Synchronous Reluctance Motor for Coal Mine Ventilation Drives

[1]Bui Minh Dinh, [2]Dinh Xuan Quyet
[123]Hanoi University Science Technology
Email: dinh.buiminh@hust.edu.vn

Abstract

In this paper, a detail electromagnetic and thermal calculation of a 15kW-660VAC synchronous reluctance motor (SynRM) SRM frame size 132mm- efficiency class IE2 are presented. The design of the machines was carried out in based on the use of finite element modeling of the magnetic field. Static and dynamic simulation of the main characteristics of the synchronous reluctance electric motor powered by electric network and frequency inverter, is carried out in analytical program. The SynRM was designed to meet efficiency class and temperature requirement which is applied for underground coal mines in Vietnam.

Keywords
Synchronous reluctance motor, drives, motor construction and characteristic, Synchronous reluctance motor (SynRM).

I. Introduction

Synchronous reluctance motor or synchronous electric motors has been applied for explosion motor applications because of main advantages such a simple design of the rotor and motor in general. Through the absence of windings on the rotor, the machines have a high efficiency, are characterized by a smaller value of overheating of the stator winding and bearing assemblies. The design of SynRM ensures maximum overheat capacity and safety operation. In this paper, the results of the design and simulation of a synchronous reluctance motor with the rated power of 15 kW is implemented and analyzed. FEA method has been calculated to investigate electromagnetic torque, efficiency and temperature of windings.

II. Motor Electromagnetic Design

Figure. 1 shows an industrial design the SynRM which is embedded explosive housing. A detail geometry parameters of four layer SRM is designed in figure 2. Subsequently, the SynRM performance is implemented by using analytical and FEA methods. The mechanical stress concentrated on each rib is analyzed by the structural analysis. The next step is the optimization of the rib thickness to improve the motor output using the response surface method. Table 1 lists the constraints and output of the SynRM.

Table 1. Specifications For Design

Contents	Value	Unit

Rated Power	15	kW
Rated torque/speed	95/1500	Nm/rpm
Voltage limit	660	Vph, rms
Dia. stator	267	mm
Length of stack	200	mm
THD limit	5	%

The design of the synchronous reluctance motor is developed using a technique based on finite element simulation of the magnetic field. The design parameters of the SynRMM1606 ie2 motor is shown in Figure.1. The

Figure 1. Industrial design of 15kW-660VAC

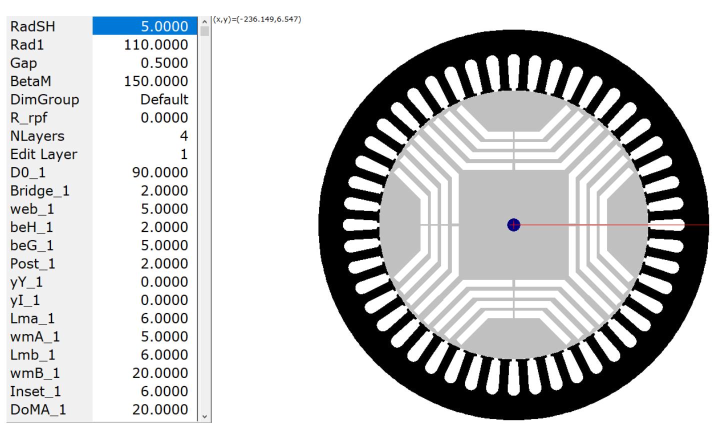


Figure 2. Four layers SynRM of 15kW-660VAC

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 position, 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.

```
1 Dimensions:-----------------------------------------------------------------

RotType          IPM        Embed          Type6        Poles            4

Stator (Armature)..
StatorOD    320.0000 mm     LamShape      Circle        Slots           48
SYoke        24.0625 mm     ASD          35.0000 mm     SP         12.0000
Rad3        160.0000 mm     Rad2        135.9375 mm     S_Slot      Square
TWS           6.0000 mm     SD           35.0000 mm     SO          2.0000 mm
TGD           5.0000 mm     SOang        20.0000 °m     Stf         0.9700

Rotor..
MOH           0.0000 mm     NLayers            4        Skew        0.0000
RotorOD     200.8750 mm     Rad1        100.4375 mm     Gap         0.5000 mm
Lme          17.6240 mm     BetaM       120.0000 °e     pupa        0.6667
RYoke        71.4200 mm     hq           18.4112 mm     RadSH      25.0000 mm
D0_1         90.0000 mm     Lma_1         6.0263 mm     Post_1      2.0088 mm
wmA_1        24.0000 mm     wmB_1         6.0000 mm     FillMag_      Rect
yI_1          0.0000 mm     yY_1          0.0000 mm     Inset_1     0.0000 mm
Bridge_1      2.0088 mm     web_1         4.0175 mm     Lmb_1       6.0263 mm
BrT1a         1.1144 T      BrT1b         1.1144 T
MuR1a         1.1000        MuR1b         1.1000
D0_2        110.0000 mm     Lma_2         6.0263 mm     Post_2      2.0088 mm
wmA_2        24.0000 mm     wmB_2         6.0000 mm     FillMag_      Rect
yI_2          0.0000 mm     yY_2          0.0000 mm     Inset_2     0.0000 mm
Bridge_2      2.0088 mm     web_2        24.1050 mm     Lmb_2       6.0000 mm
BrT2a         1.1144 T      BrT2b         1.1144 T
MuR2a         1.1000        MuR2b         1.1000
D0_3        130.0000 mm     Lma_3         6.0263 mm     Post_3      2.0088 mm
wmA_3        24.0000 mm     wmB_3         6.0000 mm     FillMag_      Rect
yI_3          0.0000 mm     yY_3          0.0000 mm     Inset_3     0.0000 mm
Bridge_3      2.0088 mm     web_3        44.1925 mm     Lmb_3       6.0263 mm
BrT3a         1.1144 T      BrT3b         1.1144 T
MuR3a         1.1000        MuR3b         1.1000
D0_4        152.0000 mm     Lma_4         6.0263 mm     Post_4      2.0088 mm
wmA_4        24.0000 mm     wmB_4         6.0000 mm     FillMag_      Rect
yI_4          0.0000 mm     yY_4          0.0000 mm     Inset_4     0.0000 mm
Bridge_4      2.4105 mm     web_4        64.2800 mm     Lmb_4       6.0263 mm
BrT4a         1.1144 T      BrT4b         1.1144 T
MuR4a         1.1000        MuR4b         1.1000
Slits           None
wMag         60.0000 mm     AmagSlot   3345.2469 mm²    MOH         0.0000 mm
Lstk        200.8750 mm     Lrotor      200.8750 mm     Lstator   201.3750 mm
```

Figure 3. Main 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.

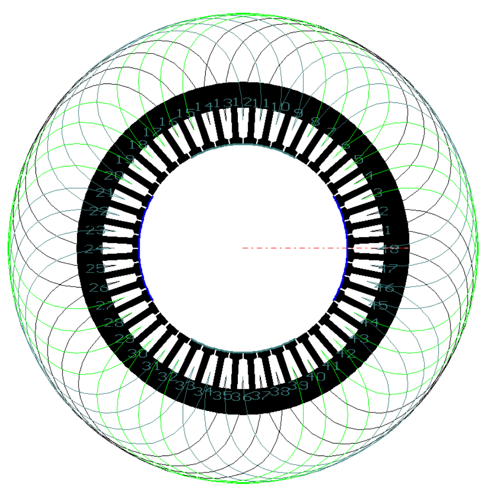
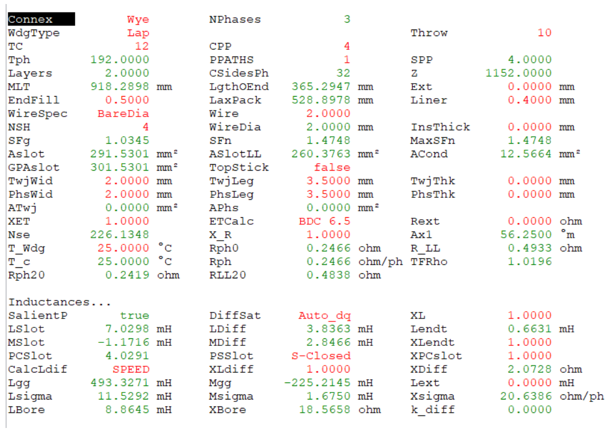


Figure 4. Winding design

The coil design of 36 stator slots is included turn coil, coils per phase and wire diameter in Figure 4.



Connex	Wye		NPhases	3				
WdgType	Lap					Throw	10	
TC	12		CPP	4				
Tph	192.0000		PPATHS	1		SPP	4.0000	
Layers	2.0000		CSidesPh	32		Z	1152.0000	
MLT	918.2898	mm	LgthOEnd	365.2947	mm	Ext	0.0000	mm
EndFill	0.5000		LaxPack	528.8978	mm	Liner	0.4000	mm
WireSpec	BareDia		Wire	2.0000				
NSH	4		WireDia	2.0000	mm	InsThick	0.0000	mm
SFg	1.0345		SFn	1.4748		MaxSFn	1.4748	
Aslot	291.5301	mm²	ASlotLL	260.3763	mm²	ACond	12.5664	mm²
GPAslot	301.5301	mm²	TopStick	false				
TwjWid	2.0000	mm	TwjLeg	3.5000	mm	TwjThk	0.0000	mm
PhsWid	2.0000	mm	PhsLeg	3.5000	mm	PhsThk	0.0000	mm
ATwj	0.0000	mm²	APhs	0.0000	mm²			
XET	1.0000		ETCalc	BDC 6.5		Rext	0.0000	ohm
Nse	226.1348		X_R	1.0000		Ax1	56.2500	°m
T_Wdg	25.0000	°C	Rph0	0.2466	ohm	R_LL	0.4933	ohm
T_c	25.0000	°C	Rph	0.2466	ohm/ph	TFRho	1.0196	
Rph20	0.2419	ohm	RLL20	0.4838	ohm			
Inductances...								
SalientP	true		DiffSat	Auto_dq		XL	1.0000	
LSlot	7.0298	mH	LDiff	3.8363	mH	Lendt	0.6631	mH
MSlot	-1.1716	mH	MDiff	2.8466	mH	XLendt	1.0000	
PCSlot	4.0291		PSSlot	S-Closed		XPCslot	1.0000	
CalcLdif	SPEED		XLdiff	1.0000		XDiff	2.0728	ohm
Lgg	493.3271	mH	Mgg	-225.2145	mH	Lext	0.0000	mH
Lsigma	11.5292	mH	Msigma	1.6750	mH	Xsigma	20.6386	ohm/ph
LBore	8.8645	mH	XBore	18.5658	ohm	k_diff	0.0000	

Figure 5. Winding parameters

III. Electromagnetic simulation

FEM has been applied to investigate magnetic performance of PM-SYNRM design. The flux density of stator and rotor has been validated by FEA model for one pole in Figure 6. Flux density curve vs rotor angle is shown in Figure 7. Average values are 0.5 tesla in good agreement with calculation.

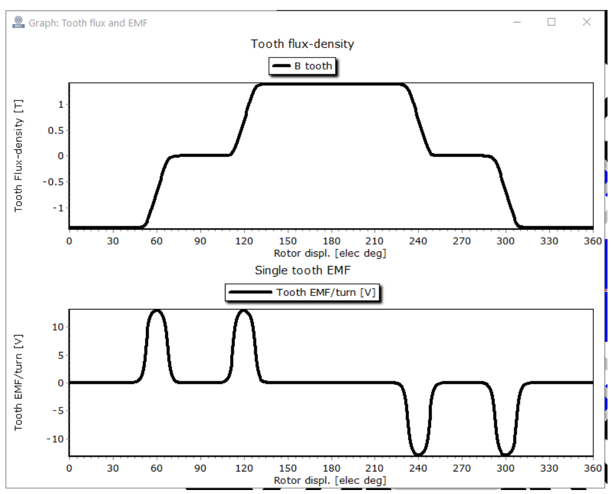


Figure 6. Flux density distribution in Stator tooth

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

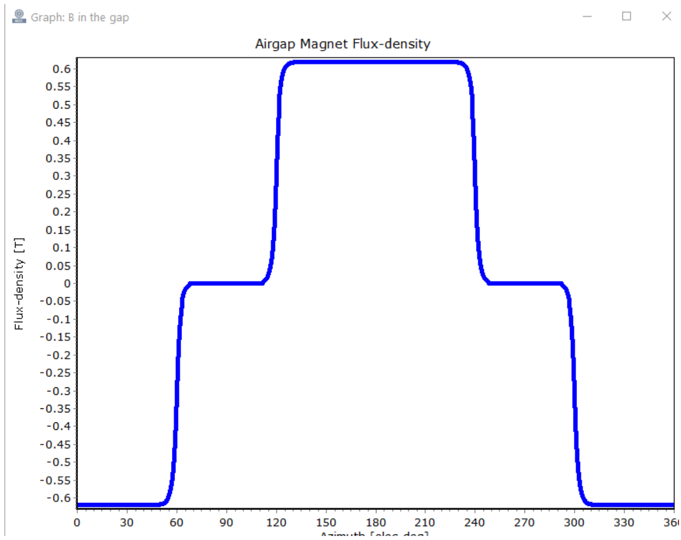


Figure 7. Flux density in air gap results

Torque and efficiency of PM-SYNRM design play an important role on implementation of this motor. The torque curves of rotor cage, magnet and motor are shown in Figure 8.

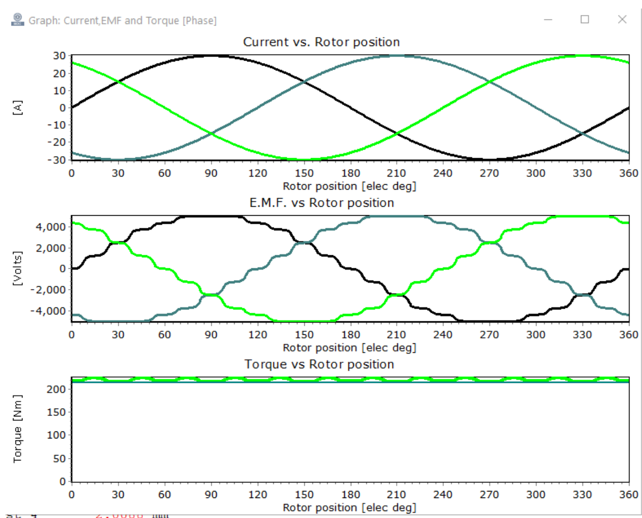


Figure 8. Phase current, voltage, and electromagnetic results

Efficiency of 91 % with 10% overload in Figure 8. The power shaft is 15 kW started direct from grid. From those results can be concluded that PM-SYNRM is higher efficiency with IE 2,3 than induction motor. Total cost of PM-SYNRM is more expensive than IM but lower operation cost of electric energy can help PM-SYNRM payback in short time.

IV. Thermal Simulation

Thermal model is setup based on stator and rotor structure and their material. The copper and iron losses from electromagnetic design result is applied for thermal model. Temperatures of rotor and stator tooth, yoke and windings have been calculated under natural convention in figure 9&10. The results of analytical and model are good agreements.

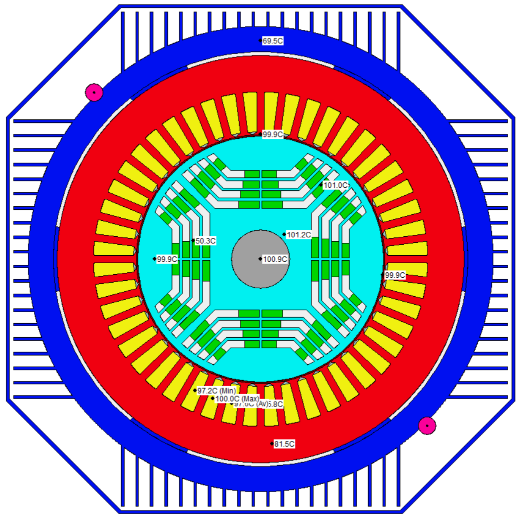


Figure 9. Temperatures of stator and rotor cross section

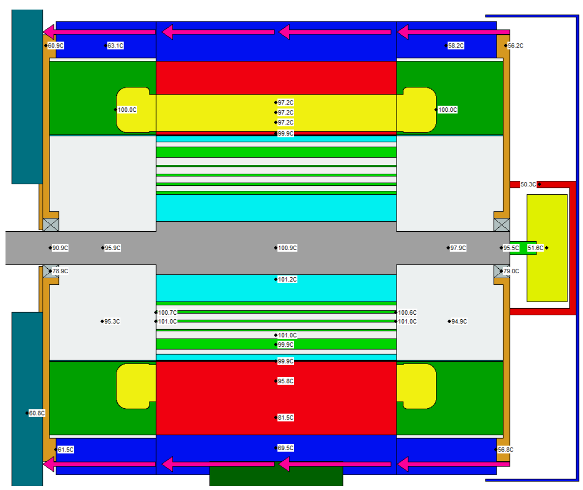


Figure 10. Temperatures of stator and rotor in axial

Normally, temperature curves will be implemented in 3 hours in order to guarantee that the motor is overheat during heat-run test plotted in figure 11.

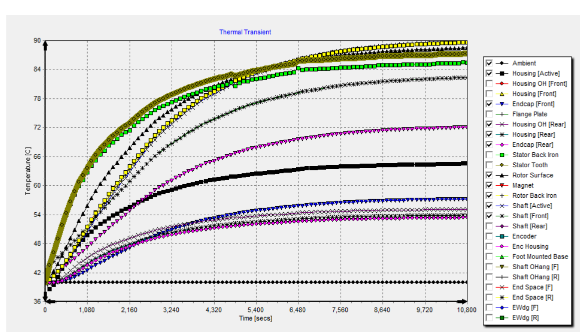


Figure 11. Temperature plots of windings and core motor

Hotspot of winding and rotor shape is 105 C degree. With Insolation class of H, the hotspot temperature is lower than limited.

IV. Experiment Test Bench

Rotor magnetic slots have manufacture by wire cutting after die-casting rotor bars and shaft assembly as Figure 12.

Figure 12. Manufactured line starts permanent magnet motor.

The whole hardware of SYNRM motor was built together as Figure 13.

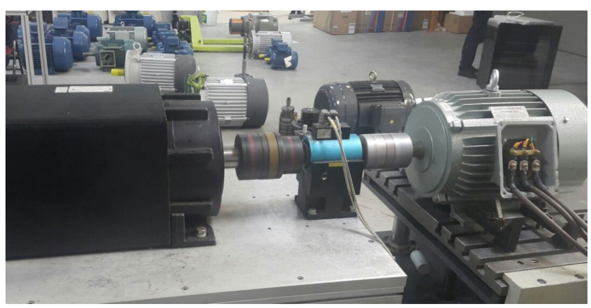


Figure 13. Hardware of SYNRM motor

The SYNRM motor was setup to evaluate synchronizing speed under different load and voltage by auto run test system as flow IEC standard.

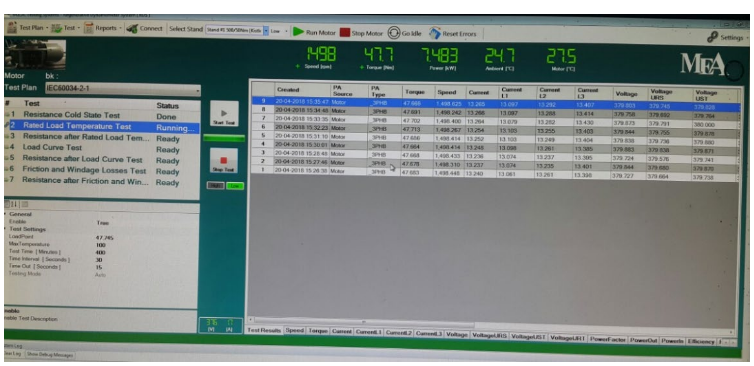


Figure 14. Experiment Interface of PM-SYNRM test in Quatest I

All static and dynamic test result has saved in IEC result template as Figure 15.

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				6.1.3.2.1 Rated load test			
Test resistance	R_I	Ω	0.668	Test resistance	R_N	Ω	0.796
Winding temperature	θ_0	°C	28.2	Winding temperature	θ_N	°C	48.7
Ambient temperature	θ_a	°C	29.3	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	$\cos\varphi$	%	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 15. Experiment Table result of PM-SYNRM test in Quatest I

V. Conclusion

The paper has presented a design program of a SYNRM 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 synchronous reluctance motor is a promising electrical machine for energy-efficient mechatronic systems and drives. The advantages of SynRM are most apparent in the field of partial loads and at low speeds in the pick-up and reverse modes.

References

1. P. Matyska, “Advantages of Synchronous Reluctance Motors”, Transactions on Electrical Engineering, 2014, vol. 3 (2014), No. 2, pp. 44 - 47.
2. S.A. Zhuravlev, A.M. Zaitsev, A.V. Zakharov, “Development and research of synchronous reluctance electric motors characteristics”.
3. Proceedings of the XVI International Conference "Electromechanical, Electrotechnology, Electrotechnical Materials and Components”, Moscow, “Znak”, 2016, pp. 100 - 103.

4. N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, E. Fornasiero, “Electric Vehicle Traction based on Synchronous Reluctance Motors”, IEEE Transactions on Industry Applications. 2016, vol. 52, No. 6, pp. 4762 – 4769. DOI
5. 10.1109/TIA.2016.2599850.
6. T. Miller, A. Hutton, C. Cossar, D. Staton, “Design of a synchronous reluctance motor drive”, IEEE Transactions on Industry
7. Applications, July-Aug. 1991, vol. 27, Issue 4, pp. 741–749.
8. D. Dorrell, “A Review of the Methods for Improving the Efficiency of Drive Motors to Meet IE4 Efficiency Standards”, in Journal of Power Electronics, vol. 14, No. 5, pp. 842-851, September 2014. http://dx.doi.org/10.6113/JPE.2014.14.5.842.
9. J. K. Kostko, “Polyphase reaction synchronous motors”, Journal Amer. Inst. Electrical Engineers, 1923, vol. 42, pp. 1162 - 1168.
10. P. Lawrenson, L. Agu, “Theory and performance of polyphase reluctance machines”, Proceedings of the Institution of Electrical Engineers, IEEE, 1964, vol. 111, No. 8, pp. 1435 - 1445.
11. Low voltage IE4 synchronous reluctance motor and drive package for pump and fan applications. A 9AKK105828 EN 06-2013. ABB Motors and Generators. 2013, 47 p.
    A. Vagati, A. Canova, M. Chiampi, M. Pastorelli, M. Repetto, “Design Refinement of Synchronous Reluctance Motors Through Finite-Element Analysis”, IEEE Transactions on industry applications, 2000, vol. 36, No. 4, pp. 1094 – 1102.
12. A.V. Zakharov. “The prospects of technical applications synchronous motors with anisotropic magnetic conductivity of the rotor”. Proceedings of International scientific-technical conference "State and prospects of development of Electrotechnology" (XVIII Benrdosovsky reading), Ivanovo, 2015, pp. 124 - 127.
13. F.A. Gelver, N.V. Belousova, V.F. Samoseyko, “The reactive electromechanical converter with anisotropic magnetic conductance of the rotor”, Proceedings of the VIII international (XIX Russian) conference on the automatic electric drive, 2014, vol. 1, pp. 394 - 398.
14. L.N. Makarov, A.V. Zakharov. “The main directions of improvement of low-voltage electric motors”, Proceedings of the Academy of Electrotechnical Sciences of the Russian Federation, 2016, Issue 18, pp. 72 - 80.
15. A.V. Zakharov, L.N. Makarov, S.V. Skitovich, “New directions of research of the JSC “NIPTIEM” in the AC electrical machines”. Proceedings of “Actual problems of electromechanics and Electrotechnology, APEET-2017”. Ekaterinburg: FGAOU VPO,
16. Ural Federal University, 2017, pp. 91 - 94.
17. F. Cupertino, G. Pellegrino, C. Gerada, “Design of Synchronous Reluctance Motors with Multi-Objective Optimization Algorithms”, in Industry Applications, IEEE Transactions on. vol. 50, No. 6, pp. 3617 - 3627, November-December 2014.

Biographies

Minh Dinh Bui 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 Science and Geology, Vietnam, in 2007.

He has graduated doctor degree at the Department of Electrical Drive, Institute for Power Engineering and Automation, Berlin Institute of Technology in April 2014. Now he is a lecturer and scientific researcher at Hanoi University of Science and Technology (HUST). His research interests are simulation and control of switched-reluctance machines and high-speed drives. He is expert of Thermal management of 5G RRU in Viettel.