Mansoura Engineering Journal, (MEJ), Vol. 29, No. 3, September 2004. E. 33

Design and simulation software (SRMcad) of Switched Reluctance Motor

برنامج محاكاة وتصميم محرك المعاوقة للتيار المقطع

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ازداد الاهتمام بمحركات المعاوقه للتيار المقطع خلال الأعوام الأخيرة نتيجة للمميزات التي يتمتع بها هذا النوع من المحركات مما يجعله يستخدم في كثير من التطبيقات الصناعية. والهدف الرنيسي لهذه البحث هو بناء برنامج متكاملا SRMCAD لتصميم محرك المعاوقة للتيار المستمر المتقطع ، مكتوب بلغة "Visual Fortran" ولا يتطلب استخدامه سوى الإلمام بالحد الأدنى من المعلومات المتعلقة بنظرية العمل وحساب الأداء والمعلومات الأساسية الخاصة بتصميم هذا المحرك. وتم بناء البرنامج المقترح SRMCAD على اساس سهولة تداول المعلومات الداخلة والخارجة ويقوم هذا البرنامج برسم موجات التيار والجهد والعزم ومسارات الطاقة الخارجة أمام المستخدم مما يحقق التفاعل التام بين المستخدم والحاسب الآلي. وكذلك يمكن استخدام هذا البرنامج لإعداد قائمة من قواعد البيانات التي تم إلحاقها مع البرنامج وهذه القواعد تفيد المصمم عند القيام بتصميم الآلة مما يؤدى إلى توفير الوقت والجهد .

Abstract

Switched Reluctance Machines (**SRMs**) are receiving significant attention from industries in the last decade. SRMs are rather inexpensive, reliable and weigh less than other machines of comparable power outputs. This paper presents an integrated computer program (**SRMcad**), written in ***Visual Fortran***. The program simulates an integrated algorithm, which is a combination of a design algorithm and a machine analysis algorithm. The program is used to build database for the switched reluctance motor. This database can be used in designing process to save time. The program can be used to study the changing of the magnetic materials, the air gap length, and the air gap type. The program is applied to study the effects of phase voltage, speed and the number phases on the dimensions and performance of the machine. The obtained results satisfy the expected results. This paper presents a powerful tool and computer package to design switched reluctance motor and analyze its performance under a variety of machine specifications.

1. Introduction

The performance calculation for switched reluctance machine is very complex without the help of the computer program. This is due to double saliency of this machine and the current waveform does not have a standard form. Its shape and maximum value differs, for a given design data, according to the switching instants **θon** and **θc**.. Therefore, a computer program is necessary to take over the design process.[1],[2],[3],[4]. This paper presents the strategy implemented to build the global computer program, SRMcad. The program contains a main program and 15 subroutines.

2. The main program

The main program creates the main menu form as shown at Figure (1). It consists of main form, which has seven menus as follow: -

1. File menu.
2. Initialize Data.
3. SRM Run.
4. SRM Performance (perf).
5. Grapher
6. Result Files.
7. Information

Accepted September 30, 2004.

Fig.(1): The main Menu for the Visual SRMcad Program.

2.1 File menu

As shown in Figure (2), the file menu consists of three submenus

a. Open Old Folder.
b. Create New Folder.
c. Exit.

Fig.(2): File Menu View

a. Open Old Folder

This menu to open an old folder to see the results, which, are done before: such as a different magnetic character and so on. When click on this menu a form as Figure (3) appears.

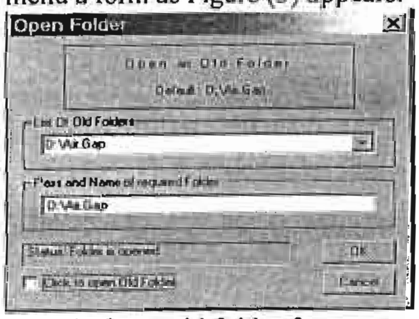

Fig.(3): Open old folder form

The user can choose the name of old folder from the list box, and click to open it as shown in Figure (3).

b. Create New Folder

For a new work, the user must create a new folder for the new run of the program. When he clicks on "Create New Folder" menu, the form of Figure (4) appears.

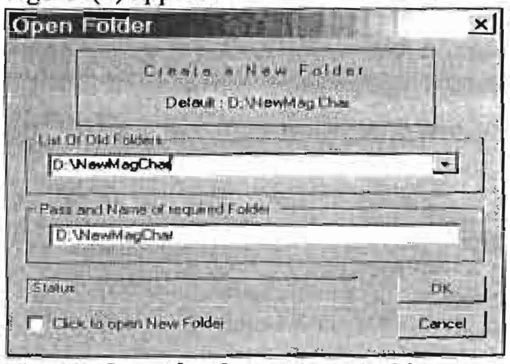

Fig.(4): Form for Create New Folder

c. Exit

To exit the program, the user can use "Exit" menu to terminate the program at any time or position.

2.2 Initialize Data

This menu is an essential one. It has all the required input data for the SRMcad program. It consists of three submenus as follows: -

a. Initialize all
b. Magnetic Material
c. Summary

This form is shown in Figure (5).

Fig.(5): Form for "Initialize data" menu

a. Initialize all

The SRMcad program needs to feed the input data firstly. These data are required to complete the program run. When the user clicks the "Initialize all" menu, Figure (6) appears.

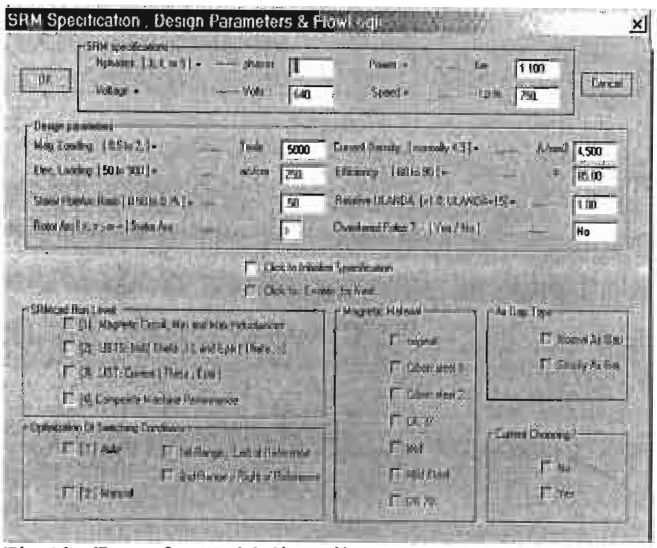

Fig.(6): Form for "Initialize all" menu

This form consists of seven parts as follows: -

1. SRM specifications
2. Design parameters
3. SRMcad Run Level
4. Optimization of Switching Conditions
5. Magnetic Material
6. Air Gap Type
7. Current Chopping

The user must edit the required specification and design parameters for the program. After that, he has to click the check box to initialize and save SRM data.[5],[6],[7]

3. <u>Run Level</u>

This level specifies the run levels for calculation. There are four levels as follows: -

1. Magnetic circuit calculations, the minimum and the maximum inductance values.
2. Lists of inductance and flux linkage as function of rotor position and current.
3. List of current as function of rotor position and flux linkage.
4. Complete machine performance.

4. <u>Choice Type</u>

The searching process about the required switching condition may be auto or manual process. For the auto process the program changes the switching on by a fixed step and makes all the calculations for the required power. Then compares this output power with the required one. If they are nearly equal, the power will be stored in a list. The user has to choose the switching on instants either to the left or to the right of the datum, where the datum is the point of starting increasing the inductance pattern. For the manual case the user himself has to enter the switching condition data.

5. <u>Magnetic Material</u>

The type of magnetic materials used in the design, has a strong effect on the performance of the SRM. It is found reasonable to select about (6) available materials that had been introduced through some pervious work by others,[6],[8]. These materials are: -

1. Carbon steel 1
2. Carbon steel 2
3. Ck-37 type
4. Losil type
5. Mild steel
6. Dk-70

6. <u>Air Gap Type</u>

The user must specify before the running, the type of air gap, whether shark type or normal one.

7. <u>Current Chopping</u>

This portion determines if the new design starts with taking the chopper current case into consideration or not.

b. <u>Magnetic Material</u>

When the user clicks the "Magnetic Material" menu, the window shown in Figure (7) appears. This form consists of seven materials as stated before.

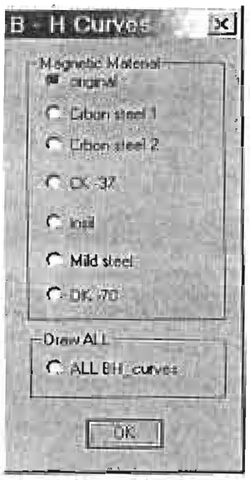

Fig.(7): Magnetic Material form

c. Summary

After finishing all the required input data for the SRMcad, the user can see a summary of the input data before the starting of calculations process.

2.3 SRM Run

After the setup of the input data, the calculations process can be started. A global program for calculation SRMcad, integrates two algorithms: the design algorithm and the expected performance algorithm. The flow chart, Figure (8), gives the main logic controlling the calculation process. Once the design specifications or parameters are given the iteration process starts.

2.3.1 The First Stage Execution

In the first design stage, the algorithm is implemented to get preliminary dimensions and phase-winding details. They are determined according to the modified expected efficiency; resulting from the pervious iteration step (n). The preliminary dimensions include the main dimensions D and L, dimensions of stator and rotor pole, and the depth of stator and rotor yoke. The main dimensions are obtained using the output equation, through a logical iterative process. This local iterative process occurs with the first stage to tolerate the design specifications, except the efficiency, to be with the permissible ranges. Once the preliminary dimensions, and the number of turns per phase are estimated, magnetic-circuit calculations can be carried out to get the different magnetization characteristics required for the second design stage. Also, the phase resistance can be determined.

In the second design stage, the expected transient and steady-state performance are calculated for each couple of switching instants; included in a given extended range of switching conditions chosen in motoring region of the inductance profile:

The transient behavior includes the current waveform, the instantaneous torque for the successive torque-strokes, as well as the instantaneous torque exerted on the motor shaft due to all phases. The steady- state performance includes the following parameters at rated power and base-speed: recommended switching conditions θon and θc, phase- current (r.m.s), average torque, input power, and efficiency are computed.

The transient and steady- state performance, and the corresponding design will be stored in a temporary list; on the condition that the steady-sate performance ensures the required machine rating. Therefore, a search process starts to pick up the best performance within list. Here, the best performance is defined as that performance expected at the highest efficiency existing in the temporary list. The highest efficiency is the modified expected efficiency; required to start the next iteration step. Finally, the best performance and the corresponding design will be stored in a permanent list. The iteration process will stop when highest efficiency shows that it becomes nearly constant.[7].[9].[10].[11].

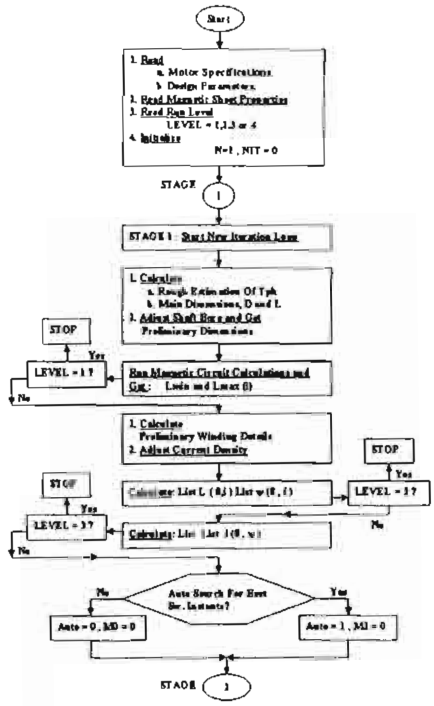

Fig.(8-a): Global Program logic , STAGE 1

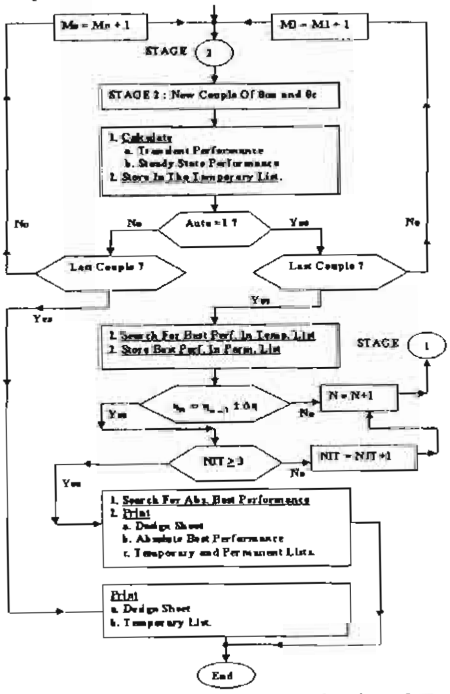

Fig.(8-b): Global Program logic , STAGE 2

It is assumed that the output equation yields the stator inner diameter D. Therefore, the air-gap length is required to estimate the outer rotor-diameter. The calculation of the air-gap length is estimated on the base of the experience gained in designing the three-phase induction motor. Relevant empirical formulas are programmed according to machine rating and speed to get an estimation of the air –gap length. The form of air gap length is shown at Figure (9). The user can accept this estimation or modify it. Also in case of shark air gap, the user must write the shark angle.

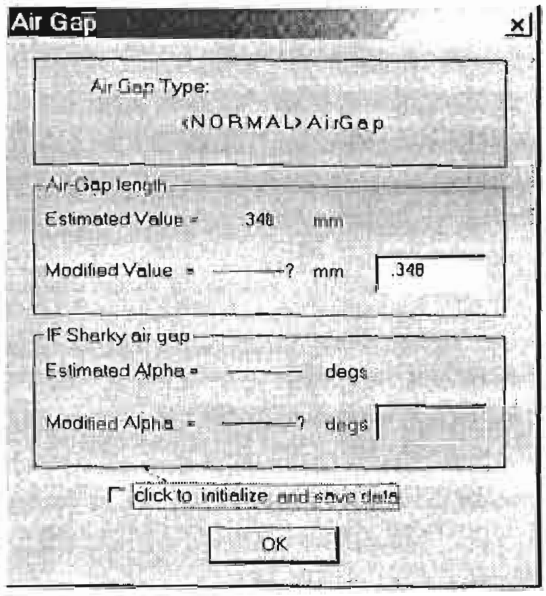

Fig.(9): Form of air gap type and length

2.3.2 The Second Stage Execution

The second stage is implemented in two steps, to calculate both transient and steady state performance. The performed calculations are directed according to the logic given in Figure (8-b). Each loop of calculations is devoted to get the machine performance expected for a given couple of switching conditions.

In case of self-creation, the user has to choose the switching-on instants to occur either to the left of the datum or to its right. In other case of manual creation, the user has to insert a group of conduction periods, followed by a group of switching instants, Figure (10). A summary of the manual process is shown at Figure (11).

In both cases, self or manual, the performance will be repeatedly calculated for a picked up conduction period and the group of switching-on instants. This step of the second stage is concerned with the calculation of the steady-state performance. Besides this performance, an additional group of specific information are calculated and registered such as:

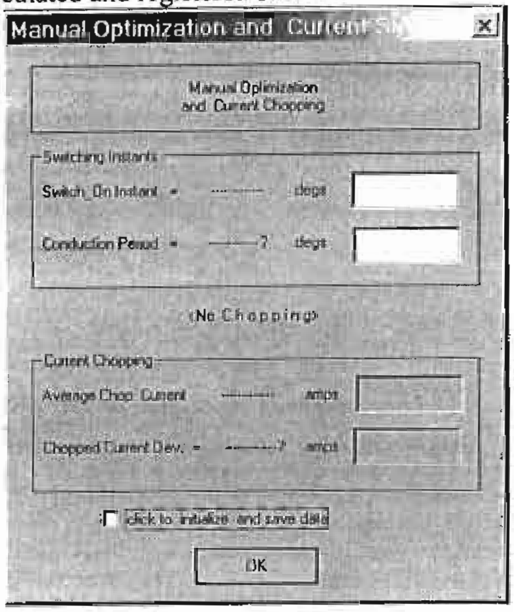

Fig.(10): Manual Optimization Choice and Current Shopping

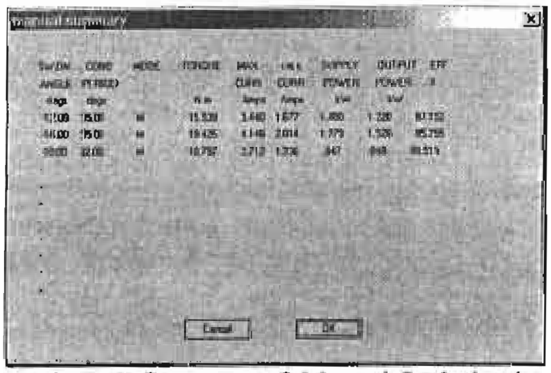

Fig.(11): Summary of Manual Optimization Choice

1. Source current
2. Maximum flux-linkage and maximum flux-density
3. Maximum current
4. Maximum and rms current densities

2.4 SRM Perf (output performance menu)

After finishing the SRMcad execution the user can see the main output data by clicking SRM Perf menu (Figure 12-a). When he clicks the SRM Perf menu the form shown in Figure (12-b) appears. This form consists of:

1. Motor Specification.
2. Design parameters
3. Limitation Dimensions
4. Pole Data.
5. Winding Data
6. The Best Performance

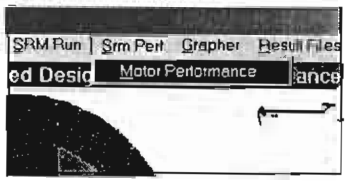

Fig.(12-a): The menu of SRM Performance

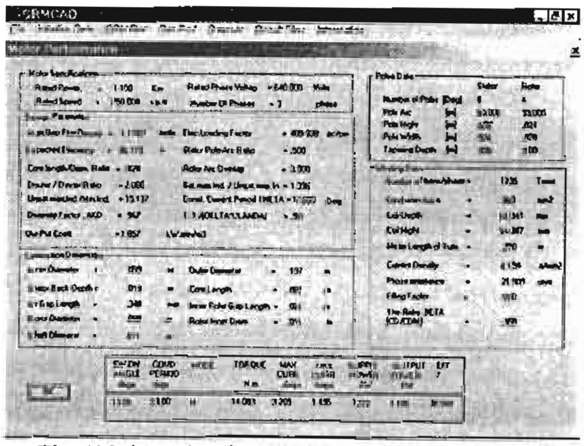

Fig.(12-b): The Form of Motor Performance

2.5 Grapher

A Grapher part is a subroutine consisting of 3651 lines. It is built using Fortran Power Station libraries version 4 [12]. It is modified for drawing all the required curves in the program. The Grapher menu is shown in Figure (13).

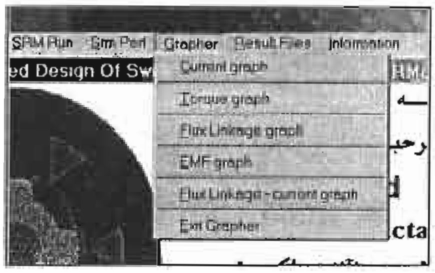

Fig.(13): Grapher Menu

The Grapher menu consists of: -

1. Current graph: This item draws the change of current (Amp), with rotor angle in mechanical degree. As shown in Figure (14-a)
2. Torque graph: This part draws the instantaneous output torque (Nm), with rotor angle in mechanical degree. As shown in Figure (14-b)
3. Flux Linkage graph: The objective of this submenu shows the relation between the flux-linkage (volt sec) with rotor angle in mechanical degree. This graph is shown in figure (14-c)
4. FluxLinkage-current graph: to draw the variation of flux-Linkage with current. This is shown in Figure (14-d)
5. EMF graph: to draw the relation between the EMF (volt) with rotor position in mechanical degree. This is shown in Figure (14-e)
6. Exit Grapher : to exit from grapher program.

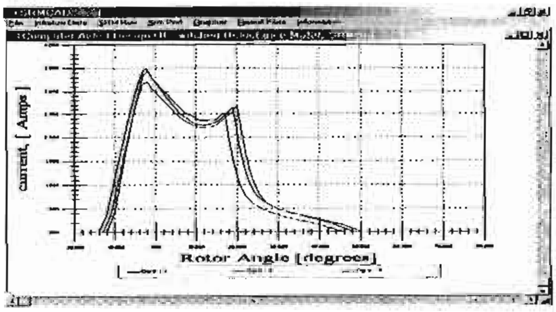

Fig.(14-a): Current graph

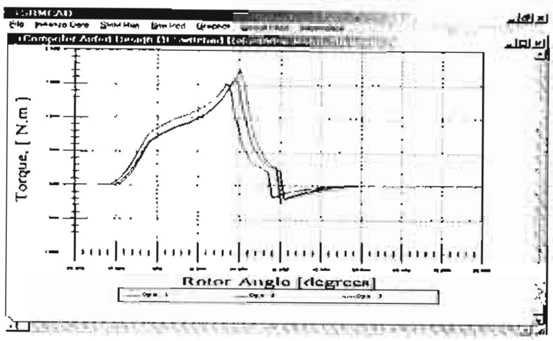

Fig.(14-b): Torque graph

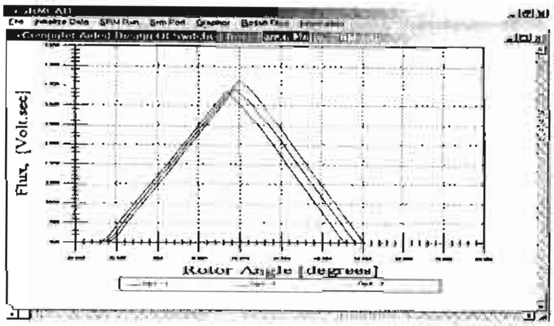

Fig.(14-c): Flux Linkage graph

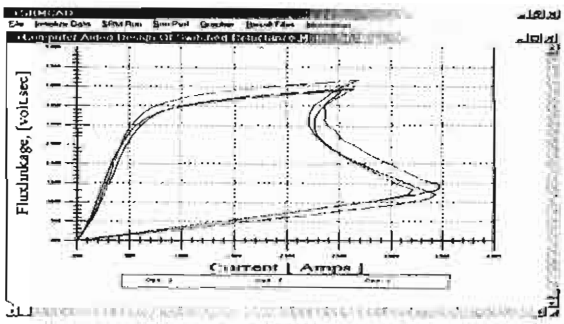

Fig.(14-d): Energy loop graph

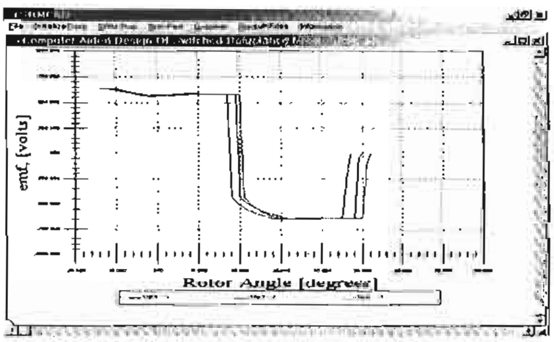

Fig.(14-e): EMF graph

2.6 Result Files

The output data can be summarized as follows:

1. Design Sheet
2. Minimum Inductance
3. Detailed Results of Magnetic Circuit Calculations
4. Magnetization Characteristics
5. Steady-State Performance
6. Transient Performance

3. Data Base

The SRM database is an important tool to study the machine design and performance. It is composed of some information about the machine parameters put in numerical or graphical forms. After finishing the SRMcad design, the author has checked the program by applying it on a reference example [2]. A good agreement was found between the obtained results and the test example. The program is then used to create a database for the SRM machine to facilitate the problem of design for unprofessional users. The program is applied for different ranges of output powers and speeds. A complete input and output data about the running are stored in numerical tables. Theses tables contain all data about the motor specifications, design parameters, run level, magnetic characteristics, air gap type and control parameters. For 3 phases, 640 voltage, and original magnetic material the database is built for a range of output power from 1 kW to 3.10 kW by step 0.1 kW and a range of speed from 750 rpm to 3000 rpm. All data such as efficiency, magnetic loading, electric loading, current density, conductor area, the maximum to minimum inductance ratio, and so on are stored in tables. A graphic form of these data are illustrated in Figures (15)- (21)

Where

- Figure (15) shows the relation between the efficiency and output power for different speeds
- In Figure (16), the current density is plotted.
- The stator inner diameter, conductor area, mean length of turn, number of turns per phase, and finally phase resistance are shown in figures (17)-(21)

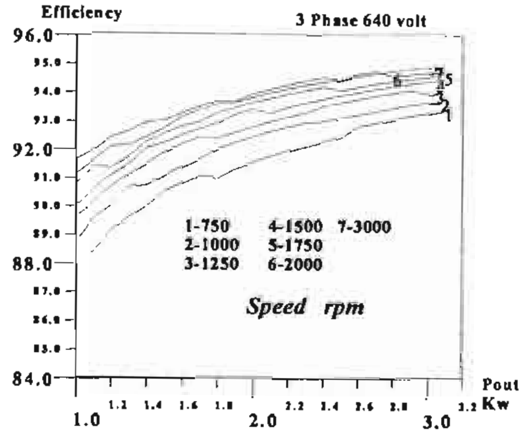

Fig.(15): The variation of efficiency with output power at 640 volt for different speeds

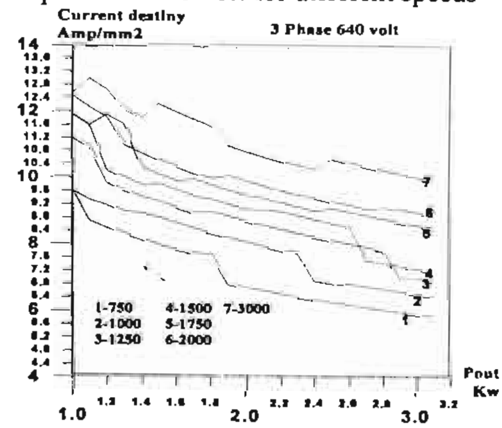

Fig.(16): The variation of current density with output power at 640 volt for different speeds

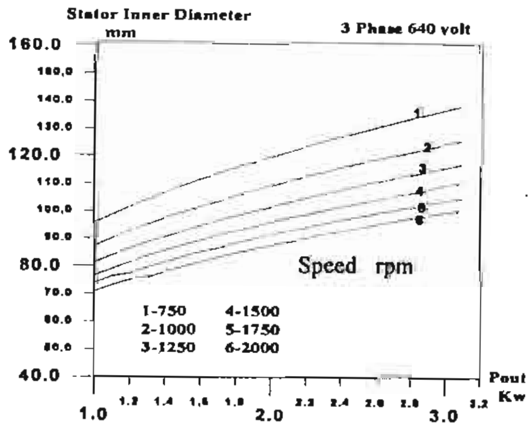

Fig.(17): The variation of stator inner diameter with output power at 640 volt for different speeds

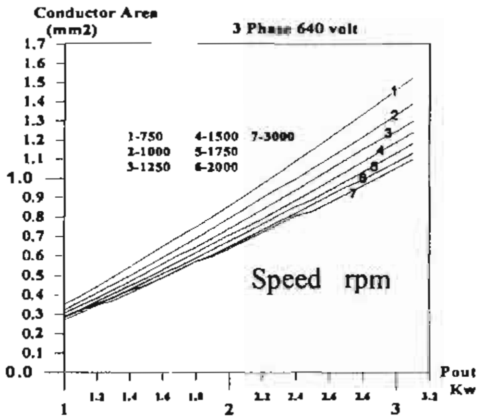

Fig.(18): The variation of conductor area with output power at 640 volt for different speeds

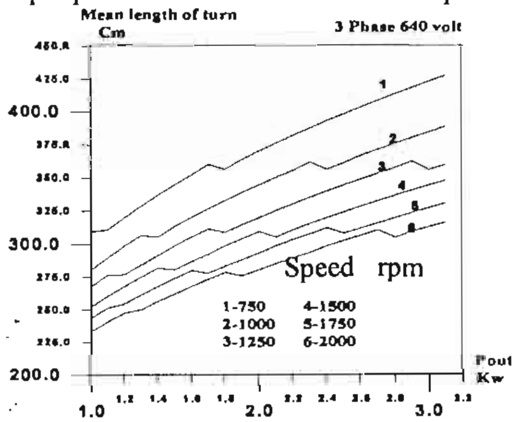

Fig.(19): The variation of mean length of turn with output power at 640 volt for different speeds

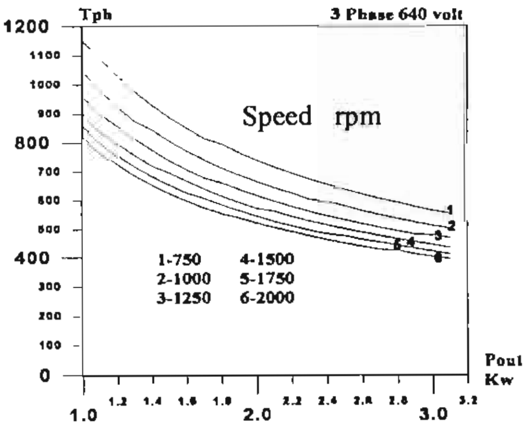

Fig.(20): The variation of Tph with output power at 640 volt for different speeds

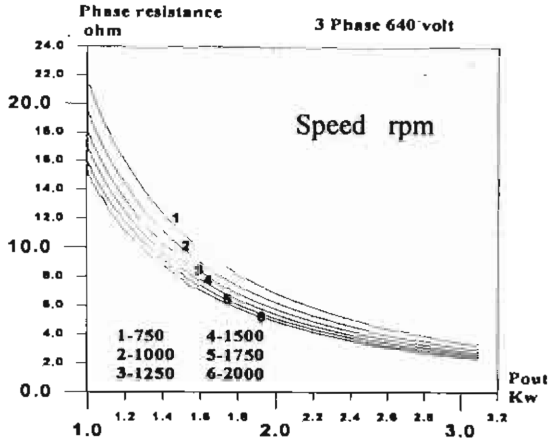

Fig.(21): The variation of phase resistance with output power at 640 volt for different speeds

4 Conclusion

The design and performance calculation of the SRM is not an easy task.. This paper presents the strategy implemented to build the global computer program, SRMcad, which is written in ***VISUAL FORTRAN.*** The program contains a main program and 15 subroutines. The main items discussed and concluded in this paper are:

- Different program menus are built and analyzed in details.
- Main flow charts for the main global process are represented.
- The program execution steps are studied in details.
- Program Grapher is modified for drawing all the required curves in the program.
- The program is used to create a database for the SRM machine to facilitate the problem of design for unprofessional users.
- The program is applied for different ranges of output powers and speeds. A complete input and output data about the running are stored in numerical tables.
- The SRM database is an important tool to study the machine design and performance. It is composed of some information about the machine parameters put in numerical or graphical forms.

References

[1] L. Henriques, P. Costa, L. Rolim and W. Suemitsu, "Automatic learning of pulse current shape for torque ripple

minimization in switched reluctance machines", European Control Conference (ECC2001), Porto – Portugal, 2001

[2]. T. Miller, "*Switched reluctance motors and their control*", Magna physics publishing and Clarendon proceedings Oxford,1993.

[3] P. Lawrenson, J. Stephenson, Blenkisop, J. Corda and N. Fulton, "*Variable-speed switched reluctance motors*", IEE proceedings, Vol. 127, Pt. B., No. 4, 1980.

[4] T. Miller, "*Brushless permanent-Magnetic and reluctance motor drives*", Clarendon proceedings, 1989.

[5] Y. Tang, "*Characterization, numerical analysis and design of switched reluctance motors*", IEEE proceedings, Vol. 33, No. 6, 1997.

[6] M. El-Sersawy, "*Analysis and experimental investigations of switched reluctance machines*", Ph. D. Thesis, Dept. of Electrical power & Machine, Faculty of Engineering, El Mansoura University, Egypt, 1989.

[7] R. Krishnan, R. Arumugam and J. Lindsay "*Design procedure for switched reluctance motors*", IEEE Vol.24, No.3,1988.

[8] Finite Element Method Magnetics (FEMM) home page at :*http://www. FEMM.htm*

[9] P. Rasmussen, F. Blaabjerg, J. Pedersen and F. Jensen, "Switched reluctance-shark machines- more torque and less acoustic noise", Conference Record of the 2000 IEEE , Vol.1, Oct., 2000

[10] J. Lindsay, R. Arumugam, and R. Krishnan, "*Finite- element analysis characterisation of a switched reluctance motor with multitooth per stator pole*", IEE proceedings, Vol. 133, Pt. B., No. 6,1986.

[11] Y. Sofiane, A. Tounzi and F. Piriou, "*A non linear analytical model of switched reluctance machines*", page at : *http://www. Eur.htm*

[12] Microsoft® FORTRAN Power Station, "Language Guide",1993