AN IMPROVED PERFORMANCE ANALYSIS OF A SHADED POLE MOTOR

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Abstract: *In this paper a methodology for an improved performance analysis of the shaded pole motor is presented. They are used different approaches to the computation of the motor characteristics. By using them, a complex analysis of the single phase shaded-pole motor is presented. On the basis of the resolving field theory, a circuit model of the motor is derived. The FEM model of the motor is also developed. By using the Finite Element Method, a set of calculations is carried out and the distribution of the magnetic flux density in the air gap is obtained. The shaded-pole motor under consideration is studied experimentally, too. The obtained results, are mutually compared. A special emphasis is given to the investigation of the shading portion of the pole and on its effect on the motor performance characteristics.*

1. Introduction

The development of automatic control devices, robotics and computer techniques recently, as well as different appliances, has caused an appearance and an expansion of special different types of fractional horsepower motors (micromotors) with enormous possibilities for their applications, hence, interesting for research. A design and a performance analysis of these motors are considerably different from the design and the performance of the classic ones, although their operation bases on the same principles of the electromechanical energy conversion. One of these particular motors is the shaded-pole motor which appertains to the class of the asymmetrical single-phase induction motors.

The shaded pole motor is well recognized as simple in construction but complicated for an analysis. Compared to other types of induction motors, the shaded-pole motor is more complicated by the fact that there exist three mutually coupled windings and an asymmetrical elliptic rotating magnetic field. The application of exact analytical methods is almost improper. Many authors over the past made a lot of research efforts [1] for an analysis and the design of this motor. But, so far, it has not been established an universal method of analysis [2]-[5].

2. Physical Model of the Shaded-pole Motor

The rated data of the shaded pole motor which is going to be analyzed are: 220 [V] voltage supply, 24 [W] input power, 2200 rpm speed and 2p=2 number of poles. The authors suggest a methodology for an improved and deepened performance analysis of the shaded pole motor. The cross section of the motor is presented in Fig. 1.

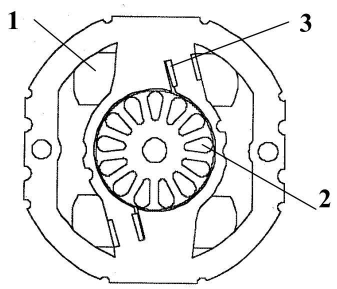

Fig. 1. Cross-section of the shaded pole motor

The first winding is the main stator winding (1) and the second one is the bar squirrel cage rotor winding (2); the third winding is the auxiliary stator winding with one shading coil per pole (3).

One pole pitch of the shaded pole motor, in the developed view, is presented in Fig. 2.

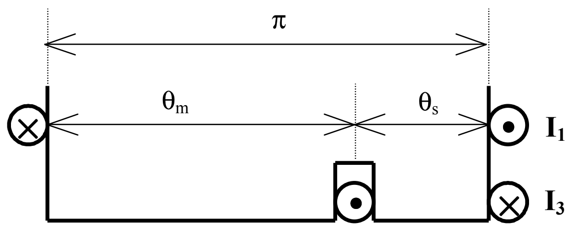

Fig. 2. Developed view of motor pole pitch

The pole of the motor is spanned to an angle of π radians. The angle θ_s is the angle of shaded pole arc in the electrical radians, meaning the shading pole portion. The angle θ_m is the angle of the rest of the pole pitch, considering the unshaded part of the pole arc in electrical radians, too.

The common effect of the main stator winding and the shading coil to the rotor circuit is equivalent to that when the first (main) winding only is carrying the current $I_s = I_1 - I_3$, where, I_1 and I_3 are the main stator winding current and the shading coil current in primary terms, respectively.

3. Circuit Model of the Shaded-pole Motor

Starting from the elliptic character of the rotating field, the modeling of shaded pole motor is carried out according to the revolving field theory. By coupling the phenomena caused by the forward and backward components of the magnetic field in the air-gap [1], the common equivalent circuit is derived in the form presented in Fig. 3.

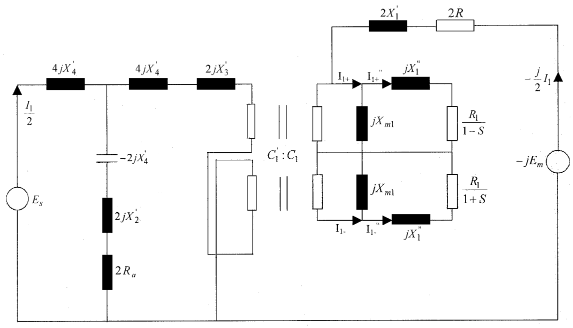

Fig. 3. Equivalent circuit of the shaded pole motor based on the revolving field theory

Note that the signs "+" and "-" are used for the forward and backward sequence components, respectively; although both currents and impedances are not specially marked, they are comprehended as complex quantities.

According to the revolving field theory the forward and the backward components of the auxiliary circuit currents are calculated as follows:

$$I_{1+} = \frac{1}{2}\left[(I_1 - I_3)\frac{C_1'}{C_1} - jI_1\right] \tag{1}$$

$$I_{1-} = \frac{1}{2}\left[(I_1 - I_3)\frac{C_1'}{C_1} + jI_1\right] \tag{2}$$

where: $C_1 = C\,sin(\theta_m/2)$ is the effective number of conductors of the main stator winding;
$C_1' = C\,sin(\theta_s/2)$ is the effective number of conductors of shading coil, i.e. the auxiliary stator winding;
while, C is the actual number of the main stator winding conductors.

The current in the main stator winding is:

$$I_1 = \frac{U}{Z_m + Z_t + R + j\left(X_1' + 2X_4'\right)} \tag{3}$$

where: $U = 220$ [V] is the voltage supply;
R is the main stator winding resistance.

According to the circuit model of the motor, the following impedances are introduced:

$$Z_m = \frac{1}{2}(Z_{1+} + Z_{1-}) \tag{4}$$

$$Z_t = -\frac{j}{2}\left(\frac{C_1'}{C_1}\right)(Z_{1+} - Z_{1-}) \tag{5}$$

$$Z_{1+} = \frac{jX_{m1}\left(\frac{R_1}{1-S} + jX_1'\right)}{\frac{R_1}{1-S} + j\left(X_1' + X_{m1}\right)} \tag{6}$$

$$Z_{1-} = \frac{jX_{m1}\left(\frac{R_1}{1+S} + jX_1''\right)}{\frac{R_1}{1+S} + j\left(X_1'' + X_{m1}\right)} \tag{7}$$

Where the variable S is the ratio of actual rotor speed n to synchronous speed of the rotating fundamental flux wave n_s. Considering that the rotor slip s is expressed by these quantities, as:

$$s = \frac{n_s - n}{n_s}$$

the following equations are obvious:

$$s_+ = s = 1 - S$$

$$s_- = 2 - s = 1 + S$$

In equations (6) and (7) R_1 is the rotor resistance and X_{m1} is the mutual reactance between the main stator winding and the short circuit coil. There are four types of stator leakage reactances. The first one is the leakage reactance X_1', due to the leakage flux linked with the stator coil only, which is going to be calculated as:

$$X_1' = 2\pi f C^2 10^{-8} \cdot \begin{pmatrix} \frac{3{,}19W}{2p}K_{s1} + \frac{span_1}{2p} + \\ + \frac{3{,}19W\lambda_p}{4l_g p}\cdot\frac{\theta_m}{\pi} \end{pmatrix} - X_{m1} \tag{8}$$

Where: W is a length of the core stack;
K_{s1} is a primary winding slot constant;
λ_p is the pole pitch;
l_g is an effective length of the air gap;
p is the number of poles.

The second one is leakage reactance X_2', due to the leakage flux linked with the shading coil only, calculated as:

$$X_2' = 2\pi f C^2 10^{-8}\left(\frac{3{,}19W}{4p}\cdot K_{s2} + \frac{span_2}{2p}\right) \tag{9}$$

In this case: K_{s2} is a shading coil slot constant;
$span_2$ is a coil span of shading coil.

The third component links the leakage fluxes between the main winding coil and shading ring placed on the same pole.

$$X_3' = 2\pi f C^2 10^{-8}\left(\frac{3{,}19W\lambda_p}{4pl_g}\cdot\frac{\theta_s}{\pi}\right) - X_{m1}\cdot\left(\frac{C_1'}{C_1}\right)^2 \tag{10}$$

The stator leakage reactance X_4', linking one shading coil with two stator coils (placed on a pair of poles), is calculated as:

$$X_4' = 2\pi f C^2 10^{-8}\left(\frac{3{,}19W}{4p}\cdot\frac{d_1}{e_1}\right) \tag{11}$$

where, e_1 is the slot opening between adjacent poles and d_1 is the depth of the slot opening.

The circuit model of shaded-pole motor is described by the rotor parameters included in the equivalent circuit, too. The rotor leakage reactance X_1'' is calculated as a sum:

$$X_1'' = X_{1slot}'' + X_{1end}'' + X_{1skew}'' + X_{1zigzag}'' \tag{12}$$

The particular components are: the slot reactance X_{1slot}'', the end regions reactance X_{1end}'', the reactance due to the slot skewing X_{1skew}'' and the "zigzag" reactance $X''_{1zigzag}$, known as teeth leakage reactance. The corresponding equations for their calculation are given below:

$$X_{1slot}'' = 2\pi f C_1^2 10^{-8}\left(\frac{6{,}38W}{S_s}\cdot K_s\right) \tag{13}$$

$$X_{1end}'' = 2\pi f C_1^2 10^{-8}\cdot\frac{\lambda_p}{2p} \tag{14}$$

$$X_{1skew}'' = 2\pi f C_1^2 10^{-8}\left(\frac{0{,}647W\lambda_p}{l_g p}\right)\cdot\left(1 - \frac{\sin\frac{\theta_{sk}}{2}}{\frac{\theta_{sk}}{2}}\right) \tag{15}$$

$$X_{1zigzag}'' = 2\pi f C_1^2 10^{-8}\left(\frac{6{,}38W}{S_s}\cdot\frac{T_f''}{4l_g}\right) \tag{16}$$

Where: S_s is the number of rotor conductors;
K_s is a rotor slot constant;
θ_{sk} is an angle of the rotor slots skew;
T_f'' is a width of the rotor tooth face.

The shading coil current is calculated from:

$$I_3 = I_1\frac{Z_a - Z_t}{Z_s + Z_a + j\left(X_3' + 2X_4'\right)} \tag{17}$$

In the above equation, R_a is the shading ring resistance, and the following impedances are introduced:

$$Z_a = R_a + j\left(X_2' - X_4'\right) \tag{18}$$

$$Z_s = \left(\frac{C_1'}{C_1}\right)^2\left(Z_{1+} + Z_{1-}\right) \tag{19}$$

The static electromagnetic torque is calculated from the circuit parameters, as follows:

$$M_{em} = \frac{9{,}55}{n_1}\left[\left|I_{1+}\right|^2 R_{1+} - \left|I_{1-}\right|^2 R_{1-}\right] \tag{20}$$

In the equation (20), the currents I_{1+} and I_{1-} are calculated from the equations (1) and (2); R_{1+} and R_{1-} are the resistive components of Z_{1+} and Z_{1-} previously given by the equations (6) and (7), respectively.

Power factor is calculated as:

$$\cos\varphi = \frac{I_1}{\left|I_1\right|} \tag{21}$$

Input power is determined from,

$$P_1 = UI_1\cos\varphi \tag{22}$$

while output power on the motor shaft is given by

$$P_2 = \frac{(1-s)n_s M_{em}}{9{,}55\cdot\left(1 + \frac{p\%}{100}\right)} \tag{23}$$

considering that mechanical losses of the motor usually are *p%=15-25%* of the output power.

Output torque on the motor shaft is calculated from the expression:

$$M_2 = \frac{9{,}55P_2}{n_s(1-s)} \tag{24}$$

and the efficiency factor is calculated as:

$$\eta = \frac{P_2}{P_1} \tag{25}$$

4. FEM Model of the Shaded-pole Motor

In order to determine parameters and characteristics of the shaded-pole motor as accurate as possible, the Finite Element Method is used. All winding currents and the rotor speed have the rated values. In the post-processing step, the distribution of the magnetic flux density is obtained. Static electromagnetic torque is computed, too. The different winding reactances could be also calculated. Some of the most interesting results are presented in the next figures.

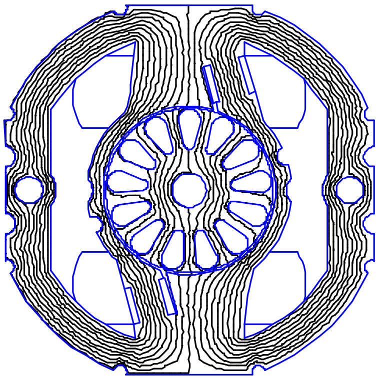

Fig. 4. Flux distribution when only the main winding is excited

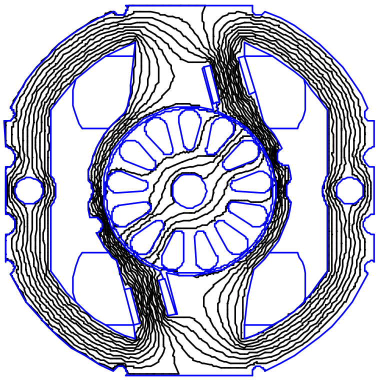

Fig. 5. Flux distribution when only the shading coil is excited

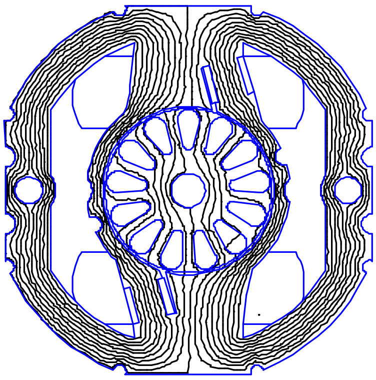

Fig. 6. Flux distribution when all motor windings are excited

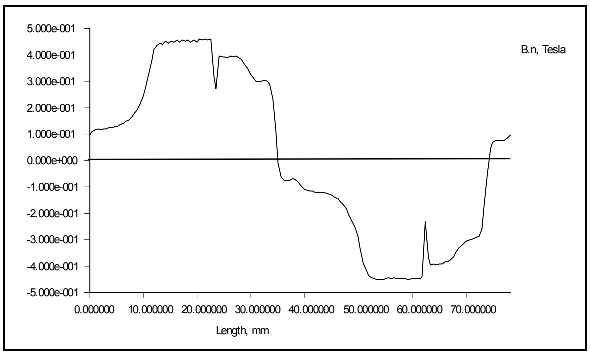

Fig. 7. Spatial distribution of the air-gap flux density when only the main winding is excited

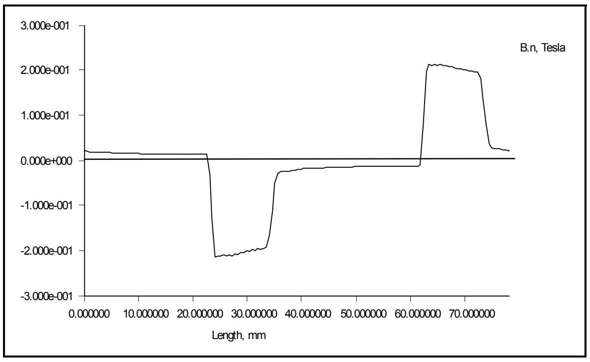

Fig. 8. Spatial distribution of the air-gap flux density when only the shading coil is excited

5. Performance Analysis

By using the developed circuit model, as well as the FEM model, the performance analysis of the shaded-pole motor under consideration is carried out. In order to prove the proposed methodology, the motor has been tested thoroughly on the computerised testing bench. The output results of the test procedure are automatically plotted on a diagram and they are presented in Fig. 9.

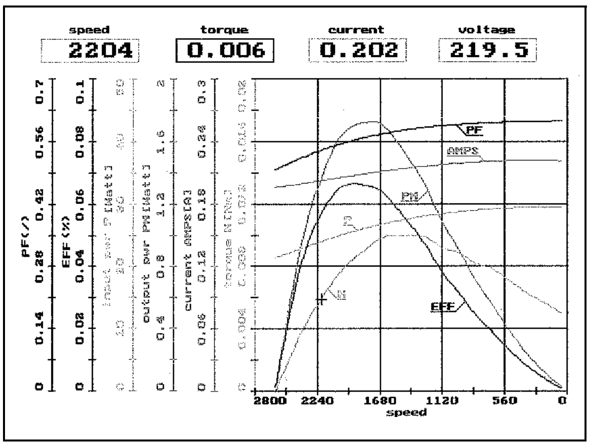

Fig. 9. Performance characteristics of the shaded-pole motor obtained experimentally

After the circuit model parameters of the shaded pole motor are determined they are included in calculations of performance characteristics by using the derived equations in previous sections. In this case as the variable parameter is accepted to be the rotor slip *s*. For better view and more evident comparison, the calculated and measured characteristics are presented on separate charts, in the figures given below.

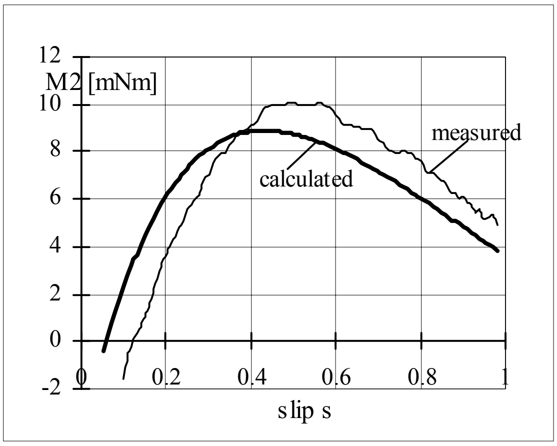

Fig. 10. Comparison of output torque characteristics

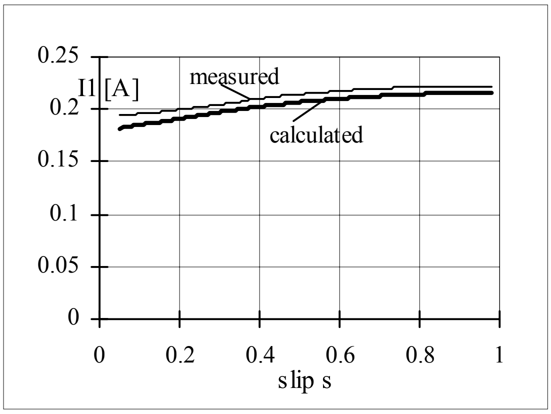

Fig. 11. Comparison of input current characteristics

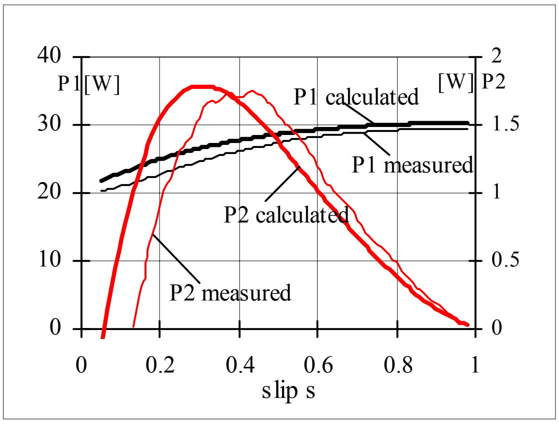

Fig.12. Comparison of input and output power characteristics

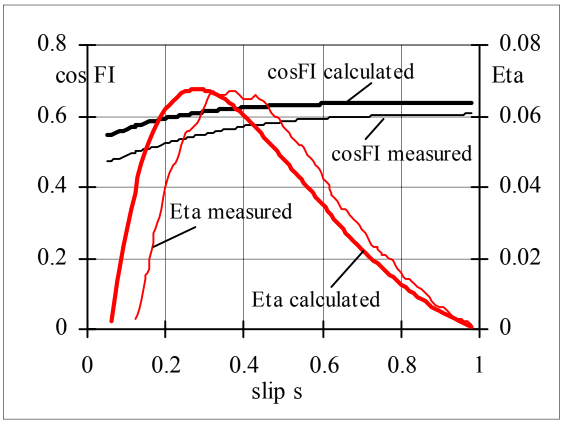

Fig. 13. Comparison of power and efficiency factor

The presented characteristics show a reasonable agreement, so the proposed methodology is proved as satisfactory accurate.

Additionally, the most interesting matter of investigation is certainly the effect of shading portion of the pole. Characteristics of rated M_n, starting M_p and peak electromagnetic torque M_{max} when the angle of shaded pole arc is varied are given figures 14, 15 and 16, respectively.

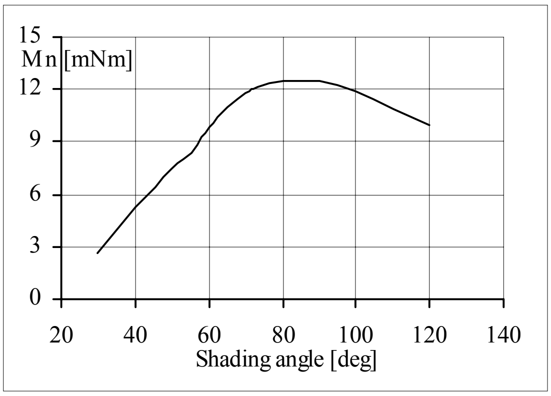

Fig. 14. Torque at rated speed plotted against variable angle of shaded pole arc

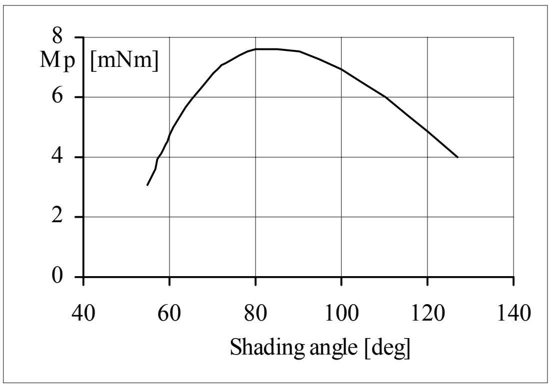

Fig. 15. Starting torque plotted against variable angle of shaded pole arc

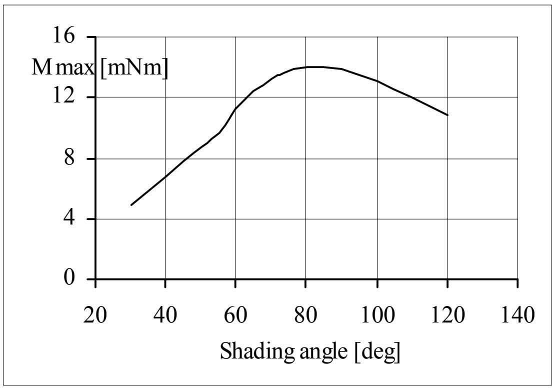

Fig. 16. Peak torque plotted against variable angle of shaded pole arc

The maximum values of electromagnetic torque in previous figures are attained at shading angle of the stator pole arc equal to $\theta_s = 80^0 \div 90^0$ electrical. This fact shows considerable agreement with the motor under consideration, knowing that the shading portion of shaded pole arc is denominated as $\theta_s = 73{,}21^0$ electrical.

In addition to the starting torque analysis at different angles of the shaded pole arc, it is interesting to present and to analyse the effect of the shading coil width on the starting currents in the main stator winding I_{1p} and in the shading coil I_{3p}. The calculated characteristics are presented in Fig.17. The average value of the input current in the main stator winding is obtained at the shading angle which determines the maximum values of electromagnetic torque.

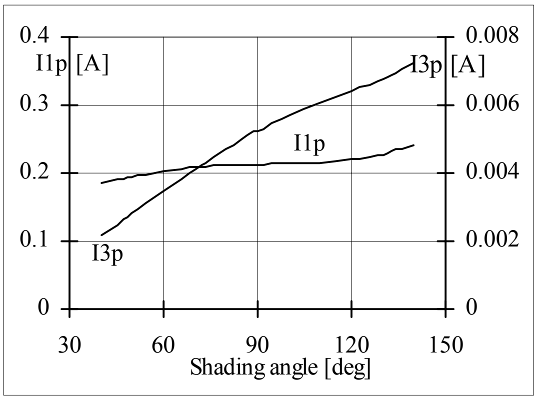

Fig. 17. Starting currents in both stator windings plotted against variable angle of the shaded pole arc

6. Conclusion

In this paper a mathematical model for calculation of shaded-pole motor performance characteristics based on the circuit model is presented. By using the method of symmetrical components in a relatively simple and fast way the performance characteristics are calculated. The obtained results are compared with experimentally obtained ones and they show very good agreement. Additionally the effect of the shaded angle variation to the electromagnetic torque and starting currents in the stator windings is analysed.

The accuracy of calculated characteristics is highly dependent on the proper and exact determination of the motor parameters. The application of the Finite Element Method is powerful and effective approach to this task.

In the paper all calculations are accomplished considering the fundamental harmonic only. Calculations can be expanded to the higher order harmonics, especially the third, the fifth and the seventh harmonic, so an analysis of their effect on the characteristics could be done, too. This work can serve as a guide in a later investigation.

7. References

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