Analytical Design of High Efficiency Line Start Permanent Magnet Motor

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Abstract

This paper will give out a flexible calculation and design of electric motor by coupling MATLAB program for analytical calculation and FEMM simulation for magnetic design. Currently, there are several EM designs such as JMAG, Ansys and Motor CAD(SPEED) well known used in EM design companies. For some special permanent magnetic and squirrel cage rotor design, it is difficult for EM designer to apply this commercial software to obtain stator and rotor laminations. An auto coupling program of MATLAB and CAD was implemented to determine a line-start permanent magnet LSPM Motor. The LSPMSM design is based on both analytical and FEMM models to maximize efficiency of LSPMSM motor configuration. The magnetic sizes and geometry parameter of stator and rotor are determined by MATLAB and export drawing to Auto CAD program. This paper is also taking account practical manufacturing factors to minimize mass production cost. The analytical program, FEMM simulation and test results have been compared and validated and good agreement.

Keywords :

Line Start Permanent Magnet Motor-LSPM Motor, Induction Motor- IM, Finite Element Method-FEM

Symbol :

B_r	Tesla	Flux Density
T	Nm	Torque
TVR	kNm/m^3	Torque density

Abbreviation :

FEM	Finite Element Method
LSPM	Line Start Permanent Magnet

1. Introduction

The growths in energy price along with stricter motor environment regulations emphasize the importance of life-cycle costs of innovative technologies. Therefore, optimizing electrical consumption and implementing measurement for improving energy efficiency become more and more popular. As electrical motors consume about 70% of electricity in the industry, the European minimum efficiency regulation has a significant impact on their design and application.

For instance, in 2011 the second edition of the International Electrotechnical Commission (IEC) 60034-30 has been presented, where a new Ultra-Premium Efficiency (IE5) Class has been introduced. Thus, the tighter regulation requires, the more efficiency of electrical motor design must achieve. Efficiency class IE curves is shown in figure 1.

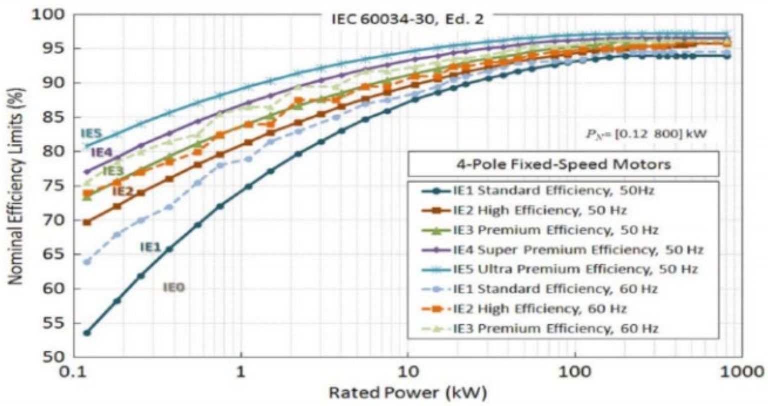

Figure 1. Efficiency class IE curves

To improve the efficiency, all dimensions of the motor must be considered. Moreover, original design process, consisting many steps for design and experiment, will require lots of time and finance. A design program is developed to calculate them, not only to achieve higher standard but also satisfy the electrical and geometrical relations.

2. Motor design and simulation program

Since FEMM was first introduced, this program has been spread widely due to several reasons, particularly, open-source code and free license. Unlike other finite element analysis program, FEMM allows the user can edit its code by themselves, to optimize and improve the calculation accuracy and speed in each problem.

Using MATLAB is also reasonable. It has a strong calculation ability, with easy to use in structure and programming. Furthermore, applying the design model in Simulink automatically with using several circuit topologies is also considered in future work.

The program was developed for the purpose of combining all design process into one program. It allows to exchange the data between design process and simulation process.

This is done by monitoring and active collecting results from both process when they were executed.

Design program is developed in MATLAB environment. The analytical calculation used and stored by MATLAB programming language; program interface was developed by MATLAB GUI. After calculation, the system can present on screen as well as export drawings in dxf type. All drawings can be the development works involve the integrated environment linking analytical calculation to simulation environment of FEMM.

This program also has ability to moving part of the motor which allow us to deal with many transient problems. To do that, it must have a code for the geometrical changes of boundary and the material assignment.

Furthermore, there are many geometrical and magnetic relationships which the program must deal with in only one problem, e.g, the permanent magnet problems, there are many positions for permanent magnet placed in rotor to achieve some electrical parameters, but because of sizing, it overlapped the rotor slot, changing the size, in the other hand, will result worse performances. The program must find the best choice for both, using regression. Collecting and responding data concept is also quite simple. There are only some special parameters of the motor to be verified, for example, output torque or the air gap flux density. The output torque is taken by a block integral of the shaft and the air gap flux density similarly can be collected by function. All result will be stored in database and used for further comparison. In addition, results which belonged to calculation progress and resulted in simulation progress are saved separately in 2 files.

The program is divided into three main parts: analytical calculation, exporting drawing and magnetic simulation. There are also some supporting parts including material library which also associate with FEMM library. Program Structure is shown in figure 2.

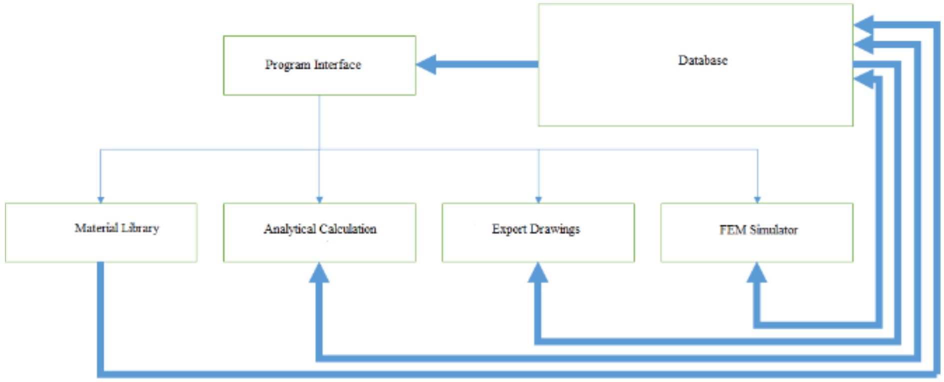

Figure 2. Program Structure

The program interface is a well set of MATLAB function to parse, manage and present data. There is some information which was provided in the program, but only some important results will be displayed and to be divided into tabs.

The interface is written by MATLAB GUIDE. There is menu, button, box, and pop-up menu to manipulate, main parameters and material library must be selected first (fig.3). The calculation progress is not activated without these parameters, e.g, power, torque, pole numbers…, however, there are default materials for each part of the motor.

The interface links to database, material library as well as calculation results. When the system receives main parameters for motors, calculations will be executed. The results will be stored in database in file. mat format. Main dimensions are shown, and the drawing is also plotted.

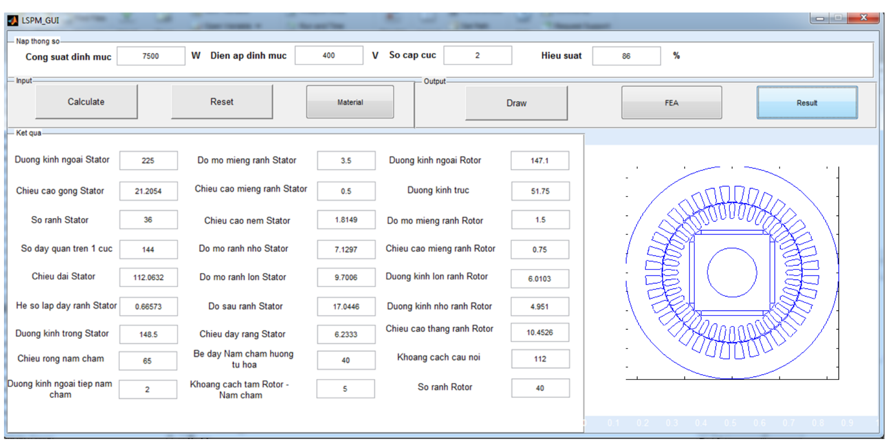

Figure 3. Program Interface

Library consists of wire, permanent magnet, electrical steel library. In the library, material will be defined by specific parameters. The wire library includes the diameter, electrical conductivity. Not like other material, which is chosen by user, wire diameter will be calculated to choose the suitable one. Its parameter will have influence in both analyzing and simulating. The permanent magnet will require relative permeability and electrical conductivity. The library support neodymium (NdFeB) magnets with various types, samarium cobalt (SmCo) magnets and ferrite ones. Electrical steel parameters consist of B-H curve and electrical conductivity.

Following main parameters and material library, there will be analytical analysis. The analyzing process will be started by choosing motor length, diameter and height based on motor standard. During the process, there are some experience coefficients must be defined. All dimensions of motor will be calculated, including stator slot, rotor slot, air gap. This process is quite like induction motor design. In details, stator slot size is calculated mainly based on stator winding which depended on power, current and experience coefficients. Then, it will come to rotor slots and airgap. These parameters depend on desired air gap flux density, geometrical relationship, experiences as well as standard. Then, the nominal mode of motor will be considered, it will allow to consider motor efficiency problems and losses. Higher efficiency design will be preferred and motor design that does not satisfy requirements will be recalculated. Starting operation is also considered. It allows to investigate several unpredicted issues such as skin effect, saturation, leakage flux...(fig.4). The equivalent circuit is also considered. Thermal problems are considered following starting characteristics to investigate insulation. This process can be reconsidered to optimize parameters and predict motor characteristics.

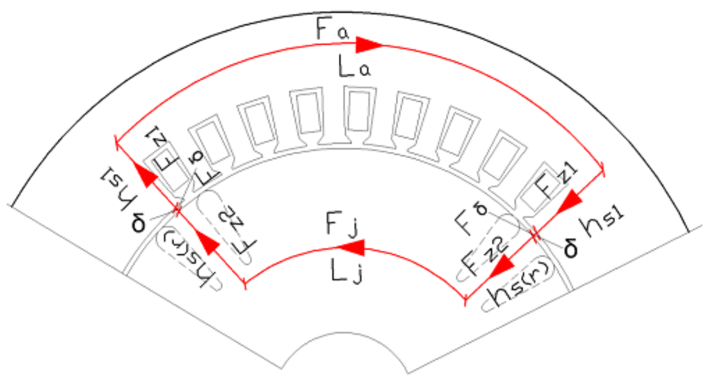

Figure 4. Magnetic circuit

Programs can also support for various types of rotor and stator slots to choose suitable design. Following these steps, permanent magnets and cooling structure is also calculated. Like permanent magnet. Motor calculation process is shown in figure 5.

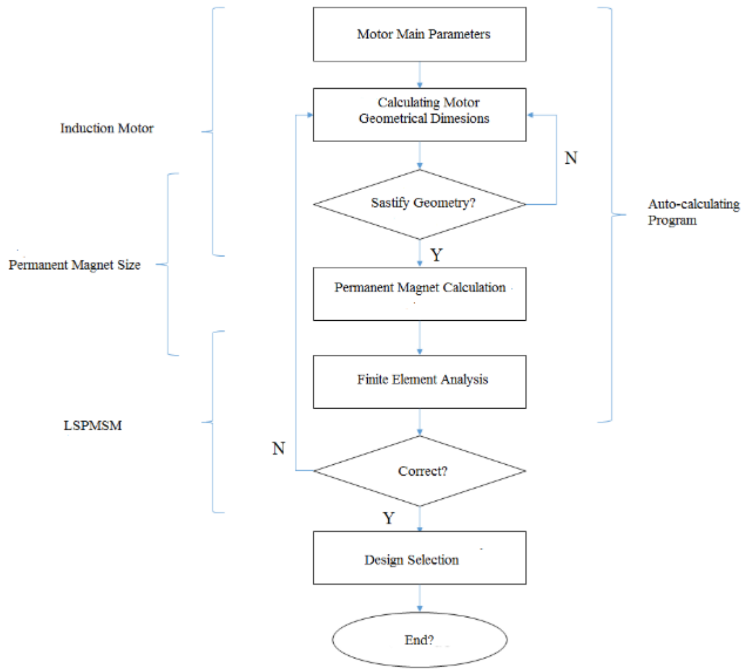

Figure 5. Motor calculation process

After analytical results are achieved, all the dimensions of motor are saved in database in matrix form. When the export command is generated, the drawing process will be executed.

The program was developed by MATLAB DXF library. Unfortunately, the library is quite simple, all difficult tasks, such as drawing circle line, rotating object, are achieved by geometrical formulas. To do this, circle line is made from several line, to draw a line, start point and end point are required. Their coordinates must be calculated. The algorithm must satisfy both requirement: ensure the shape of these line like desired curve and using least points as much as possible. Using minimum number of lines will help the system does not have to store a lot of data, which will result slowing down speed and difficulties when exporting the drawings to another software. In the other hand, rotating and mirror is also a difficult task in programming. The strategy, using loop function to redraw several times and using trigonometric function with angle steps, is applied and returns good results.

The system will export 3 drawings: motor, rotor, and stator separately. These drawings can be used in several simulation program and design and manufacturing progress (fig.6).

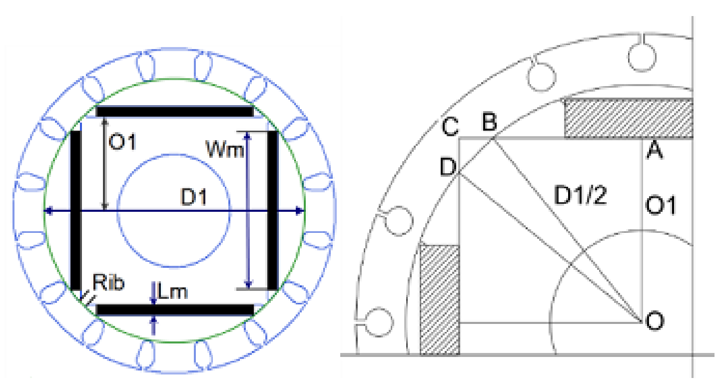

Figure 6. Permanent magnet design

As mentioned, all calculated dimensions and material information are stored in library, the program will export the drawing to FEMM (fig.7). To exchange the data, Lua programming language will be used for this task. With well-defined function, drawing can be created with simpler algorithm.

Algorithm must ensure that all regions in motor must be assigned by chosen material, furthermore, it also must apply in any kind of motor structure without mistakes. For more details, magnetizing direction must be calculated for all permanent magnet topology and having North and South magnets one next to another. In addition, winding is another problem. One of the advantages of system is that in FEMM, winding can be easily adjusted. Winding type, playing an important role in all motor structures, decides flux distribution, cost, thermal problems. It requires programs to define in each stator slot coil its corresponding winding depending on type of winding. Boundary problems is also similar. When a rotating machine is sectioned, there are usually several segments that must be joined up. Arc segments, connecting the nearly coincident mid-gap points, are drew. The arc length spanned by these segments should be rotated angle.

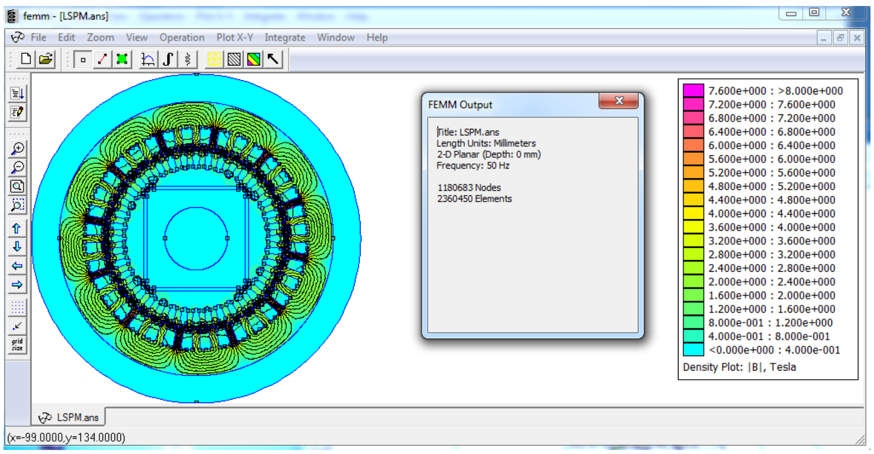

Figure 7. FEMM simulation

These boundary conditions, mesh setup and assigned materials for each part of the motor which are depend on problem conditions, are set up. To decrease the simulation time as well as depend on the motor symmetry, the motor is only be considered in smaller part. Program also considered the design in many different rotor positions, to experience magnetic behavior. Several results can be acquired such as air gap flux density, flux plots, torque, etc.… Simulation results are also compared to analytical calculation to verify them and adjust the design. The program can be easily converted to the one that can generate several designs in small time which can help the user can choose the best design. The program can also be linked to some optimize function to choose the best solution for specific objective.

3. FEM simulation results

FEM has been applied to investigate magnetic performance of LSPMSM design. The flux density of stator and rotor has been validated by FEA model for one pole in fig 8. Flux density curve vs rotor angle is shown in fig 9. Average values are 0.5 tesla in good agreement with calculation.

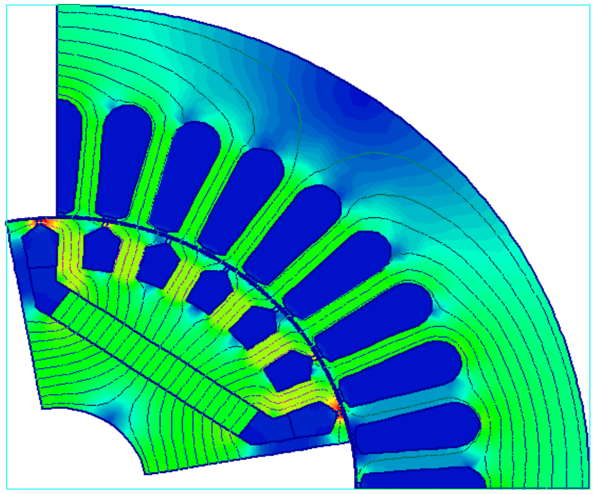

Figure 8. Flux density distribution

Magnetic circuit is obviously not saturated and magnet flux density is also adequately high (fig.9). That allows the motor to operate in overload mode which has not been defined yet.

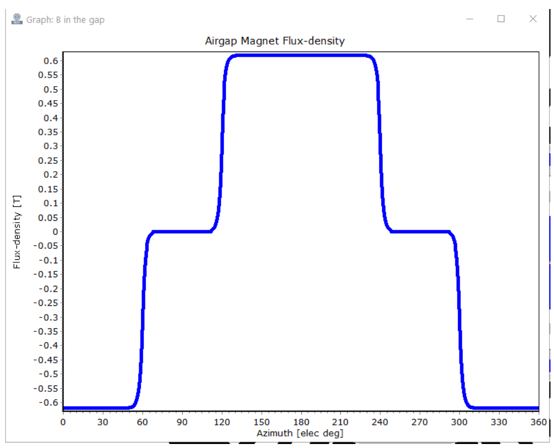

Figure 9. Flux density in air gap results

Torque and efficiency of LSPMSM design play an important role on implementation of this motor. The torque curves of rotor cage, magnet and motor are shown in figure 10.

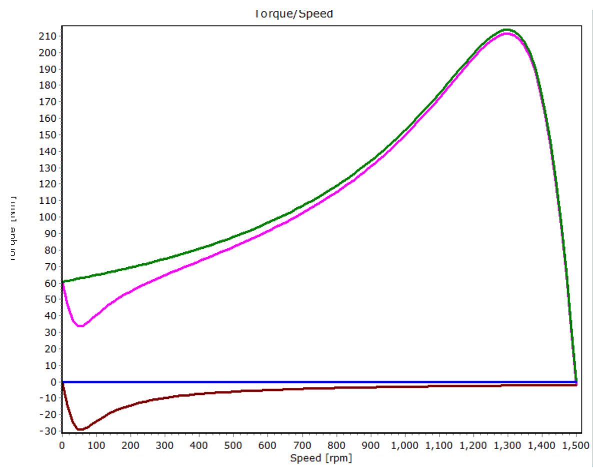

Figure 10. Torque of cage, magnet, and motor results

Efficiency of 91 % with 10% overload in figure 10. The power shaft is 8 kW started direct from grid. From those results can be concluded that LSPMSM is higher efficiency with IE 2,3 than induction motor. Total cost of LSPMSM is more expensive than IM but lower operation cost of electric energy can help LSPMSM payback in short time.

Temperatures of rotor and stator tooth, yoke and windings have been calculated under natural convention (fig.11). The results of analytical and model are good agreements.

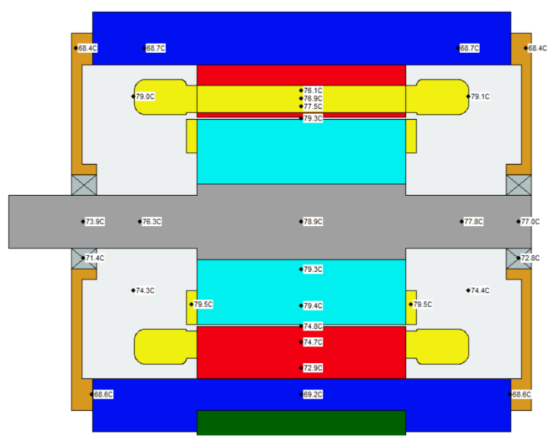

Figure 11. Temperatures of stator and rotor

4. Experiment Test Bench

Rotor magnetic slots have manufacture by wire cutting after die-casting rotor bars and shaft assembly as figure 12. The whole hardware of LSPM motor was built together as figure 13.

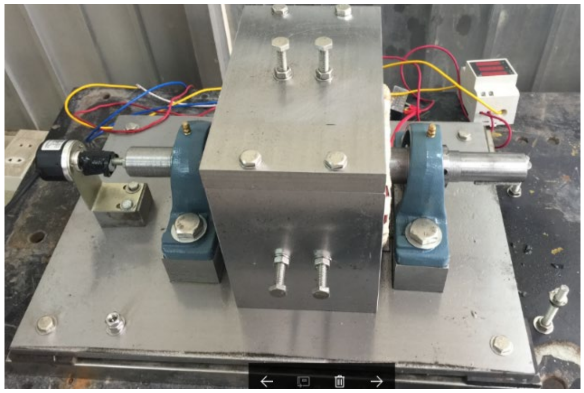

Figure 12. Hardware of LSPM motor

To control air gap of rotor and stator, adjustable screw has used to change stator position in three sides. The rotor shaft was connected to encoder to measure speed of motor though NI card and LabVIEW software. Especially, it can measure the dynamic speed performances to validate period for speed synchronizing. The LSPM motor was setup to evaluate synchronizing speed under different load and voltage by autotransformer of 10 kW. The transient time for constant speed is less than 0.8 second.

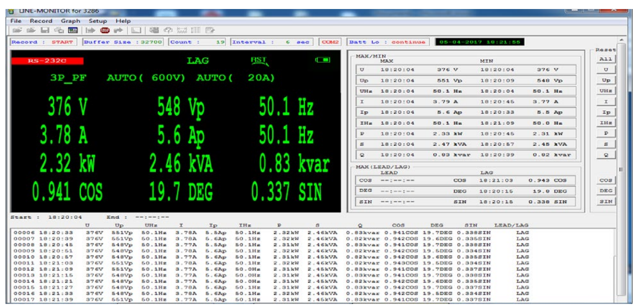

Figure 13. Experiment results of LSPMSM test

All static and dynamic test result has saved in IEC result template as figure 14.

Motor description					
Rated output power	kW	11	Manufacturer	BKHN	
Rated voltage	V	380	Model Nr.	KC.05/16-20	
Rated current	A	21.5	Serial Nr.	29450806	
Rated speed	min^{-1}	1470	Duty type IEC 60034-1		
Supply frequency	Hz	50	Design		
Number of Poles	-	4	Insulation class IEC 60085		
IEC 60034-30-1 (rated)	IE-Code		Max. ambient temperature	°C	

Initial motor conditions			
Test resistance	R_1	Ω	0.668
Winding temperature	θ_0	°C	28.2
Ambient temperature	θ_a	°C	29.3

6.1.3.2.1 Rated load test			
Test resistance	R_N	Ω	0.796
Winding temperature	θ_N	°C	48.7
Ambient temperature	θ_a	°C	28.4

6.1.3.2.3 Load curve test			Test resistance before load test			R	Ω	0.796
Rated output power		%	125 %	115 %	100 %	75 %	50 %	25 %
Torque	T	N.m	88.948	81.862	70.862	53.267	35.667	17.786
Input power	P_1	W	15126.49	13910.6	11993.61	8995.54	6071.47	3145.19
Line current	I	A	25.456	23.46	20.427	15.895	11.762	8.392
Operating speed	n	min^{-1}	1451.8	1456	1462.6	1472.1	1481.3	1490
Teminal voltage	U	V	379.8	380.2	380.2	379.3	380.1	380.5
Frequency	f	Hz	50	50	50	50	50	50
Winding temperature	θ_w	°C	48.2	48.2	48	48	48.1	48.1
			Test resistance after load test			R	Ω	0.776

6.1.3.2.4 No-load test					Test resistance before no-load		R	Ω	0.776
Rated voltage		%	110 %	100 %	95 %	90 %	60 %	50 %	40 %	30 %
Input power	P_0	W	307.3	245	220.5	199.2	117.1	95.5	71.7	58.8
Line current	I_0	A	8.092	6.884	6.392	5.921	3.683	3.034	2.439	1.831
Terminal voltage	U_0	V	417.5	380.4	361.4	341.6	227.9	190.3	152	113.9
Frequency	f_0	Hz	50	50	50	50	50	50	50	50
W. temperature	θ_w	°C	49.2	48.3	48.1	47.8	47.7	47.7	47.5	47.4
					Test resistance after no-load test		R	Ω	0.757

6.1.3.3 Efficiency determination								
Rated output power corr.	$P_{2,l}$	%	125 %	115 %	100 %	75 %	50 %	25 %
Output power corrected	$P_{2,l}$	W	13522.6	12481.7	10853.4	8211.7	5532.8	2775.2
Slip corrected	s, l	p.u.	3.15	2.87	2.43	1.79	1.18	0.6
Input power corrected	$P_{1,l}$	W	15126.5	13910.6	11993.6	8995.5	6071.5	3145.2
Iron losses	P_{fe}	W	125.5	126.8	128.6	130.5	134	137.5
Frict. and wind. losses corr.	$P_{fw,l}$	W	50.9	50.9	50.9	50.9	50.9	50.9
Additional-load losses	P_{LL}	W	126.6	107.2	80.3	45.4	20.4	5.1
Stator losses corrected	$P_{s,l}$	W	773.7	657.1	498.2	301.6	165.2	84.1
Rotor losses corrected	$P_{r,l}$	W	457.6	385	283.5	159.1	71.9	19.5
Power factor	cos φ	%	90.3	90	89.2	86.1	78.4	56.9
Efficiency	η	%	89.86	90.46	91.32	92.36	92.71	90.56

Figure 14. Experiment Interface of LSPMSM test in quartets I

Maximum efficiency is 91.93% at rated power and overload capacity is 125%, after comparing with design target, experimental results are full agreement.

5. Conclusion

The paper has presented a design program of a LSPM Motor for industrial applications meeting IEC 60034-30. The program was used to calculate design parameters by using analytical method, associate with FEMM to validate and finally export the drawings from numerical data. Program is the combination of several drawing and calculating algorithms to improve accuracy. The program is also used for induction motor and special motor designs. Thanks to decreasing time and cost in design process, the integrated tool can be applied in manufacturing electrical motor companies to design and manufacture as well as a supporting tool for researchers who can adjust motor structure design.

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Biography

Minh Dinh Bui was born on Nov, 10th, 1978 in Hanoi/Vietnam and received the B.S. degree in electrical engineering from Hanoi University of Science and Technology, Vietnam, in 2003 and the M.Sc. degree in the Department of Electrical Engineering from Hanoi University of Mining and Geology, Vietnam, in 2007. He has graduated doctor degree at Berlin Institute of Technology in April 2014. Currently, he is a teacher at Hanoi University of Science and Technology. He has some projects of design high speed Switched Reluctance Motor and High efficiency Line Start Permanent Magnet Motor.