Comparison of d,q,0 Model and Transient Finite Elements Analyses of Induction Motor

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Abstract**—** In this paper, two different analysis approaches, the solution ot the transformed d,q,0 model and the solution of Transient Finite Elements model of an Induction Motor (IM) are implemented and the results are reported. The d, q, 0 model of an induction motor is well known and widely used as an analysis tool. On the other hand, increasing computational features of computers make possible of time domain Finite Elements Analysis in both 2D and 3 D geometries. This paper focuses on the similarity of the results those which are obtained by using these different approaches. For this purpose a sample IM is designed by using a CAD software and parameters required for d,q,0 model are obtained. This design is also used to implemented 2D TFE model as well. Especially the results of the 2D Transient FE analyses and d, q, 0 model results are found as considerably close to each other. Beside this comparison, in order to demonstrate the merits of the Transient FE analysis, unbalanced voltage fed operation is simulated in 2D geometry and effects of rotor bar skew rate on the performance of IM is simulated in 3D geometry. Finally the results are discussed in brief.

Keywords**—**Computer Aided Design, d,q,0 model Finite Element Analysis, Induction Motor, Rotor Bar Skew, Transient analysis.

I. Introduction

INDUCTION motor, as the most utilised member of the electric motors in the industry, is always an important subject with respect of its design, optimization and analysis. Classical approach of the IM design is based on the analytical methods and this approach has been used for a long time [1],[2]. On the other side the method for the analysis is based either steady state T equivalent circuit or transient analysis in terms of d,q,0 transformed phase variables [3],[4],[5]. Alternatively, models in a,b,c natural phase variables and for non-sinusoidal operations can be solved [6].

By the introduction of the FEA, numerical field calculation approach has become a strong alternative in electrical machine design and analysis [7], [8]. Whilst early state of this technique, 2D FEA has been used to obtain magneto-static solutions, by the increase of the computational and storage capacity of the computers, now it is possible to solve a huge number of solutions sequentially and obtain time domain variations i.e. a transient solution [9],[10]. It is a very valuable tool for the design and analysis, since when it is applied, many performance outcomes can be assessed and optimized before the prototyping state

Besides 2D analysis, through fast implementation of numerical algorithms, 3D magneto-static and even 3D transient analysis can be implemented.

In this paper it is aimed to apply FEA as an analysis tool to a sample IM project. For this purpose, the software (Annoys' Maxwell 2D and 3D) and its electrical machine design tool (Rmxprt) have been used in the studies. Rmxprt uses analytical methods and formulas to design an electrical machine, calculates parameters of the equivalent circuit and plots a number of characteristics. After the geometry and winding arrangement are available, it is possible to transfer the geometry of the motor from Rmxprt to Maxwell. Since Maxwell allows to define an external circuit for the dedicated coils, time variation of the stator currents, torque and speed can be calculated for either normal symmetric or abnormal terminal conditions. When properly applied, it can be said that the results of this analyses are more detailed than any of those obtained by conventional d,q,0 transient analysis method.

In the last part of the study Maxwell 3D transient analysis has been used. In general, the transient 2D and 3D analyses are somewhat close to each other and produces similar results, however the effect of the rotor skew can only be analysed in 3D. Therefore, the effect of the rotor skew angle on the transient performance of the motor has been choosen as the subject of 3D analysis.

II.Computer aided design

Since an unique sample induction motor is required to perform FEA, we utilize a computer aided electrical machine design software called Rmxprt. Once initial dimensions and nameplate data are selected, Rmxprt calculates the rest of the parameters, dimensions, performance curves and produces a detailed report.

Initial design dimensions and rated values of the design output are given in Table I and II. Note that, given dimensions are approximated values of a standart 4 pole, 112 M frame, 5 kW induction motor.

Table I Initial design dimensions

Name of the item	Value / Unit
Stator Outer Diameter	170 mm
Stator Inner Diameter	103 mm
Number Of Slots of the Stator	36
Rotor Outer Diameter	101mm
Rotor inner Diameter	38 mm
Number of Slots of the Rotor	28
Stack Length	140 mm

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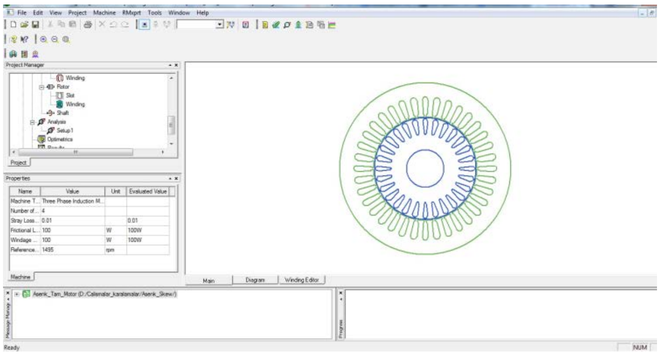
Table II. Rated design values

Name of the item	Value / Unit
Rated Voltage	Y 380 V
Frequency	50 Hz
Number of Poles	4
Rated RPM	1400 rev/min

Stator and rotor magnetic material have been chosen as M600-50A and Aluminium has been chosen as the material for the rotor bars and the end rings. As mentioned above, once it has been completed, Rmxprt produces all required parameters, operational variables and steady state curves. This parameters can be used either for the T equivalent circuit steady state analysis or transformed d,q,0 variable modelling and transient analyses. Table III. Shows calculated rated values of designed IM.

Table III. Calculated rated values of designed IM

Name of the item	Value / Unit
Rated Current	12,07 A
Rated Power	5,007
Rated Torque	34,12 Nm
Power Factor	0,768
Efficiency	81,19



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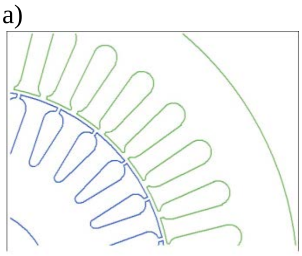

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Fig. 1 a) general view and b)stator and Rotor slot shapes of the designed IM

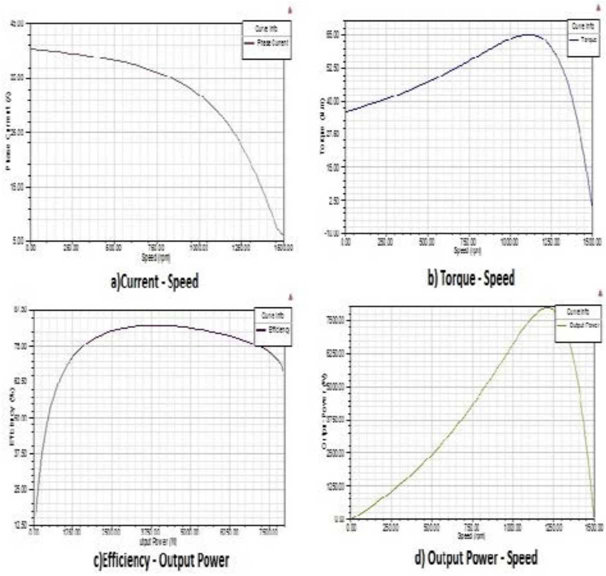


Fig. 2 basic characteristics of the design

III TRANSIENT ANALYSIS

A. d,q,0 Transient Analysis

As it is stated above, design software calculates all the basic parameters which are required to build the d,q,0 model of the induction motor such as phase resistances, phase magnetizing and leakage inductances and the inertia of the rotor. By using this parameters, a mathematical model in terms of d,q,0 variables can be practically obtained. This mathematical model, has been used to simulate two operations. The first simulation has been made to solve loaded starting of the induction motor with rated voltages and rated load torque. As second analysis, unbalanced voltage operation of the induction motor has been simulated. Note that, both of these simulations have been re-solved by 2D FE analysis. The results of d,q,0 analyses for balanced and unbalanced conditions have been given in Fig. 3 and Fig.4. Since the most indicative results of the solutions are the phase currents and electromagnetic torque, these two variables have been included in the figures. Fig. 4 shows the variation of the electromagnetic torque and the stator currents for balanced voltage fed and rated loaded operation. As it is expected, after a short time oscillatory starting, a smooth form has been observed in electromagnetic torque. Stator currents are also as how they are expected to be. Following a high starting level, phase currents have been settle down to their rated level.

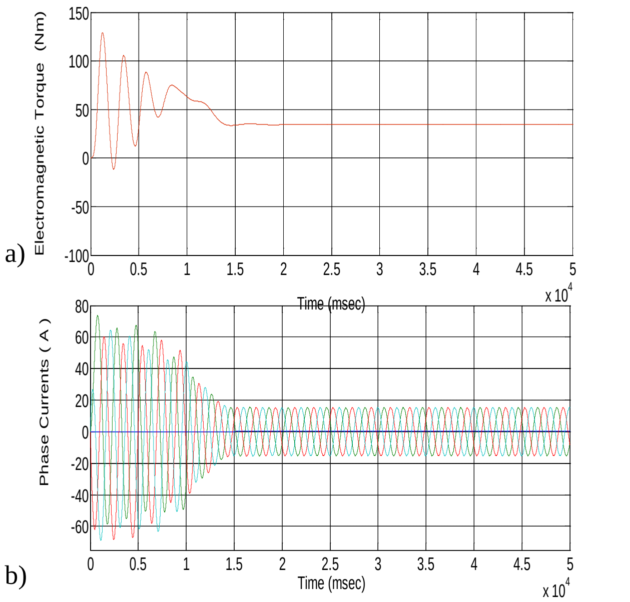


Fig. 4 solution of d,q,0 model for balanced voltage and rated loaded starting a)electromagnetic torque b) phase currents

B. 2D FE Transient Analysis

After creating the basic structure of the IM, the geometry and the materials can be transferred into the Maxwell magnetic analysis software. The software has the 2D and the 3D magneto-static and transient solver options. For this part of the study, it is preferred to use 2D analysis module. By using built in circuit editor, an external circuit with ideal sinusoidal voltage source and stator winding connected in series, has been configured and rated voltage has been applied to the stator windinds. Winding resistance is taken from the Rmxprt calculation.

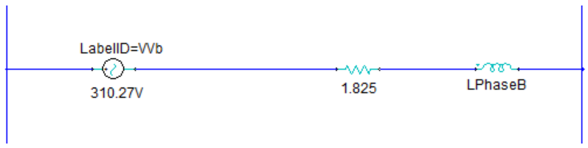


Fig. 5 external circuit for phase b

In order to implement a transient analysis, a 2D FE mesh has been configured which is shown in Fig. 6. Depending on the particular position of the rotor, mesh can be automatically refined in some areas of the overall surface. As it is shown, instead of a symmetrical part, full motor geometry has been modelled and solved.

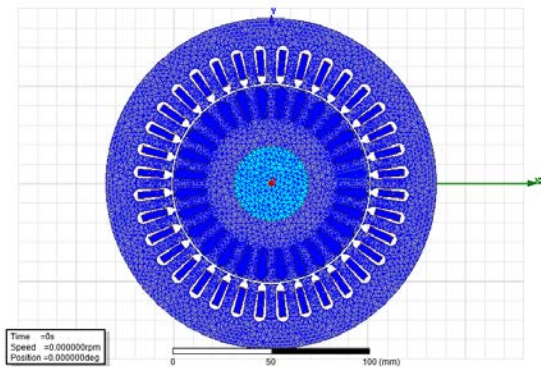


Fig. 6 finite elements mesh for the transient analysis

First transient analysis has been implemented for the full load (34 Nm), full voltage (220 V), direct on line starting of the designed IM as in the d,q,0 model simulation.. This condition has been chosen in order to obtain a reference run for a balanced and "normal" conditions. Then one can compare this results with those of unbalanced conditions. In Fig. 7. an instantaneous field distribution over the full motor cross section is shown. As expected, 4 pole field, light and heavy magnetic induction regions can be distinguished. Since sequential field maps are available after a simulation, "rotating field" and winding MMF forms can be inspected to have a better idea of a specific winding and rotor slot designs.

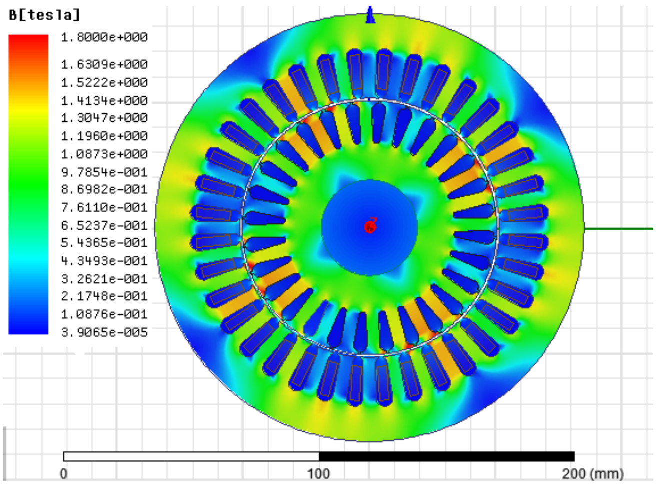
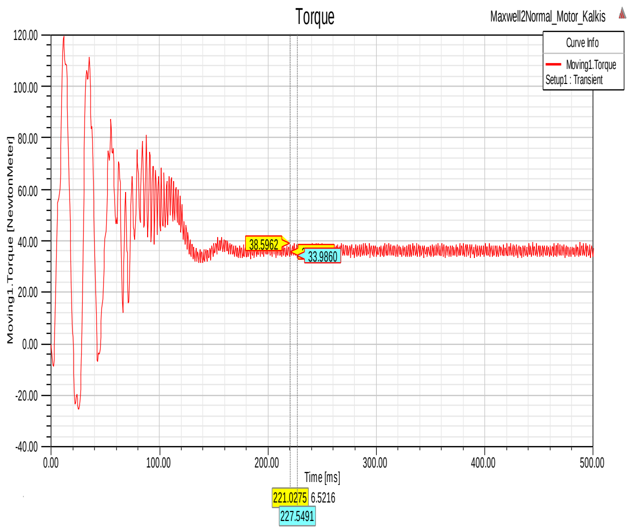


Fig.7. Instantaneous field distribution over the stator and rotor

In Fig. 8. the results of 2D transient FEA are given. The variation of electromagnetic torque is similar to that of which is obtained by d,q,0 transient analysis. Moreover a steady state ripple has been seen on the produced electromagnetic torque. This ripple is commented as the result of slotting and high order space harmonic effects of the airgap induction distribution which are normally not seen in d,q,0 transient analysis. Initially starting torque peaks up to 120 Nm have been calculated. A break-down torque about 60 Nm has been occurred around 1000 rpm at 100 milliseconds and finally a steady state torque of 34 Nm has been calculated. Starting transient is clearly shown in the stator currents and speed as well. Peak values of the stator currents have reached about 85 A and finally decayed to 15 A. The variation of the speed similar to electromagnetic torque. The results of the d,q,0 and 2D transient FE analyses are in close confirmation in terms of steady state current, speed, and torque. It should be noted that mesh size, time steps and solution types must be chosen appropriately in order to reach a better approximation. The results can be commented as a validation of the d,q,0 and analytical design parameters as well as the validation of the transient FEA. In transient FEA, electrical and mechanical behavior of the IM is based on lowest level interaction of electrical current and magnetic field [9]. Therefore the calculated variations by this way, can be supposed to be more realistic ones than those which are calculated by any form of equivalent circuits.



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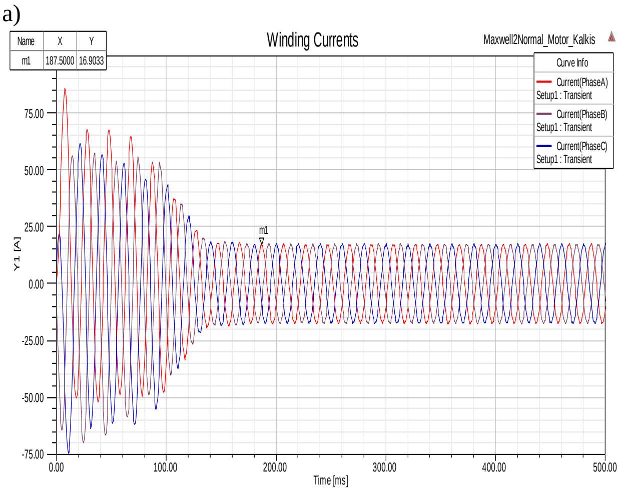

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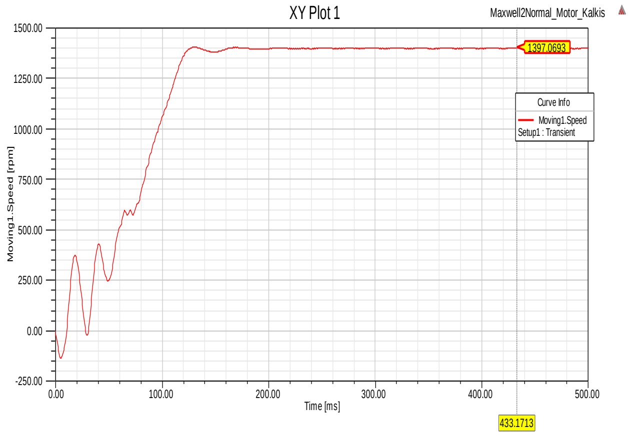
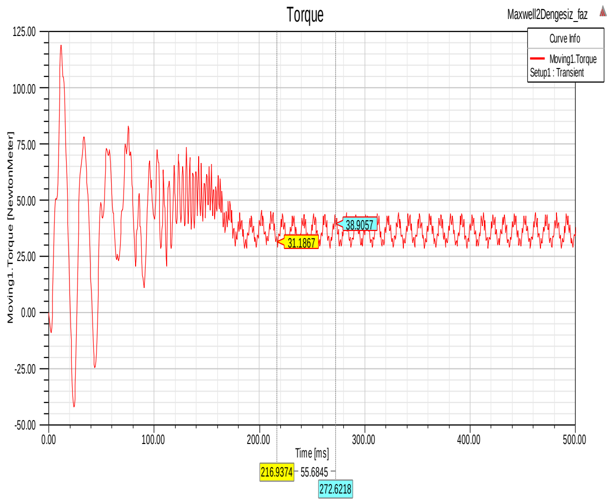
Fig. 8 transient variations for balanced stator voltages a)electromagnetic torque b) stator current



c)

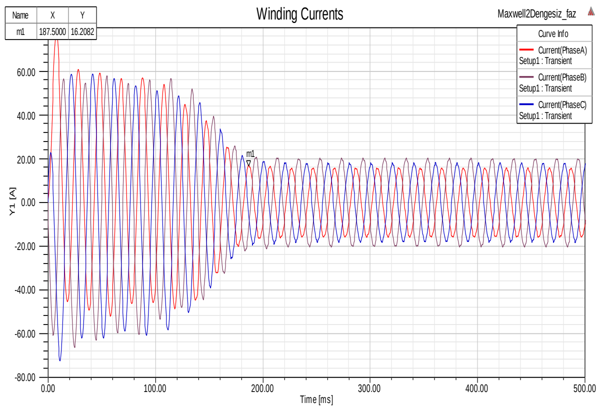
Fig. 8 (continued) transient variations for balanced stator voltages c) shaft speed

As a second 2D FE transient analysis, voltage unbalance has been considered. Unbalanced voltage operation of the induction motors can be often encountered in the real world and the effects can partly be analysed by negative and positive sequence equivalent networks. Therefore we have chosen this operating condition as a sample abnormal operating case. In this study "one phase is under voltage" condition has been analyzed. The given unbalance is 6% and unbalanced voltages are defined as; Va: 182,07 $\angle 0^{o}$ V, Vb: 219,39 $\angle 240^{o}$ V Vc: 219,39 $\angle 120^{o}$ V. Where Va,Vb and Vc are phase to neutral voltages. The resuls of the analysis have been given in Fig. 9. When compared with balanced reference operation, the effect of unbalanced voltages is obvious in torque and current waveforms.



a)

Fig. 9 Transient variations for unbalanced stator voltages. a)Electromagnetic torque



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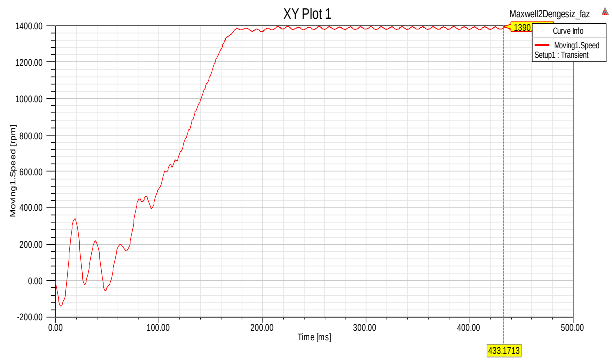

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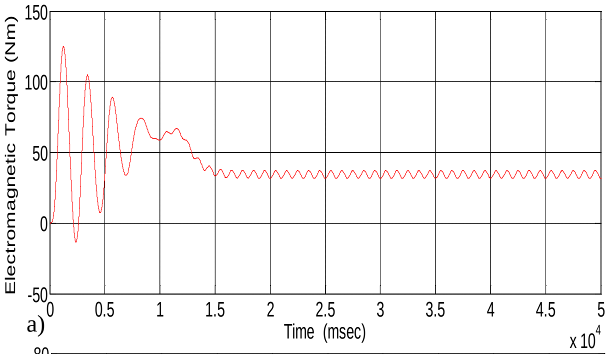
Fig. 9 (continued) transient variations for unbalanced stator voltages b) stator current c) shaft speed



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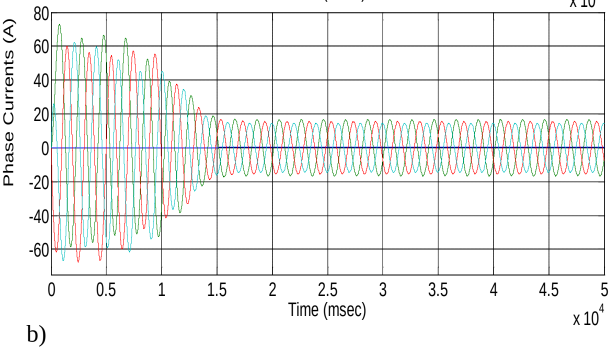


b)

Fig. 10 Transient variations for unbalanced stator voltages which are obtained by solving d,q,0 model a) electromagnetic torque, b) stator current

Transient analysis results have shown that unbalanced stator voltages caused significant oscillation in shaft speed, electromagnetic torque and an unbalance in stator currents. This oscillations in electromagnetic torque and shaft speed may lead unwanted noise, mechanical vibrations and even resonances. In Fig. 10 the results of d,q,0 model analysis have been given. The similarity in between two different approaches is clearly seen in electromagnetic torque and phase currents.

C. 3D FE Transient Analysis

After performing a 2D transient analysis, we focused FE analysis over 3D geometry of the sample IM project. In order to utilize the merits of the 3D analysis, the effect of the rotor skew angle on the motor performance has been inspected. Since rotor skew creates a variation of the geometry of the rotor along z axis, it is impossible to study rotor skew effect by means of normal 2D analysis. Even step by step segmental 2D analyses can be implemented and combined to build a 3D solution, it is only practical for the magnetostatic analysis. When properly applied and computational requirements fulfilled, transient 3D is obviously well suited for the rotor bar skew analysis. Note that, skew may either exist on rotor or on stator stack. In Fig. 11. 3D mesh of the induction motor is shown. Rotor bar skew and its angular direction are also given in Fig. 12.

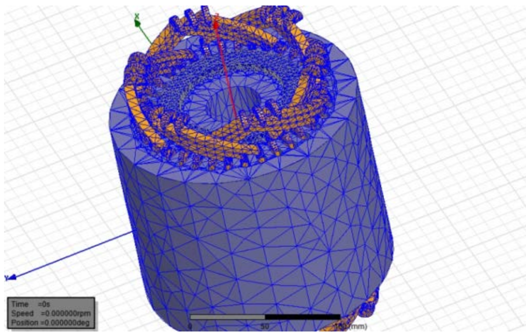


Fig. 11 3D Mesh of the induction motor

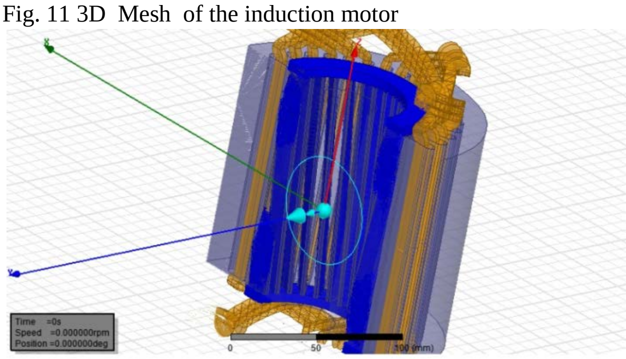
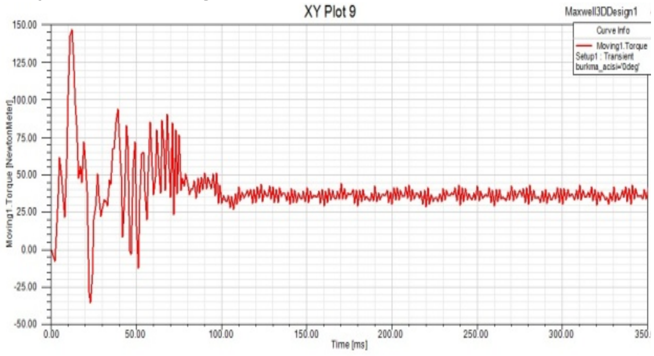


Fig. 12 Rotor bar skew and its angular direction

Rotor skew angle has been defined as a parameter and a series of transient solutions has been performed for the rotor skew angles of 10^o and 20^o degrees. Note that these parametric values can be used as a coarse estimation of the optimum values, which may then be refined and repeated with smaller angular rotor skew values. In Fig.13 the results of the 3D FE transient analysis have been given.



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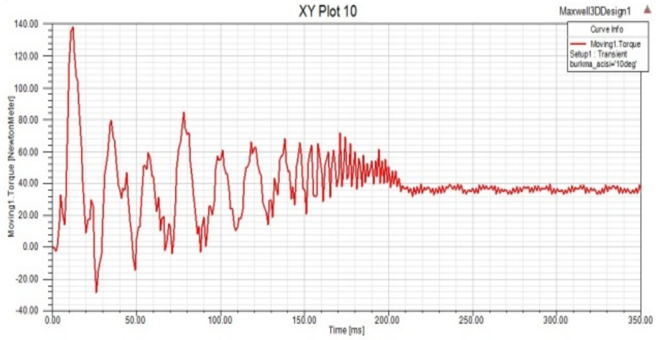

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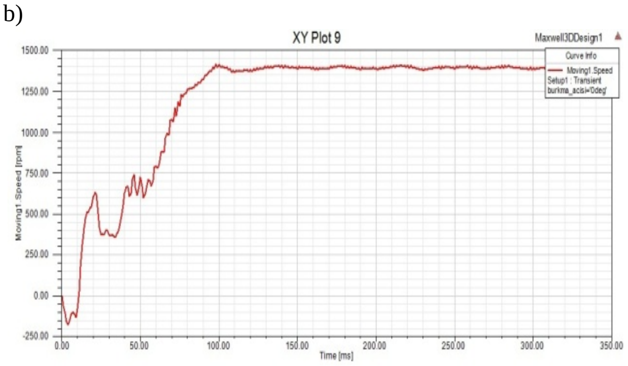

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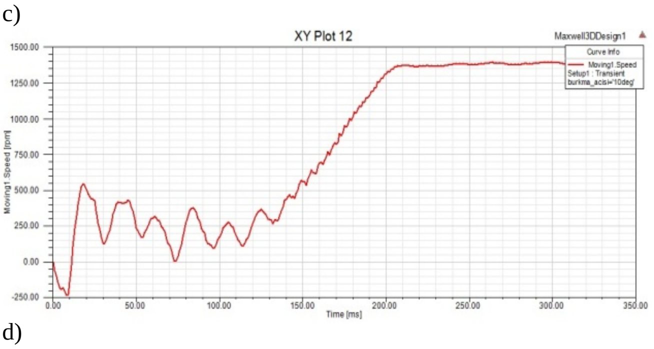

d)

Fig. 13 3D transient FEA results for two rotor bar skew
a) electromagnetic torque (skew 10^o) b) electromagnetic torque (skew 20^o) c) shaft speed (skew 10^o) d) shaft speed (skew 20^o)

The variation of the electromagnetic torque shows that when the rotor bars are not skewed, a small amplitude, high frequency ripple component is seen. When the rotor bars are skewed, even it is not completely disappear, this component significantly decreases. Another effect of the rotor skew is the decrease on the average starting torque of the motor, which has been seen in the analytical design results. The optimum skew angle must be determined by a series of 3D FE transient analyses.

IV Conclusion

In this paper, the study of computer aided design and transient FEA of an induction motor has been given. The design and analysis has been performed on the Ansys's Rmxprt and Maxwell platform. 5 kW, 4 pole induction motor geometry and parameters has been obtained by Rmxprt and the geometry and parameters has been transferred into Maxwell 2D and later into Maxwell 3D for transient magnetic analysis. The characteristics and operational data that have been calculated by Rmxprt, which are based on analytical design equations of induction machine, have been then compared to 2D transient FEA results. We have obtained a good approximation especially on the steady state values of two independent analyses. We performed a second 2D transient FE analysis on the same IM geometry and data, in which stator voltage unbalance has been considered. The results showed that significant vibration in electromagnetic torque and unbalance in the stator currents have been presented in unbalanced voltage operation. In order to implement a 3D transient FEA we extent the IM analysis in 3D. We have choosen a specific problem, rotor bar skew angle effect on the motor performance, to inspect the effectiveness of the 3D transient FEA. Results have showed an agreement to those which have been expected. The electromagnetic torque has become smoother but starting torque has decreased when the skew rate has been increased. We note that the computation times were rather long in 3D transient FEA and -at least for the time being- it should be used only for the cases which really "require" a 3D analysis. Through more powerful computers and parallel operations, computation times are supposed to be shortened

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