© 2015,
Scienceline Publication
www.science-line.com

ISSN: 2322-5114
Journal of World's Electrical Engineering and Technology
J. World. Elect. Eng. Tech. 4(2): 58-66, Dec 25, 2015

JWEET

Line Start Permanent Magnet Synchronous Motor Performance and Design; a Review

Hamidreza Behbahanifard* and Alireza Sadoughi**

Malek Ashtar University of Technology, Shahinshahr, Isfahan, Iran
Corresponding author's Email: *h-behbahani@mut-es.ac.ir; **sadoughi@mut-es.ac.ir

Abstract *– Line-start PM synchronous motor can be used immediately instead of the conventional induction motor for many applications because of its advantages like high efficiency, high power factor and high power density compare to induction motor, especially for small motor sizes. This paper is a review on research about different aspects of LS-PMS motors presented in literature. LSPMS motor model and parameters, starting and synchronization, cogging torque, pm demagnetization and harmonics are the topics covered in the paper. Besides many researchers designed, simulated and prototyped different LSPMS motors which their results are summarized in this paper.*

Keywords*: Line Start Permanent Magnet Synchronous Motor, LSPMSM*

REVIEW
PII: S232251141500010-4
Received 29 Jun. 2015
Revised 03 Nov. 2015
Accepted 20 Nov. 2015

INTRODUCTION

Electric Motors in Industrial applications consume between 30% and 40% of the generated electrical energy worldwide. So higher efficient electric motors can lead to significant reductions in energy consumption and also reduce environmental impact. Despite the wide variety of electric motors available in the market, three-phase, squirrel-cage induction motors (IMs) represent, by far, the vast majority of the market of electric motors. For many applications, a permanent magnet (PM) synchronous motor can be designed smaller in size and more efficient as compared to induction motor. In particular, line-start PM synchronous motor can be used immediately instead of the conventional induction motors for applications in pumps, air conditioners and fans [1, 2].

LS-PMS motor model

An LS-PMS motor consists of a single or poly-phase stator as same as induction motor and a hybrid rotor involving electricity conducting squirrel cage and pairs of permanent magnet poles.

Different combinations of the cage, pole shapes and pole locations have been presented for the rotor so far.

The motor starts as an induction motor by the resultant of two torque components i.e. cage torque and magnet opponent torque (breaking torque). When the motor speed reaches near synchronous speed, a synchronization process begins and motor operation is transferred to synchronous state when no eddy current flows into the cage bars except harmonics field currents. In synchronous state two torque components i.e. a reluctance torque component and a synchronous torque component cause the rotor motion.

A two-axis dynamic model of three phase line start permanent magnet synchronous motor in rotor reference frame can be given by voltage, flux, and torque equations. The dynamic performance of LS-PMS motor in a stationary d-q reference can be described by this model. [1].

In Marcic et al. [3] study the magnetically linear two-axis LSIPMSM dynamic model with the flux linkage due to permanent magnets as a parameter is presented. In this work the parameters of the model are determined by the differential evolution (DE). The authors showed that the DE is a very suitable tool for determining parameters of the LSIPMSM dynamic model.

NdFeBr magnets are very temperature sensitive. Abbas et al. [4] studied the effect of temperature variation on the performance of an industrial LS-IPMSM is carried out by finite element method. Inductances sensitivity analysis of these motors is also studied and finally, the PM demagnetization due to abnormal operating conditions is presented.

Štumberger et al. [5] presented the usage of a lumped parameter dynamic model with current-dependant variable parameters in LSIPMSM dynamic performance

To cite this paper: Behbahanifard H and Sadoughi A. 2015. Line Start Permanent Magnet Synchronous Motor Performance and Design; a Review. *J World Elec. Eng. Tech.*, 4 (2): 58-66.
Journal homepages: http://www.jweet.science-line.com/

evaluation. For the identification of model parameters the finite element method procedure, is used. The variations of model parameters

(squirrel-cage resistances, stator and rotor self-inductances, and mutual inductances in d- and q-axis) are determined by post-processing of FEM output data.

Lu et al. [6] studied a simple experimental method to determine the magnetization characteristics of an LSPMSM are proposed. Numerical and experimental investigations have been performed to validate the determined characteristics. The results obtained from experiments are found to closely match with that of the numerical investigations. Also Lu et al. [7] studied exclusively a novel magnetic circuit model to design LSPMSM with improved starting performance is proposed. Further, a detailed procedure to deal with the design issues with the help of the developed magnetic circuit model is discussed and validated by developing a machine where the trade-off between their starting performance and efficiency post-synchronization has been reached.

Starting and synchronization

Starting and synchronization of LS-PMS motors have been challenging issues concerned by many researches so far. Magnet braking torque is not the only deficiency of LS-PMS motors starting. The motors also suffer from a sensitive dependency of starting process on input voltage, shaft inertia momentum and cages resistance. With a reduced input voltage, the motor starts more slowly and even may fail in synchronization. The settling time of speed curve also increases with falling of input voltage. There is an optimal value for cage resistance out of which the motor does not start properly.

By increasing the load inertia, the motor starting deteriorates. This may lead to high torque pulsations in induction mode, not reaching the synchronous operation at all. [1]

In Honsinger et al. [8] study, the permanent magnet machine during asynchronous operation has been treated using generalized machine theory. The main body of the paper is concerned with the calculation of torques and currents during run-up.

Miler [9] described the synchronizing process in line-start PM Ac motors, with particular emphasis on the analysis of factors that influence the synchronizing capability. He showed that of the two components of synchronous torque, the magnet alignment torque contributes much more to the synchronizing capability than the reluctance torque, and this leads to a better starting capability for PM motors than for pure reluctance motors of the same size.

Soulard and Nee [10] studied a simple method to define the maximum load torque that can be synchronized by LSPM motors has been presented. Authors defined a pull-in criterion by using a Lyapunov function. The model is derived and a Lyapunov function is defined using the Lagrange-Charpit method. Experiments and simulations are compared to check the validity of the model. Finally a criterion to define the capability of synchronization of LSPM motors is presented.

In Fengbo et al. [11] study, the starting process of high-voltage permanent magnet synchronous motor is calculated and analyzed by the time-stepping Finite Element Method coupling with field and circuits. The starting performance is analyzed by calculating the equations of transient electromagnetic field and mechanical movement equations. In this paper showed that increasing the number of cage bars can enhance Pull capacity of the HV-PMSM. The Pull-in torque was improved, the starting time was reduced. But the change will also increase the starting current, so the number of cage bar should be selected according to different requirements in practical application.

In Takegami et al. [12] study, the purpose of calculating asynchronous starting characteristics of an LSPMM, the method of the constant decision is described. In addition, the calculating results are confirmed by a comparison with an experimental result.

Stoia et al. [13] has proposed a study of synchronization capability of LSPMSM with very high cage resistance and small saliency ratio. The high value of the rotor resistance of the designed motor has beneficial effects on the early start, but the synchronization occurs at a large value of the slip and is relatively difficult. A minimal optimum value of synchronization energy has been found for the no-load voltage which maximizes the critical electromagnetic torque.

In Hassanpour Isfahani et al. [14] study, a simple analytical method for finding critical slip in synchronization assessment of LSPMS motors is presented. Appropriate approximations are employed in the method resulting in significant simplification of the method with reasonable accuracy. The proposed method is time efficient and can be easily included in iterative design procedures. Accuracy of the proposed method is evaluated by dynamic analysis of two different motors. Also, the experimental results are presented to support the analytical and simulation results. Also in Hassanpour Isfahani et al. [15] study, different effects of magnetizing inductance of line start permanent magnet synchronous motors on the motors starting performance are investigated in three different ways. First, the relation between the magnetizing inductance value and the average and pulsating torques during asynchronous operation of motors is discussed. A critical load value is determined to assure the motor start-up. It is shown that this critical load significantly depends on the value of magnetizing inductance. It is also shown that an increase in the magnet flux and saliency reduces this critical load effectively, especially when the magnetizing inductance is small. A dynamic model of motors is then presented to study the starting performance of two motors with different magnetizing inductance values to support the discussions. Finally, the finite-element method is utilized to take into account the saturation, cross magnetization, asymmetrical rotor cage bar resistance, etc. The FEM results verify the results obtained from dynamic simulations.

In Nedelcu et al. [16] study, influence of various geometrical design parameters (i.e. geometry of PMs, flux barriers and rotor bar cross section) on the starting characteristics of a LSPMSM is carried out. The effect of modifying the geometrical configuration of PMs, rotor bars and flux barriers on the LSPMSM starting capability is analyzed using the FLUX software package. This study is proved to be useful for the optimal design of the machine with the purpose of improving its start-up capability, one of the most sensible points of LSPMSM.

Rabbi et al. [17] studied a simplified analytical method to determine the critical slip and the critical inertia of a line start IPM motor based on average torque analysis is presented. The synchronization process of a line start IPM motor has been explained in details. Also, the mathematical formulations of braking torque, cage torque and synchronous torque have been presented. An experimental investigation has also been carried out to determine the synchronization performances of a laboratory 1 hp, 3-phase, 4-pole IPM motor fed from a fixed 3-phase 60Hz ac supply.

Cogging torque

Cogging torque arises from interactions between permanent magnets mounted on the rotor and the anisotropy originated by stator windings slots. These cause variations of the magnetic field energy during the rotation. Cogging torque lowers torque quality and affect smooth running of the machine, producing vibrations and mechanical noise [18].

In Yang et al. [19] study, the analytical method is used to find the relationship between the pole arc coefficient and cogging torque. Then, according to the analytical result, the feasible region of the pole arc coefficient of the PM is derived. With the feasible region of pole arc coefficient, the improved domain elimination method and finite-element method are combined to optimize the pole arc coefficient of the PM to minimize the cogging torque of permanent magnet motor. The authors showed with this method, the computing time decreases notably, and the cogging torque is greatly reduced.

Bing-yi et al. [20] studied, a novel structure of motor which the number of slots per pole per phase q is less than 1 is proposed. The authors showed that the line-start PMSM with a new structure has good starting and running performance. The value of cogging torque is smaller than conventional PMSM. Simulation and prototype test results show that this novel structure is reasonable.

In Chu and Zhu [21] study, the influence of skewing on the torque ripples in PM machines with different magnet shapes and loads is investigated. Although the investigation is carried out on the SPM machines, the conclusions are also applicable to the interior PM machines and the electrically excited machines, where the influence of armature field and magnetic saturation is more significant.

In Bianchini et al. [22] study, an overview of the methods for cogging torque reduction in IPM synchronous machines is presented. The various methods are compared on a common reference machine (12-slot 4-pole IPM machine) by extensive FEM simulations. The results show that some techniques d2eveloped for SPM machines can be easily applied to IPM machines as well.

The authors suggest that care should be used when adopting design solutions for cogging torque reduction in IPM machines as, in some cases; they could negatively affect the torque quality at full load. For best results, during optimization it is advisable not to focus only on cogging torque reduction but to monitor the side effects as well.

In Lee et al. [23] study, torque ripple in the IPMSM according to the rotational speed is presented. The authors showed that torque ripple of the IPMSM tends to increase when flux weakening control is applied. They proposed a method to find harmonic injected current to achieve minimization of torque ripple. This method can be used to improve the accuracy of speed and position when flux weakening control is applied.

Permanent Magnet

The irreversible demagnetization of permanent magnet due to the armature reaction during the starting process of line-start permanent magnet synchronous motor (LSPMSM) has tremendous influence on its performance, even makes the machine unable to work. In Kang et al. [24] study, the irreversible demagnetization characteristics of a ferrite-type permanent magnet in the line-start PM motor is carried out by using the two-dimensional finite element method. The demagnetizing currents are calculated from the transient analysis in combination of voltage equation and mechanical dynamic equation, and peak currents are applied to the irreversible demagnetization analysis computed by 2-D FEM. The nonlinear characteristic of the magnetic cores has been considered as well as that of a permanent magnet on the B-H curve in the analysis of irreversible demagnetization.

In Lu et al. [25] study, the armature reaction demagnetization during the starting process of LSPMSM has been calculated, and the variety of influencing factors has been studied. Analysis results shows that demagnetization is more prone to occur when start-up time is longer because of larger load or larger inertia or lower supply voltage, or because of a specific initial rotor position especially during the light-load starting process.

In Lu et al. [26] study, authors made an effort to study the causes and effects of permanent magnet demagnetization in permanent magnet machines and proposed an exclusive artificial neural network (ANN) based permanent magnet demagnetization detection scheme. A laboratory 2.8 kW line-start permanent magnet synchronous machine (LSPMSM) is used in the numerical investigations for initiating permanent magnet demagnetization and detecting the fault.

In Shen et al. [27] study, four rotor configurations are proposed to protect the magnets from demagnetization, and their effectiveness is comparatively studied. It is shown that the configuration with both dual cages and magnetic barriers performs the best to protect the magnets, and hardly deteriorates the normal operation performance. The line start permanent magnet motor is noted as an alternative to the induction motor because it offers a very high efficiency and unity power factor. However, a high manufacture cost as compared to an induction motor is disadvantage. Thus, the post-assembly magnetization of the NdFeB magnet is considered to reduce the material and the manufacturing costs. In Lee et al. [28] study, the magnetizing fixture that magnetizing the NdFeB in the rotor of LSPM is designed and its characteristics of magnetization are analyzed. The eddy current occurring in rotor bars disturbs the magnetization of NdFeB. To reduce the eddy current occurring in the rotor bars the authors have investigated the magnetization characteristics for various coil-turn and dimension of rotor bars by time stepping the FEM with model. The analysis results agree well with experiment results.

In Lee and Kwon [29] study, the design procedure and methods for designing the post-assembly magnetization system of the LSPM are proposed. The design procedure is focused on the design of the capacities of the magnetizer and the coil-turns. The methods for designing the post-assembly magnetization system are to increase the number of coil-turns and to reduce the rotor bar size in order to reduce the eddy current. In order to improve the efficiency, the rotor is redesigned and manufactured. In addition, the magnetization system for it is designed and manufactured.

In Stoia et al. [30] study, a graphical-analytical method for the size up procedure of PMs used in LSPMSM is proposed. Using this theoretical approach the amount of magnet for the required dynamic and steady state performances of this motor can be calculated. The designed operating point of the PM offers the advantage of a large magnetic energy density, near of its maximum.

HARMONICS

One of the drawbacks of LSPMSM is higher harmonic contents of flux density, as well as current and electromagnetic torque in comparison to an induction motor.

In Kurihara et al. [31] study, a method for analysis to obtain steady-state currents and torques of permanent magnet synchronous motors including space harmonics is presented. Time-stepping finite element techniques including the rotor movement are proposed, where both terminal voltage and load angle are given as the known values. The agreement between calculated and measured results of the synchronous performance in an experimental motor is good.

In Zawilak and Zawilak [32] study, on the basis of field-circuit calculations, investigation of higher harmonics of flux density, back emf, armature current and electromagnetic torque in a Line-Start Permanent Magnet Synchronous Motor have been conducted. The paper presents a new construction of rotor with variable slot width. It is characterized by much lower amplitudes of magnetic field zonal harmonics. This new design has been compared with a typical LSPMSM construction.

In Rong and Manfeng [33] study, authors focus on the harmonic suppression function of the damper windings for air-gap magnetic field of line-start permanent magnet synchronous motors (LSPMSM) using finite element analysis. The simulations and the tests for the line-start PMSM designed by the author were compared, and the results shown in this paper have confirmed the validity of harmonic suppression function of the damper windings, and it is practical value for the reasonable design of line-start PMSM.

Design Aspect

In Kurihara and Azizur Rahman [34] study, a successful design of a high-efficiency small but novel line start PM motor using NdFeB magnets was developed and tested. It is designed to operate both at line and variable frequencies. The IPM motor can start and synchronize with large load inertia. Time-stepping finite-element analysis has been used to successfully predict the dynamic and transient performance of the prototype motors. It has been found that the proposed design has yielded successful simulation and experimental results. The maximum load inertia corresponding to the rotor-bar depth has been given from the simulation results.

In Bingyi et al. [35] study, the structural characteristics of the multi polar line-start PMSM for the low-speed and high torque gearless driver system has presented. The special structures of the stator and rotor have been analyzed. And how temperature influences the performance of the motor is also indicated. Moreover, how to select the length of air-gap and the size of permanent magnet is discussed. Also a high performance multi polar line-start PMSM is designed by MATLAB. The computer simulation results of starting process of the motor are given by ANSOFT base on FEM. The simulation results indicate the design scheme for the multi polar line-start PMSM is feasible.

Yang et al. [36] study, aims at optimal analysis and design of a three-phase line-start PMSM with simple structure, low cost and good performance. A prototype with 4 magnet poles is designed and manufactured. Simulation and experimental results are approximately the same and the prototype essentially satisfies the design request.

In Lu and Ye [37] study, a large capacity LSPMS motor which keeps the configuration as much as that of induction motor in order to reduce the manufacture cost is proposed. Its transient and steady-state performance is predicted by a useful dynamic FEM model that is validated by experiment on an induction motor. Compared with the induction motor, this LSPMSM not only has higher efficiency and power factor, but also has sufficient starting ability on full load.

In Xiaochen et al. [38] study, a solid rotor permanent magnet synchronous motor (PMSM) is developed for the electric propulsion part in electric vehicles (EV). The rotor in this kind of motor is composed of splits solid rotors, interior permanent magnets and starting bars. In this paper, a 30kW solid rotor PMSM with simply structure was taken as the analysis model, and the numerical calculation model under assumptions, as well as the solving regions of the derived model, is proposed. Starting performance and operation performance are analyzed, and some parameters as stator current, power factor and torque-speed characteristic are obtained. The calculated results show good agreement with the experimental data.

In Kim et al. [39] study, a comparison between three architectures of line-start PM motors for oil-pump application is presented. This paper is focused on the performances in synchronous operation as well as the self-starting operations. Effects of electrical parameters on the starting and steady performance characteristics are demonstrated to find a satisfying design to meet required performances.

In Peralta-Sánchez and Smith [40] study, a new form of line-start PM machine that uses a simple canned rotor construction with surface mounted magnets has described. The rotor can acts as the induction winding to provide the line-start capability and also provides a dual role as an environmental shield for applications where this is necessary. This paper has also developed a transient electromechanical model using a classical two-axis model combined with a layer model to determine certain motor parameters. This paper also includes experimental results of the dynamic starting and synchronization performance from a prototype 2.5-kW motor and examines the influence of certain key design features on synchronization.

In Fei et al. [41] study, a high-performance line-start permanent magnet synchronous motor which is developed by simple modifications of an off-the-shelf small industrial three-phase IM with minimized additional costs is presented. Two-dimensional dynamic finite element analysis models are employed to assess the machine performances, which are validated by comprehensive experimental results. The experimental comparison between the amended LSPMSM and the original IM have indicated that significant improvements in efficiency and power factor can be achieved by the proposed motor.

In Stoia et al. [42] study, an analytical design method for the LSPMSM, considering the asynchronous starting and the synchronous steady state parameters is proposed. Using this theoretical approach, all the synchronous and asynchronous starting characteristics can be calculated.

In Yaojing and Kai [43] study, a two-pole three-phase high power line-start permanent magnet synchronous motor is introduced.

The authors described the operating principle and structural features of the line start PMSM . An interior PM rotor structure is presented, which adopts a radial-set of permanent magnets with multi-section for each pole. A motor model is then established by employing the finite element analysis software JMAG-Studio. The transient electromagnetic field is calculated and analyzed using the time-stepping FEM coupling with magnetic field analysis with electrical circuits. The starting process and steady-state performance are simulated.

A high-efficiency Line Start Permanent Magnet Synchronous Machine is designed in Jazdzynski and Bajek [44] work, to meet efficiency requirements, which can be expected for motors of a class IE4 in a new standard classification. A magnetically linear analytical model of the LSPMSM has been developed and investigated. The task to find a best design solution has been defined as a bi-criterial optimization problem, with criteria functions representing the interest of both the producer and end user. Calculation results were validated by means of a magnetically non-linear FEM model, before and after the optimization.

In Feng et al. [45] work, the supper premium efficiency LSPMSM is researched and developed. The challenges and key design techniques are introduced. Also the advanced digital simulation is used for designed performance evaluation. The prototypes have been built, tested, analyzed and compared with calculated data. The results show that the supper premium LSPMSM has much better efficiency, power factor, and power density, smaller frame size and less material consumption compared with Premium efficiency IM, leading to cost down and energy saving in various applications.

In Ruan et al. [46] study, a comparison between two architectures of line-start permanent magnet motors is presented .The authors focused on the performances in synchronous operation as well as the self-starting operations. Time stepping finite element analysis has been used to predict the dynamic and transient performances of the two prototype motors. It has been found that the motor with series magnetic circuit structure has yielded an impressive performance.

A high performance LSPMSM with consequent pole arrangement of magnets is proposed and studied in Ugale and Chaudhari [47] work. The proposed magnet arrangement results in improved air gap flux density when compared with other magnet configurations used earlier, for same magnet volume. The performance of proposed rotor is significant when benchmarked with the induction motor of the same rating and size. The proposed rotor has better power factor, less value of rated current and greater energy saving potential. Performance indicators such as no load power factor, open circuit induced emf, no load current, the rated current, the rated efficiency, rated power factor, torque angle, maximum torque ability are in favor of proposed motor. The proposed rotor can be used in 2 pole or 4 pole machines just by changing the magnet orientation for the arc magnets.

An optimal design of a new line-start permanent magnet synchronous shaded-pole motor (LSPMSSPM) is proposed in Shamlou S, Mirsalim [48] work. A genetic algorithm optimization method based on transient two-dimensional finite-element method (FEM) is applied to reach a global optimum design. Advantages and challenges of the proposed LSPMSSPM are investigated, and its performance characteristics are calculated. Efficiency, power factor, starting behavior and cost as important key factors are analyzed. FEM results are verified with experimental tests.

In Lu et al. [49] study, the electromagnetic parameters with different bar design parameters are calculated, and the influences of them on the starting performance are also studied. The authors showed with the increase of the bar width or material conductivity, the starting impedance decreases, and thus the starting current and the pull in torque increase. However, there is a maximal value of the starting torque with a specific bar design. Based on the analysis results, the rotor bar design can be optimized for the demand of the higher starting performance of LSPMSM.

CONCLUSION

In this paper research about different aspects of LS-PMS motors presented in literature, in last three decades, were reviewed. To make LS-PMS motor a real competitor to induction motor in a wide variety of applications, more investigations should be done.

In this respect, the starting performance must be considered the primary measure. Also demagnetization of permanent magnets should be considered in design of LSPMS motors. Generally in the design of LSPMS motors, a tradeoff between the motors parameters is needed. In fact the LSPMSM designer has to find many compromises in the design process. The compromise between the value of starting torque, which depends mainly on the squirrel-cage design and material, and the starting current. The compromise between the value of braking torques (due to the presence of PMs in the asynchronous operating region) which depends mainly on the placement, dimensions and the value of energy product of PMs, and motor's synchronization capability. The compromise between an adequate starting characteristic in the asynchronous operating region and the torque capability, power factor and efficiency in the motor's synchronous operating region.

Acknowledgment

The authors gratefully acknowledge all the researchers that their papers have been reviewed and addressed in this article.

REFERENCES

[1] Isfahani A. H. and Vaez-Zadeh S., “Line-start permanent magnet synchronous motors: Challenges and opportunities,” J. Energy, vol. 34, pp. 1755–1763, 2009.

[2] De Almeida, A., Ferreira F .I. T. E., Fong I., "Standards for Efficiency of Electric Motors", IEEE Industry Applications Magazine, Vol 17, No. I, pp. 1 2- 1 9, Jan./Feb. 20

[3] Marcic T, Stumberger G, Stumberger B, Hadziselimovic M, Virtic P. Determining parameter of a line-start interior permanent magnet synchronous motor model by the differential evolution. IEEE Trans Magn vol. 44, no. 11 November. 2008

[4] Abbas A., Yousef H.A., and Sebakhy O.A.; FE Parameters Sensitivity Analysis of an Industrial LS Interior PM Synchronous Motor. Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century , 2008 IEEE

[5] Štumberger B, Marčič T, Štumberger G, Hadžiselimović M, and Trlep M. Evaluation of Line-Start Interior Permanent Magnet Synchronous Motor Model Parameters Using Finite Elements. 14th Biannual IEEE Conference on Electromagnetic Field Computation (CEFC) , 2010

[6] Lu X, Lakshmi K., Iyer V, Mukherjee K, and Narayan C. Kar. A Novel Two-Axis Theory-Based Experimental Approach towards Determination of Magnetization Characteristics of Line-Start Permanent Magnet Synchronous Machines. IEEE Transactions on Magnetics, Vol. 49, No. 8, August 2013

[7] Lu X, Lakshmi K., Iyer V, Mukherjee K, and Narayan C. Kar. Development of a Novel Magnetic Circuit Model for Design of Premium Efficiency Three-Phase Line Start Permanent Magnet Machines With Improved Starting Performance. IEEE Transactions on Magnetics, Vol. 49, No. 7, July 2013

[8] Honsinger V.B., Permanent Magnet Machines: Sychronous Operation. IEEE Transactions On Power Apparatus And Systems, Vol. PAS-99, No. 4 July/Aug 1980

[9] Miller T.J.E. Synchronization of Line-Start Permanent-Magnet Ac Motors. IEEE Transaction on Power Apparatus and Systems, Vol. PAS- 103, No. 7, July 1984

[10] Soulard J, Nee H-P. Study of the Synchronization of Line-Start Permanent Magnet Synchronous Motors. IEEE Industry Applications Conference, 2000

[11] Fengbo Q, Z Li, Shukang Ch, Weili L. Calculation and Simulation Analysis on starting performance of the High-voltage Line-start PMSM. 2010 International Conference on Computer application and System Modeling (ICCASM 2010)

[12] Takegami T, Tsuboi K, Hasegawa M, Hirotsuka I, Nakamura M. Calculation Method for Asynchronous Starting Characteristics of Line-Start Permanent Magnet Synchronous Motor. International Conference on Electrical Machines and System (ICEMS) 2010

[13] Stoia D, Chirilă O, Cernat M, Hameyer K, Ban D, The Behaviour of The LSPMSM in Asynchronous Operation, 14th International Power Electronics and Motion Control Conference, EPE-PEMC 2010

[14] Hassanpour Isfahani A., Vaez-Zadeh S., Rahman M. A. Evaluation of Synchronization Capability in Line Start Permanent Magnet Synchronous Motors, 2011 IEEE International Electric Machines & Derives conference (IEMDC)

[15] Hassanpour Isfahani A, Vaez-Zadeh S, Effects of Magnetizing Inductance on Start-Up and Synchronization of Line-Start Permanent-Magnet Synchronous Motors, IEEE Transactions on Magnetics, Vol. 47, No. 4, APRIL 2011

[16] Steluta N, Tudorache T, Ghita C. Influence of design parameters on a line start permanent magnet machine characteristics,13th International conference on optimization of Electrical and electronic equipment (OPTIM) , 2012

[17] Rabbi S. F., Rahman M. A., Determination of the Synchronization Criteria of Line Start IPM motors, IEEE International Conference on Electric Machines and Derives (IEMDC) 2013

[18] Bianchini C, Immovilli F, Bellini A, Davoli M, Cogging Torque Reduction Methods for Internal Permanent Magnet Motors: Review and Comparison, XIX International Conference on Electrical Machines - ICEM 2010, Rome

[19] Yang Y, Wang X, Zhang R, Ding T, and Tang R, The Optimization of Pole Arc Coefficient to Reduce Cogging Torque in Surface-Mounted Permanent Magnet Motors ,

IEEE Transactions on Magnetics, Vol. 42, No. 4, April 2006
[20] Bing-yi Z, Cui G, Wang S, Feng G-H, Study of Cogging Torque in Line-Start PMSM With Proper Fractional Slot Winding , International conference on E- product, E-Service and E-Entertainment (ICEEE) , 2010
[21] Chu W. Q. and Zhu Z. Q., Investigation of Torque Ripples in Permanent Magnet Synchronous Machines With Skewing, IEEE Transactions on Magnetics, Vol. 49, No. 3, March 2013
[22] Bianchini C, Immovilli F, Lorenzani E, Bellini A, and Davoli M, Review of Design Solutions for Internal Permanent-Magnet Machines Cogging Torque Reduction, IEEE Transactions on Magnetics, Vol. 48, No. 10, October 2012
[23] Lee G-H, Kim S-I, Hong J-P, and Bahn J-H, Torque Ripple Reduction of Interior Permanent Magnet Synchronous Motor Using Harmonic Injected Current , IEEE Transactions on Magnetics, Vol. 44, No. 6, June 2008
[24] Kang G-H, HurHyuk Nam J, Hong J-P, and Kim G-T, Analysis of Irreversible Magnet Demagnetization in Line-Start Motors Based on the Finite-Element Method , IEEE Transactions on Magnetics, Vol. 39, No. 3, May 2003
[25] Lu W, Liu M, Luo Y, Liu Y, Influencing Factors on the Demagnetization of Line-start Permanent Magnet Synchronous Motor during Its Starting Process , International Conference on Electrical Machines and System (ICEMS) 2011
[26] Lu X, Lakshmi K., Iyer V, Mukherjee K and Narayan C. Kar, Study and Detection of Demagnetization in Line Start Permanent Magnet Synchronous Machines Using Artificial Neural Network, 15th International Conference on Electrical Machines and System (ICEMS) , 2012
[27] Shen J-X, Li P, Jin M-J, and Yang G, Investigation and Countermeasures for Demagnetization in Line Start Permanent Magnet Synchronous Motors, IEEE Transactions on Magnetics, Vol. 49, No. 7, July 2013
[28] Lee C. K., Kwon B. I., Kim B.-T., Woo K. I., and Han M. G., Analysis of Magnetization of Magnet in the Rotor Of Line Start Permanent Magnet Motor , IEEE Transactions on Magnetics, Vol. 39, No. 3, May 2003
[29] Lee Ch.K. and Byung Il Kwon, Design of Post-Assembly Magnetization System of Line Start Permanent-Magnet Motors Using FEM, IEEE Transactions on Magnetics, Vol. 41, NO. 5, May 2005
[30] Stoia D, Mihai CERNAT, Dănuţ ILEA, Educational Bench of Line-Start Permanent Magnet Synchronous Motors Part I: Operating Point Of Permanent Magnet , The 4th International Conference on Interdisciplinarity in Education ICIE'09, May21-22, 2009, Vilnius, Lithuania
[31] Kurihara K, Wakui G, and Kubota T, Steady-State Performance Analysis of Permanent Magnet Synchronous Motors Including Space Harmonics, IEEE Transactions on Magnetics, Vol. 30, No. 3. May 1994
[32] Zawilak T, Zawilak J, Minimization of Higher Harmonics In Line-Start Permanent Magnetsynchronous Motor, Studia i Materiały Nr 29, 2009
[33] Rong Fu, Dou M, Study on Harmonic Suppression of Damper Windings for Air-gap Magnetic Field of Line-start Permanent Magnet Synchronous Motors , International Conference on Electrical Machines and System (ICEMS) , 2011
[34] Kurihara K and Azizur Rahman M., High-Efficiency Line-Start Interior Permanent-Magnet Synchronous Motors, IEEE Transactions on Industry Applications, Vol. 40, No. 3, May/June 2004
[35] Bingyi Z, Wei1 Z, Fuyu Z, Guihong F, Design and Starting Process Analysis of Multipolar Line-Start PMSM , Proceeding of International Conference on Electrical Machines and Systems 2007, Oct. 8~11, Seoul, Korea
[36] Yang G, Ma J, Shen J-X, and Wang Y, Optimal Design and Experimental Verification of a Line-Start Permanent Magnet Synchronous Motor, International Conference on Electrical Machines and System (ICEMS), 2008
[37] Lu QF and Ye YY, Design and Analysis of Large Capacity Line-Start Permanent-Magnet Motor, IEEE Transactions on Magnetics, Vol. 44, No. 11, November 2008
[38] Xiaochen Z, Shukang C and Weili L, Development of Line-start PMSM with Solid Rotor for Electric Vehicles , IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008, Harbin, China
[39] Kim W-H, Kim K-Ch, Kim S-J, Kang D-W, Go S-Ch, Lee H-W, Chun Y-D, and Lee J, A Study on the Optimal Rotor design of LSPM Considering the Starting Torque and Efficiency, IEEE Transactions on Magnetics, Vol. 45, No. 3, March 2009
[40] Peralta-Sánchez E and Smith A. C., Line-Start Permanent-Magnet Machines Using a Canned Rotor, IEEE Transactions on Industry Applications, Vol. 45, No. 3, May/June 2009
[41] Fei W., P. C. K. Luk, J. Ma, J. X. Shen, and G. Yang, A High-Performance Line-Start Permanent Magnet Synchronous Motor Amended From a Small Industrial Three-Phase Induction Motor , IEEE Transactions on Magnetics, Vol. 45, No. 10, October 2009
[42] Stoia D, Cernat M, Jimor AA., Nicolae DV., Analytical Design and Analysis of Line-Start Permanent Magnet Synchronous Motors, IEEE AFRICON 2009 23 - 25 September 2009, Nairobi, Kenya
[43] Yaojing F, and Kai Y, A Two-pole High-power Line-start Permanent Magnet Synchronous Motor, International Conference on Electrical Machines and System (ICEMS), 2008
[44] Jazdzynski W., Bajek M., Modeling and Bi-Criterial Optimization of a Line Start Permanent Magnet Synchronous Machine to Find an IE4 Class High-Efficiency Motor , XIX International Conference on Electrical Machines - ICEM 2010, Rome
[45] Feng X., L. Liu, J. Kang, Y. Zhang , Super Premium Efficient Line Start-up Permanent Magnet Synchronous Motor, XIX International Conference on Electrical Machines - ICEM 2010, Rome
[46] Ruan T, Haipeng Pan Yongming Xia , Design and Analysis of Two Different Line-Start PM Synchronous Motors, 2nd International Conference on Artificial Intelligence Management Science and Electronic Commerce (AIMSCE) , Aug. 2011
[47] Ugale R. T. and Chaudhari B. N., A New Rotor Structure for Line Start Permanent Magnet Synchronous Motor , IEEE International Conference on Electric Machine & Drives (IEMDC), 2013
[48] Shamlou S, Mirsalim M, Design, optimisation, analysis and experimental verification of a new line-start permanent magnet synchronous shaded-pole motor , IET Electric Power Applications , 2012

[49] Lu W, Luo Y, and Zhao H, Influences of Rotor Bar Design on the Starting Performance of Line-start Permanent Magnet Synchronous Motor , 6th International Conference on Electromagnetic and field Problems and Applications (ICEF) , 2012