GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

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TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

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GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the Second International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA*.**
ETIMA has a goal to gather the scientists, professors, experts, and professionals from the field of technical sciences in one place as a forum for exchanging the ideas, strengthening the multidisciplinary research and cooperation, and promoting the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.
Conference ETIMA was held as online conference. More than sixty colleagues contributed to this event, from five different countries with more than thirty papers.
We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'23 by presenting the results of their current research and by launching the new ideas through many fruitful discussions.
We invite you and your colleague to attend ETIMA Conference in the future as well. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information as well as to involve as much as possible the young researchers into this scientific event.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот „Гоце Делчев".
ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.
Конференцијата ЕТИМА се одржа online и на неа дадоа свој придонес повеќе од шеесет автори од пет различни земји со повеќе од триесет труда.
Сакаме да ја искажеме нашата благодарност до сите колеги кои придонесоа за успехот на ЕТИМА'23 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Организационен одбор на конференцијата

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IMPACT OF CORE SATURATION ON OPERATING CHARACTERISTICS OF THREE-PHASE SQUIRREL CAGE MOTOR

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Abstract

The induction motors are considered to be the largest electricity consumers worldwide. Therefore, the exact calculation of their operating characteristics in various operating modes is important for determining their operation, electricity consumption and the various types of losses that occur during their operation that have the considerable impact on efficiency of the motors. Paper analyses two models of three-phase squirrel cage induction motor, modeled in Simulink. The first model is considered to have linear magnetizing characteristic while in the second model the core saturation is taken into account by introducing the non-linearity of the magnetization characteristic. The models are analyzed with fifteen percent increased voltage which shifts the operating point into the saturated part of magnetizing characteristic for the saturated model. The impact of core saturation on motor current, speed and torque is observed. The obtained results of the transient characteristics from Simulink are compared with data of current and torque from steady-state models. The core saturation increases the motor current, losses and decreases the motor efficiency. The areas where the core saturation occurs, mainly located in stator teethes, are also observed in Finite Element models (FEM). The derived models contribute to the better understanding of effect of core saturation and its impact on motor operation, thus providing the guidelines for the motor designers.

Key words

Core saturation, squirrel cage induction motor, transient characteristics, steady-state characteristics, FEM models

Introduction

Three phase squirrel cage motors can be found in many industrial applications and they still represent the major portion from all of the industrial motors, in comparison to other types of motors. Therefore, it is important to calculate as accurate as possible, the operating characteristics of this type of the motor in various operating regimes (no-load, rated load and short circuit) as well as to take into account the various operating factors that have impact on the motor performance i.e. its operating characteristics such as the no-load current, the core losses or the efficiency factor. One of them is the core saturation that increases the no-load current and consequently the no-load losses. Furthermore, the core saturation implies higher magnetizing current, lower power factor and current harmonics feeding back to the line. The majority of the mathematical models and equivalents circuits of the three-phase squirrel cage motor do not take into account the core saturation which can be considerably enhanced during motor operation at lower speeds or at lower frequencies. These can result in noticeable deviations of the calculated dynamic and static characteristics of the induction motor from real ones [1]. The steel losses in high saturation mode can reach up to 50 % of the total losses for induction motor, for transformers more than 20% and for the induction generators with capacitor excitation about 20-60 % [2]. The saturated model of AC machine with taking account of harmonic components of air gap flux is presented in [3]. The model is generated from classical model of AC machine with modification that takes into consideration the saturation. This modification depends on making the air gap length as a function of the air gap flux position and amplitude. It is shown that as a consequence of saturation a third harmonic flux component exists and the response of the rotor cage to this component is a third harmonic current which will create a ripple in total torque [4]. Due to core saturation it is observed distortions on the air gap flux as a result of non-linear magnetic characteristics that lead to appearance of space harmonics in the resultant flux density distribution [5]. l. The impact of magnetic saturation, considering the stator currents and magnetization flux in the (d–q) axis as a state variables for six-phase induction machine is presented in [6]. If high accuracy is required, conventional saturation models used in conjunction with equivalent-circuit models may not be sufficient. In controlled drives, for example, an oversimplified saturation model may result in poor accuracy of the produced torque or even instability in speed-sensorless drives. Explicit functions are proposed for the saturation characteristics—including the mutual saturation in [7]. The inductances become functions of two variables (fluxes or currents) [7]. The power quality has become a paramount in electricity distribution utilities as the voltage fluctuations may have impact on core saturation which has been analyzed in [8]. Improvement of the mathematical models of the induction machine and their modeling by taking into account the core saturation has been present in [9]. According to findings of this research there is an increase in the starting current of a machine with a nonlinear magnetic characteristic. This can be explained by the fact that to obtain a certain value of flux linkage in the saturation zone, a larger magnetizing current is required than to obtain the same value of flux linkage in an unsaturated machine [9]. This paper presents the Simulink model of three phase squirrel cage motor where the core saturation has been considered in motor modeling and obtaining the motor transient characteristics of speed, current and torque. The 2.2 kW three-phase squirrel cage motor and its parameters have been input in Simulink models of the machine. The comparison of transient characteristics when motor is operating with core saturation and without it is presented. The transient characteristics are presented for two typical operating regimes: no-load and rated load. Adequate conclusions are derived in terms of increase of motor current when motor core is saturated at no-load operating regime. The increase of current has impact on increased motor losses and decreased efficiency of the motor. Moreover, the steady-state characteristics of the motor when it operates with and without saturation are calculated and presented as well. The obtained data from the steady-state characteristics should verify the results from Simulink models. The distribution of magnetic flux density in motor cross-section is presented in motor FEM models, enabling detection of local areas where the core saturation occurs. The presented analysis is useful in designing electric drive systems, especially in developing motor protection. Neglecting to take into account the increase of the current when the motor is saturated can be the reason for arbitrary shutdown of the electric drive by protection devices.

2. Simulink models and transient characteristics

Simulink models of the asynchronous squirrel cage motor requires motor nameplate data such as motor power, number of poles, motor inertia but also the motor parameters (the resistances and reactances) to be input in the Simulnik block that represents three-phase squirrel cage induction motor (IM). Therefore, IM type: H5AZ 100LA-4 of 2.2 kW was modeled in software module Rmexprt of Ansys program and its parameters and steady-state characteristics are calculated. Motor data are presented in Table 1 [10].

Table 1 Motor data

Parameter	H5AZ 100LA-4
Output power [kW]	2.2
Rated speed [rpm]	1445
Rated torque [Nm]	14.5
Current [A]	4.8
Power factor [/]	0.76

Efficiency full load [%]	86.7
Locked-Rotor Torque Ratio [/]	3.5
Locked-Rotor Current ratio [A]	7.1
Break-Down Torque Ratio [/]	3.8

Source: author based on Končar, Electric motors-catalog

The Simulink model is presented in Fig.1. It contains two machine blocks. The upper machine block is modeled with saturation. The saturation is incorporated in the machine block by inputting the no-load charactersitics of the analyzed motor (Fig.2).

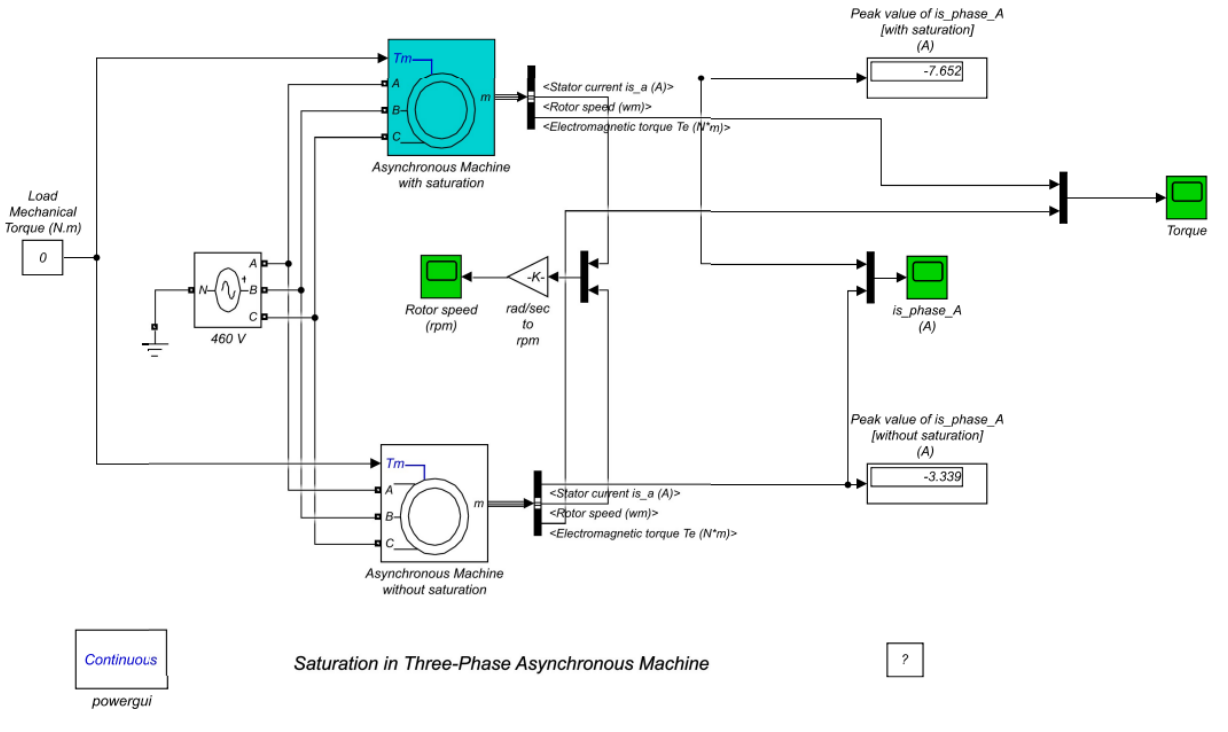


Fig. 1 Simulink model of saturated three-phase squirrel cage motor
Source: Simulink Simcape Power Systems Examples

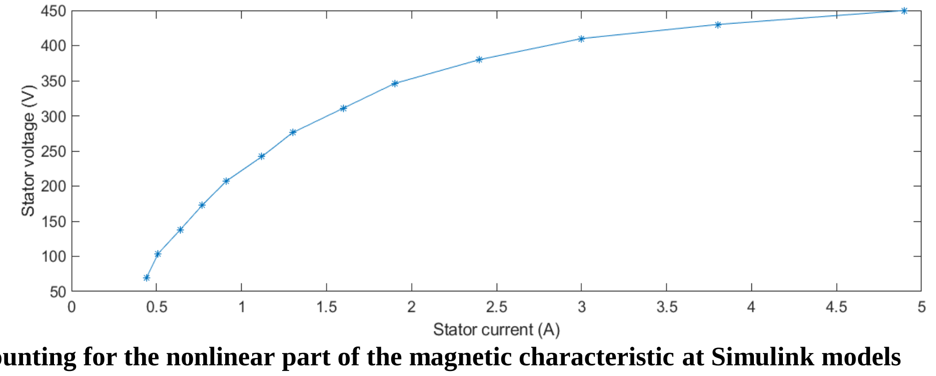
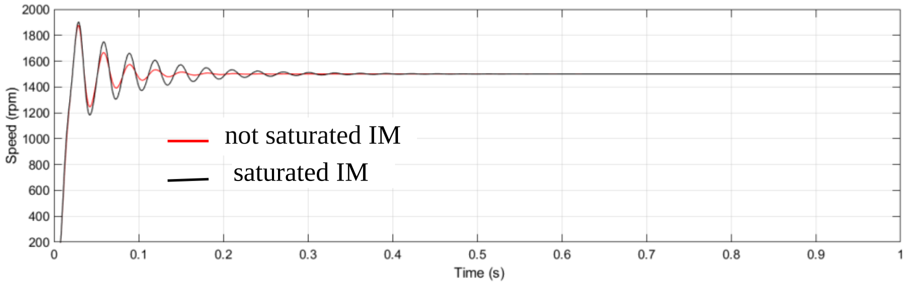
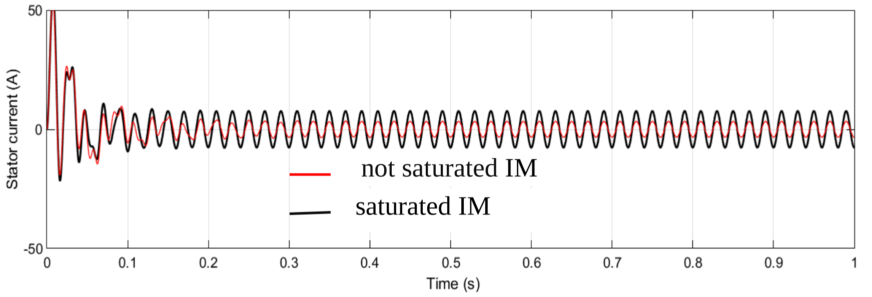


Fig. 2 Accounting for the nonlinear part of the magnetic characteristic at Simulink models

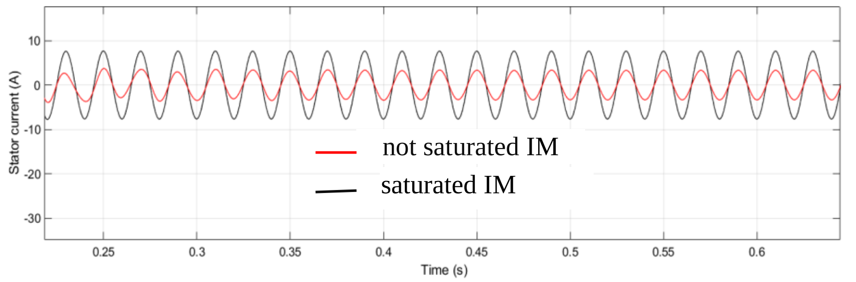
Transient characteristics are simulated for two operating regimes: no-load and rated load. The transient characteristics at no-load for motor speed, current and torque are presented in Fig. 3.



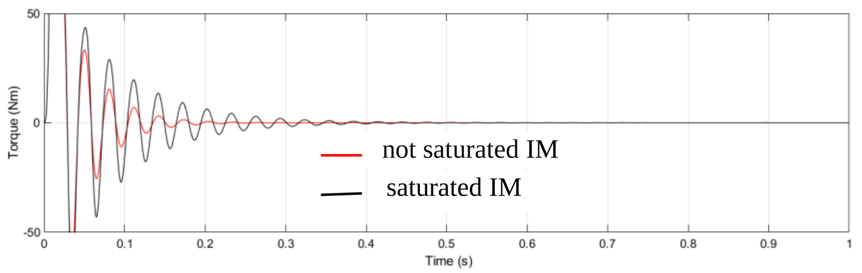
(a) speed



(b) current



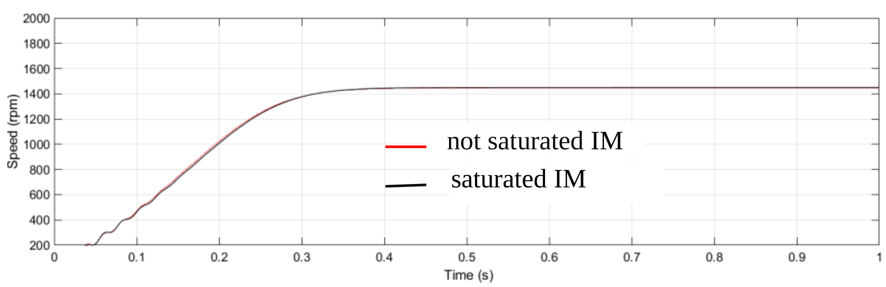
(c) current-detail



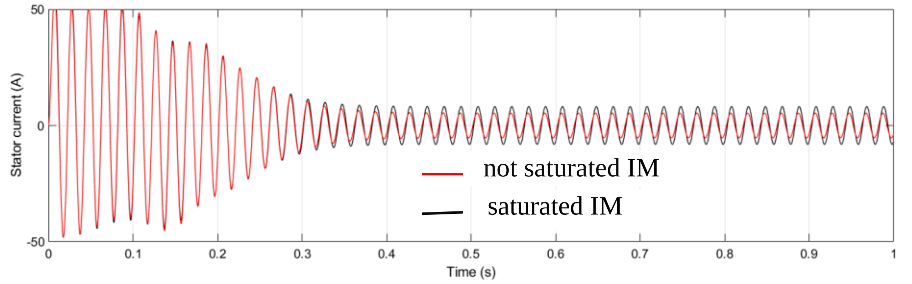
(d) torque

Fig. 3 Transient characteristics at no-load

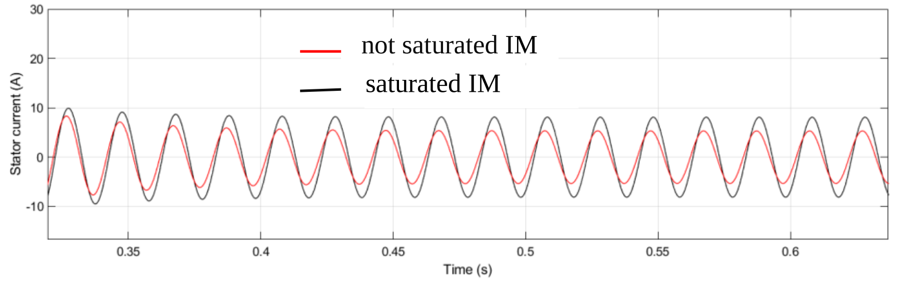
The transient characteristics at rated load for motor speed, current and torque are presented in Fig. 4.



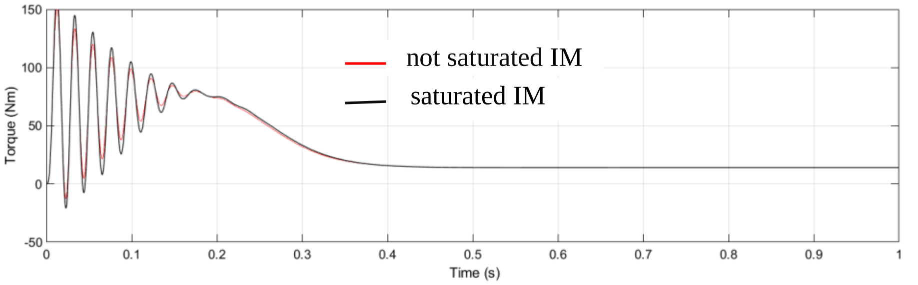
(a) speed



(b) current



(c) current-detail



(d) torque

Fig. 4 Transient characteristics at rated load

The effect of core saturation is enhanced at no-load and evident in transient characteristic of current. No significant impact of core saturation on motor speed and torque can be observed. The presented results of Simulink models are compared with the results and characteristics from the steady state models for their verification.

3. Steady-state and numerical models

The steady-state characteristics of the IM are calculated in Rmxprt, a software module, in Ansys program. The motor is modeled based on its geometry and properties of the materials. The non-linear B-H curve of magnetization of the iron core is input according to the data presented at Fig. 5.

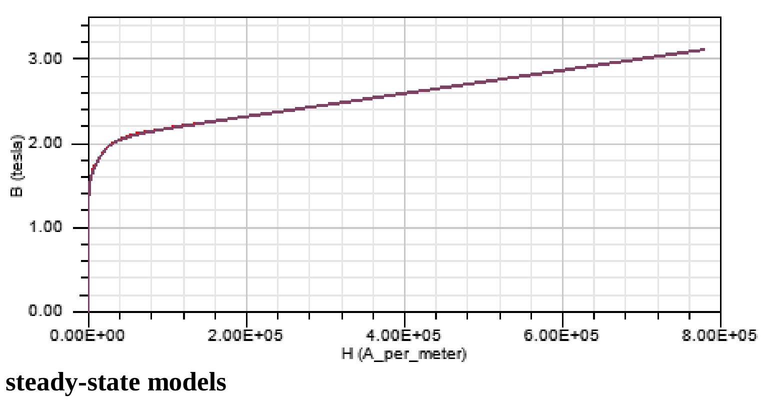
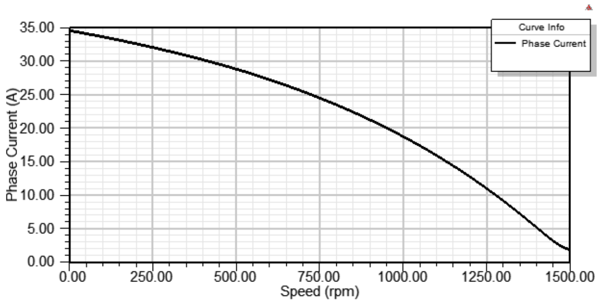
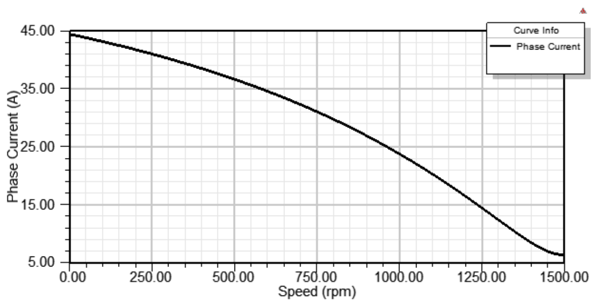


Fig. 5 B-H curve in steady-state models

The core saturation occurs at increased voltage that shifts the operating point above the knee of B-H curve. Therefore, the fifteen percent increased voltage than the rated one, is applied at saturated model in order to study the impact of core saturation on steady state characteristics of current and torque. The core saturation is even more evident in FEM models that present the distribution of magnetic flux density in motor cross-section. In Fig. 6 motor current for saturated and unsaturated machine is presented. In Fig. 7 the motor torque for saturated and unsaturated model is presented. In Fig. 8 the distribution of flux density in motor cross-section for no-load operation is presented. In Fig. 9 the flux density distribution for the rated load operating regime is presented.

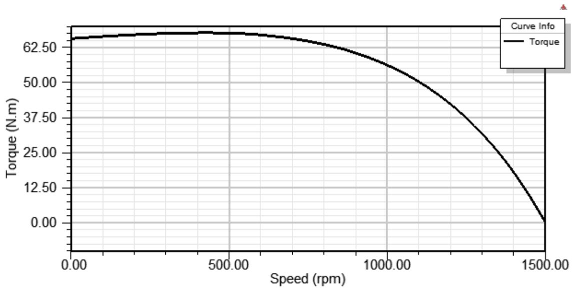


(a) unsaturated model

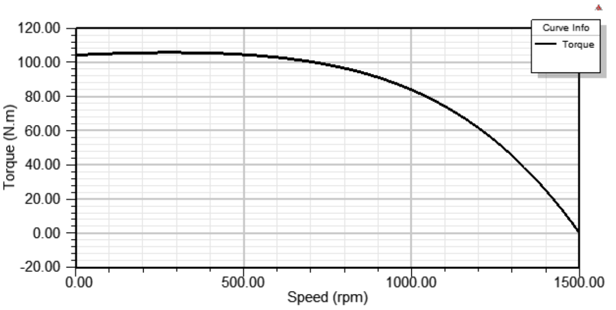


(b) saturated model

Fig. 6 Stator current in steady-state models

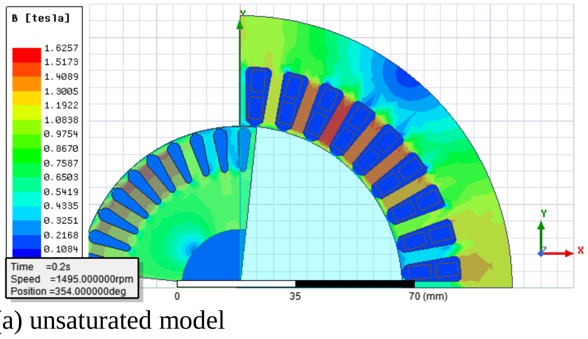


(a) unsaturated model

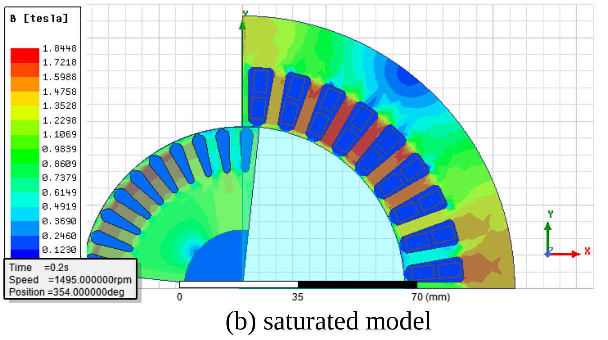


(b) saturated model

Fig. 7 Torque in steady-state models

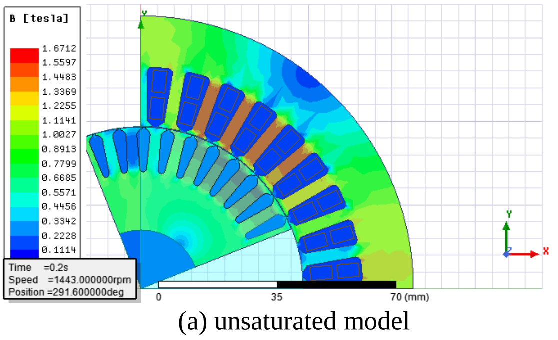


(a) unsaturated model

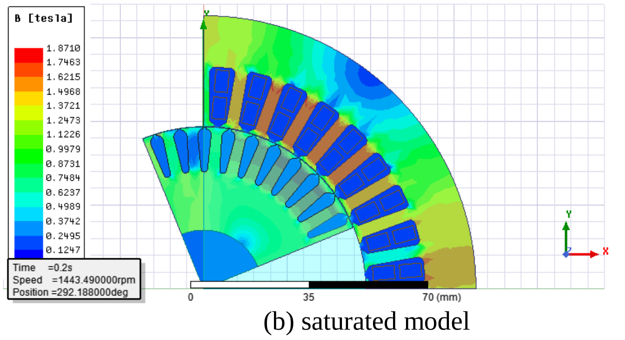


(b) saturated model

Fig. 8 Flux density distribution at no-load



(a) unsaturated model

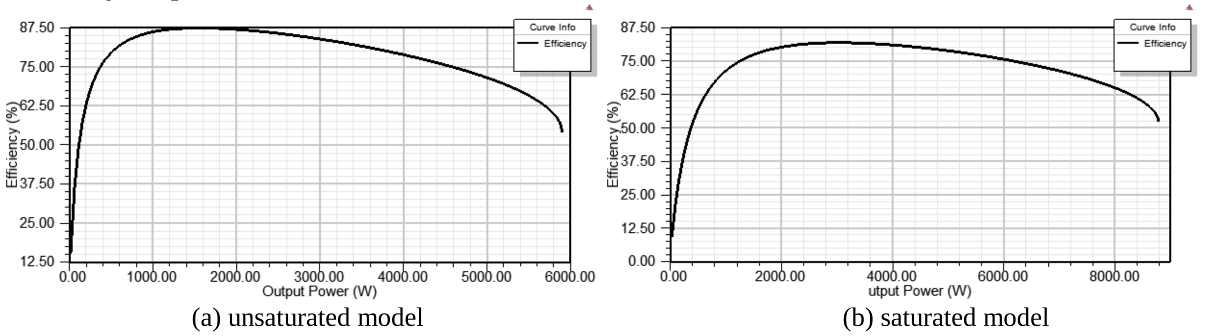


(b) saturated model

Fig. 9 Flux density distribution at rated load

4. Discussion of the results

The Simulink model gives transient characteristics of speed, current and torque for the saturated and unsaturated motor. From the Figs. 3 and 4 it can be observed that effect of the core saturation is more pronounced in stator current which is increased, especially at no-load operating regime. The increased current, increases the motor losses and consequently the efficiency factor of the motor is decreased. In Fig. 10 is presented the steady –state characteristic of the efficiency factor for the saturated and unsaturated model, where it is evident the decrease of the efficiency in saturated model. Moreover, the motor heating is increased and the overall motor performance is deteriorated. The core saturation has no impact on motor speed, acceleration time or the developed torque in both operating regimes: no-load and rated load. The presented results from Simulink models are verified with the results from the steady-state models, modeled in Ansys. They are presented in Figs 6 and 7, where for the specified speed (1495 rpm-no load or 1443 rpm-rated load) the corresponding current and torque can be read it. The comparison between unsaturated and saturated models in Simulink and Ansys is presented Table 2.



(a) unsaturated model (b) saturated model

Fig. 10 Steady-state characteristics of efficiency

Table 2 Comparison between dynamic and steady-state models

Parameter	Simulink		Ansys	
	Unsaturated model	Saturated model	Unsaturated model	Saturated model
Output power [kW]	2.2	2.2	2.2	2.2
Rated torque [Nm]	15	15	14.55	14.55
Rated current [A]	5	6.3	4.4	7
No-load current [A]-rms value	2.1	5.7	1.95	6.4
Efficiency full load [%]	/	/	86.47	80.8
Rated speed [rpm]	1425	1425	1443	1443

From the presented results in Table 2 it is evident the increase of current in saturated model, which worsen the power factor and motor efficiency due to increased copper and core losses. Therefore, the proper design of the motor core is essential for efficient and reliable motor operation. The last step in the analysis was to present the distribution of magnetic flux density in motor cross-section by calculating the magnetic flux density with finite element method. The good design of the induction motor should have cca 1.3-1.4 T in motor yoke and 1.6 to 1.7 T in rotor teethes. Therefore, the FEM models of the saturated and unsaturated motor are calculated, and according to the results, presented in Figs. 8 and 9, the rise of the flux density in stator teethes to cca. 1.89 T in the saturated model is evident, which is the value of the flux density on the knee of characteristic of magnetization or in the beginning of saturated area. The saturation is simulated by increasing the motor voltage which shifts the motor operation point above the knee of characteristic of magnetization in order the effect of core saturation on motor operating characteristics and magnetic flux density distribution to be easily observed. From the results, presented in Figs. 8 and 9, it can be concluded that the initial design of the machine under normal operating conditions with rated voltage is good, the magnetic core of the motor is properly designed and under these terms, no core saturation is expected to occur. The saturated models serve as an example to present the effect of the core saturation on the motor operating characteristics, transient and steady-state. If under rated operating conditions, the saturation of the magnetic core is observed due to the obtained results from the flux density distribution in the machine cross-section, then the geometry of the motor should be modified i.e. increase of core cross-section is recommended. The new motor design with increased dimensions should again be verified with FEM for the flux density distribution.

Conclusions

The design of the motors is a challenging task involving many different types of parameters from electric, magnetic and geometrical nature that should be successfully combined in order to obtain the good design with satisfactory operating characteristics: high efficiency, good power factor and good overloading capability. Nowadays, the motors efficiency has become of paramount importance in the world that needs more energy with limited resources. Around of the half of the electricity consumption worldwide is attributed to the electrical motors, being the largest electricity consumers. Therefore, the regulations regarding their efficiency, under various standards worldwide, are becoming more and stricter. One of the factors that have impact on motor efficiency is the core saturation. The paper has analyzed and presented the transient and steady-state operating characteristics of the unsaturated and saturated model of the induction motor obtained from software models in Simulink and Ansys. From results, presented throughout the paper, it is evident that core saturation increases the motor current, losses and decreases the motor efficiency. The results from transient and steady-state models have satisfactory similarity which proves the accuracy of the derived models. In general, core saturation deteriorates motor performance due to lower efficiency and power factor, increased losses and heating. The areas of core saturation can be easily detected in the numerical models by the aid of FEM which calculates the flux density distribution in motor cross-section. In the saturated model obtained by FEM and presented in the paper, it is evident the increase of flux density in stator teethes. The core saturation is simulated for increased supply voltage. If such condition occurs during rated operation of the motor, the revision of motor geometry is recommended, until the recommendations regarding the flux density in certain areas of motor cross-section are satisfied.

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