonic losses are 414 W.

2.2.2. Comparison with finite element analysis

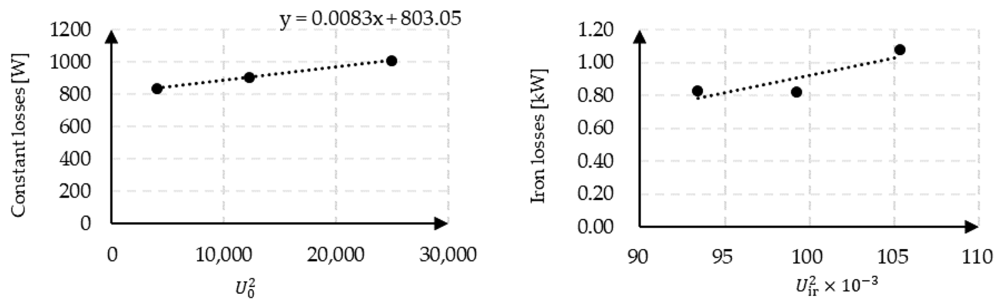
The confidence level of the above iron losses from the experiments is unknown, therefore, the author will not provide, for example, detailed validations, however, will provide the comparative results with finite element analysis (FEA). The FEA with sinusoidal currents and the experiments are presented in Table 2. It shows surprisingly good agreement between the FEA results and the experiments.

Even though the differences in the iron losses seem acceptable, the apparent results will not prove the validity of the above loss separation method. The *d*-axis magnetic characteristics of the SynRM are highly non-linear that it

Table 2. Comparison of finite element analysis and experiments.

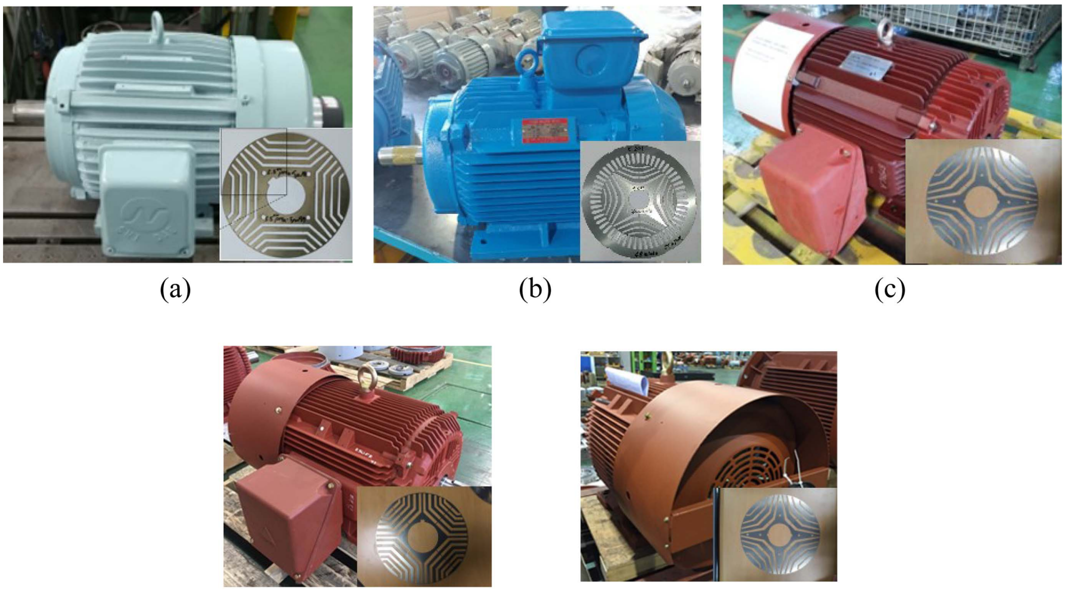
Quantity	FEA	Exp.	FEA	Exp.	FEA	Exp.
Rated output [kW]	15		37		132	
Copper losses [W]	327	353	750	818	1030	1105
Iron losses [W]	309	326	221	263	870	885
Residual losses [W]		156		341		414

Note: Exp. indicates experiments



(a) (b)

Fig. 3. Linear regressions over square voltage: (a) and (b) respectively, show constant losses and iron losses.



(a) (b) (c)

(d) (e)

Fig. 4. (Color online) Prototypes of the SynRMs. (a) 5.5 kW, (b) 15 kW, (c) 37 kW, (d) 75 kW, (e) 132 kW.

can be affected by the current and its angle.

However, the separation of the losses is an important procedure for reflecting the experimental results in the further design stage. The IE4-class SynRMs which will be seen later have been tested according to the above procedure for the separation of each loss component. The concern is the uncertainty of the measured iron losses. Even though, the iron loss results from the test are given, the reader should note that it is used for a specific purpose with the understanding that the resulting iron losses are not real, and that the test procedure is not according to the standard.

3. Results

Five IE4-class SynRMs were designed and manufactured, and then subjected to experimentation (see Fig. 4). The test bench for the 132 kW SynRM is shown in Fig. 5.

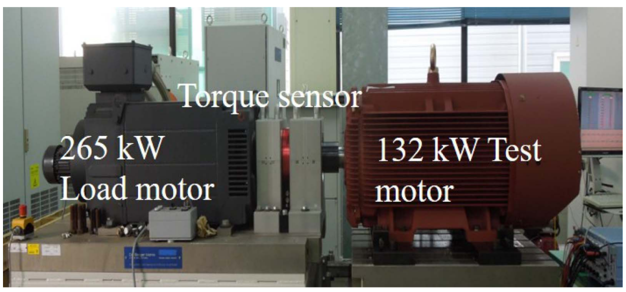


Fig. 5. (Color online) Motor test bench with the 132 kW synchronous reluctance motor.

Their rated output power and overall dimensions are given in Table 3 along with those of several IMs for comparison. An rms line voltage of 380 V was supplied to the driver for all motors. The given efficiency values of the SynRMs are the results of direct measurement. The 75 kW SynRM failed to achieve the desired IE4-class efficiency due to underestimation of additional load losses, and this will need to be adjusted in the future. Among several IMs available in the laboratory, the motors of minimum overall dimension were chosen. Unfortunately, they were direct drive IMs, for which the additional harmonic losses are not presented. The given IMs will require more active material usage to achieve the same efficiency at the rated operation with a variable speed drive. It is interesting to see the dimensions of the presented motors. The SynRMs in the lower rated power range show higher IE class with similar outer dimensions,

Table 3. Specifications of experimental synchronous reluctance motors and induction motors.

	Rated power [kW]	5.5	15	37	75	132
SynRM	Stator outer dia. [mm]	228	260	343	432	476
	Stack length [mm]	100	205	200	250	475
	Efficiency [%]	93.8	94.3	95.6	95.4	97.6
	IE class	IE4	IE4	IE4	IE3	IE4
IM	Stator outer dia. [mm]	230	260	343	432	476
	Stack length [mm]	110	180	200	230	350
	Efficiency [%]	91.7	93.4	93.5	95.5	95.9
	IE class	IE3	IE3	IE2	IE3	IE2

(a) (b)

Fig. 6. (Color online) Inverter drivers of the SynRMs. (a) 50 kW, (b) 150 kW.

even in the presence of additional harmonic losses.

The low to mid-power rated SynRMs can achieve the IE4-class efficiency with a stator outer dimension similar to that for corresponding IE3-class IMs. The benefit may be more significant when compared to the inverter-fed IMs of low to mid-power rating. It can be seen that the benefit in volume decreases with increase in the rated output power. This may be explained as follows. The amount of additional harmonic losses would be increased with their rated output power; therefore, the active material usage needed to compensate for the additional harmonic losses would rise according to increase in the rating of the motors. Unfortunately, SynRMs of 75 and 132 kW are operated in a flux-weakening region in which the optimum performance of the motors cannot be achieved. The trend of copper losses in the IMs generally decreases with their rated output power [4], thus the reduction of copper losses in the SynRMs would be smaller at higher ratings.

The experimental results of the SynRMs and the IMs are given in Table 4. The controller of the SynRMs feeds the optimum currents and the current angle results in the highest efficiency at the rated operation under the given voltage limitation. The 50 kW rated inverter was used to drive the SynRMs up to 37 kW, and the other two SynRMs were driven by the 150 kW rated inverter. They are shown in Fig. 6.

The rise in winding temperature of the SynRMs was lower when compared to that of the IMs thanks to lower overall losses, even with similar outer volumes. Therefore, the overload capability of SynRMs could be better due to the lower temperature rises [11]. However, this may not hold for all circumstances. The overload capability of SynRMs imposed by the kVA rating of their inverters may not be better when compared to the IMs owing to saturation of the *d*-axis under high-load operation, which further decreases the achievable power factor of the machines. The maximum value of the fundamental apparent power factor which neglects winding resistance and stator leakage reactance is [12]:

$$\mathrm{PF}_{\max} \approx \frac{\xi - 1}{\xi + 1}, \tag{9}$$

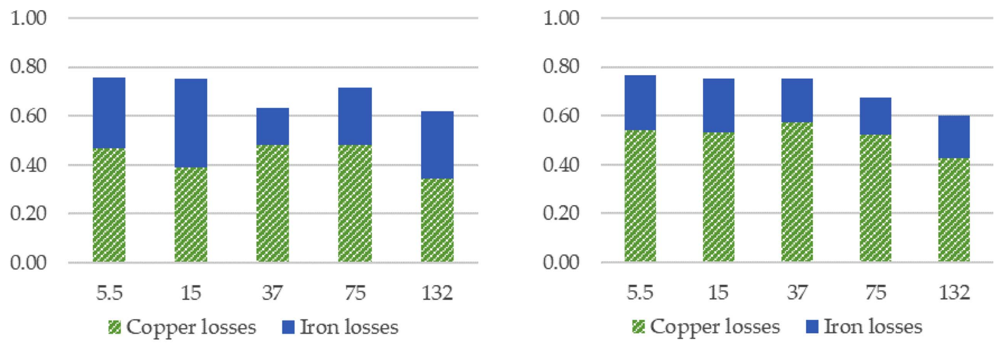
where ξ is the saliency ratio. The power factor would be degraded with decreasing the saliency ratio due to the saturation as consequence of the increased stator current. Even though this paper only presents experimental results for the SynRMs at their rated operations, lower power factors under over-load operation would be a potential issue.

The power factor between two motors over their entire power range can differ greatly. It should be noted that the given power factor of the SynRMs is recorded on the inverter input side. The fundamental power factor of the SynRMs, when only the fundamental voltage and current are measured on the input side of the motors, is in the range of 70-80 %. It is unclear if the power factors of the IMs are further decreased when they are fed using inverters.

The loss fractions of the presented motors are compared in Fig. 7. The 15 kW SynRM was manufactured with a cost-effective iron core, which resulted in a high fraction

Table 4. Experiment results of the synchronous reluctance motors and the induction motors.

Output power [kW]	5.5	15	37	75	132
			SynRM / IM		
Stator copper losses [W]	144/185	353/327	818/940	1758/1228	1105/1619
Rotor copper losses [W]	-/92	-/242	-/530	-/602	-/832
Sum of the copper losses [W]	144/277	353/569	818/1470	1758/1830	1105/2451
Iron losses [W]	89/115	326/232	263/468	842/527	885/987
Mechanical losses [W]	53/45	65/128	283/290	478/621	803/974
Additional losses [W]	22/76	156/138	341/342	556/512	414/1303
Total losses [W]	308/513	900/1067	1705/2570	3634/3490	3207/5715
Temperature rise [°C]	21/38	43/59	53/72	48/48	27/48
Power factor [%]	61/80	68/85	73/87	79/88	82/90



(a) (b)

Fig. 7. (Color online) Loss fraction of copper losses and iron losses with the rated output power in kilowatts: (a) and (b) respectively, show those of the SynRMs and the IMs.

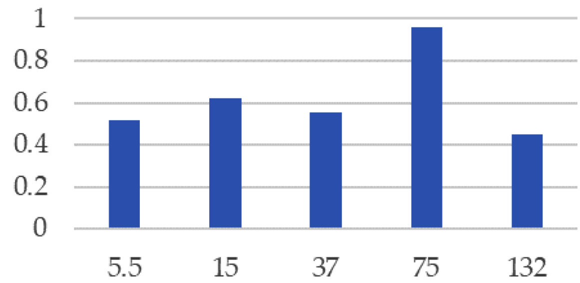


Fig. 8. (Color online) Fraction of copper losses in the SynRMs with their rated power in kilowatts referred by those of the IMs.

of iron losses; however, the motor achieved IE4-class efficiency. The amount of iron losses of the SynRMs and IMs may be quite similar considering the additional harmonics when the IMs are fed using an inverter, if operation only around 60 Hz is concerned. The results for the SynRMs indicate that almost equivalent copper and iron losses can be achieved.

The majority of loss reduction is owing to the absence of the secondary copper losses as discussed in various studies of SynRMs [13, 14], and this resulted in the reduction of the overall copper losses. Moreover, according to studies on the load stray losses of IMs [15, 16], elimination of the rotor cage would reduce the spatial harmonic joule losses in the rotor cages, which would have appeared as load stray losses. However, such losses cannot be directly measured via the standards. The higher efficiency of SynRMs than of IMs would appear at low-speed operation, where significant reduction of the copper losses would be expected.

The copper losses of the SynRMs relative to those of the IMs, are shown in Fig. 8. Except for the 75 kW SynRM, which failed to achieve IE4 efficiency, around 40-50 % reduction of the copper losses indicates higher efficiency. The current fed to the 75 kW SynRM was beyond the anticipated rated current, which yielded almost the same copper losses compared to the 75 kW IM. It is interesting to note that the efficiency of the two 75 kW motors was nearly identical.

Table 5. Determined system efficiency and calculated inverter kVA.

Rated power [kW]	5.5	15	37	75	132
Motor& driver efficiency	91.0	91.8	92.7	92.9	94.9
Inverter kVA	10.0	24.0	55.0	102.5	169.2
Switching frequency [kHz]	8	6	6	5	4

The combined rated efficiency and the required minimum inverter ratings for the rated operations are given in Table 5. The 5.5 kW rated SynRM demands almost two times higher kVA rating of the inverter. These results may cause hesitation to adopt SynRMs; however, it should be noted that SynRMs of up to the 37 kW rating are driven by the 50 kW rated inverter. The experiment with relatively over-rated inverter is a potential reason for resulted demands on high inverter kVA.

4. Conclusions

SynRMs of different ratings intended to meet the IE4-class efficiency were manufactured and then used in experiments. The results were compared with those of direct drive IMs corresponding to the equivalent rating of each SynRM. The SynRMs were tested according to a standard identical to that for the IMs. The fundamental losses were determined using only the fundamental voltage and currents measured by the power analyzer, and the resulting residual losses were treated as the additional harmonic losses. The calculated iron losses of the SynRMs, however, are uncertain although the results well matched the iron losses projected using FEA. The SynRMs up to 37 kW showed that these motors could provide better efficiency. In fact, they achieved the IE4-class with almost identical stator outer volume, even in the presence of additional harmonic losses. For higher power motors, the SynRMs seemed to lose their advantages; however, in the work reported in this paper it was not possible to compare them with the inverter-fed IMs of the IE4 class. The author expected that the advantages of SynRMs over IMs would be more significant in the low to mid-power range, owing to the high portion of copper losses in their total losses.

The majority of the loss reduction in the SynRMs relative to those of the IMs is owing to the reduced copper losses. Therefore, it was foreseen that the SynRMs would show superiority in efficiency during low-speed operation. This paper also expected that the reduced temperature increase of the SynRMs may not indicate overload capability. It could be restricted by the kVA rating of the inverter due to the reduced power factor under high load. Performance evaluation of SynRMs over their entire operating range, including overload conditions, remains for future work.

Acknowledgments

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