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doi:10.15199/48.2018.05.02

The impact of the rotor slit number on the behavior of high-speed induction motor

***Abstract**. The impact of the rotor slit number on the behavior of high-speed induction motor is investigated. High-speed induction motor with the axially slitted rotor is examined and studied from the perspective of additional rotor losses, torque ripple and undesirable magnetic force. More than ten rotor slits are simulated with finite element method, where the simulated motor is under fully load. Finite element transient analysis is used to respect relative rotor movement to the stator. This article will demonstrate that the number of rotor slits should be chosen wisely.*

Streszczenie.** W pracy zbadano wpływ liczby szczelin na właściwości wysokoobrotowych silników indukcyjnych. Badano powstawanie dodatkowych strat, zafalowania momentu napędowego. Wykorzystano metodę elementu skończonego. Wykazano że liczba szczelin w wirnku powinna być dobierana rozważnie. **Wpływ liczby szczelin na właściwości wysokoobrotowych silników indukcyjnych

Keywords: high-speed drive, induction motors, rotor slits, torque ripple, finite element analysis.
Słowa kluczowe: wysokoobrotowe silniki indukcyjne, szczeliny wirnika, metoda elementów skończonych.

Introduction

After many years of researches, high-speed electrical machines (HSEMs) commences to be part of industrial applications [1], [2]. The complicated system can be replaced or even improved by one electrical machine directly attached to the load. The positive sides of this concept are in an omission of the mechanical gear box and therefore it reduces the size, install area, initial cost, overall weight and it even safe space for transporting [1].

The predominant market place belongs to high speed permanent magnet synchronous machines (HSPMSMs) due to its better efficiency, better power unit per volume and less loss distribution in active parts. The main drawback of (HSPMSM) is that modern NdFeB-permanent magnets are vulnerable to high operational temperatures, and therefore, the cooling solution could be very complex [2], [6]. Nevertheless, high speed induction motors (HSIMs) excels in simple construction and low initial cost [3]. Furthermore, when utilizing solid rotor, HSIMs rotor tolerates high operational temperatures. Area of the application can be large. HSIM can be employed for a drive of the compressor for a gas pressure, spindle drive, large energy storage fly wheel or in the automotive industry for electrically assisted turbocharger [2-5].

Together with output power and supply frequency we also classified HSIMs according to circumferential speed. HSIMs with solid rotors are capable of reaching very high tip speeds. According to [1], the tip speed can be up to 350 m/s with solid rotors. Mechanical stresses on the rotating parts puts high demands on rotor material. Consequently, the rotor in HSPMSMs uses titanium sleeve or carbon fiber bandage to hold the magnet in the right position while HSIM rotor is based on solid steel. Solid rotor, made of one steel can withstands high mechanical stresses and therefore laminated rotor is being replaced by solid, see Fig. 1. On the other hand, rotor made of solid steel do not have sufficient electromagnetic properties. The solid rotor is impacted by higher harmonics, causing additional rotor eddy current losses and magnetic saturation causing an increase of Joule loss. Feature modification in the form of axial slits is made to cut eddy current path and reduce additional power losses in the rotor. Axial slits decrease mechanical robustness and increase mechanical ventilation loss [3].

High-speed induction motor with an axially slitted rotor, unlike classical laminated rotor has poor electromagnetic properties, nonetheless this concept can be used in application, where motors works in harsh environment [4]. Classical laminated rotor is not suitable because it cannot withstand high temperature and great mechanical stress [4]. Every proper design of high-speed induction motor with solid rotor should be made with special care.

Solid rotor, which is made from one piece of steel suffer from higher air gap harmonics and for this reason number of higher harmonics should be minimized to reduce additional rotor surface loss [7]. Firstly, the number of higher harmonics in air gap can be reduced by winding arrangement. Distribution factor respect that the winding is distributed in slots. The more number of stator slots is, the smoother magneto-motive force is. Pitch factor respects the opportunity of reducing full pitch and suppress of fifth and seventh higher order of harmonic. Secondly, higher harmonics are also generated due to the permeance variation, which is caused by stator and rotor slots. The combination of stator/rotor slots should be chosen wisely with respect to parasite torques and forces. Generally odd number of rotor slits should be avoided so that machine does not reach high level of noise [8].

Finally, saturated magnetic materials and asymmetrical supply voltage also contribute to higher harmonics content. Motor, which is supplied from frequency converter have higher magnetic iron losses, depending on switching frequency, modulation waveform and the modulation index of inverter. Non-sinusoidal supply voltage will bring extra harmonics to the motor from outside and decrease efficiency because of higher iron loss due to higher frequencies of the pulse width modulation (PWM) supply [9]. It was shown in [9] that not only eddy current losses mainly contribute in the iron loss, but also hysteresis losses, which are associated with so-called minor loops. High speed induction motors usually work with lower magnetic flux density to eliminate iron losses in operating state.

Additional rotor losses and impact of slotting can also be reduced by increasing of air-gap length. A small length of air gap increases magnetization inductance, but impact of slots will generate massive loss in rotor due to eddy currents. On the other hand, increasing air gap will negatively affect joule loss due to lower magnetization inductance and higher magnetization current. The air gap length needs to be chosen wisely where the tradeoff between rotor and joule loss need to be set to reduce overall losses in operating state. In general, the advantage of small air gap is not suitable for this type of rotor concept.

Stator and rotor magneto-motive force create together the air-gap magnetic flux density distribution which varies in time and space [7]. Harmful pulsating torque is produced when there is same order harmonics in stator and rotor [8]. The aim of this article is to find optimal stator slot/ rotor slit combination in HSIMs with respect to rotor eddy current losses, torque ripple and axial and radial forces. For every combination of stator/rotor slots comprehensive analyze will be done. Air gap magnetic flux density distribution for every slot combination is decomposed and significant harmonics are studied in detail. In addition, forces apply in radial and axial direction are examined to avoid an odd number of rotor slits. In conclusion, paper could be used as guideline for designing of proper stator/rotor slot combination.

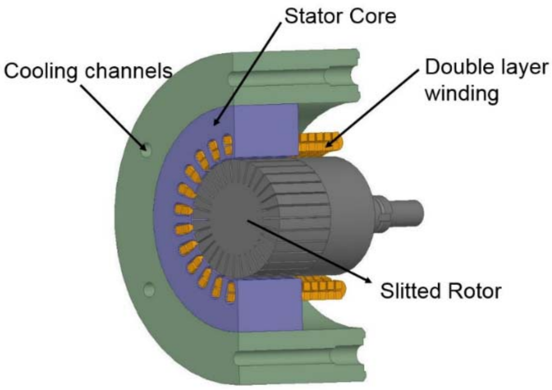

Fig. 1: 3D cross section of HSIM

Analyzed motor

The test motor was a 3-phase, 2-pole, 750 Hz, solid rotor with axial slits. The rated output power of the motor is 12 kW and synchronous speed is 45000 min^{-1}. The main parameters are in Table 1. A number of rotor slits vary from 15 to 31. The depth and width of slits are kept constant as well as rotor diameter. This paper follows article where air gap length was studied and the air gap length was chosen as a tradeoff between stator Joule loss and rotor losses [11]. The radial air gap length was chosen to be 1.4 mm. As a material for rotor, standard steel with label EN S355J2G3 is used as a material.

Table 1: The main parameters of the studied HSIM

Number of stator slots [-]	24
Line to line rated voltage [V]	400
Rated output power [kW]	12
Turns per stator slot [-]	6
Number of rotor slits (variable parameter) [-]	15-31
Outer diameter of stator [mm]	124
Inner diameter of the stator [mm]	65
Air gap length [mm]	1.4
Stator stack length [mm]	100
Width of rotor slits [mm]	1
Depth of rotor slits [mm]	12
Winding factor [-]	0.925
Number of turns in series per phase [-]	24
Short pitching [-]	10/12

Method of analysis

Finite element method approach in ANSYS Maxwell software is used for analysis of presented machine. Transient analysis has been taken to respect the relative movement of the rotor and time varying of electromagnetic field. The analysis was carried out at rated load.

Winding of HSIM is supplied from sinusoidal voltage source. The finite length of the rotor and the fact that current need to go from one pole to another is considered by *Russel* correction factor [10]. During last period, 1000 samples were taken to take into account higher harmonics from stator slots. The finest mesh was made around air gap and on rotor surface where higher harmonics penetrated the rotor. The magnitude of elements created on rotor surface is three times smaller than the penetration depth of higher harmonic from the stator. More than ten simulations with different stator/rotor combination has been made so that combination can be studied in general.

Reduction of rotor eddy current losses

As it was mentioned before, solid rotor eddy currents additional loss can be reduced by increasing of radial airgap length, see Fig. 2. This option was already subject of interest in [11] and optimal airgap length was chosen to be 1.4 mm. In Fig. 2 can be see proportion of rotor eddy current losses, joule losses as a function of air gap length. Total losses are sum of rotor eddy current, stator core and mechanical losses. Mechanical losses were in this case calculated analytically and it slightly changed due to different rotor slip.

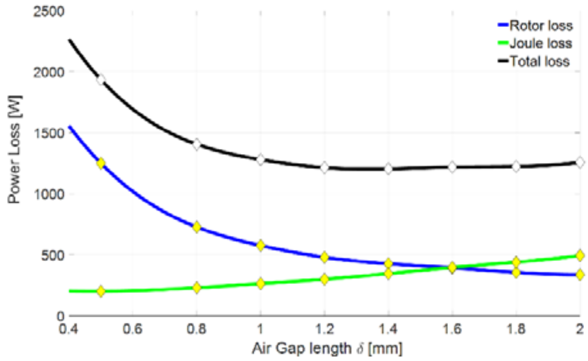

Fig. 2: Power loss division in HSIM with variable airgap

In this paper, simulation with different stator/rotor slot combination is made where the air gap length is kept constant for every simulation according to above results, Fig 2. In all simulations, the mechanical losses were calculated analytically with respect to mechanical speed and it slightly changed due to different rotor slip, see Fig.3. A portion of power losses for every stator/rotor combination can be seen in Fig. 3. Firstly, it can be seen that tendency of reducing the rotor eddy current losses are in the beginning, where number of rotor slits goes from 0 to approximately 25. By increasing number of rotor slits from 0 to 25, slip of rotor decrease with the number of rotor slits, see Fig 4. With ever increasing number of rotor slits from 25 to 40 slits, rotor slip starts to increase, see Fig. 4. Power loss in solid rotor cause by first harmonic increase with the slip. By increasing number of rotor slits, where the width of slit is kept constant, cross section of rotor teeth decrease and accordingly rotor resistivity and slip is becoming larger.

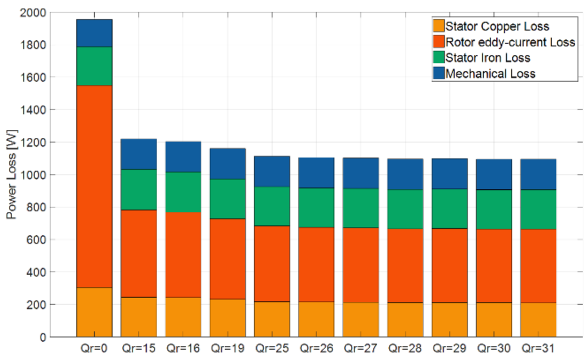

Fig. 3: Power losses in HSIM with different rotor slits

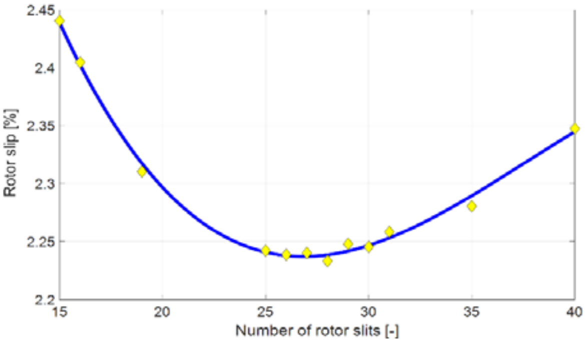

Fig. 4: Slip of rotor versus number of rotor slits

Harmonics and torque ripple

It has been observed [8] that small change of number of rotor slits could have caused that machine cannot reach proper nominal speed or its level of noise is high and motor cannot be produced. Several publications [7], [8] has been concerning about a number of rotor slits.

The waveform of distribution of magnetic flux density can be decomposed into many harmonic waves. Each of these harmonics acts on the rotor and generates the additional torques. The resulting torque consist of fundamental torque and parasitic torques which are developed by higher harmonics. Radial air gap flux density distribution of presented machine for 16 and 26 rotor slits can be seen in Fig. 5 and these waveforms are decomposed into harmonic spectrum in Fig. 6.

Higher harmonics are caused by effect of winding arrangement, magnetic saturation and by stator and rotor slotting.

According to [8], symmetrical three phase winding with integer number of stator slots per pole and phase produce higher harmonics of order:

(1) $$\nu_w = p\cdot(6\cdot k\pm 1) \text{ where } k = 0, 1, 2, \dots$$

where: *p* – basic number of pole pairs, *k* – integer.

By that winding arrangement only odd multiples of 1st harmonic can occur, except multiples of three [8]. By substituting integer into equation (1), we get two types of higher harmonics. All higher harmonics of order (1p, 7p, 13p, 19p, 25p, etc.) rotate in positive direction, i.e. in the same direction as the fundamental wave. Other harmonics (5p, 11p, 17p, 23p, etc.) rotates in the opposite direction. In Fig. 6, all higher harmonics of air-gap flux density distribution are shown. The amplitudes of higher harmonics, which are produced from stator winding, are small compare to harmonics from slotting.

Additional higher harmonics are also generated by the magnetic saturation. The fact that material loses its magnetic permeability effects air gap magnetic flux density and flattens the curve. It means that there are not only 1st harmonic of magnetic flux density but whole spectrum [8]. This additional higher harmonics rotate with synchronous speed to excited magneto-motive force with all odd multiples. [8] Therefore higher harmonics are:

(2) $$\nu_{sat} = \nu_w(2\cdot k+1) \text{ where } k = 0, 1, 2, \dots$$

where: ν_w – is order of higher harmonics produced by winding arrangement, *k* – integer.

Higher harmonics produced by magnetic saturation from the first order of magneto-motive force are (1, 3, 5, 7, etc.). The more saturated magnetic circuit is, the bigger amplitudes of generated harmonics are. Lastly, there are harmonics related to geometry caused by variable air gap length where stator and rotor are slotted. As a result of slotting additional spatial harmonics are created with following order:

(3) $$\nu_s = Q_s \pm p$$

where: *Qs* – number of stator slots.

By substituting into equation 3, from table 1 and for fundamental wave, first higher harmonics order for the stator is 25th rotating in the same direction as fundamental harmonic and 23rd rotating in the opposite direction. The same approach can be made for rotor slits. All higher harmonics mentioned above can negatively affect rotor, where additional torques may occur. In general, according to [8], moment act between stator and rotor could be written in the form (4), where energy is changing with changes of rotor position:

(4) $$T = -\frac{\partial W}{\partial \vartheta},$$

where: *W* – magnetic energy accumulated in the air gap, ϑ – circumferential angle in the radians which describes the rotor with respect to the standing stator.

From a generally known relationship to magnetic field energy, it can be written for electromagnetic torque:

(5) $$T = -\frac{l\cdot\delta}{2\cdot\mu_0}\cdot\frac{\partial}{\partial\vartheta}\cdot\int_0^{2\pi}[B(\alpha,t)]^2 d\alpha,$$

where: δ – air gap length, l – active length of stator stack, μ_0 – permeability of vacuum.

Distribution of magnetic flux density can be written in form:

(6) $$B(\alpha,t) = \frac{\mu_0}{\delta}\cdot F(\alpha,t),$$

where: $F(\alpha,t)$ – overall magneto-motive (MMF) force given by sum of stator $F_s(\alpha,t)$ and rotor $F_r(\alpha,t)$ magneto-motive forces.

Resulting torque is: [8]

(7) $$T = \sum_{\rho}\sum_{\nu=1}^{\nu=\infty} sin\{[\rho\cdot\omega_r \pm (\pm\omega - \nu\cdot\omega_r)\pm\omega]t - \varphi_\rho\}$$

where: ρ – order of rotor harmonic, ν – order of stator harmonic, ω – angular synchronous speed, ω_r – angular speed of rotor, t – time, φ_ρ – phase difference

Time independent torque occur only if term in brackets is equal to zero. [8]

(8) $$\rho\cdot\omega_r \pm (\pm\omega - \nu\cdot\omega_r)\pm\omega = 0$$

This condition can be fulfilled in two cases. The first case is when $\rho = \nu$ and it means that certain stator harmonic excites harmonic in the rotor with same order as an exciting one. In the second case, the condition is fulfilled only at certain rotor speed ω_r. The equation can be written as:

(9) $$\omega_r = \frac{\pm\omega - \nu\cdot\omega_r}{\rho} = \pm\frac{\omega}{\rho}$$

Equation 8, in this case can be fulfilled only when rotor and stator harmonic have same speed in air gap, i.e. only at certain rotor speed. When torque is non-zero and rotor harmonic of order ν is excited by stator harmonic ρ with same order $\rho = \nu$, *asynchronous* torque is produced. For example, when 1st stator harmonic produced 1st rotor harmonic, their interaction creates asynchronous torque. Secondly, when in the spectrum of stator and rotor harmonics are harmonic of the same order, but rotor harmonic is produced by different stator harmonic, then *synchronous* torque is produced. For example, when rotor harmonics created by slots in the rotor are met by same harmonic from the stator, harmful *synchronous* torque is created.

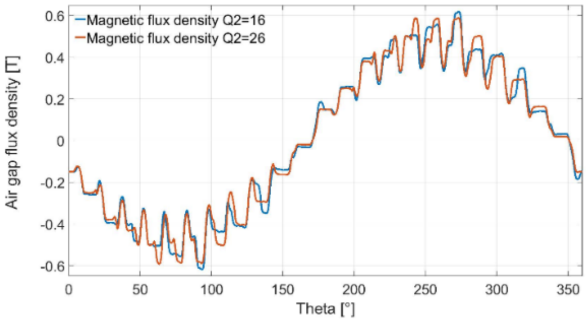

Fig. 5: Radial air-gap flux density distribution with respect to angular position

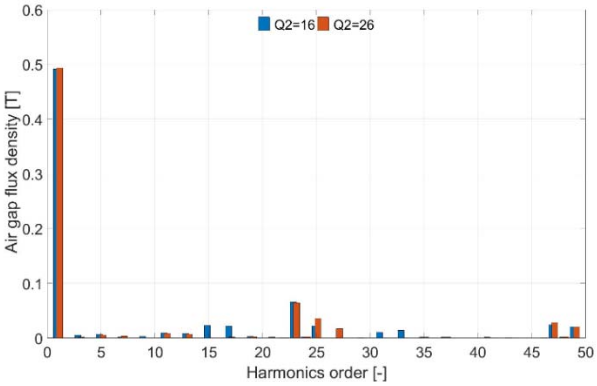

Fig. 6: Air gap flux density harmonic spectrum

Decomposition of the magnetic flux density distribution with respect to its angular position from Fig.5 can be seen in Fig. 6. If the amplitude of the first harmonic is left aside, there could be seen other higher harmonics contained in the graph, since the length of the air gap is not constant due to the stator and rotor slots/slits. Flux density amplitudes of the first order from stator (23rd and 25th), from the rotor with 16 slits (15th and 17th) and from the rotor with 26 slits (25th and 27th). Second order of higher harmonics from the stator is (49th and 47th) and (31st and 33rd) generated from the rotor with 16 slits. Moreover, the third order harmonics (49th and 47th) from rotor with 16 slits can also be seen in Fig. 6. Other harmonics contained in Fig.6 are produced by winding arrangement and by magnetic saturation.

It is important to note, that big amplitude of high order air gap harmonics will create high rotor surface losses because that angular speed of the rotor harmonics is very low compared to stator angular speed of fundamental frequency. The speed of harmonics with respect to the stator is inversely proportional to the order of harmonics and therefore rotor surface sees high harmonics slip frequency. The big magnitude of high order air gap harmonics caused big eddy current losses in the solid rotor. As it was mentioned before, when certain harmonics are met, torque is produced. Not only fundamental torque produced by 1st stator and rotor harmonics is developed but other higher torques are also produced. It can be seen from Fig. 7, that electro-magnetic torque for particular rotor slits at steady state operation is rippled. In the Fig. 7, there can be seen the magnitude of torque ripple in percentage for all examined rotor slits. The torque ripple was calculated in one working period under steady state condition according to equation 10.

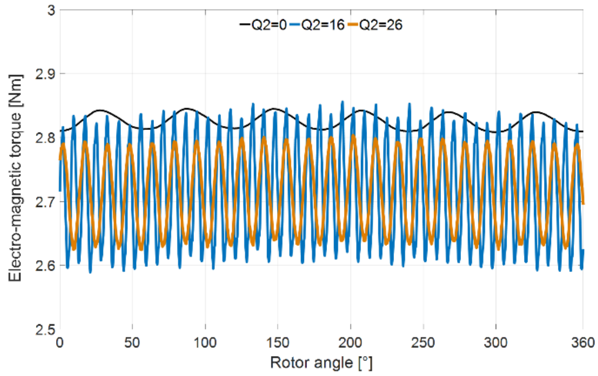

Fig. 7: Electromagnetic torque vs. rotor mechanical angle where number of rotor slits is Q2=0, 16, 26

(10) $$T_{ripple} = \frac{T_{max} - T_{min}}{T_{avg}} \cdot 100\ [\%],$$

where: T_{max}, T_{min}, T_{avg} – maximum, minimum and average torque during one steady period.

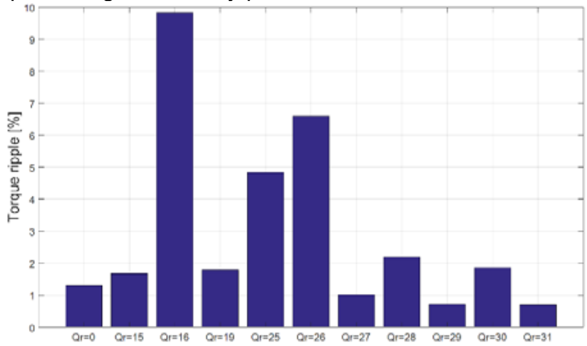

Fig. 8: Magnitude of torque ripple with variable rotor slit number

It can be seen from the Fig. 7 and 8, that worst number for choice would be 16 rotor slits together with 25 and 26 rotor slits. Best choice appears to be 29, 31, 27 and even 30 rotor slits could be used with torque ripple less than 2 %.

It can be seen from Fig. 7 that torque ripple of the smooth rotor is small compared with a slitted rotor with 16 and 26 slits. In Fig.9, air gap flux density harmonic spectrum of smooth rotor is presented. Except 3rd higher harmonic created by magnetic saturation, there can also be seen harmonics created by winding arrangement (5p, 7p, 11p, 13p). Those harmonics will interact with fundamental radial flux and generate pulsating torque, pulsating six times during one period, see Fig. 7. It can be written as [13]:

(11) $$T_6 \sim \emptyset_1^m \cdot (I_5^r - I_7^r) \cdot sin(6 \cdot \omega \cdot t),$$

Where: ω – angular synchronous speed, $\emptyset_1^m$ – represent a combined mutual flux,I_5^r – represent rotor MMF for 5th harmonic.

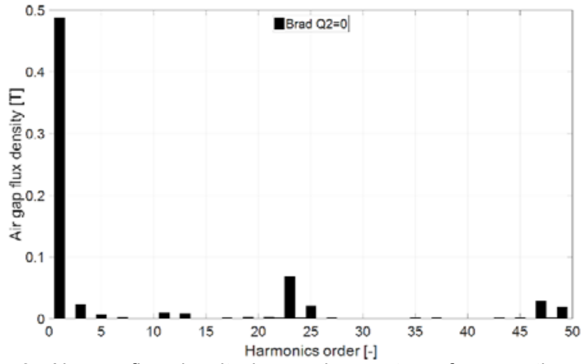

Fig. 9: Air gap flux density harmonic spectrum for smooth rotor, without rotor slits

Unlike smooth rotor where pulsating torque varying six times during one period, torque in slitted rotor with 16 and 26 rotor slits varying with different times per cycle. In slitted rotor with 16 and 26 slits, the effect of higher harmonics by winding arrangement is minor. The rotor slit number 16 and 26 should be avoided because harmful synchronous torque is produced. In general, for 26 rotor slits, when the magnetic higher harmonic 25th is generated by stator slots and is met by rotor higher harmonics 25th due to rotor slits, which is produced by 1st stator harmonics, the condition for developing synchronous harmful torque is fulfilled and undesirable torque occurs. It can be seen from harmonic spectrum of electromagnetic torque, that dominant higher harmonic in the spectrum is 24th, due to the fact that stator and rotor harmonic met each other, see Fig. 10. Spectrum under no-load is presented to avoid rotor slip influence. On the other hand, when slit number of rotor is 16, higher harmonics created by rotor slits are (15th, 16th, 31st, 33th, 47th and 49th), see Fig. 6. By stator slotting harmonics of order (23rd, 25th, 47th and 49th are produced. Only met is in harmonics of order 47th and 49th. Synchronous harmful torque condition is fulfilled and pulsating torque of order 48 is produced, see Fig.11. Not only higher harmonic of order 47th and 49th developed pulsating torque, but its influence is major.

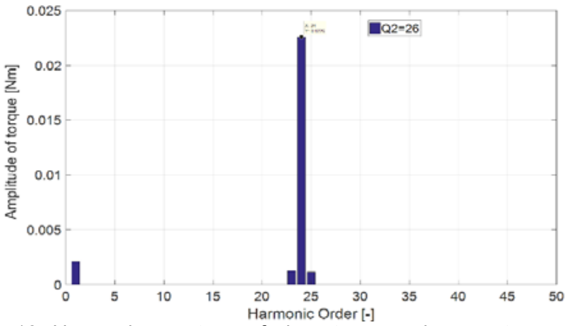

Fig. 10: Harmonic spectrum of given torque, where motor operate under no load, Q2=26

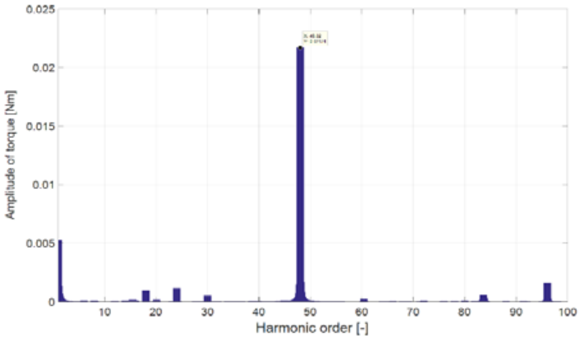

Fig. 11: Harmonic spectrum of given torque, where motor operate under no-load, Q2=16

Forces acting on the rotor

The other perspective, which is considered are forces acting on the rotor. The choice of an ideal number of rotor slits should also be examined, in order to properly evaluate a number of rotor slits. In the Fig. 12, is shown the average total net force. Total net forces are average values taken from forces in Fx vs Fy graph, during one period of steady state condition. In general, the ideal total net force value would be zero and forces in x and in y direction would be negligible. This situation describes smooth rotor, where the total net force takes minor effect. Unfortunately, this rotor, due to great eddy-eddy current losses cannot be used.

The maximum force that is produced in one period and act on rotor is shown in Fig.13. It should be cleared from obtained results that 15 or 25 rotor slits are not suitable due to high magnitude of force.

Another aspect, which should also be considered is odd or even number of rotor slits. Due to asymmetry, the magnitude of force during one period in steady state are high with an odd number of rotor slits compare to even number of slits. The difference can be seen from Fig. 14 and Fig. 15, where odd and even number of rotor slits are examined.

From obtained results, Fig.12, 13, 14, 15, is seen that proper rotor should have even rotor slits. Best choice appears to be 16, 26, 30 and even 31 rotor slits could be used even the number is even. All this numbers were chosen with respect to rotor force. Unfortunately, number 16 and 26 is not suitable from torque ripple perspective.

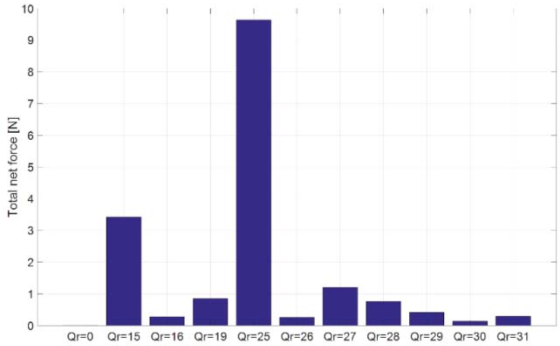

Fig. 12: total net force with variable rotor slit number

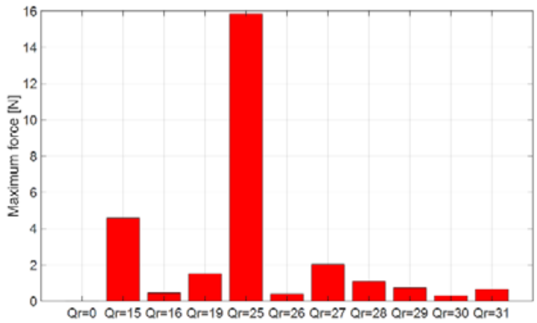

Fig. 13 Maximum force with variable rotor slit number

Optimal number of rotor slits with 24 stator slots

To minimize the effect or all impacts. The number of rotor slits should be chosen with special care and according to all above mentioned criteria. First criteria K1 are generated power losses and it was stated that number of rotor slits should be within the range between 25 and 30. Anything below or above that range will cause bigger rotor loss due to increasing slip. Second criteria K2 is torque pulsating and it was shown that rotor where number of rotor slits is 27, 29, and 31 has lowest torque ripple. Number of rotor slits could also be 28 or 30 with minimal torque pulsating effect.

The third criteria K3 is considered about unbalanced magnetic pull and it was shown that number 15 and 25 of rotor slits should be avoided. In addition, from the mechanical perspective, the number of rotor slits which is divisible by three provide mechanical advantage. For any position of the rotating system, the area moment of inertia is constant, unchanging and there is no fluctuation in bending stiffness of the rotor and no other aspect connected with that fact is occurred.

Concerning all criteria K1, K2, K3 and mechanical advantage in number of slits which is divisible by three, the ideal number of rotor slits is 30 or 27. .

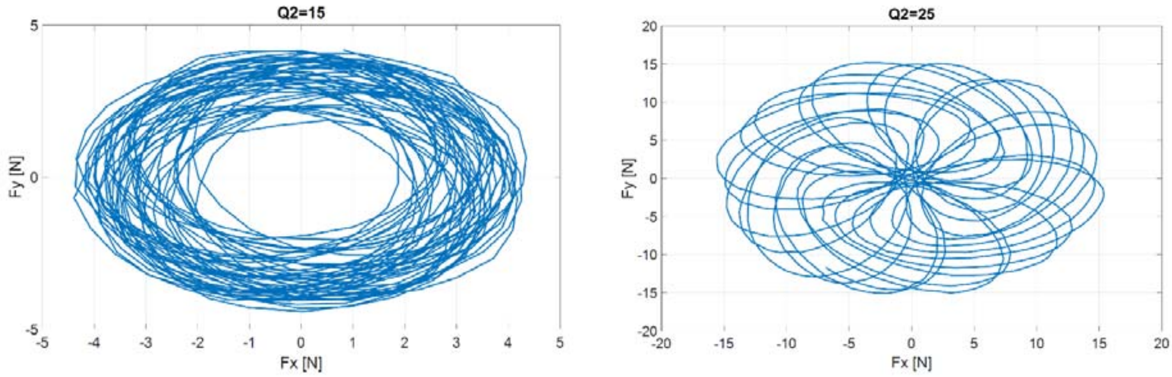

Fig. 14: The trace of forces in x and in y direction with odd number of rotor slits 15 and 25

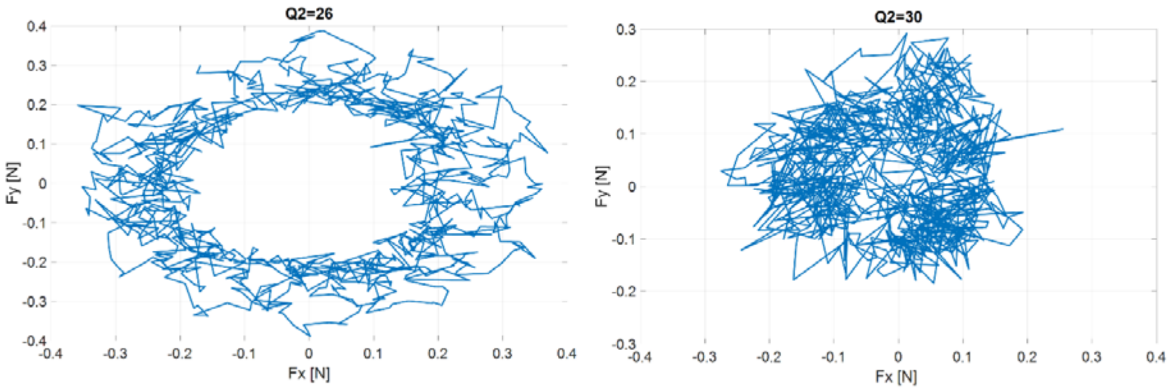

Fig. 15: The trace of forces in x and in y direction with even number of rotor slits 26 and 30

Conclusion

It has been shown in this paper that a number of rotor slits has a great impact on motor behavior. Firstly, for the elimination of rotor power loss, a number of rotor slits should be examined from power loss perspective. It was shown, that number of rotor slits should be greater that 25 to minimize rotor eddy current loss. It was also shown than by increasing number of rotor slits, where width of slit is kept constant, the cross section one tooth decrease, rotor resistivity increases and the slips of the rotor tends to increase as well. By that fact, rotor eddy current increased as well. In order to minimize rotor loss, the number of rotor slits should be in a range of 25 and 30 rotor slits.

Secondly, torque ripple was examined on the motor with variable rotor slits, where the ideal number was 29, 31 and 27. All this number gives us torque ripple under one percent. It could also be chosen 30 rotor slits, where torque ripple is under 2 percent. It was shown that certain combination of stator rotor slot/slit should be avoided. For example, 16 and 26 slit on rotor do no cooperate very well due to synchronous harmful torques. The spectrum of magnetic flux density and spectrum of given torque of motor under no load condition gives us the reason of this consequence.

Lastly the number of rotor slits was executed from force perspective in x and in y direction. The result of this act is that odd rotor slits produce undesirable large of force, which act on rotor surface. From this point of view, 15 and 25 rotor slits should be avoided to minimize disturbance cause by large net force.

Ideal number of slits for slitted rotor was chosen to be 27. To maintain lower effort in production, 27 slits should be chosen, where another advantage is in mechanical strength where lower number provide greater tooth root width.

Acknowledgement:

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Authors gratefully acknowledge the financial support from the Ministry of Education, Youth and Sports of the Czech Republic under NPU I program (project No. LO1210).

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