01 Oct 2005

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Recommended Citation

J. W. Kimball and M. Amrhein, "Machine Design Considerations for the Future Energy Challenge," *Proceedings of the Electrical Insulation Conference and Electrical Manufacturing Expo (2005, Indianapolis, IN)*, pp. 448-453, Institute of Electrical and Electronics Engineers (IEEE), Oct 2005.
The definitive version is available at https://doi.org/10.1109/EEIC.2005.1566339

MACHINE DESIGN CONSIDERATIONS FOR THE FUTURE ENERGY CHALLENGE

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Abstract – Motors consume a significant fraction of electricity in the United States and in the world. As part of the International Future Energy Challenge, student teams are endeavoring to improve the efficiency of fractional-horsepower machines. The present work summarizes the motor design and construction process for a 500 W prototype induction machine targeting efficiency above 80%. Analytical and finite-element results are shown.

I. INTRODUCTION

The International Future Energy Challenge (FEC) is a biannual international student competition for innovation, conservation, and effective use of electrical energy. The first competition in 2001 focused on dc-ac converters for fuel cell power systems. It was organized by the U.S. Department of Energy (DOE), in partnership with the National Association of State Energy Officials (NASEO), the IEEE, and the Department of Defense (DOD). The theme of the 2003 Future Energy Challenge was "Energy Challenge in the Home," and was aimed at new design innovations that could demonstrate dramatic reductions in residential electricity consumption. One of the topics was a single-phase adjustable speed motor drive, with the goal of designing low power, cost-effective, and efficient motor-drive combinations running from a residential single-phase power source. A team from the University of Illinois at Urbana-Champaign (UIUC) participated successfully in this topic [1], gaining second place overall. The single-phase adjustable speed motor drive is again a topic at the 2005 Future Energy Challenge [2].

The "single-phase adjustable speed motor drive" topic is aiming at innovations in motors and motor drive system that drastically decrease losses and cost when used in home appliances such as refrigerators, or that could replace universal motors in residential applications. The goals are to construct a 500 W motor drive system for a manufacturing cost of less than $40 per unit in a high-volume production. A target efficiency of 70% is desired for shaft loads ranging from 50 W to 500 W in a speed range of 150 rpm to 5000 rpm. The system has to meet an acceptable standard in reliability and safety. The weight should not exceed 8 kg, and the volume should be less than 4 L. In addition, acoustic noise should be kept to a minimum (less than 50 dBA sound level measured 0.5 m from the unit). The complete specifications of the single-phase adjustable speed motor drive topic are given in [2].

The critical part of the complete system is the motor, which must maintain high efficiency over a large power and speed range, and must deliver 3.18 N-m from 150 rpm to 1500 rpm. The motor construction needs to be open drip proof, suitable for indoor and outdoor domestic applications in ambient temperatures of –20°C to 40°C. The motor must be no larger than a NEMA 48 frame size. The motor technology and other motor design choices are not restricted.

In the 2003 Future Energy Challenge, the UIUC team built an integrated drive system based on a three-phase induction machine, Fig. 1. Although some of the specifications were not met, the system demonstrated a proof of concept. Valuable experience was gained in this competition, in particular about building motor prototypes, which was applicable again in the 2005 competition.

In the current work, the motor design considerations for the FEC 2005 team from UIUC are discussed. First, possible machine topologies and their trade-offs are discussed. Then, the design of the motor and the prototype construction are discussed in detail in the following section. Finally, simulation results are presented.

II. CONSIDERED MACHINE TOPOLOGIES

A. Switched Reluctance Machine

The switched reluctance machine (SRM) is a possible alternative to a permanent magnet machine or an induc-

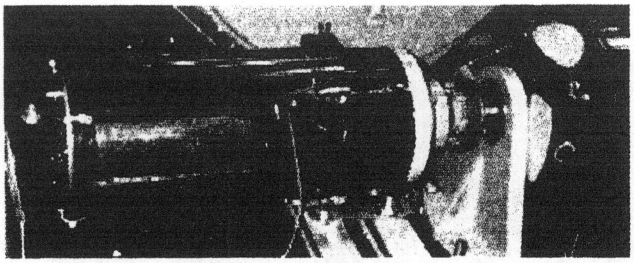

Fig. 1. iDRIVE – Integrated Drive from the University of Illinois for the 2003 Future Energy Challenge.

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tion machine for the given application. The simple concept of operation and the trivial rotor setup of an SRM, compared to other machine types, are attractive for a cost-effective solution. A basic design estimated the total cost of the machine to be about $9, which is significantly lower than the other machine types considered, as will be seen later. With an SRM, there are no expensive magnets to purchase, and exact speed control is possible without speed feedback. An SRM has a high reliability due to the absence of high maintenance parts such as brushes and an inherently strong, all-steel rotor.

The initial design of the machine yielded some basic parameter values of the performance and the physical dimension. In particular, the physical dimensions of the machine did not agree with the maximal dimensions given for this project. The weight of the machine was estimated to be 14 kg, already 6 kg higher than the proposed limit, demonstrating the low output power per unit mass inherent to this technology. Typical commercial designs improve power density by increasing speed, which is not an option for the FEC. To decrease the torque ripple as well as the audible noise, a substantial number of phases are required, which increases the cost of the machine as well as the cost and complexity of the power electronics components. For these reasons, the team considered SRM technology to be inappropriate for this competition.

B. Permanent Magnet Synchronous Machine

Another well-known machine technology is the permanent magnet synchronous machine (PMSM). The key advantage of PMSMs is that they are highly efficient compared to other machine types due to the large air gap flux densities. Further, this high air gap flux also allows smaller machines, improving the output power per unit mass. A PMSM is reliable due to its absence of brushes. Some of features considered to be disadvantages compared to other machine topologies are the construction complexity of the machine due to the permanent magnets in the rotor, and the overall cost of the machine due to the permanent magnets. Another significant disadvantage of a PMSM is the necessity to have precise knowledge of the rotor position, which requires including sensors in the machine construction, again increasing the cost.

A basic design of a PMSM for the purpose of the challenge yielded an efficiency of roughly 85%. The proposed dimensions yield an estimated machine volume of roughly 1 L, resulting in a high power density of the machine. However, the cost of the machine is high. The permanent magnets alone would cost roughly $8. The steel laminations and copper were estimated to be another $8, resulting in a $16 machine.

PMSMs inherently trade high efficiency and small mass for high cost. In addition the increased complexity in building a PMSM compared to other machine types, the team decided that the cost was too important for this competition. These considerations were confirmed by the automotive industry, where design trade-offs like these have been made for the last several years [3], [4].

C. Induction Machine

The induction machine has several advantages that would make it the preferred machine choice in the FEC project. The main benefits of the induction machine are that it is robust, easy to use, and low cost in fabrication and service compared to other motor topologies. (The initial cost estimation of the induction motor is about $11.) The natural disadvantage of a standard induction machine is that the efficiency is low if the machine is not operated at rated load and speed. However, due to the experiences with induction machines accumulated in the 2003 FEC competition [1], [5], the team's decision was to use the induction machine as the machine topology. The goal was to design an induction machine with high efficiency over a larger load range when operated from a power electronics drive.

A multi-phase machine topology is preferred compared to a single-phase machine due to the efficiency. Since the induction machine has in general a lower efficiency than, for example, a permanent magnet synchronous machine, a single-phase induction machine would limit the efficiency of the complete system even more. Thus, to target a total system efficiency of 70% or more, a multi-phase induction machine needs to be considered. Preferably, it will be a three-phase induction machine, since solutions for control and power electronics already exist for three-phase machines.

D. Exterior-Rotor Induction Machine

The mechanical design of the machine will have a strong impact on the rest of the drive system. Two different induction machine topologies were considered. The first topology is the standard induction machine with the fixed stator on the outside and the rotor on the inside. The machine will have a relatively low inertia, and the mechanical setup is very simple. The second topology is an induction machine with the rotor on the outside, and the stator on the inside, a so-called exterior-rotor machine. The reason for this design is to increase the inertia of the machine, thus increasing its mechanical time constant. The team considered taking advantage of the energy stored in the inertia to offset energy storage in dc bus capacitors, which are a significant fraction of the size and cost of the power electronics.

The rotor rotates around the stationary center of the machine, where all the stator windings are incorporated. The stator windings are connected via a hole in the stationary

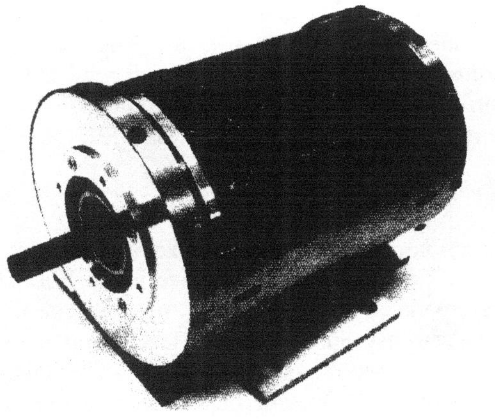

Fig. 2. Model of exterior-rotor machine. Seen through the cut-away is a stereolithograph approximating the rotor.

shaft. This design is mechanically very challenging. High-precision bearings are required because with the higher inertia, there will be more vibration. Since large high-precision bearings are too expensive, this design uses the same size bearings as the interior rotor induction motor design. In order to assemble and disassemble the motor, a spacing disk must be fabricated to allow the rotor to fit around the stator during assembly. The estimated moment of inertia for this design is 8 to 10 times larger than for a conventional induction machine of the same size.

Although the exterior-rotor induction machine was a valuable option, the challenges in its mechanical and electrical design were more difficult than for a standard machine design. As a proof of concept, a model of the outer-rotor machine was built to show the mechanical design aspect of the machine, Fig. 2. The electrical design was not completed due to the lack of tools and experiences for designing an exterior-rotor induction machine. Moreover, the methodology for taking advantage of the mechanical energy storage has not been adequately explored. Thus, the team's final decision was to design a standard induction machine for the 2005 FEC competition.

III. DESIGN PROCESS

The detailed specifications that the induction machine needed to meet are given in Table I. The nominal speed of the machine is 1500 rpm, with a torque of 3.18 N-m, resulting in a nominal shaft power of 500 W. The speed range of the machine ranges from 150 rpm up to 5000 rpm. The efficiency anticipated is at least 80% at nominal load, such that the overall system efficiency of 70% could be achieved, allowing for some losses in the electronics. The dimensional limitations of the machine are given in Table I as well.

TABLE I

INDUCTION MACHINE SPECIFICATIONS

Parameter	Specification
Speed range	150 rpm – 5000 rpm (1500 rpm nom.)
Nominal torque	3.18 N-m from 150 rpm – 1500 rpm
Shaft power	500 W from 1500 rpm – 5000 rpm
Efficiency	> 80% at nominal load
Audible noise	< 50 dBA 0.5m from the unit
Overall length (incl. shaft)	< 197 mm
Stator diameter	< 153.2 mm
Mounting	NEMA Frame Size #48
Environment	Open drip proof
Storage temperature	-20°C to 60°C

Initial design work included the choice of the number of poles, the number of stator and rotor slots, the stator inner diameter, the lamination stack length, and the airgap length. These parameters were used as inputs to a design software, RMxprt from Ansoft, as well as various other parameters concerned with the stator winding, stator and rotor slot sizes. Rotor endring design could be considered, in addition to optimizing the initial design parameters.

Due to the large speed range and the nominal speed of 1500 rpm, the number of poles of the machine was chosen to be four. This requires electrical frequencies of 16.7 Hz up to 167 Hz in order to satisfy the speed requirements, well within the normal capabilities of lamination steels. A two-pole machine could have been chosen, which would yield a higher efficiency, but the low speed requirement might have been difficult to satisfy. The dimensional parameters were determined using basic calculations from [6], [7]. Assuming an average flux density B_{av} of about 0.8 T, an electric loading ac of 10,000 ampère-conductors per meter, a winding factor K_w of 0.955, and a power factor of 0.8, the D^2L coefficient was determined as

$$D^2L = \frac{P}{1.11\eta \cdot \cos(\phi) \cdot n_s \cdot \pi^2 \cdot B_{av} \cdot ac \cdot K_w}, \qquad (1)$$

where n_s is the synchronous speed in rev/s, D the stator inner diameter and L the stack length. Assuming a ratio of stack length to pole pitch, L/τ, of about 1.1, and knowing that the pole pitch τ is

$$\tau = \frac{D \cdot \pi}{p}, \qquad (2)$$

where p are the number of poles, D and L can be determined to be 75.6 mm and 63 mm, respectively. These dimensions consider enough space for the stator back iron, and take the maximum motor length into account.

The airgap was initially chosen to be 0.3 mm. The number of stator slots was chosen to be 24, meaning that there are 6 slots per pole. The number of rotor slots was selected to be 17, according to rules for slot combinations given in [6], [7]. For the stator winding, a two-layer lap winding with a coil pitch of 5/6 of the pole pitch was selected, resulting in a coil pitch of 5 slots.

With this initial design, RMxprt was used to design and optimize the complete stator winding, the slot geometries, and the endrings. RMxprt uses analytical formulas to calculate the performance of a machine based on its physical design. The design goal was a highly efficient motor at nominal load and speed, as well as a steep torque-speed characteristic close to synchronous speed, which would minimize speed variations at small load changes. Initially determined parameters were also altered in order to meet the given criteria.

The important parameters of the final design are tabulated in Table II. The stator and rotor lamination designs are shown in Fig. 3. On the stator laminations, a small part on the bottom needed to be cut off in order to satisfy the size requirements of the NEMA 48 frame. The material chosen for the laminations was M15-26 gage steel, and aluminum A356 for the rotor bars and endrings. The steel was selected to minimize the core loss, whereas the aluminum was selected as a compromise between conductivity and suitability for casting.

IV. PROTOTYPE

After laser-cutting the laminations, the stator lamination stack was assembled, pressed and welded into a tube of rolled steel with an outer diameter equal to the maximal allowed size. The pressing of the stack guaranteed a high stacking factor, and thus increases the effective stack length as well as the shaft torque of the machine. The stator was then wound with 12-lead configuration, allowing us to connect the windings in four possible winding arrangements. The intended design was a high-voltage wye connection of the windings.

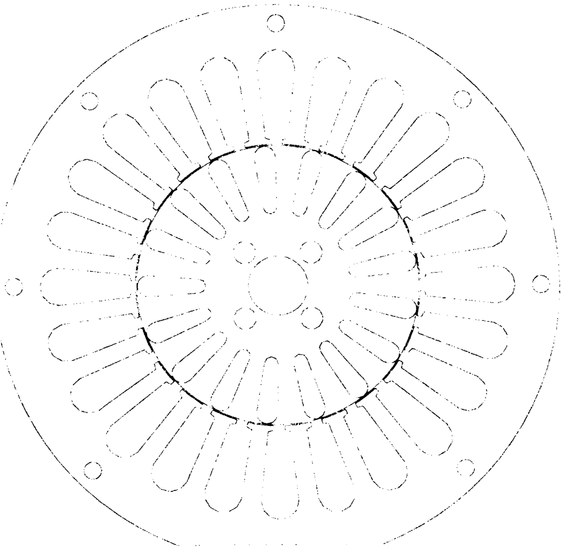

Fig. 3. Stator and rotor lamination design.

TABLE II
FINAL DESIGN PARAMETERS

Parameter	Value
General	
Number of poles	4
Iron core length	63 mm
Type of steel	M15-26G
Stator	
Number of stator slots	24
Outer diameter	150 mm
Inner diameter	75.6 mm
Rotor	
Number of rotor slots	17
Airgap	0.34 mm
Shaft diameter	15.875 mm
Ventilation holes	4
Endring width	10 mm
Endring height	18.1625 mm
Skew width	0
Stator winding	
Winding type	2-layer lap winding
Number of conductors per slot	50
Number of wires per conductor	3
Wire size	21 AWG
Coil pitch	5 slots
Conductor slot-end adjustment	15 mm
Half-turn length of coil	190 mm
Winding factor K_w	0.933
Slot fill factor	45.8%

The rotor laminations were first assembled and pressed on the shaft. Then, the rotor was cast using a steel mold that fits the rotor, according to a procedure described in [8]. The same procedure was successfully applied in the 2003 FEC competition. Basically, the mold with the un-cast rotor was heated close to the melting temperature of aluminum, and then melted aluminum was cast into the mold. By preheating the mold, the melted aluminum filled out all rotor bar slots and endring spaces in the mold, without creating any air pockets. This is usually not a serious issue in industry, where die-casting is used to produce the rotors. For our prototype, however, die-casting was not a feasible option. The rotor endrings then needed to be machined from the aluminum. The final rotor can be seen in Fig. 4.

Stator and rotor were then assembled and connected to a mounting plate such that the motor could be mounted like a standard NEMA 48 frame motor. The assembled induction machine can be seen in Fig. 5.

V. SIMULATION RESULTS

The induction machine was designed to operate at rated torque of 3.18 N-m at a speed of 1500 rpm. Since the machine is operated with an inverter, the stator frequency was set to 53 Hz, and the line-to-line terminal voltage of the stator winding to 120 V_{RMS}. This voltage was deliberately set low, because the dc bus voltage of the inverter was set to 200 V, appropriate for a power-factor-corrected

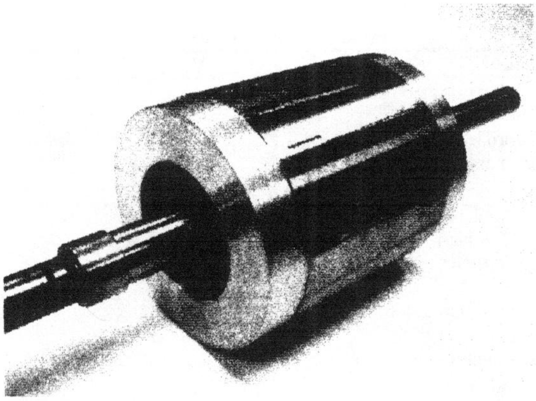

Fig. 4. Prototype squirrel-cage rotor.

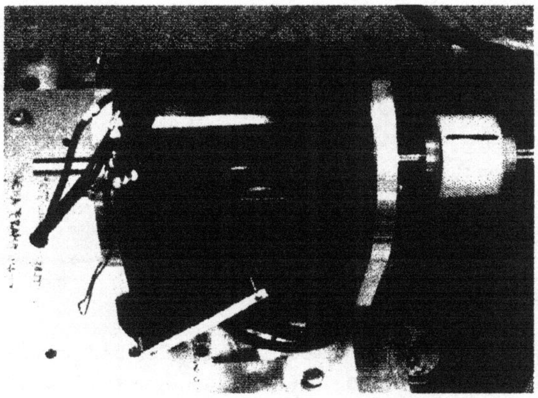

Fig. 5. Assembled prototype induction motor on test-bed.

rectifier fed by 110 V. Results from simulations in RMxprt and a 2-D finite element analysis tool are presented here, assuming the motor is operated with the frequency and voltage given above. Due to time constraints, adequate measurements on the machines were not available to support the simulation results.

A. Numerical Results

Table III gives a summary of theoretical results obtained for no-load and rated load operation. In the no-load case, the agreement between RMxprt and FEA is good, with the exception of the input power. However, the 2-D FEA results do not include an adequate calculation of the core losses, which are the largest factor of the no-load input power, and thus predicting the correct input power values is difficult. Similarly, the results for the rated load test case are in good agreement. The torque of the FEA simulation is about 6% lower than calculated RMxprt, and so is the shaft power. The efficiency is about one point higher in the FEA simulation, which can be explained again with inadequate core loss estimation. However, it can be assumed that the measured results will deviate from the simulated results, as various effects were not included in the model, in particular 3-dimensional effects such as exact endring and end turn behavior.

TABLE III
NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

Parameter	RMxprt	2-D FEA
No-load operation		
Voltage [V_{RMS}]	120	120.3
Current [A_{RMS}]	2.30	2.21
Frequency [Hz]	53	53
Speed [rpm]	1589	1590
Input power [W]	49	24
Rated load operation		
Voltage [V_{RMS}]	120	120.3
Current [A_{RMS}]	4.17	4.00
Frequency [Hz]	53	53
Speed [rpm]	1500	1500
Torque [N-m]	3.51	3.31
Shaft power [W]	550	519
Input power [W]	679	632
Efficiency [%]	81.0	82.1
Power factor	0.774	0.759

B. Graphical Results

To compare a wider set of results, and to verify the analytical results obtained from RMxprt, the 2-D FEA model was simulated at several different speed levels. Time-domain (transient) solutions were obtained of current, torque, and shaft power, which were translated into steady-state values. Only the region of interest, which is the low slip region or the steady-state operating region, was simulated. Fig. 6 shows the RMS values of the stator phase current vs. the slip for both simulation tools, and Fig. 7 the torque. For both cases, the two solutions agree, with differences of less than 10%. The shaft power is shown in Fig. 8. Small errors can be observed around the peak power, but the solutions agree around the nominal power of 500 W. Finally, Fig. 9 shows the efficiency and the power factor. The power factor results are close to each other, however, the efficiency has a significant error around the peak efficiency, where the machine is supposed to be operated. An explanation for this is that in the 2-D FEA, some losses such as core losses need to be estimated after the simulation using the RMxprt data, giving some room for error. In general, the two methods agree well in the region of interest. We would expect larger errors in the results in the high-slip region, where analytical modeling of the induction machine is more difficult.

VI. CONCLUSION

A 500 W induction motor design intended for use in a motor drive system in residential applications was presented. Basic design choices are given, which lead to analytical optimizations and solutions of the design using RMxprt from Ansoft. These solutions were verified with 2-D FEA simulations. Experimental results were not available at this time, but will be reported in the technical report of the 2005 FEC competition.

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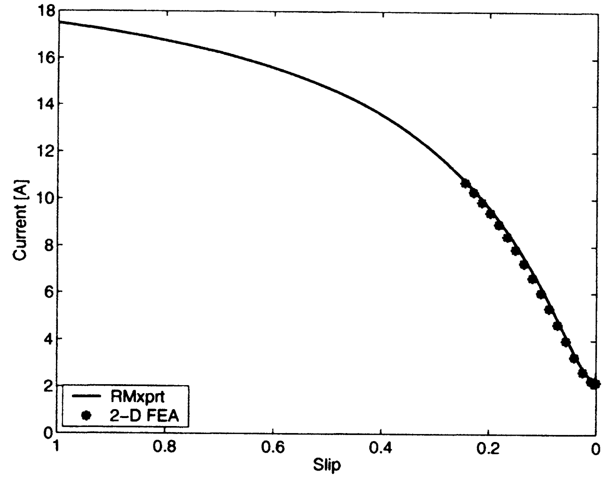

Fig. 6. Simulated stator phase current (RMS) vs. slip.

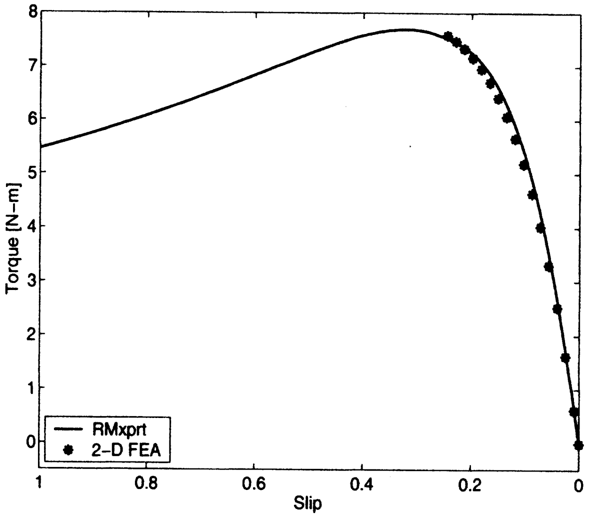

Fig. 7. Simulated torque vs. slip.

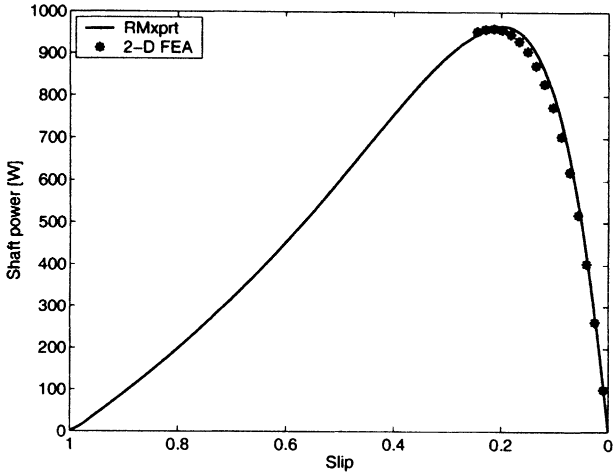

Fig. 8. Simulated shaft power vs. slip.

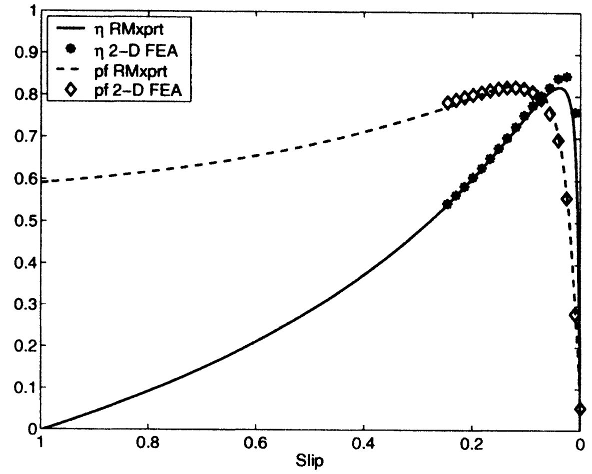

Fig. 9. Simulated efficiency and power factor vs. slip.