Line Start Permanent Magnet Synchronous Motor for Underground Mining Drive Application

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Abstract

Line Start Permanent Magnet Synchronous Motor (LSPMSM) is one of the highest efficiency motors due to no rotor copper loss at synchronous speed and direct starting. LSPMSM has torque characteristics of both induction motor IM and Permanent Magnet Synchronous Motor-PMSM. To maximize efficiency, an optimal design method of cage-bars and magnet shape has to be considered [1]. This paper will design a high efficiency of LSPMSM 11kW-1500 rpm with harsh environment, non-sparking, and explosive conditions such as in underground mining and oil-gas industries. The goal of this work is to design a high efficiency of LSPMSM with insulation of H Class, explosion-proof motor, total closed housing IP55 and high ambient temperature of 55^{0}C. Therefore, electromagnetic performance and temperature rise calculation is play an important part in this paper.

Keywords
Line Start Permanent Magnet Synchronous Motor-LSPMSM, Finite Element Method-FEM

1. Introduction

The growths in energy price along with stricter motor environment regulations emphasize the importance of life-cycle costs of innovative technologies. Therefore, improving energy efficiency is 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 as Figure 1.

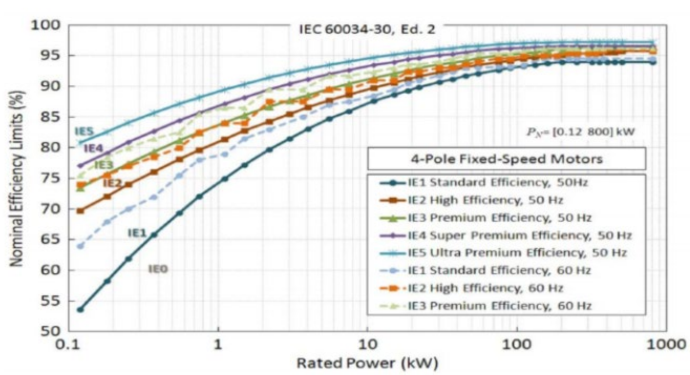


Figure.1 Nominal efficiency class limits proposed in the second edition of IEC 60034-30, for four-pole motors (0.12–800-kW power range) [2]

Thus, the tighter regulation requires, the more efficiency of electrical motor design must be achieved. Line start permanent magnet synchronous motor (LSPMSM) are well known as high efficiency motor due to outstanding advantages compared to other types of induction motor such as high efficiency, robust structure and high power density. LSPMSM has rotor cage and permanent magnet to maximum starting torque and efficiency because rotor bar loss will be minimized at synchronous operation. The LSPMSM can apply for many areas of ventilation and fan drives in mining industry. Many other of industrial drive motor can be replaced by LSPMSM high efficiency, it saves from 3% to 5% energy of total electric energy consumption. However, it has some drawbacks of cogging torque during starting mode [3]. Efficiency and torque of LSPMSM motor depends on permanent magnet and rotor cage. Moreover, Overheat temperature problem of permanent magnet is supposed to affects the efficiency and torque performances. The stator consists of stacked steel laminations with windings placed in the slots whereas the rotor is embedded permanent magnet that can vary from two to eight pole pairs with alternate north and south poles. In LSPMSM design, rotor magnetic structure has a significant effect of starting torque performances [3,4] because the balance of magnet and rotor cage is to speed up motor over loading torque to reach synchronous operation. The permanent magnet will pull rotor to synchronous speed with high efficiency.

Table 1 LSPMSM Specification

MOTOR PARAMETER	VALUE
Number of slots/poles	36/4
Rated current (rms) (A)	15
Rated voltage (rms) (V)	690/380
Power/max Power (kW)	11/13.5
Rated speed (rpm)	1500
Frame size	132
Efficiency	>=88.4%

To improve the efficiency, geometry dimensions and material properties of the motor component are investigated by analytical or FEA simulation.

2. Magnet Rotor Design of LSPMSM

In order to determine operation points of permanent magnet circuit, some basic parameters of magnetic circuit were calculated in a analytical model. This point depends on remanent flux density and silicon steel material. In this paper, the magnet of LSPMSM 11kW-1500 rpm has been carried out by analytical model in Figure 2. Magnet NdFeB35 is magnet material used due to its good thermal stability and remanent flux density (~1,3T) allowing its use in applications exposed to high temperature about 180^{0}C. The flux density is selected about 0.75 T.

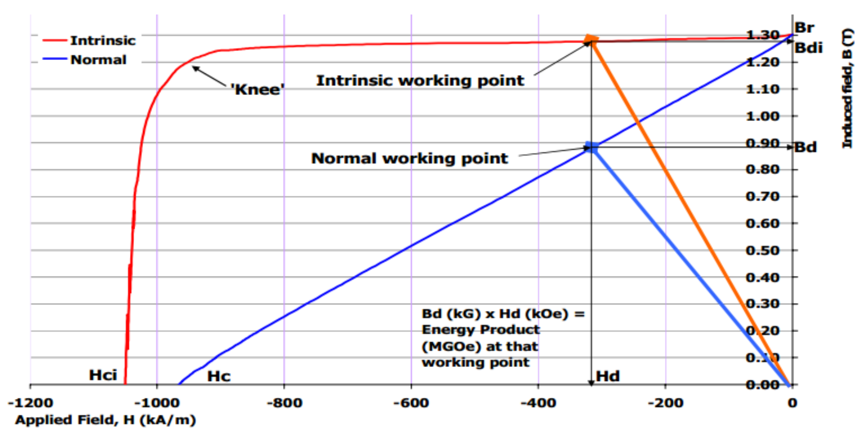


Figure 2. Magnetic properties of NdFeB35

Based on the analytical method, some geometry parameters of stator and rotor can be calculated as follow chart in Figure 2. An analytical model was undergone many calculation steps to define basic parameters. Based on torque volume density TVR from 20 to 30 kNm/m^3 [5], if we assume rotor diameter equal to rotor length, the rotor diameter D and length L sizes of LSPMSM is determined as follow:

$$D = L = \sqrt[3]{\frac{T}{\frac{\pi}{4} \cdot TVR}} = \sqrt[3]{\frac{47.75}{\frac{3.14}{4} \cdot 25}} = 134.5\,mm$$

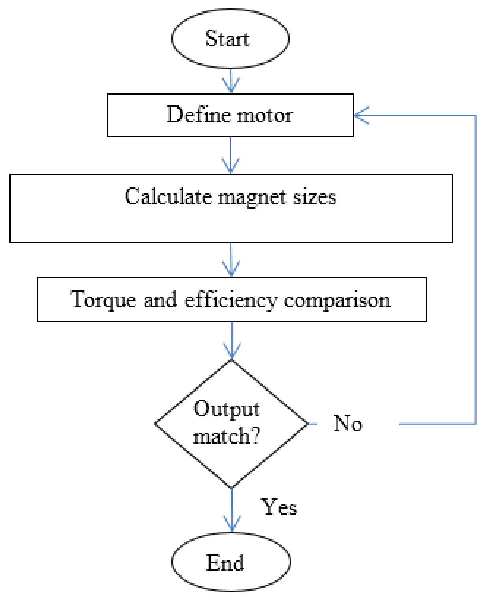


Figure 3. Calculation process

In general, the design process of LSPMSM is like that of induction motor. The main parameters (such as outer diameter, rotor diameter, motor length, stator slot, airgap length) are defined by considered some practical factors with desired input requirements [3]. The main part of the process is to design the rotor configuration which is embedded permanent magnet. The PM configuration needs to create sufficiently magnetic voltage for magnetic circuit. In fact, there are some possible configurations sorted by the shape and position of PM inside rotor as listed below:

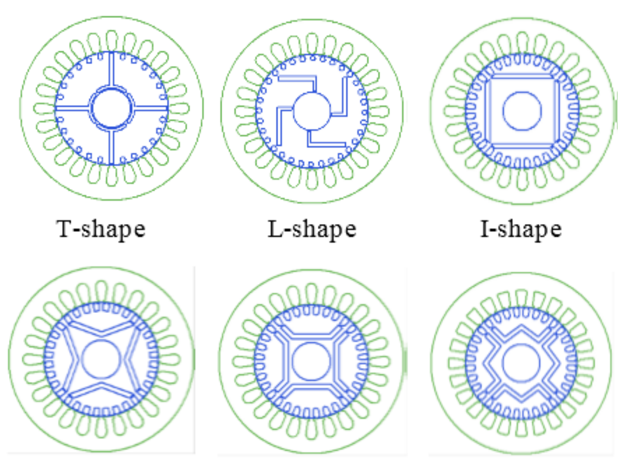


Figure 4. LSPMPM configurations

The PM configuration has a great influence on motor efficiency. He also pointed out that the V-shape PM gives the highest efficiency. However, the decision on choosing PM configuration depends on the possibility of manufacturing it. In other word, the technique (includes the cost of procedure) and material properties are crucial criteria that impact the configuration selection. By considering them, the I-shape PM is applied in this design. Layout of LSPMSM 11kW is show in Figure 5.

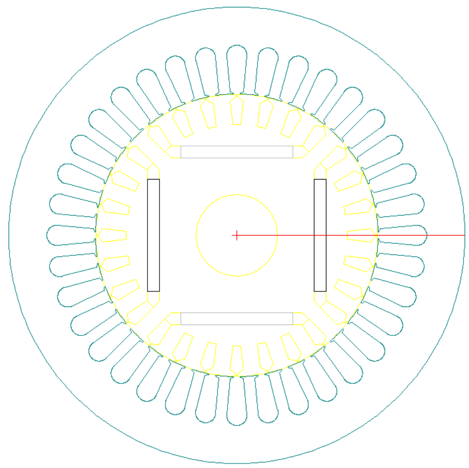


Figure 5. Layout of LSPMSM 11kW-1500 rpm

3. Analytical Model Design

From main parameters and material properties, analytical will be built to evaluated static torque and dynamic. 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 were defined. All dimensions of motor will be calculated, including stator slot, rotor slot, airgap. 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 pre-determined, and their results are compared with requirements, many running steps will be recalculated. Starting torque is also considered and checked with rated torque load. It allows to investigate several unpredicted constrains or boundary conditions such as skin effect, saturation, leakage flux. Thermal problems are considered following starting characteristics to investigate insulation. This process can be reconsidered to optimize parameters and predict motor characteristics.

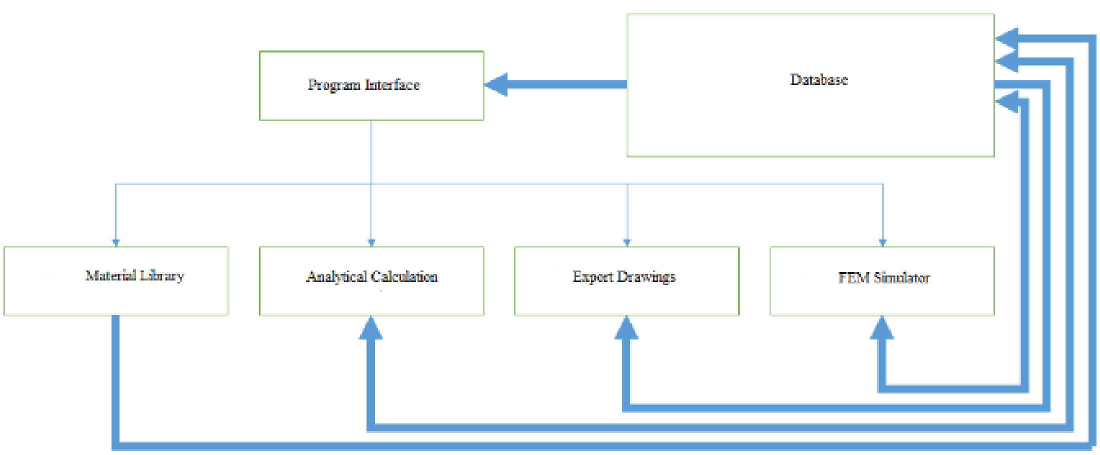


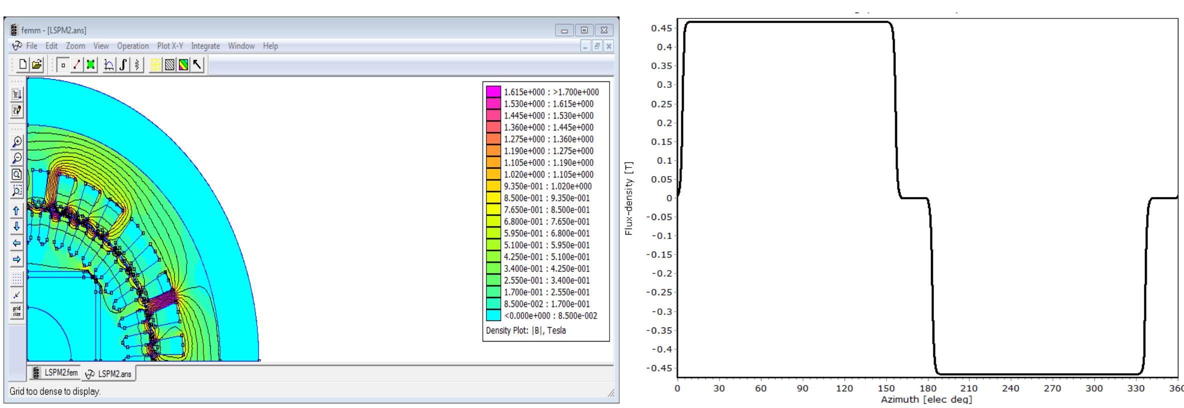
Figure 6. Program flow chart

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, a straight line is drawn from start point to end point by Matlab commands. Their coordinates are re-calculated automatically.

The algorithm will meet both requirement: ensure the shape of these line is as desired curve and using least points as much as possible. Using minimum number of lines will help the system to store less 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.

4. Simulation and Experiment Analysis

As mentioned, all calculated dimensions and material information are stored in library, the program will export the drawing to FEM (Finite Element Method) 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 is 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. These boundary conditions, mesh setup and assigned materials for each part of the motor which are dependent 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.



(a) Flux density distribution *(b) Airgap Fluxdensity*

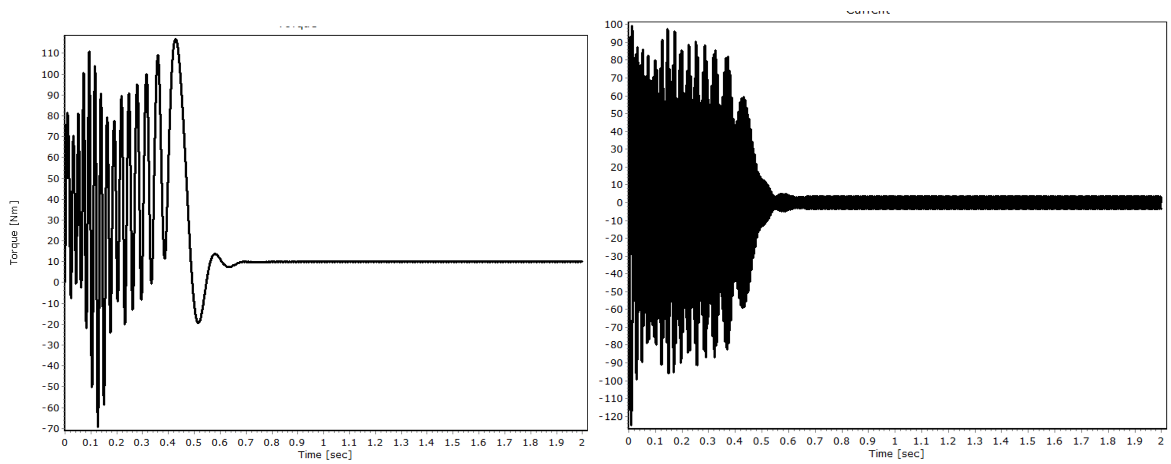
Figure 7. LSPMSM flux density results

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. 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 Figure 7. Flux density curve vs rotor angle is shown in Figure 7b. Average values are 0.5 tesla in good agreement with calculation. Magnetic circuit is obviously not saturated, and magnet flux density is also adequately high. That allows the motor to operate in overload mode which ensure to run 125% of rating load. The shaft torque and efficiency of LSPMSM design play an important role on electromagnetic design of this motor. With torque shaft is 92Nm, the efficiency is 94.9% at 125% load, the phase voltage is 380V in Delta connection. The AC line voltage of underground mines is 660VAC. The three phase will be change to start connection.

Table 2. Power, torque, and efficiency results

OpMode	Motoring		Vs	380.0000	V	RPM	1500.0000	rpm
Tshaft	92.9926	Nm	Pshaft	14607.2415	W	Eff	94.9723	%
WCu	749.1621	W	WFe	24.1205	W	WWF	0.0000	W
WMagnet	0.0000	W				MechLoss	24.1205	W
WTotal	773.2826	W	TempRise	5.0000	°C	Jrms	2.5321	A/mm²
IWpk	45.0000	A	IWav	28.6477	A	IWrms	31.8198	A
ILpk	45.0000	A	ILav	28.6477	A	ILrms	31.8198	A
IDC_P	40.4751	A	WFeCalc	OC		Pelec	15380.5241	W
Eq1	153.2731	V	Vph1	2958.0579	V	VLL1	5123.5065	V
Iq1	31.8198	A	Id1	0.0000	A	gamma	0.0000	°
Vq1	161.1211	V	Vd1	-2953.6666	V	delta	86.8776	°
Vtph	2958.0579	V	phi	86.8776	°	PF	0.0545	
VtLL	5123.5065	V	phIs	86.8776	°	SPF	0.0545	
RI1	7.8480	V	jXdId1	0.0000	V	jXqIq1	2953.6666	V
Psi_1	9414.4630	mVs	Psiad1	0.0000	mVs	Psiaq1	9401.8128	mVs
Bqad	8.2464	T	Phida1	0.0000	mWb	Phiqa1	72.5463	mWb
BqAvg	3.8227	T	hBq	56.3325	mm²	Bg1Load	0.1925	T
BmLoad	0.3858	T	Bma	0.0000	T	Fda1	0.0000	At/gap
Tgap_PS	93.1461	Nm	TEI_PS	93.1461	Nm	Trel_PS	0.0000	Nm
Tgap	93.1461	Nm	Tei	93.1461	Nm	Trel	4.3058E-13	Nm
Tloop	93.1450	Nm						

For starting mode, the total torque curve of rotor cage, magnet and motor is shown in Figure 8. The LSPMSM 11 kW started direct from grid and the torque and current starting is ended after 0.5s, The period of starting time is shorter, it means the overload capacity is better.



(a) *(b)*

Figure 8. Torque curve (a) and current curve (b) under staring mode

From those results can be concluded that LSPMSM is higher efficiency with IE4 motor. The frame size of LSPMSM 11kW is the same with IM 7.5kW F132M

5. Thermal simulation

Temperatures of rotor and stator tooth, yoke and windings have been calculated under rated load. The temperature results of phase winding are 80^0C with ambient temperature of 40^0C after 3h heat run test. With the temperature rise is 40^0C and isolation class H 180^0C, the hot spots or over temperature are not exceeded limit vales.

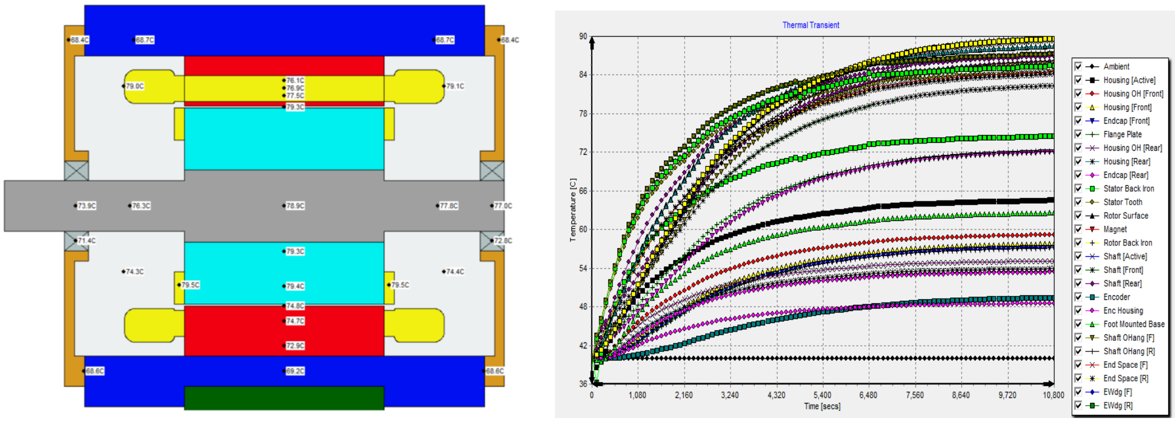


Figure 9 Temperatures points and curves

The temperature results are calculated from copper losses and iron losses in table 2. Hotspot teamperature values of the line start permanent magnet motor under ground mines 90 degree lower than over heat limit level.

6. Experiment Test Bench

The LSPMSM 11kW motor test bench has setup with shaft to PMSM generator assembly as Figure 10. The torque transducer TM320 is in between motor and generator as load.

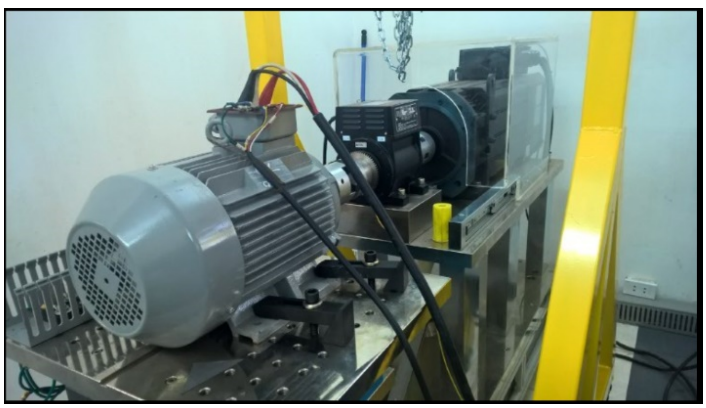


Figure 10. LSPMSM test bench

The LSPM motor was setup to evaluate synchronizing speed under different load and voltage by auto run test system as flow IEC standard. Total losses, in/output power and efficiency were implemented IEC regular 60034-30-1. All power result has saved in IEC result templates as table 3.

Table 3. Experiment Result of LSPMSM

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_I	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	$P_{1,r}$	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

Maximum efficiency of 91.32% at rated power and 91.32% at 125% rated power is higher 88.4 requirement. In comparison with simulation result, the experiment efficiency is lower 1-2% because the windage and fiction losses was not added in analytical model.

7. Conclusion

The paper has presented a design program of a LSPMSM 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. The thermal simulation was implemented to verify maximum temperature of windings lowed than insolation withstands class H. Efficiency vales of simulation and experiment methods are good agreement, small error was analyzed.

8. References

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Biography

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