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ADVANCED DESIGN TECHNIQUES FOR SUPER–PREMIUM ENERGY–EFFICIENCY THREE–PHASE CAGE INDUCTION MOTORS

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Abstract: Rising concerns regarding the reduction in global energy consumption and greenhouse gas emissions have led to the increasing demand for energy–efficient electric motors. The average life–cycle of a line–operated, three–phase cage induction motor is 20 years, during which the energy consumption of the motor covers more than 95% of its total life–cycle cost. The challenge for super–premium energy–efficiency line–operated, three–phase cage induction motor designers and manufacturers lies in reducing internal power losses of the motor along with its performance improvement, not only in terms of energy efficiency when running the motor on 50 to 100% of load, but also of noise, vibration, temperature rise, starting torque and stator–phase current strength, power factor, and motor life–cycle cost. In this paper, all kinds of power losses in the line–operated, single–speed, low–voltage, three–phase cage induction motor are assessed, and some advanced design techniques for their reduction are reviewed in order to meet motor super–premium energy–efficiency level requirements.

Keywords: line–operated three–phase cage induction motor, power losses, design techniques, super–premium energy efficiency

1. INTRODUCTION

More than 300 million electric motors are currently installed in the industrial sector worldwide, and their amount is increasing by 15% annually. As a result, electric motors represent about 70% of the global industrial electric energy consumption, of which three–phase cage induction motors account for 80–90% [1]. Rising concerns regarding the reduction in global energy consumption and greenhouse gas emissions have led to the increasing demand for energy–efficient electric motors.

In order to harmonize energy–efficiency classifications for line–operated, three–phase cage induction motors manufactured and sold in the global market, the International Electrotechnical Commission (IEC) introduced the standard IEC 60034–30–1:2014 [2], which defines four energy–efficiency classes with IE (i.e. the acronym of '*International Efficiency*') code: IE1 – Standard Energy Efficiency, IE2 – High Energy Efficiency, IE3 – Premium Energy Efficiency, and IE4 – Super Premium Energy Efficiency (Figure 1). It should be underlined, that a relatively small improvement in the energy–efficiency percentage of a line–operated, three–phase cage induction motor is equivalent to a substantial reduction of power losses in the motor. For example, the difference in the energy efficiency percentages of 45 kW, four–pole, 50 Hz line–operated, three–phase cage induction motors of IE4 and IE3 energy–efficiency level, respectively, is only 1.2%, but this is equivalent to 22% reduction in motor power losses (i.e. from 2771 [W] to 2170 [W]). In addition to defining energy–efficiency classes for line–operated, low–voltage, three–phase cage induction motors, the IEC has also developed the standard IEC 60034–2–1:2014 [3], that specifies how to determine motor power losses and energy efficiency based on established testing methods.

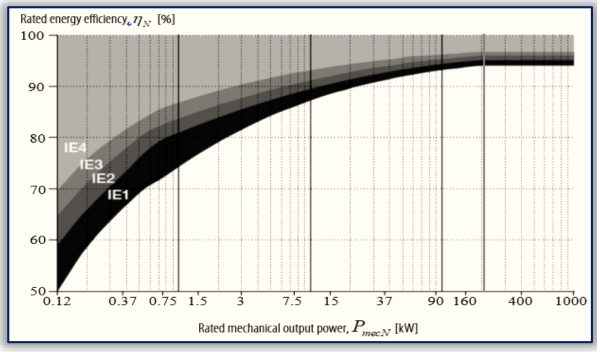

Figure 1. Definition of energy–efficiency classes (IE1 – IE4) for line–operated, low–voltage, four–pole, three–phase cage induction motors, according to IEC 60034–30–1:2014 standard.

The average life–cycle of a line–operated, three–phase cage induction motor is 20 years, during which the energy consumption of the motor covers more than 95% of its total life–cycle cost. Although super–premium energy–efficiency (IE4) line–operated, three–phase cage induction motors require higher initial costs – since the motor purchase cost constitutes less than 3% of the motor life–cycle cost – benefits in terms of energy savings, greater output mechanical power, as well as lower maintenance cancel the motor initial costs out. This is proved with the following example: if a premium energy–efficiency (IE3) line–operated three–phase cage induction motor, purchased for 4452 Euro, and delivering 90 [kW] of rated mechanical output power for 8000 [hours/year] with an energy efficiency of 95.2% is replaced by a super–premium energy–efficiency (IE4) line–operated three–phase cage induction motor, purchased for 5016.71 Euro, and delivering the same 90 [kW] of rated mechanical output power for 8000 [hours/year] but with an energy efficiency of 96.1%, it results electric energy saving of 7083 [kWh/year], i.e. from 756303 [kWh/year] to 749220 [kWh/year]; for 1 [kWh] cost of 0.06 Euro, this annual energy saving equates to 425 Euro/year saved money, so that the replacing super–premium energy–efficient motor is paid back in 16 months.

The European Union (EU) Commission regulation 2019/1781 [4] mandated that, from 1st July 2023, the super–premium energy–efficiency (IE4) class will apply for line–operated, two–, four– or six–pole, three–phase cage induction motors with rated mechanical output power from 75 [kW] to 200 [kW]. Today, comercially–available super–premium energy–efficiency (IE4) line–operated, two–, four– or six–pole, three–phase cage induction motors are offered in the rated mechanical output power range

- from 2.2 [kW] to 1000 [kW] by Siemens, Germany;
- from 11 [kW] to 900 [kW] by ABB, Switzerland;
- from 5.5 [kW] to 315 [kW] by WEG, Brazil,

thus exceeding the requirements of the EU Commission regulation.

The challenge for super–premium energy–efficiency line–operated, three–phase cage induction motor designers and manufacturers lies in reducing internal power losses of the motor along with its performance improvement, not only in terms of energy efficiency when running the motor on 50 to 100% of load, but also of noise, vibration, temperature rise, starting torque and stator–phase current strength, power factor, and motor life–cycle cost.

2. POWER LOSS ASSESSMENT OF THREE–PHASE CAGE INDUCTION MOTORS

Power losses in the line–operated, three–phase cage induction motor comprise Joule–Lenz effect losses in stator three–phase winding $(p_{J,s})$ and rotor cage winding $(p_{J,r})$, core (iron) losses (p_{core}), mechanical losses (p_{mec}) and additional losses (p_{add}). The energy efficiency (η) of the motor can be expressed in terms of internal power losses of the motor as

$$\eta = \frac{P_{mec}}{P_s} = \frac{P_s - \sum p}{P_s} = 1 - \frac{\sum p}{P_s}, \tag{1}$$

where P_s represents the input electric active power absorbed by the stator, P_{mec} stands for the mechanical output power, and

$$\sum p = p_{J,s} + p_{J,r} + p_{core} + p_{mec} + p_{add} \ . \tag{2}$$

The typical power loss share in line–operated, three–phase cage induction motors is shown in Figure 2, revealing that the percentage of Joule–Lenz effect rotor losses, core losses and mechanical losses increases slightly with rated output power, while the percentage of Joule–Lenz effect stator losses decreases considerably and of additional losses increases greatly with rated output power.

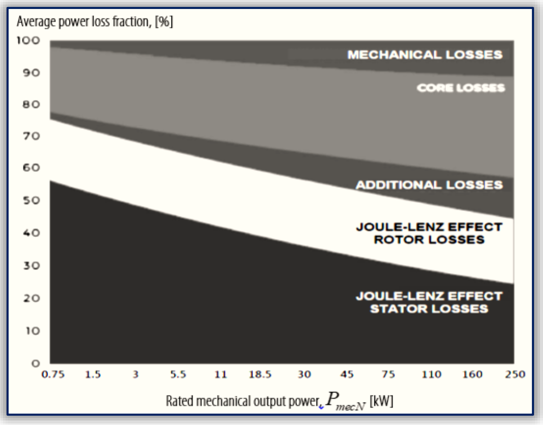

Figure 2. Average power loss distribution in 50–Hz line–operated, low–voltage, four–pole, three–phase cage induction motors as a function of rated mechanical output power [5].

— Joule–Lenz effect losses in stator three–phase winding

The Joule–Lenz effect losses in the stator three–phase winding represent approximately 35–50% of the motor internal power losses; they are expressed by the product of stator–phase electrical resistance and squared rms value of stator–phase current strength.

— Joule–Lenz effect losses in rotor cage winding

The Joule–Lenz effect losses in rotor cage winding are proportional to the equivalent electrical resistance of the cage bar and short–circuit ring, and account for about 20 % of internal power losses of the motor.

— Core (iron) losses

Core (iron) losses refer to core losses due to space fundamental airgap alternative and rotational magnetic flux density components, and contain only magnetic hysteresis and eddy current losses in the teeth and yoke of stator lamination – as in normal motor operation, the frequency of magnetic flux in the rotor core is very small (usually, of l–3 [Hz]), so that the rotor iron losses can be ignored; for the 15–75 [kW] rated output power motors of common use, fundamental stator core losses account for 20–30 % of the internal motor power losses; for motors with the same output power, the larger the magnetic pole number and the greater the motor volume, the bigger the fundamental stator core losses.

— Mechanical losses

The mechanical losses consist of bearing friction losses and incorporated ventilation system losses; bearing friction losses are mainly related to bearing model, level of installation, and lubricant used; ventilation system losses depend on the fan material and efficiency, and the rationality of the air duct's design; bearing friction losses are proportional to squared motor speed, while ventilation losses are proportional to the cube of motor speed.

— Additional losses

Additional losses are produced by airgap magnetic flux density space harmonics as (i) no–load rotor surface core losses, rotor and stator tooth magnetic flux pulsation core losses and unskewed rotor tooth magnetic flux pulsation cage losses and as (ii) stray–load losses, which comprise all components of no–load additional losses augmented by load conditions, and also the uninsulated skewed rotor–cage inter–bar current losses.

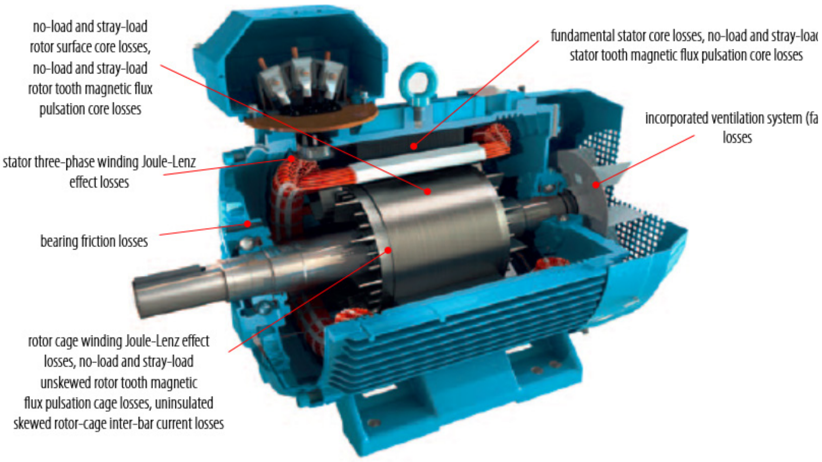

Figure 3. Locating of the power losses in a line–operated, three–phase cage induction motor

Knowing exactly where the power losses occur in the line–operated, three–phase cage induction motor (Figure 3) is the key in improving design and manufacturing processes to reduce them.

3. ADVANCED DESIGN TECHNIQUES TO REDUCE THE POWER LOSSES IN THREE–PHASE CAGE INDUCTION MOTORS IN ORDER TO REACH THE SUPER–PREMIUM ENERGY–EFFICIENCY LEVEL

— Single–layer series–combined star–delta three–phase stator winding

In order to improve the energy efficiency of line–operated, low–voltage, three–phase cage induction motors, their internal power losses must be decreased either in the magnetic circuit or in the winding electrical circuits. A design technique with little additional cost to increase the motor energy efficiency consists in using a single–layer series–combined star–delta three–phase winding in the stator (Figure 4); it enables lowering the content of airgap magnetic flux density space harmonics and, thus, improving the motor energy efficiency, if two basic conditions are fulfilled [6, 7]: (i) the magnetic axes of the star– and delta–connected windings must be mutually shifted in space by 30 electrical degrees; (ii) the ratio of the number of turns per phase for the delta–connected winding to that for the star–connected winding must be $\sqrt{3}$; especially, the second condition cannot be exactly fulfilled in practice.

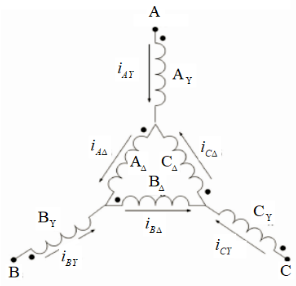

Figure 4. Electrical circuit scheme of series–combined star–delta three–phase stator winding for a line–operated, three–phase cage induction motor

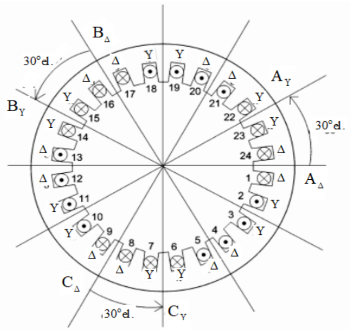

Figure 5. Distribution in slots of the single–layer series–combined star–delta three–phase stator winding (with four slots per pole and phase) for a line–operated, three–phase cage induction motor [6]

In the case of the induction motor with series–combined star–delta three–phase stator winding shown in Figure 4, and fed from a three–phase power network, it is possible to eliminate (or, at least, considerably reduce) the 5th, 7th, 17th, 19th, 29th, 31st, ... space harmonics of the airgap magnetic flux density. The star–connected winding parts denoted by the subscript Y are mutually shifted in space by 120 electrical degrees, and also the delta–connected winding parts denoted by the subscript Δ are mutually shifted in space by 120 electrical degrees; there are six stator–winding parts, in total, in Figure 4. The arrangement in slots of a series–combined star–delta three–phase stator winding (with four slots per pole and phase) is displayed in Figure 5, where positions of magnetic axes of winding parts are pointed out.

In Table 1, comparative experimental results for two 8 [kW], line–operated, three–phase cage induction motors having the same 24–slot stator core and the same rotor, but one equipped with classical three–phase stator winding, and the other one with a single–layer series–combined star–delta three–phase stator winding. It can clearly be seen that the energy efficiency of the motor equipped with the series–combined star–delta winding is increased by 0.72%; this is due to the reduction of Joule–Lenz effect losses in the three–phase stator winding (as a result of decreased stator–winding electrical resistance) and of additional losses (as a result of lower content of airgap magnetic flux density space harmonics). Besides, the fundamental core losses of the motor equipped with series–combined star–delta three–phase stator winding are slightly increased due to somewhat higher fundamental airgap magnetic flux density. Furthermore, the harmonic leakage factor of the series–combined star–delta three–phase winding being lower in comparison to that of the classical three–phase stator winding, the starting torque of the motor equipped with series–combined star–delta three–phase stator winding is superior; however, the starting current strength increases as well.

Table 1. Comparative design data and experimental results for two 8 [kW], line–operated, three–phase cage induction motors [7]

	Motor equipped with classical three–phase stator winding	Motor equipped with series–combined star–delta three–phase stator winding
Number of magnetic poles	2	2
Number of stator slots	24	24
Fundamental winding factor	0.9577	0.9914
Harmonic leakage factor	0.0089	0.006
Stator–winding resistance (between two stator terminals)	0.79 [Ω]	0.735 [Ω]
Joule–Lenz effect losses in the three–phase stator winding	290 [W]	266 [W]
Joule–Lenz effect losses in the rotor cage winding	239 [W]	223 [W]
Fundamental core losses	165 [W]	173 [W]
Additional losses	172 [W]	123 [W]
Mechanical losses	22 [W]	24 [W]
Rated energy efficiency	90.1%	90.82%

Table 2. Comparative experimental results for two 15 [kW], line–operated, three–phase cage induction motors [9]

	Motor with die–cast aluminium rotor cage winding and standard electrical steel stator laminations	Motor with die–cast copper rotor cage winding and thinner high–quality silicon steel stator laminations
Joule–Lenz effect losses in the three–phase stator winding	363.92[W]	351.27 [W]
Joule–Lenz effect losses in the rotor cage winding	336.23 [W]	142.17 [W]
Stator core losses	202.33 [W]	152.57 [W]
Total power losses	1462.67 [W]	1210.8 [W]
Rated energy efficiency	91.11 %	92.53 %

- Die–cast copper rotor cage winding and high–quality silicon steel stator lamination

Since electrical conductivity of copper is more than 1.5 times of aluminum, it is obvious that employing die–cast copper for rotor cage winding instead of die–cast aluminium leads to significant decrease of rotor cage winding Joule–Lenz effect losses, and thus to energy efficiency increase of the line–operated, three–phase cage induction motors. In copper die–casting process, manufacturing cost is rather expensive due to the high melting temperature (1084°C) of copper. However, recent improvement of the copper die–casting technologies has made die–cast copper rotor cage winding an economically viable solution for mass production. Beside the increase in energy efficiency of line–operated, three–phase cage induction motors, the die–cast copper rotor cage winding enables both reducing the rotor temperature and down–sizing the motor volume. It must be also noticed that (i) rotor–cage bars of die–cast copper are about three times heavier than of aluminium, so there is required sufficient strength in the laminations above rotor–cage bars; (ii) the starting torque of copper rotors is lower than that of aluminium rotors. Another issue encountered with die–cast copper rotor cage winding is the deterioration of slot insulation during the manufacture, possibly leading to inter–bar current additional losses [8, 9]

To further increase the energy efficiency of line–operated, three–phase cage induction motors with die–cast copper rotor cage winding, the fundamental and additional stator core losses may be decreased by replacing standard electrical steel laminations by thinner high–quality silicon steel sheets, without changing motor frame. The newly developed single–stage cutting–extrusion technology (with lower manufacturing cost) can produce high silicon–content steel sheets (with increased electrical resistivity) of 50–150 mm in width and 0.3–0.5 mm in thickness.

In Table 2, comparative experimental results for two 15 [kW], 2–pole, line–operated, three–phase cage induction motors of the same frame, one equipped with die–cast aluminium rotor cage winding and standard electrical steel stator laminations, and the other one with die–cast copper rotor cage winding and thinner high–quality silicon steel stator laminations. It can be seen that the energy efficiency of the latter motor is increased by 1.42 % ; this is due to the significant reduction of Joule–Lenz effect losses in the rotor cage winding and of fundamental and additional stator core losses; however, the motor starting current strength is slightly increased, whereas the starting torque is somewhat decreased.

4. CONCLUSION

The paper firstly has outlined IEC standards and EU regulations related to energy efficiency classes for line–operated, single–speed, low–voltage, three–phase cage induction motors. Then the internal power losses of these induction motors are assessed, and two advanced design techniques for their reduction are reviewed in order to achieve the motor super–premium energy–efficiency level, i.e. single–layer series–combined star–delta three–phase stator winding and die–cast copper rotor cage winding associated with high–quality silicon steel stator laminations.

Note: This paper was presented at XX^th^ National Conference on Electric Drives – CNAE 2021/2022, organized by the Romanian Electric Drive Association and the Faculty of Electrotechnics and Electroenergetics –University Politechnica Timisoara, in Timisoara (ROMANIA), between May 12–14, 2022 (initially scheduled for October 14–16, 2021).

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