Transient Analysis of Induction Motor Using Different Simulation Models

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Abstract. Squirrel cage induction motors have wide range of applications in many industrial drive systems due to their simple construction, robust design and low operational costs. Their application becomes even wider as a result of implementation of voltage inverters providing very good speed-torque control characteristics. In this paper a dynamic behaviour of a squirrel cage induction motor type 2AZ 155-4 is analysed. Two simulation models are developed, the first one in Matlab/Simulink and the second one in PSIM enabling motor transient characteristics to be analysed. Information about the distribution of the magnetic flux density inside the motor cross section is gained by application of the Finite Elements Method (FEM).

Keywords: *induction squirrel cage motor, MATLAB/Simulink and PSIM simulation models, FEM motor model*

1. Introduction

Squirrel cage induction motor has wide application in many industrial drive systems due to its simple construction, robust design and low operational costs. Its application becomes even wider as a result of voltage inverters enabling very good speed-torque regulation characteristics. In this paper the dynamic performance of squirrel cage induction motor type 2AZ 155-4 produced by Rade Koncar is analyzed. The motor has the following rated data: voltage U_n (Δ/Y) = 220/380 V, number of poles $2p = 4$, rated current 8.7/5 A, power factor $\cos\varphi = 0.81$, rated speed $n_n = 1410$ rpm, frequency 50 Hz. The first simulation motor model is developed in MATLAB/Simulink [1], for situation when the motor is connected to symmetrical power supply. For that purpose a motor mathematical model is developed based on the motor d, q transformation into synchronously rotating system. From the simulation motor transient characteristics of speed, electromagnetic torque and currents are obtained. The analysis is extended with simulation model when the motor is fed by a voltage inverter. In this case the motor transient speed, current and electromagnetic torque characteristics are obtained, for rated frequency as well as for frequencies lower and higher than the rated one. The results obtained from the simulation in Simulink are verified with the results obtained from the second simulation model developed in the software program PSIM. The distribution of the magnetic field in the motor cross section is obtained by using the Finite Element Method (FEM) for all the motor operation regimes.

2. Simulation models

Simulation of the motor transient characteristics in SIMULINK is performed by building a simulation model based on *d,q* transformation. In Fig. 1 a block diagram of the simulation model consisted of following four main parts is presented:

- Power supply
- Transformation of *a*, *b*, *c* variables into variables in *d,q* system that rotates synchronously.
- Modelling of motor model and obtaining motor speed, currents and electromagnetic torque as output variables.
- Transformation from *d,q* system into *a*, *b*, *c* system in order stator and rotor voltages and currents to be obtained.

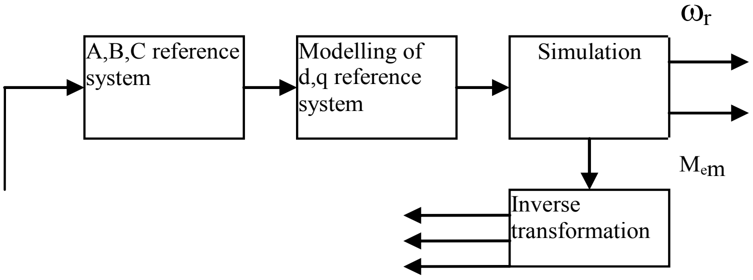


Figure 1. Block chart of Simulink motor model

Firstly the motor power supply (three phase symmetrical power supply) is transformed from three phase system into *d,q* system which rotates with synchronous speed as it is presented with equations (1) and (2).

$$U_{ds} = -\frac{1}{\sqrt{3}}\left(U_b - U_c\right)\cos\theta + U_a \sin\theta \tag{1}$$

$$U_{qs} = \frac{1}{\sqrt{3}}\left(U_b - U_c\right)\sin\theta + U_a \cos\theta \tag{2}$$

where: $\omega = \frac{d\theta}{dt}$ i.e. $\theta = \int_0^t \omega dt$

Since the power supply is a three phase symmetrical supply in that case $\omega = \omega_e = 314\left(rad/s\right)$. The simulation model is based on the following equations:

$$\begin{aligned} i_{qr} &= \frac{L_s R_r}{L_m^2 - L_s L_r}\int_0^t i_{qr}\,dt + \frac{\omega L_s L_r}{L_m^2 - L_s L_r}\int_0^t i_{dr}\,dt + \\ &\frac{L_{sr}\omega}{L_m^2 - L_s L_r}\int_0^t \psi_{ds}\,dt + + \frac{L_{sr}^2 - L_s L_r}{L_m^2 - L_s L_r}\int_0^t \omega_r i_{dr}\,dt - \\ &\frac{L_{sr}}{L_m^2 - L_s L_r}\int_0^t \omega_r \psi_{ds}\,dt + \frac{L_{sr}}{L_m^2 - L_s L_r}\psi_{qs} \end{aligned} \tag{3}$$

where i_{qr} and i_{dr} are rotor currents transformed d,q systems and L_s, L_r and L_{sr} are stator, rotor and mutual inductance respectively.

$$\begin{aligned} i_{dr} &= \frac{L_s R_r}{L_m^2 - L_s L_r}\int_0^t i_{qr}\,dt - \frac{\omega(L_{sr}^2 - L_s L_r)}{L_m^2 - L_s L_r}\int_0^t i_{dr}\,dt - \\ &- \frac{L_{sr}\omega}{L_m^2 - L_s L_r}\int_0^t \psi_{qs}\,dt - \frac{(L_{sr}^2 - L_s L_r)}{L_m^2 - L_s L_r}\int_0^t \omega_r i_{qr}\,dt \\ &+ \frac{L_{sr}}{L_m^2 - L_s L_r}\int_0^t \omega_r \psi_{qs}\,dt + \frac{L_{sr}}{L_m^2 - L_s L_r}\psi_{ds} \end{aligned} \tag{4}$$

In the equations (3) and (4) flux linkages Ψ_{qs} and Ψ_{ds} are unknown variables and they can be expressed from:

$$\psi_{qs} = \int_0^t U_{qs}\,dt - \frac{R_s}{L_s}\int_0^t \psi_{qs}\,dt + \frac{L_{sr}R_s}{L_s}\int_0^t i_{qr}\,dt - \omega\int_0^t \psi_{ds}\,dt \tag{5}$$

$$\psi_{ds} = \int_0^t U_{ds}\,dt - \frac{R_s}{L_s}\int_0^t \psi_{ds}\,dt + \frac{L_{sr}R_s}{L_s}\int_0^t i_{dr}\,dt + \omega\int_0^t \psi_{qs}\,dt \tag{6}$$

Motor speed is calculated from:

$$\frac{d\omega_r}{dt} = \frac{6L_{sr}}{J}\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) - \frac{2}{J}M_s - \frac{2}{J}M_0 \tag{7}$$

where M_s is load torque, M_0 is a torque as a result of acceleration at no-load.

The second simulation model is built in PSIM software for symmetrical sinusoidal power supply as well as for the case when the motor is fed by a voltage inverter with variable frequency (Fig. 2).

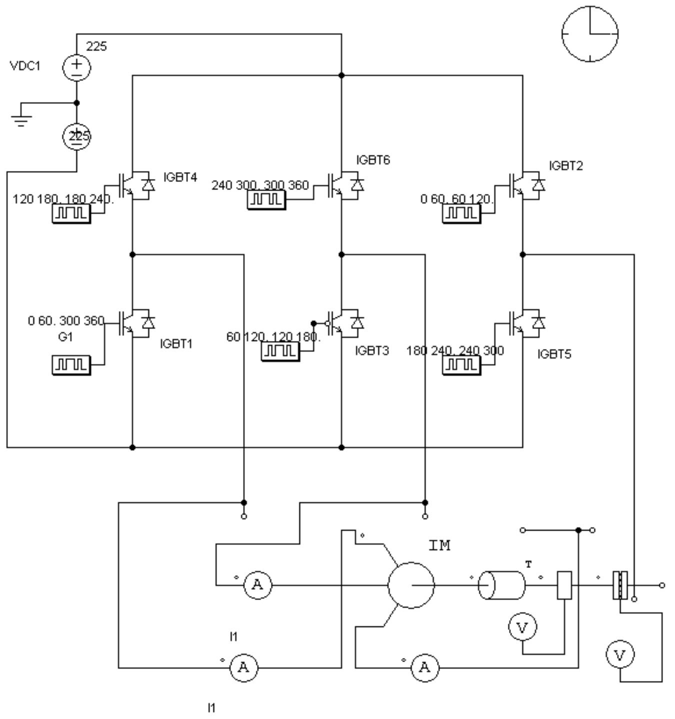
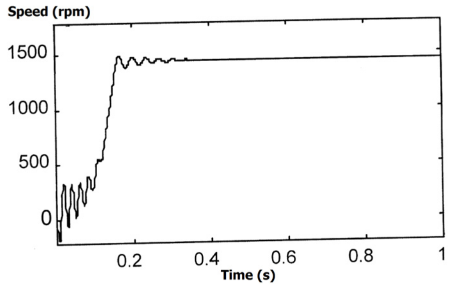


Figure 2. Simulation model in PSIM

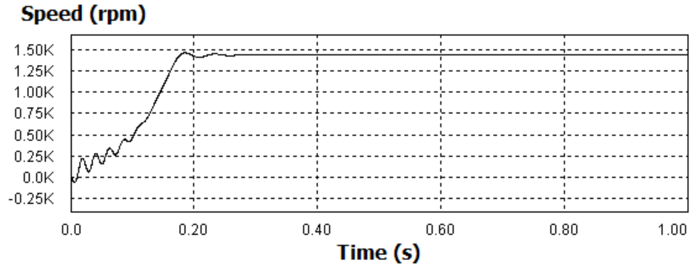
3. Simulation results

3.1. A. Simulation results at symmetrical power supply 50 Hz

First, the motor simulation models are developed for power supply from network. As an output from SIMULINK and PSIM models, motor transient characteristics can be obtained for different operating regimes: no-load as well as for rated load. In Fig. 3 transient speed characteristics for rated load condition meaning constant load of M_s = 14 Nm, using both simulation models, are presented.

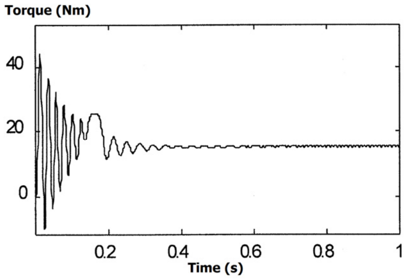


(a) Simulink model

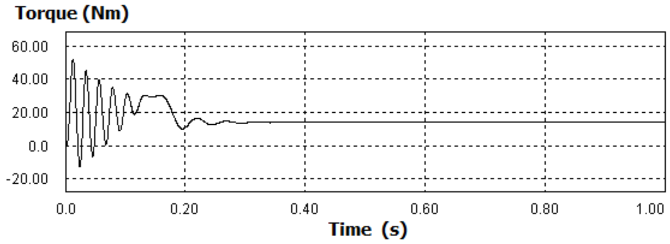


(b) PSIM model

Figure 3. Motor speed at power supply from network, f=50 HZ

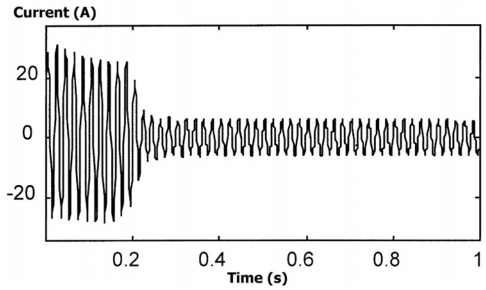


(a) Simulink model

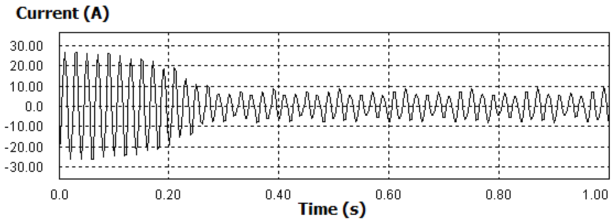


(b) PSIM model

Figure 4. Torque for power supply from network, f = 50 Hz



(a) Simulink model



(b) PSIM model

Figure 5. Stator current for power supply from network, f=50 HZ

From Fig. 3 it can be concluded that the motor is reaching the speed of 1440 rpm after acceleration time of 0.2 seconds. After the acceleration time has expired electromagnetic torque is achieving steady-state value of approximately 15 Nm. For the same period the value of the current is dropping from the value of starting current which is five times rated current to the maximum value of 6 A. Comparison of obtained results from Simulink model and PSIM model for the transient characteristics of speed, electromagnetic torque and stator current shows satisfactory agreement among them, which consequently proves the accuracy of both simulation models.

3.2. B. Simulation results using inverter as power supply

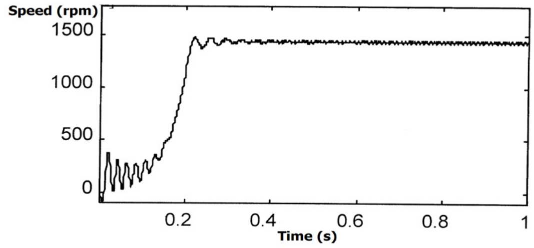
In order speed regulation to be achieved a voltage inverter is used as power supply of the motor. Motor speed is related to power supply frequency with equation (8):

$$n = \frac{60f}{p}(rpm) \tag{8}$$

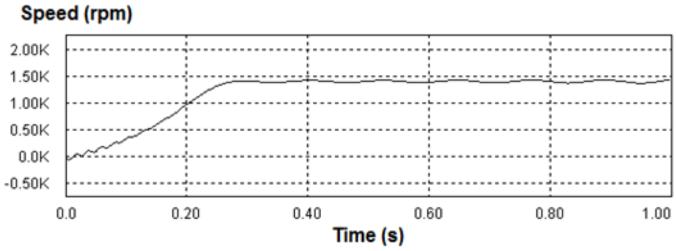
f is the power supply frequency and p is the pair of poles. In this application constant torque should be maintained at constant value of $M_s = 14$ Nm, ratio between magnitude of power supply voltage and frequency should be kept constant. In that case equation (9) is applicable:

$$\frac{n^*}{n} = \frac{f^*}{f} \tag{9}$$

Symbol * denotes speed and frequency different from the rated one. In case when motor is supplied with variable frequency power supply, adequate values of frequencies are input in the model of voltage inverter as well as in equations for direct and inverse transformation from *a*, *b*, *c* system into *d*,*q* system in Simulink model while adequate firing angle of thyristors is implemented in PSIM model for different operating frequencies. In Fig. 6 and Fig. 7 transient characteristics of speed and torque when the motor is fed from inverter with frequency 50 Hz for operating regime of constant load $M_s = 14$ Nm are presented, respectively.

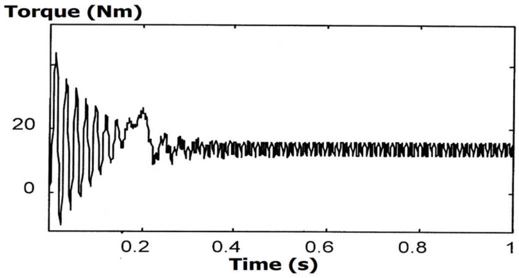


(a) Simulink model

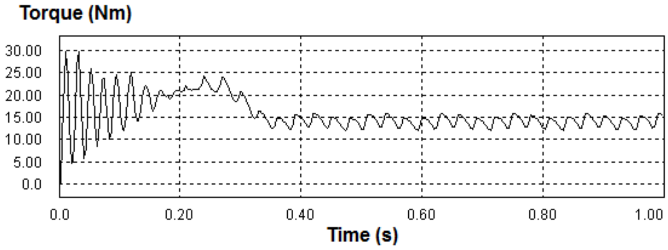


(b) PSIM model

Figure 6. Speed for power supply from inverter at 50 Hz



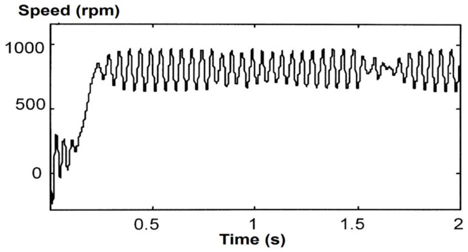
(a) Simulink model



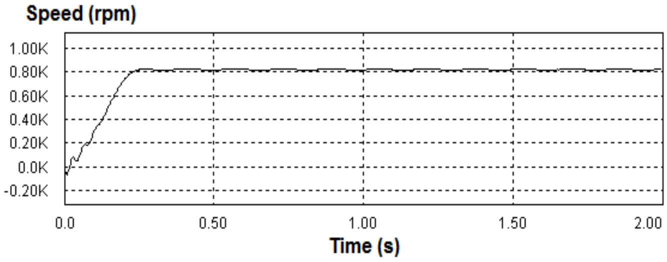
(b) PSIM model

Figure 7. Torque for power supply from inverter at 50 Hz

Comparison of Figs. 3 to 5 and Figs. 6 to 7 leads to the conclusion that the transient characteristics are quite similar with respect to the acceleration time and the final steady state values of speed, torque and current. The pulsations of torque and speed when the motor is in steady state are much higher in Figs. 6 to 7, due to the work of the inverter as a result of which higher order odd harmonics are present in their characteristics. In Figs. 8 and 9 are presented transient characteristics of speed and torque when motor is fed from voltage inverter with frequency 30 Hz for operating regime of constant load $M_s = 14$ Nm.

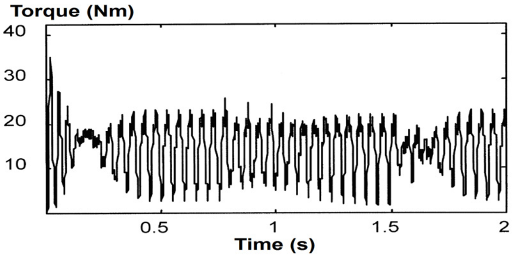


(a) Simulink model

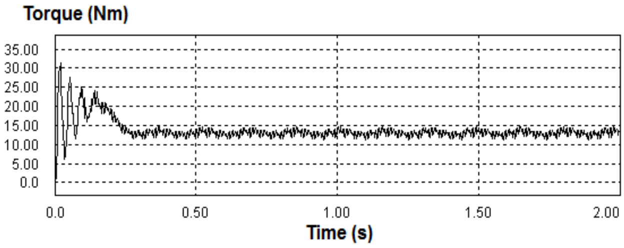


(b) PSIM model

Figure 8. Speed for power supply from inverter at 30 Hz



(a) Simulink model



(b) PSIM model

Figure 9. Torque for power supply from inverter at 30 Hz

As it is expected, according to equation (8), after the acceleration time has expired motor speed is reaching the value of 810 rpm. In Table 1 comparison of obtained results of speed, current and torque from different simulation models when the motor is supplied by voltage inverter, is presented.

Table 1. Comparison of results motor supplied from the inverter

f = 50 Hz		
	Simulink model	PSIM model
Speed (rpm)	1437	1440
Electromagnetic torque (Nm)	14	13.5
Stator current (A)	5.67	6
f = 30 Hz		
Speed (rpm)	850	810
Electromagnetic torque (Nm)	15	14
Stator current (A)	5.4	5.67

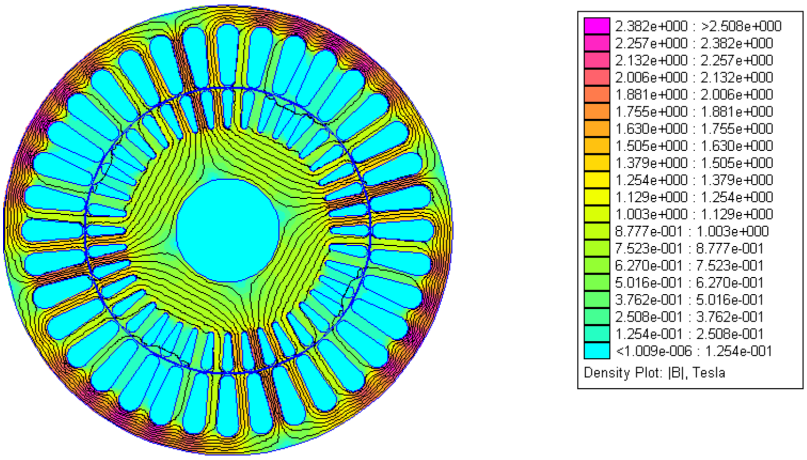


Figure 10. Flux distribution at motor cross section supply from network

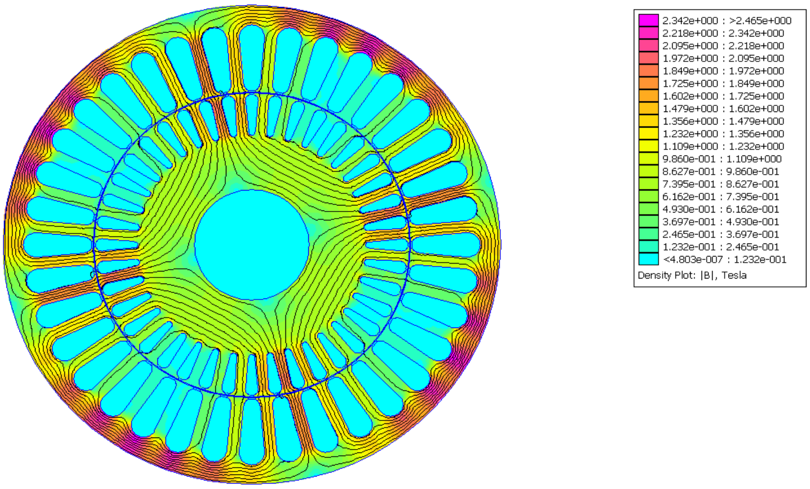


Figure 11 Flux distribution at power supply from inverter f = 30 Hz

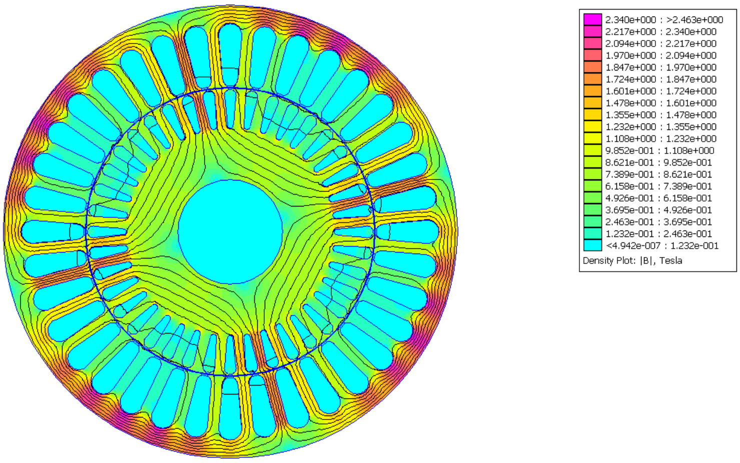


Figure 12 Flux distribution at power supply from inverter f = 100 Hz

4. FEM analysis

The Finite Element Method (FEM) is widely used for electromagnetic field calculations in electrical machines, in general. It is usually used as a non-linear magnetostatic problem which is solved in the terms of magnetic vector potential A. However, when analyzing induction machines, considering their AC exci¬ta¬ti¬on, the air-gap magnetic field is always a time-varying quantity. In materials with non-zero conductivity eddy currents are induced; consequently, the field problem turns to magneto-dynamic, i.e. non-linear time harmonic problem. When rotor is moving, the rotor quantities are oscillating at slip frequency, quite different from the stator frequency.

The problem is solved by adjusting the rotor bars conductivity □, corresponding to the slip. With respect to the compound configuration of the motor, both in electrical and magnetic sense, and taking into consideration the particular meaning of the slip s, a motor model suitable for FEM application is derived [2]. The magnetic flux distribution in the motor cross section for rated load condition at symmetrical power supply from the network with $f = 50$ Hz as well as when motor is supplied by voltage inverter with frequency $f = 30$ Hz and $f = 100$ Hz are presented in Fig. 10, Fig. 11 and Fig. 12, consequently.

5. Conclusion

Complex analysis of induction squirrel cage motor is performed by developing mathematical, simulation and numerical motor models for calculation of motor transient performance characteristics as well as for calculation of distribution of magnetic flux density in motor's cross section.

Simulation models in SIMULINK and PSIM are developed for both cases of power supply: from the network and from voltage inverter. From obtained transient characteristics of speed torque and current in case of power supply from the network it can be concluded that simulation results of speed 1440 rpm in Simulink model and 1437 rpm in PSIM model, electromagnetic torque of 15 Nm and maximum value of current 6 A in both simulation models are showing good agreement with the data given from the producer: rated speed 1410 rpm, torque 14.9 Nm and effective value of current of 5 A. This verifies the simulation model as accurate enough to be applied in variable speed applications when motor is fed from voltage inverter. In order variable motor speed to be achieved constant Volt-Herz characteristic is maintained which results in constant electromagnetic torque. Simulation model is built for frequency 30 Hz in Simulink as well as in PSIM. Model is showing good simulation results of speed of 810 rpm, which is adequate to the power supply frequency while electromagnetic torque is kept on value of 15 Nm. In order magnetic flux density distribution in the motor cross-section to be obtained motor model suitable for application of Finite Elements Method is developed. Obtained results proved that there is no significant increase of magnetic flux density since constant flux is maintained in all operational regimes.

References

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[2] Sarac, V., Cvetkovski, G.: *Different motor models based on parameter variation using method of genetic algorithms*, Przegląd Elektrotechniczny, R.87, NR3/2011, pp. 162–165.