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Application of FEM to Provide the Required Database for MCSA Based On-line Fault Detection System on 3-phase Induction Motor using ANSYS Maxwell2D

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ABSTRACT

This research deals with the design and implementation of an on-line monitoring system for a 3-phase induction motor. This subject is widely considered by many researchers in different approaches, but the most difficult step is to perform an efficient, accurate, and all inclusive database. The Finite Element Method (FEM) performs a flexible model of the induction motor, able to simulate all the expected faults without doing any destructive tests. The methodology used in this research is to compare the model data with that obtained from a real faulty machine. The designed system adopts Maxwell2D computer package for this purpose. The Motor Current Signature Analysis (MCSA) technique applied in conjunction with Fast Fourier Transform to performing on-line data from the motor. A LabView environment used to match the computer and the hardware of the monitoring system. The proposed system results in an efficient monitoring, fault diagnosis system. But this work leads to conclude that the 2D FEM can simulate the most expected faults so, a 3D analysis required for this purpose, also such study is not suitable for an inverter fed motors.

KEYWORDS: MCSA, FEM, ANSYSMaxwell2D, Induction Motor, Electrical Fault, Flux Distribution.

INTRODUCTION

It is already known that the IM is the mostly used derive in the industry, and its sudden fault will cause a severe effect on workflow, and will lead to spending a lot of time, money and efforts. Hence, to avoid these losses, especially in case of high ratings machines, a need arises to perform an online monitoring system for the most important machine in the plant.[1] Such a system will be able to alarm the operators about the machine faults as soon as it occurs, to avoid the total shutdown of the plant. The clearest phenomenon of the faulty machine is the distortion that appears on its stator currents, so the Motor Current Signature Analysis (MCSA) technique is intended in such monitoring systems[1].These distorted current waveforms can be analyzed using Fast Fourier Transform (FFT) in order to determine its harmonics. Hence, these harmonics can provide wealthy information fed to learn an Artificial Neural Network (ANN). This learned ANN can be considered as an on-line identifier able to detect and diagnose the faults of the simulated IM depending on the (MCSA) technique[2].

To perform such a database, all the faults must be done artificially on a huge quantity of IM samples, and the associated currents spectrums achieved by conducting real tests on these faulty motors will perform the database for the ANN to be able to diagnose the fault cases. This process requires testing huge quantity of

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artificially destroyed IM, which is unreasonable and uneconomical. Hence, the only way to perform such a large database without losing any motor is by simulating this machine using an accurate simulation method[2].

The objective of this research is to perform an accurate simulation for a certain 3-phase IM required to be monitored. This package is intended to simulate all the expected faults in the 3-phase IM such that the distortion in the stator currents for any fault can be determined.

The only approach to reach this target is by using a numerical method to solve Maxwell's equations describing the flux distribution inside the machine, taking into consideration the nonlinearity in the magnetic characteristics of its core. This task can be done using the Time Stepping Finite Element Method (TSFEM). The current waveforms of the actual test of a healthy motor compared with that obtained from the FEM simulation. Since, they show a good agreement, then this approves the accuracy of the model and it will be suitable for this job.

Two electrical faults only will be considered in this paper to show the methodology of this approach using 2D analysis. To perform all the expected faults data, especially the mechanical faults and the mixed faults, a 3D analysis have to be done. ANSYS Maxwell2D used for this purpose[3].

2. Fundamentals of Finite Element Method:

FEM for modeling of electrical motors includes three processing steps: pre-processing, processing and post-processing. In the preprocessing step, that geometry of the electric motor is drawn. The material, electrical and magnetic characteristics of the stator, rotor, and the shaft are fed. The boundary conditions (BCs) applied to the external border of the stator geometry. Since the shaft not included throughout the process, therefore an additional BCs have been applied to the inner border of the rotor. At this stage, the size of mesh elements must be determined. The final step in this stage is applying load to the model. In the processing part, a set of Maxwell's equations is solved and the magnetic field distribution will be calculated. In the post-processing stage, all results of nodes and elements will be obtained. Speed and electromagnetic torque have been calculated. Stator and rotor currents and flux density and all other electromagnetic variables have been obtained. The general FEM model for motor comprises two major parts, the 2-D magnetic part representing the machine, and the part representing power supply connection with the electric circuit. Those two parts must be coupled together specifically utilizing a unique kind of coupling equations. After that the magnetic and electric equations are tackled at the same time utilizing uncommon sorts of solvers in ANSYS software.

Finite element analysis (FEA) is the implementation of FEM for solving such type of problems. FEA includes three analysis methods [3]:

a) Magneto static analysis.
b) Magneto harmonic analysis
c) Magneto transient analysis (Time stepping analysis)

2.1 Maxwell's Equations:

The partial differential forms of Maxwell's equations that characterize the quasi stationary fields can be expressed as blow [4,5]:

$$\nabla\times H = J(Ampere'slaw) \quad (1)$$

$$\nabla\times E = -\frac{\partial B}{\partial t}(Faraday'slaw) \quad (2)$$

$$\nabla\cdot B = 0\ (Magneticfluxcontinuity) \quad (3)$$

$$J = \sigma E \quad (4)$$

$$B = \mu H \quad (5)$$

Where;

H is the magnetic field strength (A/m)
J is the total current density (A/m^2)
E is the electric field strength (V/m)
t is the time (s)
B is the magnetic flux density (Wb/m^2)
σ is the conductivity of the material (Ω.m)
μ is the magnetic permeability of the material (H/m)

The relations of equations (4) and (5) indicate the constitutive equations; they are used with Maxwell's equations. It explains correlation between field amounts based on the magnetic and electric characteristics of materials μ and σ.

The above equations can be placed in terms of magnetic vector potential (MVP) A, where:

$$B = \nabla\times A \quad (6)$$

Substitute equations(5) and (6) in (1), yields:

$$\nabla\times\left(\frac{1}{\mu}\nabla\times A\right) = J \quad (7)$$

With$\nabla\times(\nabla\times A) = \nabla\cdot(\nabla\cdot A)\nabla^2 A$, Equation (7) becomes

$$\nabla^2 A = -\mu J \quad (8)$$

Utilization of Maxwell's equations in IM leads to divided them into two sorts, known as Laplace's equation and Poisson's equation (equations 9, 8).The first equation explains the electromagnetic field distribution in the core and air-gap regions. The other is applied to perform the field parameters in stator and rotor winding.

$$\nabla^2 A = 0 \ldots \quad (9)$$

Depending on Faraday's law and substituting the magnetic vector potential A and electric scalar potential Vin Eq. (2) gives:

$$E = -\frac{\partial A}{\partial t} - \nabla V \quad (10)$$

$$E = -\left(\frac{\partial A}{\partial t} + \nabla V\right) \quad (11)$$

Then by substituting Equation (11) in Equation (4) to find the current density [6] results in:

$$J = \sigma \cdot E = -\sigma\left(\frac{\partial A}{\partial t} + \nabla V\right) \quad (12)$$

$$J = J_s + J_b + J_d \quad (13)$$

Where;J_sIs the voltage supply current density;J_bIs eddy current density, andJ_dIs the displacement current density.

Sub. Equation (12) in Equation (8), leads to:

$$\nabla^2 A = -\mu J_s - \left(\sigma\mu\frac{\partial A}{\partial t} + \sigma\mu\nabla V\right) \quad (14)$$

2.2 A 2-D Finite Element Method:

In spite of the increase of using the 3-D FEM, most of the electromagnetic field analysis related to electric motors can be made using a 2-D FEM. It has many features listed below [7]:

a) Short implementation time.
b) Simple and easy meshing the simulation.
c) Less space of computer memory.
d) It has limited unknown parameters to be solved.

2.3 Modeling assumptions:

The following assumptions are made in the analysis part [8, 9]:

a) The current density (***J***) and the magnetic vector potential (***A***) have only z-axis component. As a result, the flux density (***B***) has only components in the x-y plane.
b) The cores of the stator and rotor are represented using a magnetization curve of the steel.
c) The stator and rotor cores are laminated.
d) There is insulator used to insulate the stator windings from the stator core.
e) The power supply is a balanced sinusoidal voltage source.

2.4 Modeling Steps of Induction Motor Using Finite Elements:

The induction motor model can be modeled according to the following steps:-

a) Create the geometry of the IM.
b) Designation materials of the different parts of the motor.
c) Meshing all parts of motor.
d) Determines type and location for BCs.
e) Applying supply voltage as a load.
f) Make coupling between electrical circuit and magnetic field areas.
g) Solving using FEM.
h) Getting results.

2.5Building of the Stator and Rotor FE Models:

In this work the test motor basic information are 2-pole, squirrel cage 3-phase, 380V, 50Hz, 3000rpm, 2.2 kW, induction motor as detailed in Tables (1) and (2), the motor wiring diagram is given in Figure (1), and the detailed dimensions of the stator and rotor lamination plates are given in Figure (2).

Table1: Motor Design Data

Parameter	Unit
Stator Outer Diameter	137.8 mm
Stator Inner Diameter	78 mm
Stator - Number of Slots	24
Rotor Outer Diameter	77.4 mm
Rotor Inner Diameter	29 mm
Rotor Number of Bars	20
Stack Length	95 mm
Number of Poles	2
Rated Voltage	380V
Rated Power	2.2kW
Frequency	50Hz

Table 2: Test motor winding formations

Wiredia. (mm.)	Turns/Slot	Turns/Phase	Current Path	Layers	Windingpitch (Slots)	R / Phase (Ω)
2×0.67	46	184	1	1	1-12 2-11	2.302 ± 3.5% (20ºC) 3.158 (115ºC)

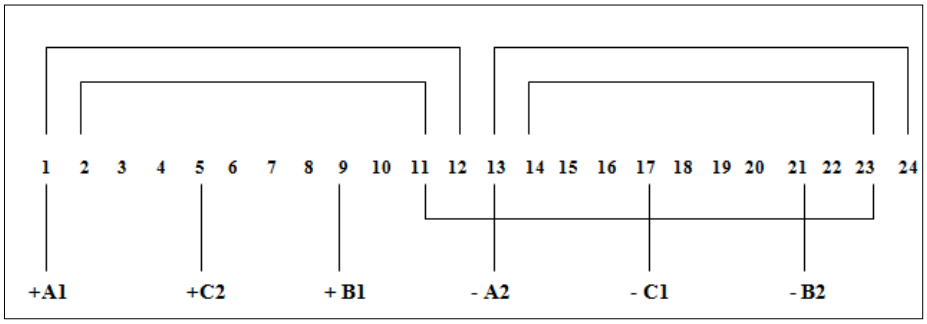

Fig. 1: Test motor winding diagram

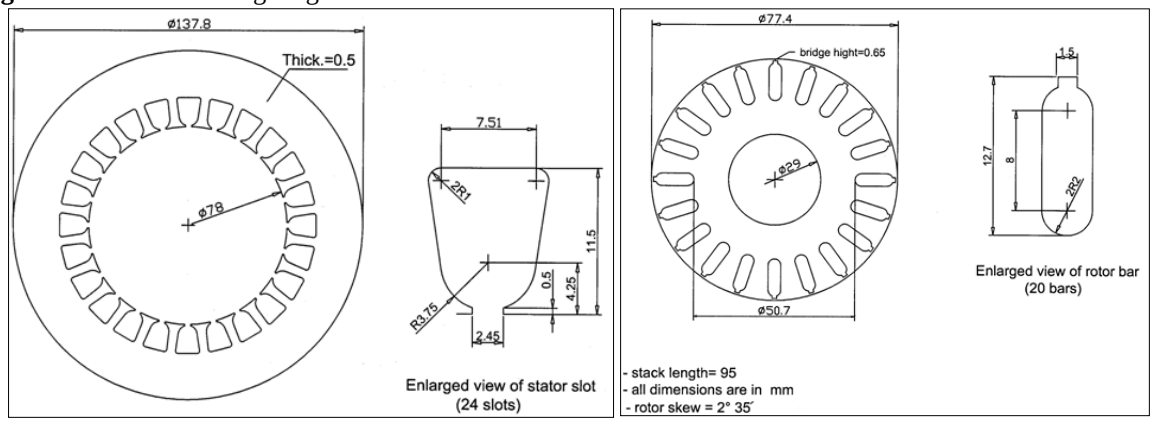

Fig. 2: Stator and rotor dimensions

The user interface of RMxprt is shown in Figure (3).

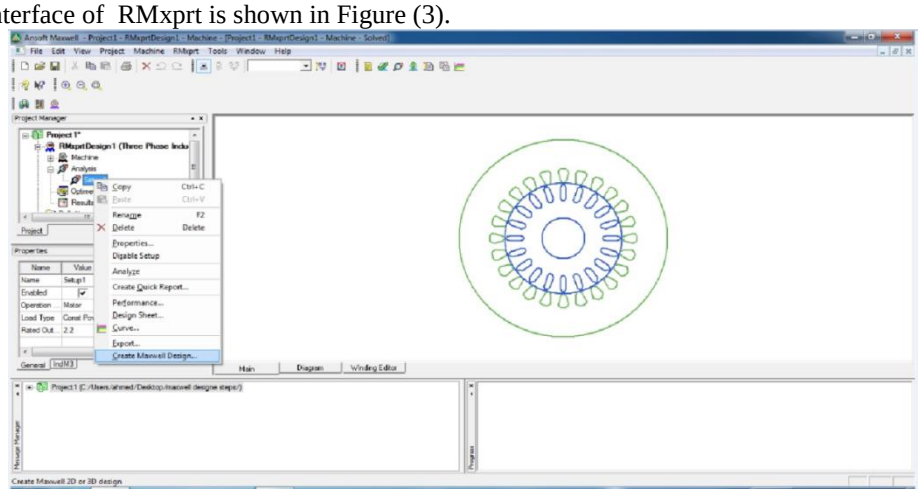

Fig.3: RMxprt user interface

2.6 Simulation of a Squirrel Cage IM with Maxwell2D:

The motor cross section shown in figure (3) above is transferred from RMxprt to Maxwell2D with a direct link. Maxwell2D uses the accurate finite element method to solve static, frequency-domain, and time varying electromagnetic and electric fields. Infigure (3,16), the user interface of Maxwell-2D and the linkage menu with RMxprt is presented.

By this model two types of faults are studied; the broken bar, and the inter turn short circuit. The Maxwell2D model of a healthy motor shown is shown in figure (4).

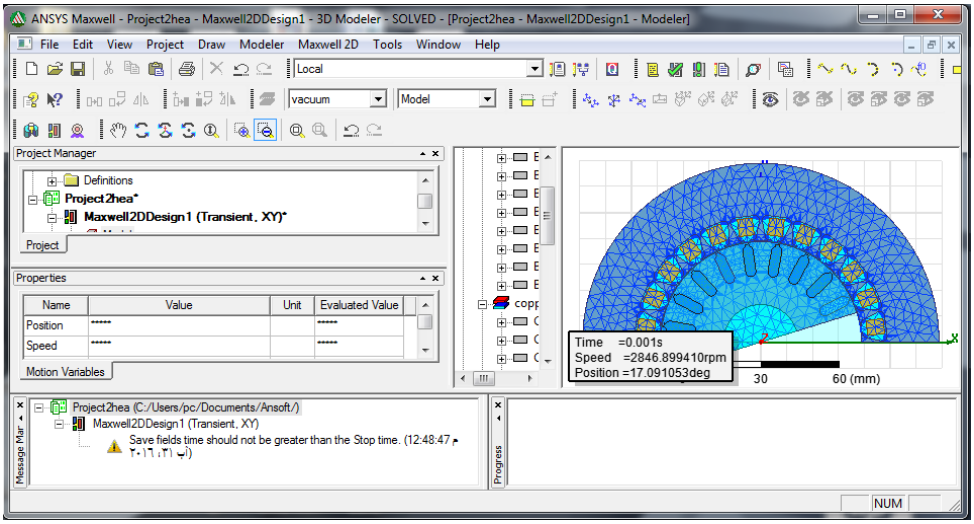

Fig.4: Maxwell2D model for a healthy 3-phase induction motor

3.Simulation Results of ANSYS Maxwell2D:

A 2-D, transient analysis has been used to solve a set of Maxwell's equations based on FEM. The magnetic field distribution of the healthy model calculated and the time variations of the stator current at no-load condition are illustrated in Figure (5).

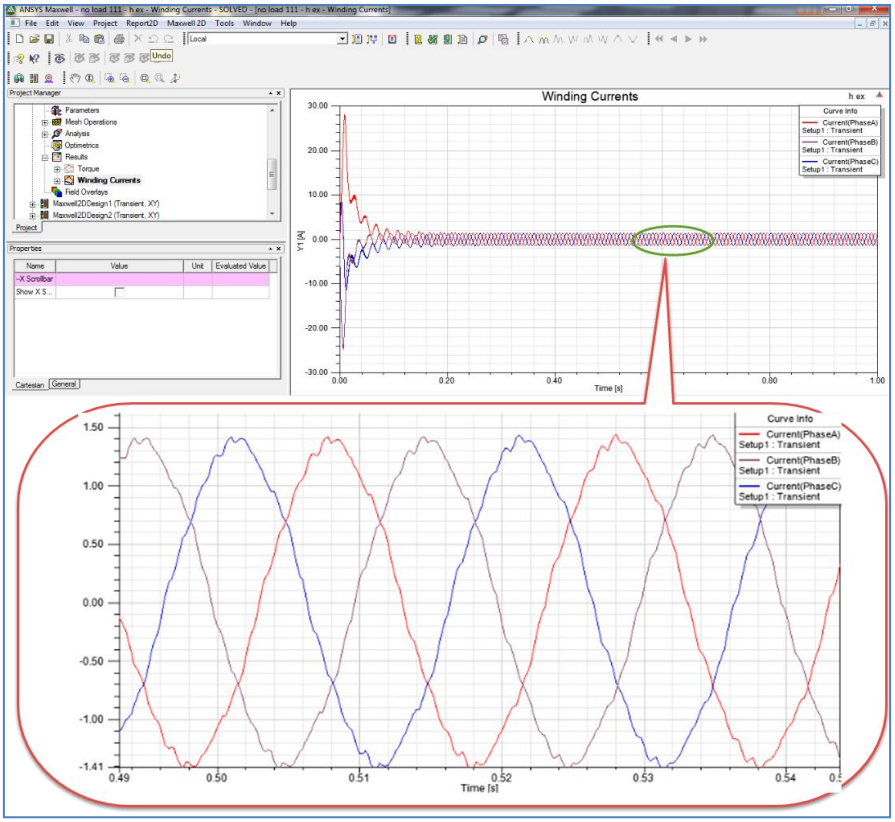

Fig. 5: The results of healthy motor currents at no-load

Some ripples in figure (5) appear. It is clear that there are twenty ripples in each cycle due to the number of rotor aluminum bars. The magnetic reluctance of the air-gap increased near the rotor slots leading to a generation of these ripples.

The comparison between the current waveform obtained in ANSYS Maxwell and that from practical test of the healthy motor in figure (6) shows a good symmetry between the two waveforms. This approves the accuracy of the ANSYS Maxwell model adopted to study other faults.

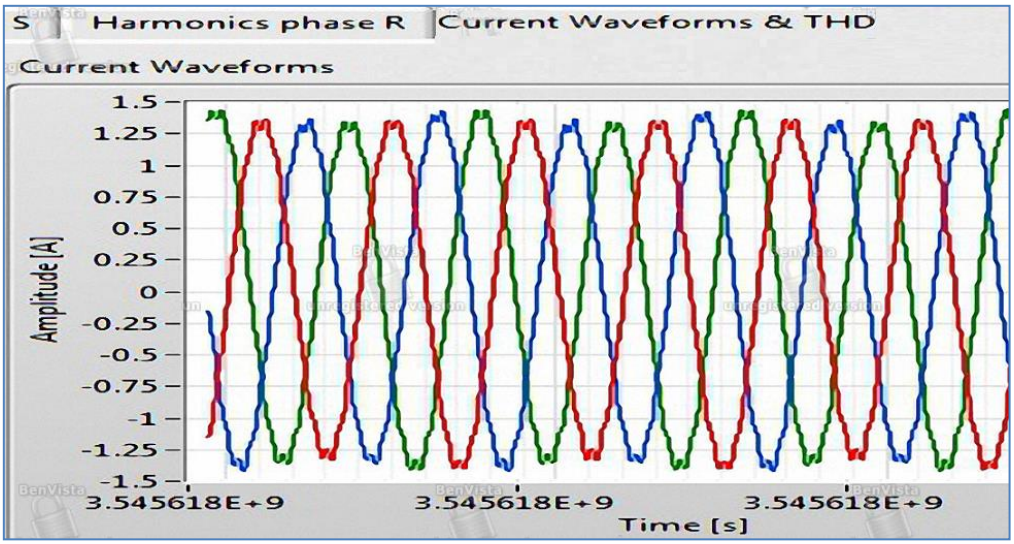

Fig.6: Currents waveforms of a healthy motor test at no load

Figure (7) shows the flux distribution of healthy induction motor at no load condition.

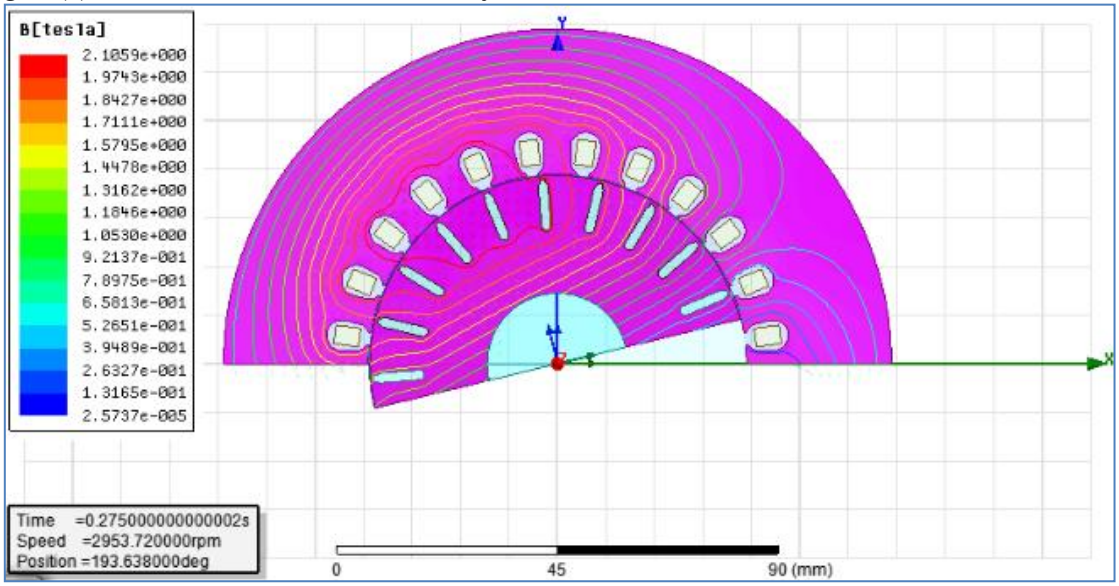

Fig.7: Flux distribution lines for healthy case at no load.

Fig.(7) Shows the flux distribution on stator and rotor. It appears that flux lines are uniformly distributed.

4. Results of Broken Rotor Bar fault:

The resistivity of rotor bars in case of faulty motor has been assumed to have a high value**.** The time variations of the stator current for one, two, and four broken bars are shown in Figure (8,9 and10).

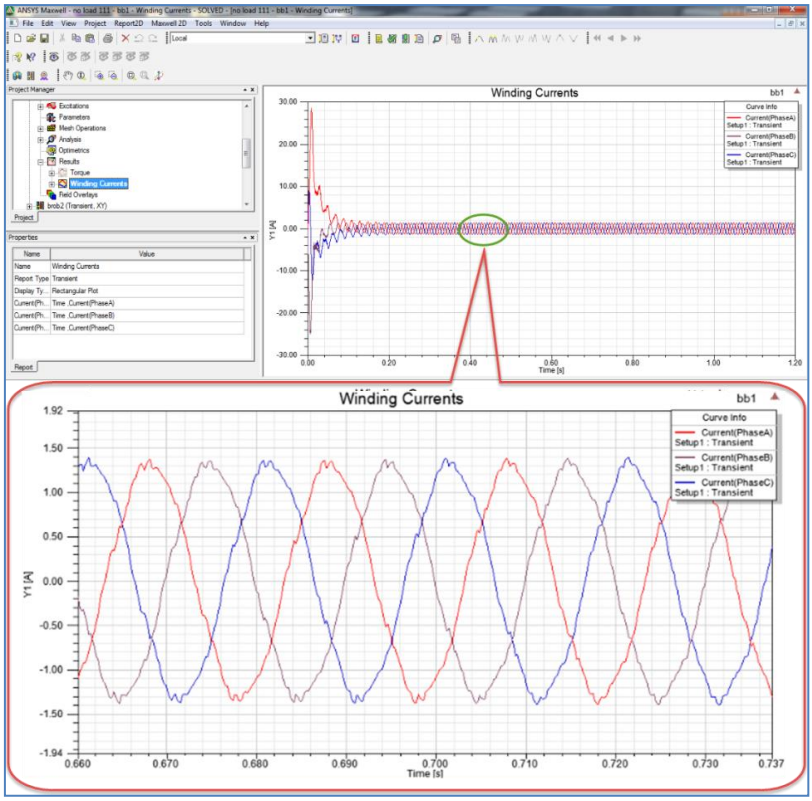

Fig. 8: Stator current at one bar broken

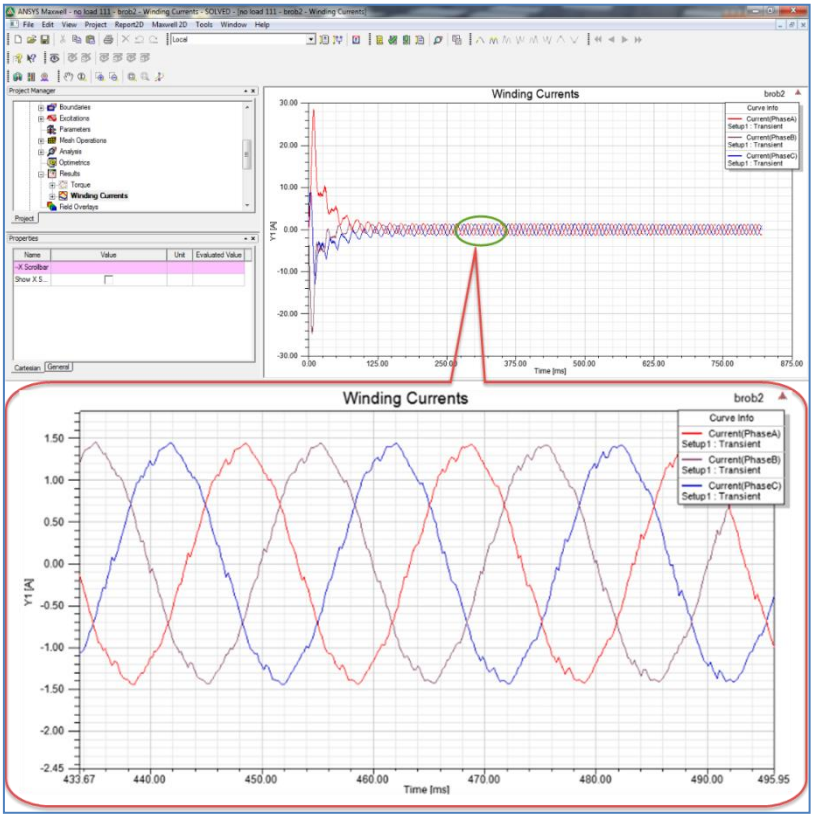

Fig.9: Stator current at two bars broken

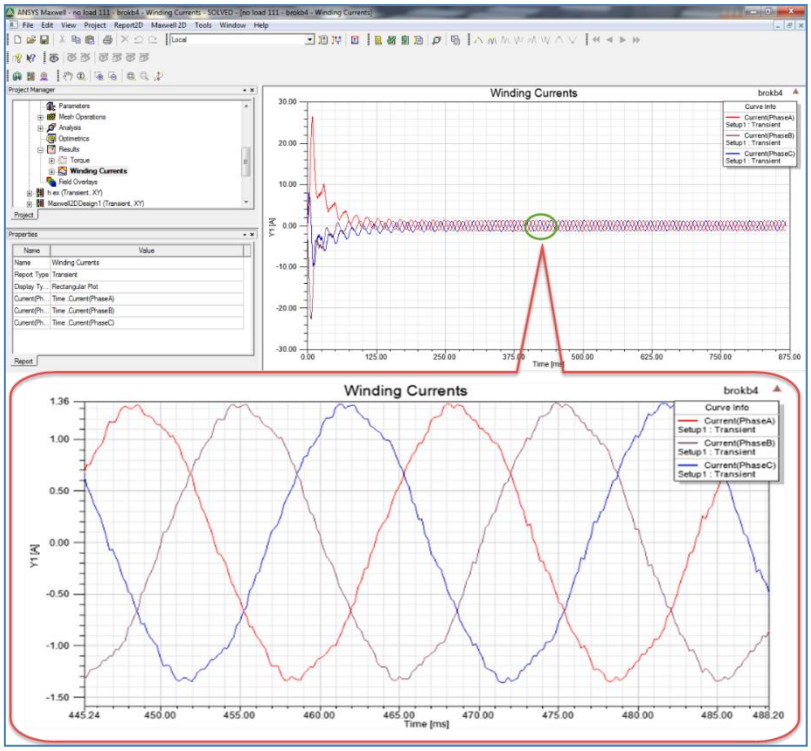

Fig.10: Stator current at four broken bars

From figures (8, 9, 10) the stator line current has a distorted shape due to a fault. Increasing the number of broken bars leads to an increase in the severity of deformation due to harmonics caused by the distortion in flux distribution and the increase of rotor impedance.

Figure (11) shows the magnetic flux density distribution for two broken rotor bars as a sample for show the effect of broken bars on the flux distribution.

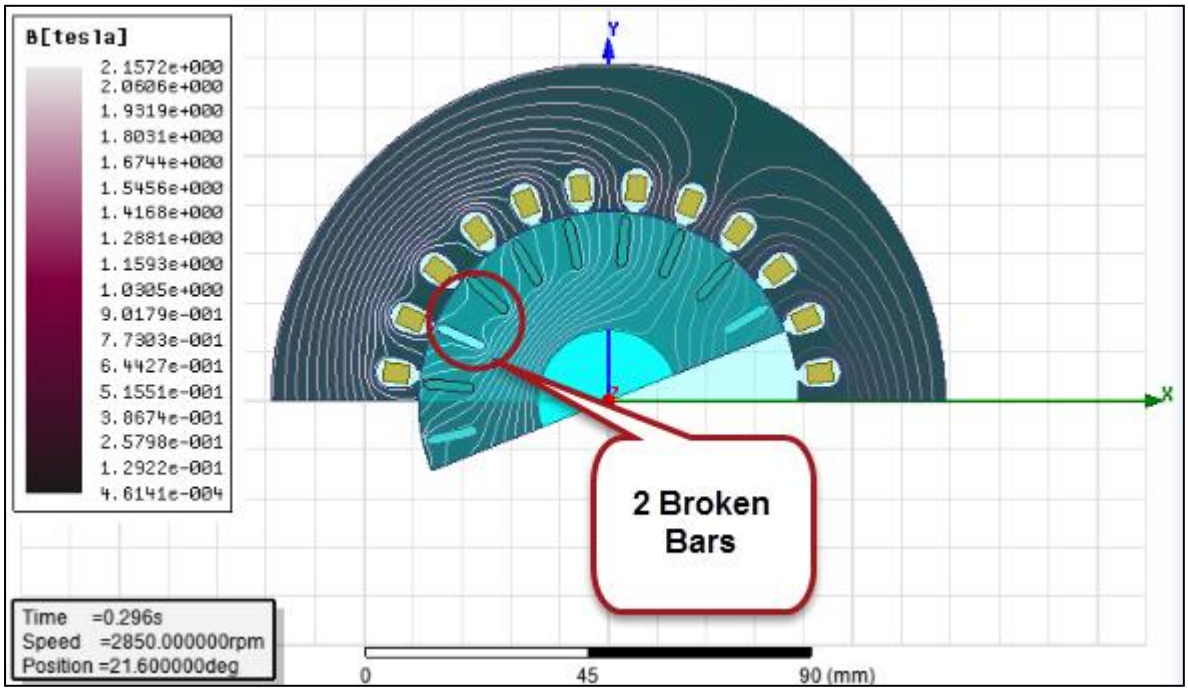

Fig.11: Fluxlines, distribution of two broken bar fault.

As shown in figure (11), the flux lines distribution is distorted around the broken bars, which will lead to the distortion in the stator currents waveform. This explains the behavior of the distortion in the current waveform in this fault which is not similar to that in other faults in that the position of the highest ripples are not

in the same position in the cycle and the current cycles are not symmetrical. This happens due to the slip in the rotor speed which leads to change the position of the broken rotor bars with respect to the stator.

5. Inter Turn Short Circuit fault:

Stator slots of the motor have one coil on each slot. In the present work, a short circuit has been expected between two adjacent coils of the same phase. Since the number of stator winding is reduced because of the fault, the stator current will be increased. This kind of faults will lead to unbalance in the number of winding w.r.t. other phases. As a result, the amplitude of harmonic components is increased. Figures (12, 13,14 and 15) present the three phase line currents of 5%. 10%. 15% and 20% of total turns short circuit respectively.

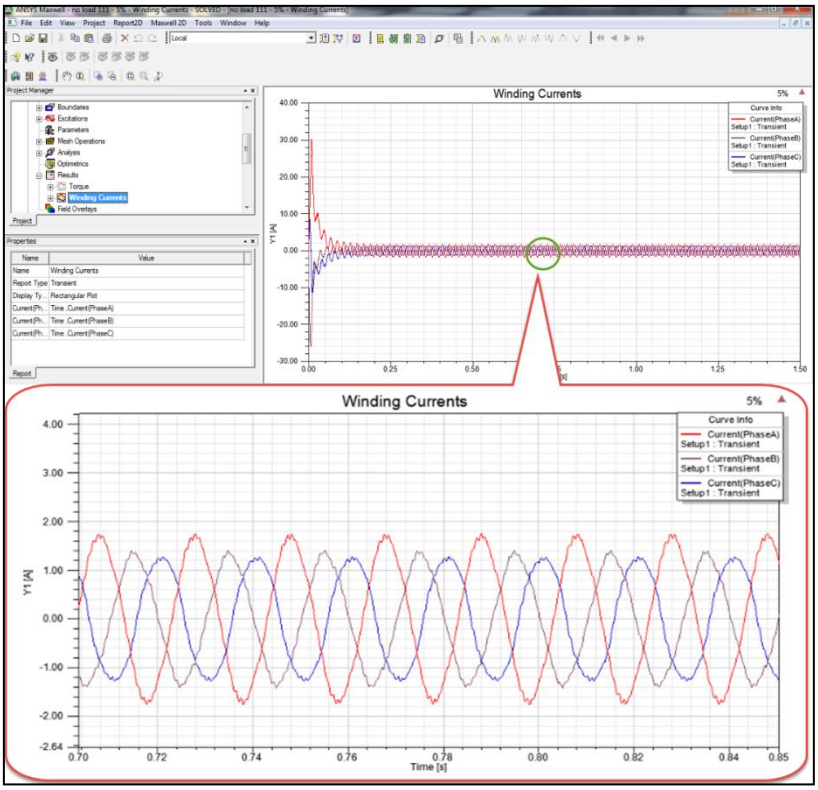

Fig. 12: Stator currents at 5% turn short circuit.

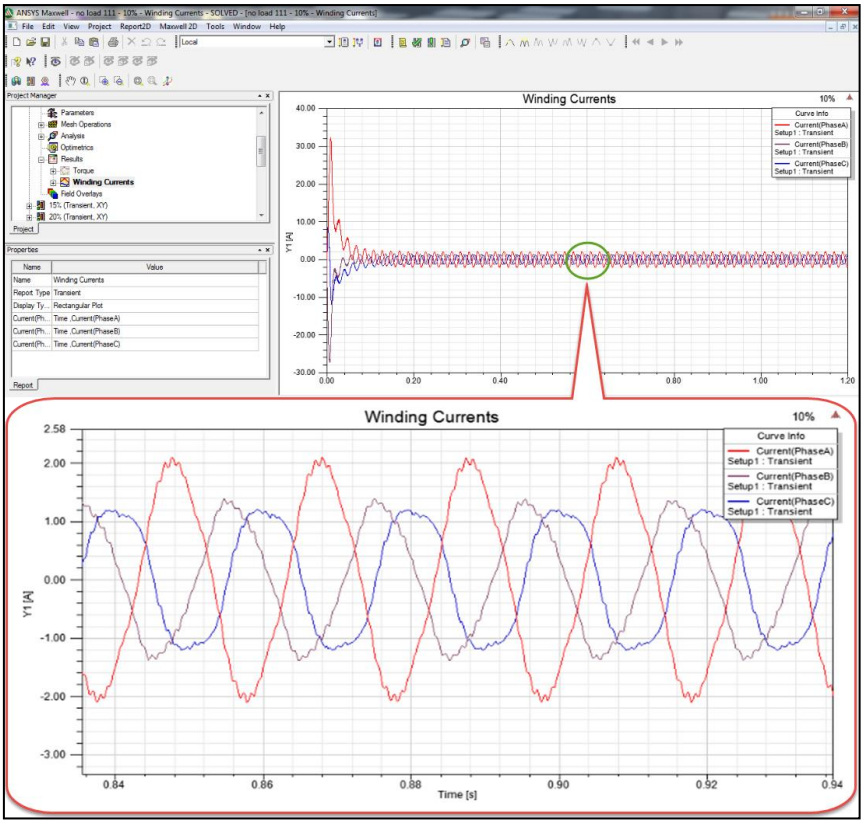

Fig. 13: Stator current at 10% turn short circuit

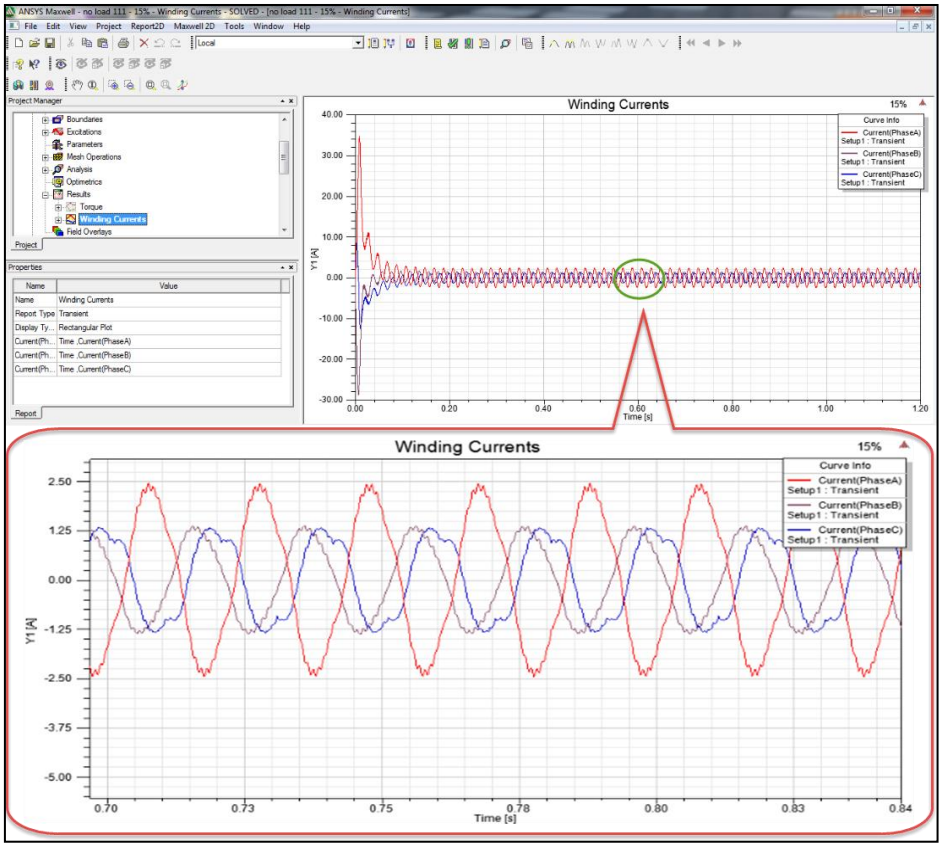

Fig. 14: Stator current at 15% turn short circuit

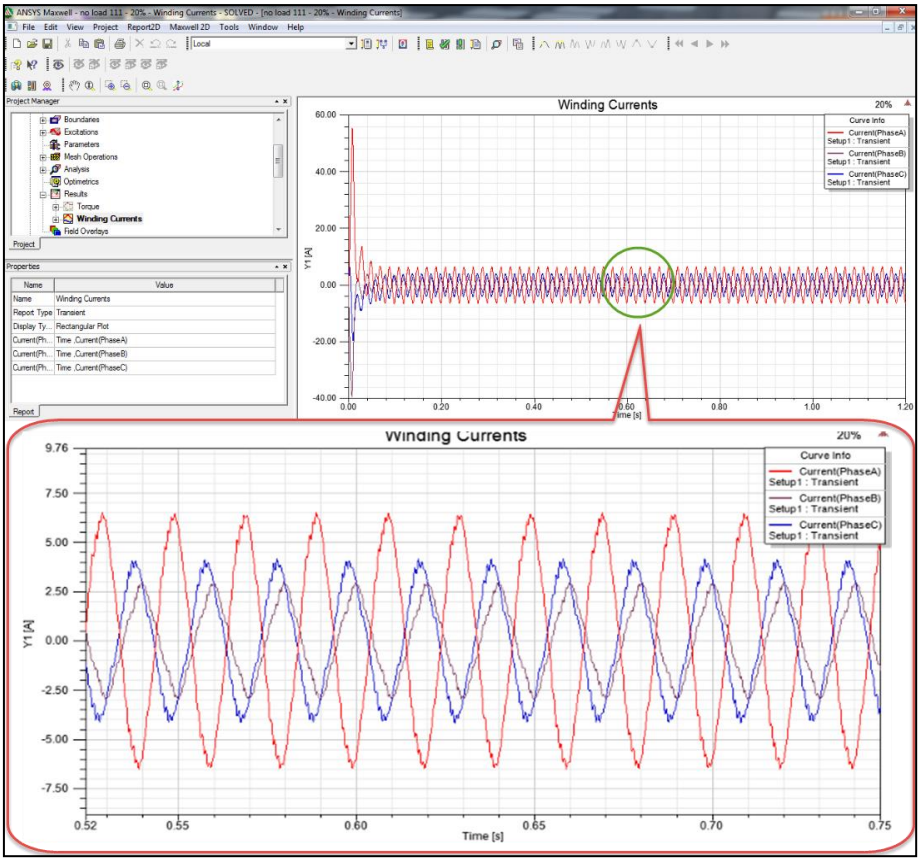

Fig. 15: Stator current at 20% turn short circuit

Figures(12,13,14, and15) show that the amplitudes of faulty phase current increased due to the decrease in phase impedance, and the ripples increased too, because of the increasing distortion of flux density, in addition the phase shift specially in 20% turn short circuit appeared in figure(15) is not exact 120º due to the reduction in the resistance and the reactance of the faulty phase leading to a considerable change in the phase shift of its current, as well as the deformation in flux distribution change the phase shift angle of other phases due to the change in their inductances affected by the flux linkage, since $L = N(d\varphi/di)$.

Conclusions:

In this research it is proved that the numerical simulation of the machine to be monitored is the best way to provide the database for the on-line monitoring system about the healthy and faulty conditions during any loading case. The 2D analysis is not able to simulate all the fault cases, but it can be used for the most probable faults. The assumptions of this simulation are difficult to be obtained practically, so heavy restrictions must be applied to achieve accurate diagnosis. Also, the occurrence of unbalanced operation during faults reveals that; this study is suitable for machines supplied from rotary synchronous generators only. It cannot be applied to an inverter fed motors, because it will show another behavior during faults, since, the inverters designed to feed balanced load only, and it can bear a small unbalance. The inverter fed motor simulation must include the inverter circuit in the model in order to study its effect on the current waveforms during faults.

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