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Development of Simulation Models of Induction Squirrel Cage Motor for Variable-Speed Applications

Vasilija Sarac, Goce Stefanov

Electrotechnical Faculty, University Goce Delcev-Stip, P.O. Box 201, 2000 Stip , Macedonia
e-mail: vasilija.sarac@ugd.edu.mk, goce.stefanov@ugd.edu.mk

Abstract

Complex analysis of operational regimes of induction squirrel cage motor is performed. First mathematical model for calculation of motor's operational characteristics in FORTAN is developed. As a result of developed model motor's static characteristics of electromagnetic torque , current , speed and power factor are calculated. Further on, motor operating regimes when motor is fed by voltage inverter are analyzed and for this case motor static characteristic of electromagnetic torque is plotted. SIMULINK is used for developing motor simulation models for both cases, when motor is supplied with sinusoidal power supply as well as when it is fed by a voltage inverter. Obtained simulation results for symmetrical sinusoidal power supply are compared with data from the producer showing reasonable agreement. Different operating regimes of motor fed by voltage inverter are analysed: with increased and decreased frequency compared to the rated one while motor flux and electromagnetic torque are maintained constant. In both cases when motor is fed from voltage inverter with increased and decreased frequency compared to the rated one, obtained results of speed and electromagnetic torque are showing good agreement with expected results from analytical calculations.

Key words: *induction squirrel cage motor, simulation models, variable speed transient characteristics*

Introduction

Squirrel cage induction motor has wide application in many industrial drive systems due to its simple construction, robust design and operational behaviour. Its application becomes even wider due to voltage inverters which enable very good speed-torque regulation characteristics. In this paper squirrel cage induction motor type 2AZ 155-4 from producer Rade Koncar-Zagreb is analyzed with respect to its dynamic behaviour. Motor has following rated data: voltage Un (Y/Δ)=220/380 V, number of poles 2p=4, rated current 8,7/5 A, power factor cosφ=0,81, rated speed n_n=1410 rpm, frequency 50 Hz. First mathematical model in FORTRAN for calculation of motor operational static characteristics is developed. Motor simulation model when motor is supplied with symmetrical sinusoidal power supply is developed in Simulink [1]. As a result motor transient characteristics of speed, electromagnetic torque and current are obtained. Analysis is extended in mathematical motor model with calculation of static characteristic of electromagnetic torque when motor is supplied with voltage from voltage inverter. Simulation model is extended as well for this kind of power supply and as a result are obtained motor transient characteristics of speed , current and electromagnetic torque for rated frequency as well as for frequencies lower and higher than the rated one resulting in motor variable speed transient characteristics.

Mathematical Model

On the base of the software calculation in FORTRAN motor operational characteristics are calculated: stator current-I_1, efficiency factor-η, power factor-$\cos\varphi$, input power-P_1, speed-n and output torque M_2 versus output power P_2: $I_1=f(P_2)$, $\eta=f(P_2)$, $\cos\varphi=(P_2)$, $P_1=f(P_2)$, $n=f(P_2)$, and $M_2=f(P_2)$. Mechanical characteristic of electromagnetic torque M_{em} for different motor slips-s is calculated from motor T-equivalent circuit.

Table 1. Motor operational characteristics

I_1 [A]	η [%]	$\cos\varphi$ [/]	s p.u.	P_1 [W]	n [rpm]	M_2 [Nm]	P_2 [W]
2.17	0.128	0.119	0.00062	171.32	1499.07	0.21	22
2.22	0.59	0.255	0.00433	372.62	1493.5	1.48	220
2.32	0.73	0.392	0.00858	600.87	1487.13	2.9	440
2.49	0.79	0.508	0.01298	834.26	1480.53	4.34	660
2.71	0.82	0.601	0.01754	1073.14	1473.69	5.79	880
2.97	0.835	0.673	0.0223	1317.98	1466.56	7.25	1100
3.27	0.841	0.727	0.02727	1569.3	1459.1	8.73	1320
3.60	0.843	0.768	0.0325	1827.73	1451.26	10.23	1540
3.97	0.84	0.799	0.03802	2094.09	1442.97	11.74	1760
4.37	0.836	0.822	0.4389	2369.36	1434.16	13.28	1980
4.79	0.83	0.838	0.05019	2654.83	1424.72	14.85	2200

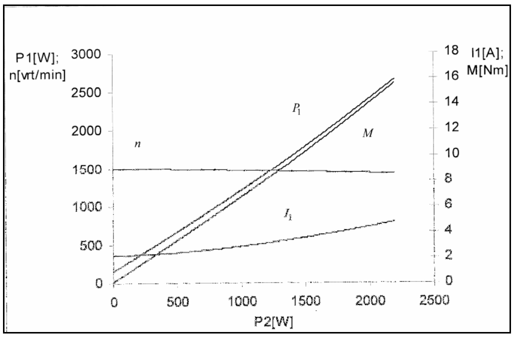


Fig. 1. Operational characteristics $n=f(P_2)$, $M_2=f(P_2)$, $I_1=f(P_2)$ and $P_1=f(P_2)$

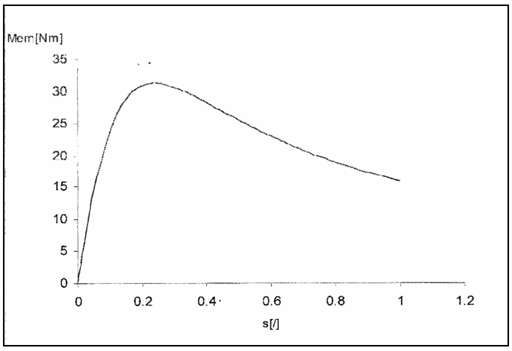


Fig. 2. Electro-mechanical characteristic $M_{em}=f(s)$

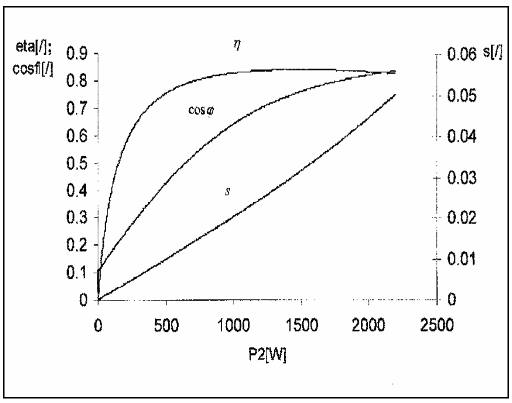


Fig.3. Operational characteristics $\eta=(P_2)$, $\cos\varphi=f(P_2)$ $s=f(P_2)$

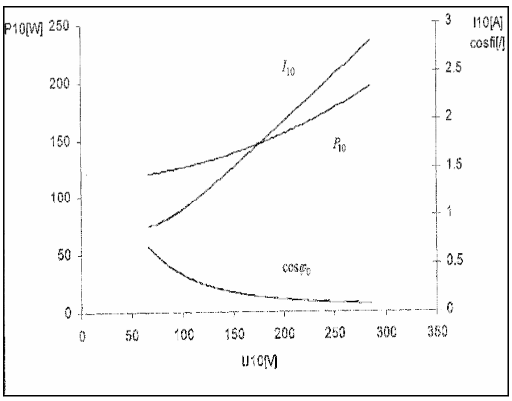


Fig. 4. No-load characteristics $I_{10}=(U_{10})$, $P_{10}=(U_{10})$ and $\cos\varphi_0=(U_{10})$

In case when motor is supplied with voltage from voltage inverter as a result of non-sinusoidal voltage supply time harmonics of odd order are present and in that case voltage power supply is considered to be:

$$u=\frac{2\sqrt{3}}{\pi}U\left[\cos\omega t-\frac{1}{5}\cos\omega t+\frac{1}{7}\cos 7\omega t-\frac{1}{11}\cos 11\omega t\right] \quad (1)$$

From equation (1) it can be deduced that fundamental harmonic as well as harmonic of seventh order are in the direction of fundamental electromagnetic field inside the machine while harmonics of fifth order are rotating in opposite direction of fundamental electromagnetic field. As a result in Fig. 5 is presented electro-mechanical characteristic of resulting electromagnetic torque by taking into consideration the time harmonics.

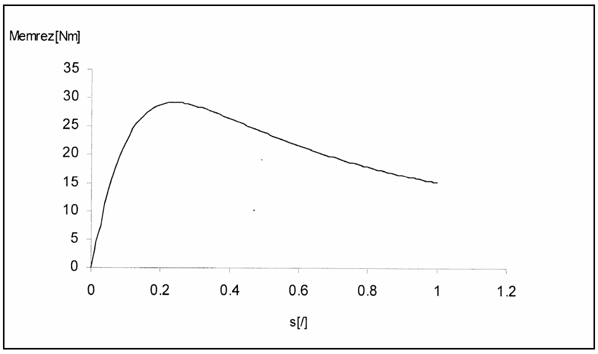


Fig. 5. Electro-mechanical characteristic M_{em}=f(s) when motor is supplied by voltage inverter

Simulation Models

Simulation of motor transient characteristics in SIMULINK is performed by building a simulation model. In Fig. 6 is presented a block diagram of simulation model consisted of following four main parts:

- Power supply
- Transformation of a,b,c variables into variables in d,q system which rotates synchronously.
- Modelling of motor model and obtaining motor speed 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.

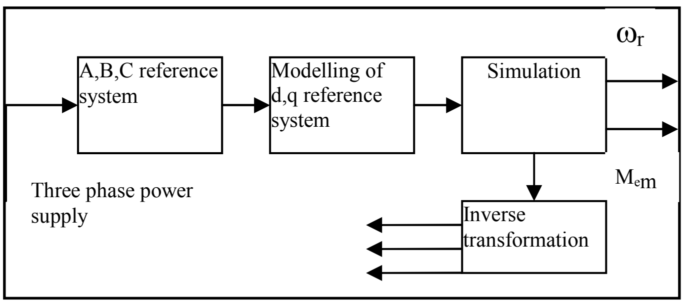
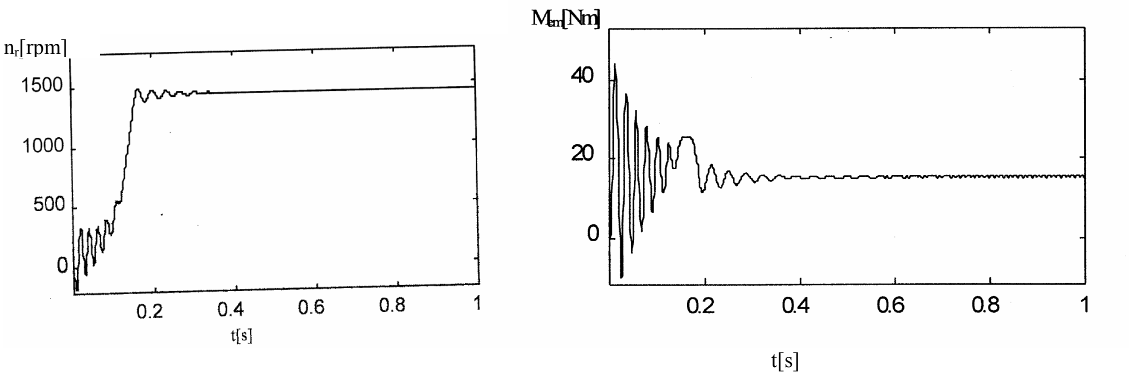


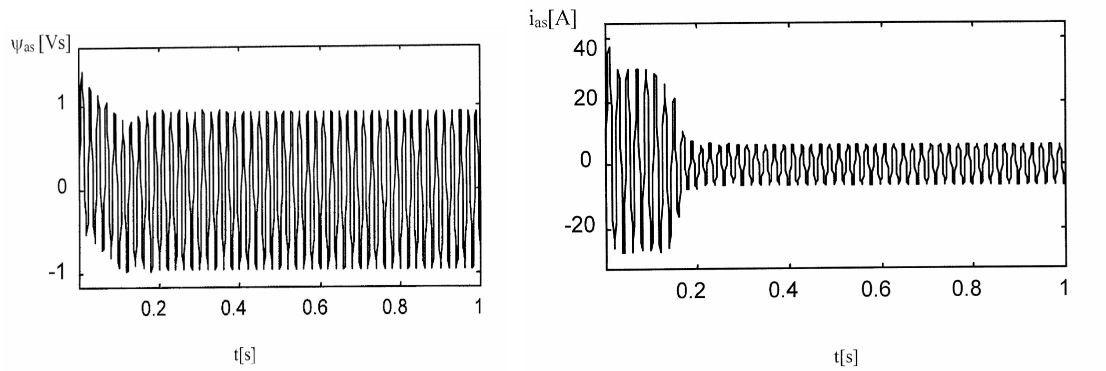
Fig. 6. Block chart of Simulink motor model

First, motor simulation model is developed for symmetrical sinusoidal supply. As an output from simulation model motor transient characteristics can be obtained for different operating regimes: no-load as well as rated load. In Figs 7 and 8 are presented transient characteristics of speed, torque, stator current and flux consequently, for rated load condition meaning constant load of M_s=14 Nm.



(a) speed (b) torque

Fig. 7. Transient characteristics of speed and torque at rated load , symmetrical sinusoidal power supply



(a) flux (b) current

Fig. 8. Transient characteristics of flux and current at rated load , symmetrical sinusoidal power supply

As it can be concluded from Figure 7 motor is reaching the speed of 1440 rpm after time of 0.2 seconds. After acceleration time has expired electromagnetic torque is achieving steady-state value of approximately 15 Nm. For the same period value of the current is dropping from the value of starting current which is five times rated current up to the maximum value of 6A.

In order speed regulation to be achieved voltage inverter is used for the power supply of the motor. In that case it is assumed that voltage wave forms have a rectangular shape as it is presented in Fig. 9.

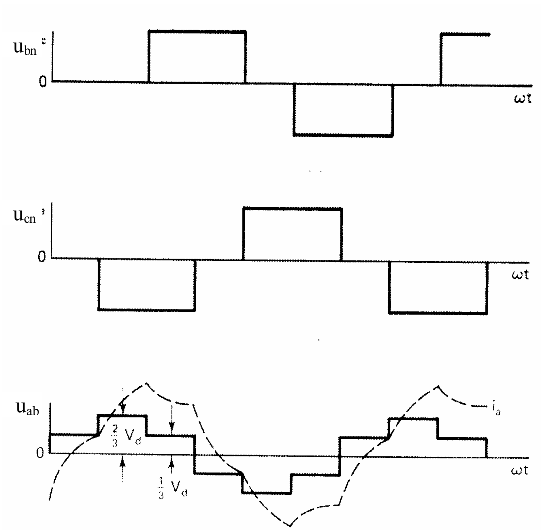


Fig. 9. Phase and line voltages from voltage inverter

Motor speed is related to power supply frequency with equation :

$$n = \frac{60f}{p}[rpm] \tag{2}$$

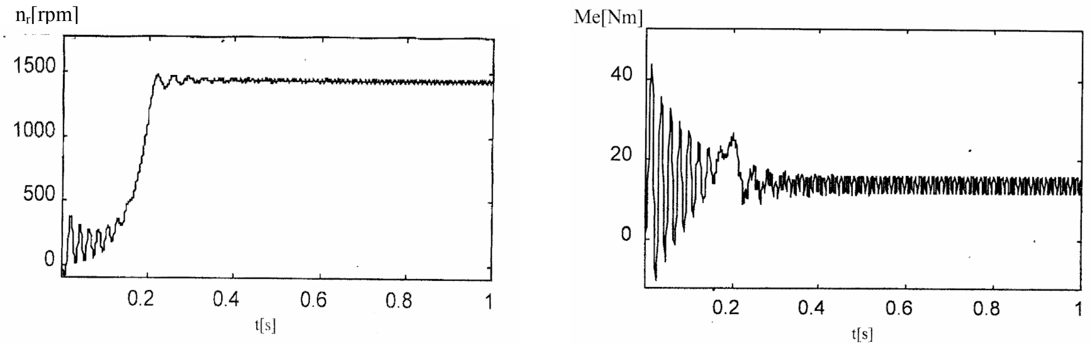
f is the power supply frequency and p is the pair of poles.

In order constant torque to be maintained for the purpose of application of driving constant load M_s=14 Nm, ratio between magnitude of power supply voltage and frequency should be kept constant. In that case following equation is applicable:

$$\frac{n^*}{n} = \frac{f^*}{f} \tag{3}$$

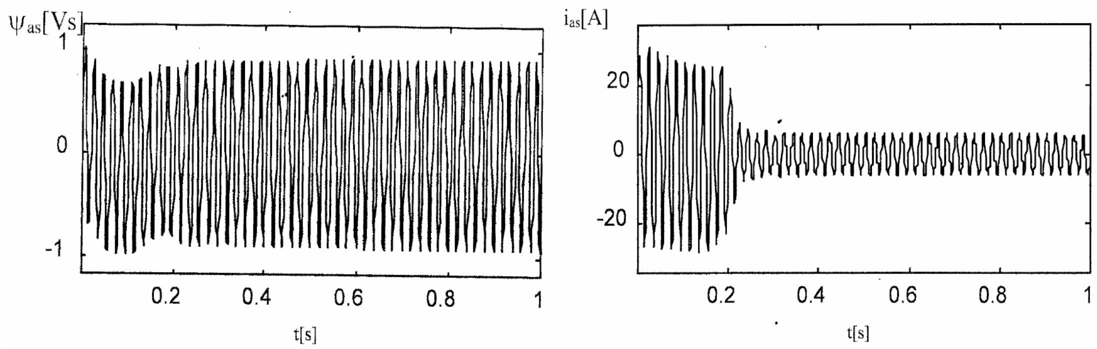
Symbol * denotes speed and frequency different from the rated ones.

In case when motor is supplied with variable frequency power supply, adequate values frequency 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 Fig.10 and 11 are presented transient characteristics of speed and torque as well as of stator flux and current when motor is fed from voltage inverter with frequency 50 Hz for operating regime of constant load M_s=14 Nm.



(a) speed (b) torque

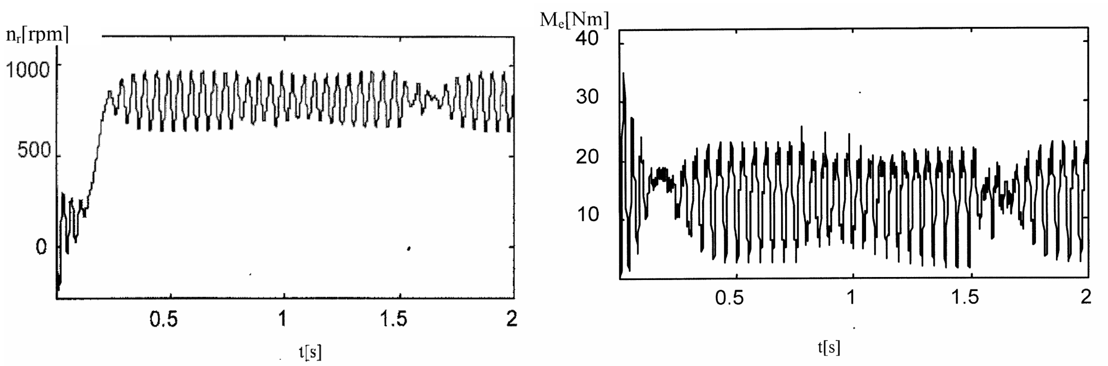
Fig. 10. Transient characteristics of speed and torque at rated load , supply from inverter frequency 50 Hz



(a) flux (b) current

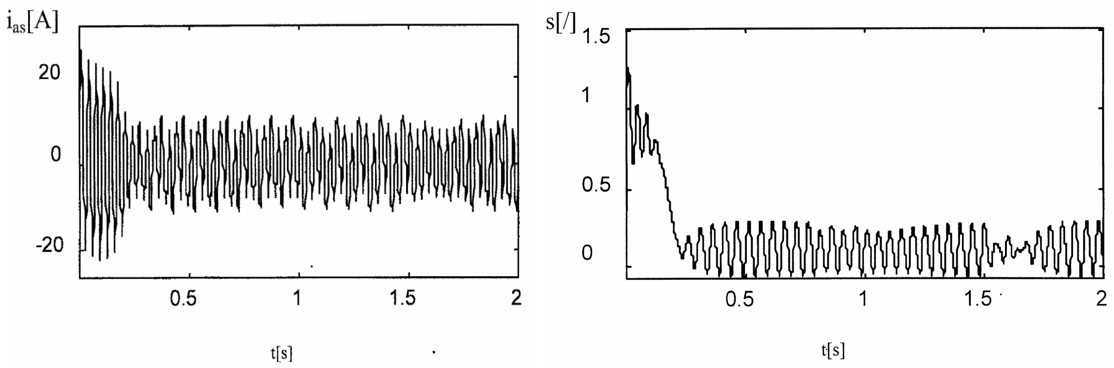
Fig. 11. Transient characteristics of stator flux and current at rated load , supply from inverter, f=50 Hz

Comparison of Figs.7,8 and 10,11 leads to conclusion that transient characteristics have similarity with respect to acceleration time and final steady state values of speed, torque and current but oscillations in steady state values are much higher in Figs. 10 and 11 due to the presence of high order odd harmonics. On Figs. 12 and 13 are presented transient characteristics of speed and torque as well as of current and slip when motor is fed from voltage inverter with frequency 30 Hz for operating regime of constant load M_s=14 Nm.



(a) speed (b) torque

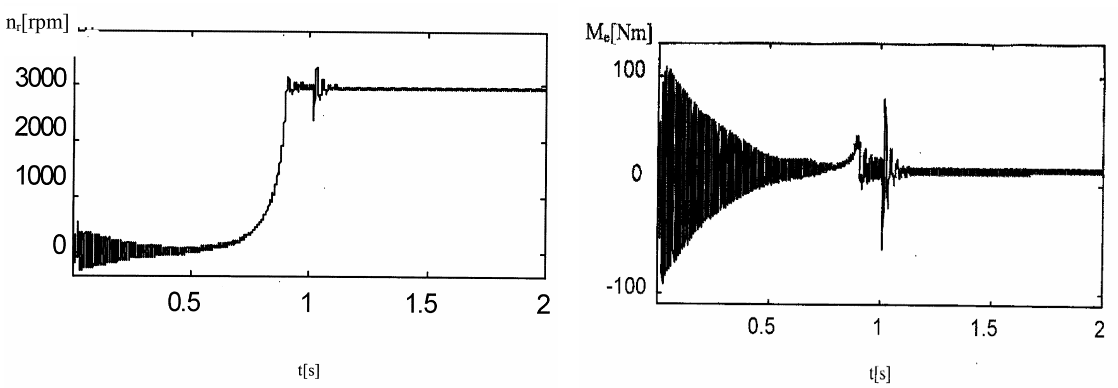
Fig. 12. Transient characteristics of speed and torque at rated load , supply from inverter f=30 Hz



(a) current (b) slip

Fig. 13. Transient characteristics of current and slip at rated load , supply from inverter f=30 Hz

As it is expected, according to equation (3), after the acceleration time has expired motor speed is reaching the value of 900 rpm. The mean value of current and electromagnetic torque after motor's acceleration is the same as it was in case of power supply from inverter with frequency of 50 Hz. On Figs. 14 and 15 are presented transient characteristics of speed and torque as well as of stator current when motor is fed from voltage inverter with frequency 100 Hz for operating regime of constant load M_s=14 Nm.



(a) speed (b) torque

Fig. 14. Transient characteristics of speed and torque at rated load, supply from inverter f=100 Hz

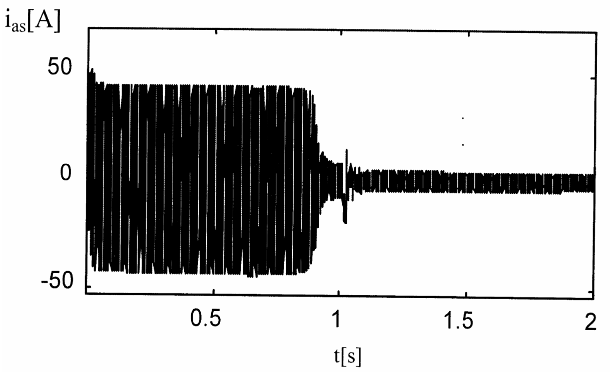


Fig. 15. Transient characteristics of current at rated load , supply from inverter f=100 Hz

As it is expected motor speed is reaching steady-state value of 3000 rpm at power supply with frequency 100 Hz while electromagnetic torque is reaching the value of 15 Nm same as in case of power supply from inverter with frequency 50 Hz. This result is expected, since inside the motor constant flux is maintained, which results in constant electromagnetic torque due to proportional increase of value of voltage and frequency. After acceleration time is expired current is reaching the value of rated current 5 A.

In Table 2 is presented comparison between data obtained from calculation, experiment and given by the producer for basic simulation motor model supplied with symmetrical sinusoidal supply and frequency 50 Hz. The similarity of obtained results verifies the simulation model as accurate enough to be performed simulations with non-sinusoidal power supply i.e. with power supply from voltage inverter with variable voltage and frequency.

Table 2. Comparison of results obtained by different methods.

	Producer	Analytical calculation	Experiment	Simulation model
P_n[W]	2200	2200	2200	
n_n [rpm]	1410	1424,72	1410	1440
I_{neff} [A]	5	4,8	4,87	4,5
s_n[/]	0,06	0,058	0,06	0,053
$\cos\varphi$[/]	0,81	0,838	0,78	/
η [/]	/	0,828	0,79	/
M_n [Nm]	14,9	14,67	13,8	/
$M_{em\,n}$[Nm]	16	16,58	13,88	15,2

Conclusions

Complex analysis of induction squirrel cage motor is performed by developing mathematical and simulation motor model. Mathematical model developed in FORTRAN is used for calculation of motor operation characteristics as well as electromechanical characteristics. Further on simulation model in SIMULINK is 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, electromagnetic torque of 15 Nm and maximum value of current 6 A 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 5A. 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. Two simulation models are built for frequency of 30 and 100 Hz. Both models are showing good simulation results of speed of 900 rpm and 3000 rpm which is adequate to the power supply frequency while electromagnetic torque is kept on constant value of 15 Nm.

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Dezvoltarea modelelor de simulare a motoarelor asincrone cu rotorul în scurtcircuit pentru aplicații cu viteza variabilă

Rezumat

A fost realizată o analiza complexa a regimurilor de funcționare a motorului asincron cu rotorul in scurtcircuit. A fost dezvoltat primul model matematic pentru calculul caracteristicilor motorului, operațional în FORTAN. Cu modelul dezvoltat, s-au calculat caracteristica statică a cuplului electromagnetic, viteza actuală, şi factorul de putere. SIMULINK este folosit pentru dezvoltarea de modele cu motor de simulare pentru ambele cazuri, atunci când motorul este alimentat cu sursa de alimentare sinusoidală precum şi atunci când este alimentat printr-un invertor de tensiune. Rezultatele obținute din simulare pentru alimentarea cu energie sinusoidala simetrica sunt comparate cu datele de la producător care arată acord rezonabil. Sunt analizate diferite regimuri de funcționare a motorului alimentat prin invertor de tensiune.