

## Comparative Study for Machine Candidates for High Speed Traction Applications

Ahmed A. Abdelhafez<sup>a,b\*</sup>, Majed A. Aldalbehi<sup>a</sup>, Naif F. Aldalbehi<sup>a</sup>, Fawaz R. Alotaibi, Naif A. Alotaibi<sup>a</sup> and Reyan S. Alotaibi

<sup>a</sup>Electrical Engineering Department, College of Engineering,  
Shaqra University, KSA,

<sup>b</sup>Electrical Engineering Department, Faculty of Engineering,  
Assiut University, Assiut, Egypt,

### Abstract

Intra cities traction arrangements require a machine topology that enjoys advantages in terms of kW/kg ratio, efficiency and volumetric dimension. Moreover, these applications demand simple machine structure without sophisticated gearbox systems. This article compares different machine topologies: conventional topologies as induction machine, permanent magnet and switched reluctance machine and linear motor topologies for High Speed Traction (HST) application. The comparison addresses different design criteria for HST area as cost, reliability, efficiency, fault-torque, fault-tolerance ability, excitation arrangements and power density.

**Index Terms:** High Speed Traction, Rotary Machine Topologies, Environment compatibility, Linear Machine topologies, Magnetic Levitation. Linear Induction Motor, Linear Synchronous Motor.

### 1. INTRODUCTION

HST gains more interest recently, due to the advantages of mass people and product transportation ability [1-4]. HST applications are considered the future trendsetter for transportation; they could probably be powered from renewable energy sources, which have economical and environmental advantages [4-6]. More countries are

building such high-speed railways to increase the economic exchange with their neighbors and different regions within their territories [2,3,5]. Different machine topologies are examined in the literature for HST applications either rotating or linear topologies [5-9].

Choice of traction motor in HST applications is a key issue [1,2,6-9]. The selection of electric propulsion systems for HST applications relies on technical and economical advantages of the drive such as torque/thrust versus speed characteristics, vehicle restrictions, energy source, driver cost and efficiency [6-9]. Rotary machine topologies as DC motor, Induction Motor (IM), Permanent Magnet (PM) and Switched Reluctance (SR) synchronous motor are examined for electric drive in all/hybrid electric vehicle [10-14]. These topologies offer merits of high power density and efficiency as PM. However, less literature is reported regarding their application in HST applications.

Linear machine topologies are proved to be preferred option for HST area. This is due to the salient features of these topologies [1-9] :

1. Linear topologies allow the adoption of magnetic levitation framework, which reduces friction forces allowing extremely high speed to be achieved.
2. Developed powers are converted directly into thrust without losing a fraction in the conversion from rotational into translational energy. This yields autonomous adherence factor between wheel and rail.
3. The maintenance of the wheel-set and rails are reduced particularly for magnetic levitation where virtue contact-free drive forced is developed.
4. Ability to deliver wide range power/thrust suitable for different cruise stages.
5. Adopting the drive power framework in the track reduces the vehicle weight and allows the ability to be coordinated to the track areas.

A number of limitations that linear machine topologies are reported in the literature [1,2,4-9], and they are briefly mentioned in the following :

1. The linear machine topologies require extremely wider air gap than the rotary machine topologies, which increases magnetic resistance and reduces the efficiency. Air gaps of linear motor are nearly 10 mm, while 1 mm is the typical length in rotary machine.
2. The efficiency of linear topologies are lower than the rotary topologies, due to the end effect. Moreover, the long-stator linear machines have even more reduced efficiency, because the vehicle (inactive part) is shorter than the active stator.

The main target of this article are:

1. Providing concise and adequate highlighting for rotary and linear machine topologies in the area of HST.
2. Comparing the linear and rotary machine topologies to identify the most appropriate option for HST field.

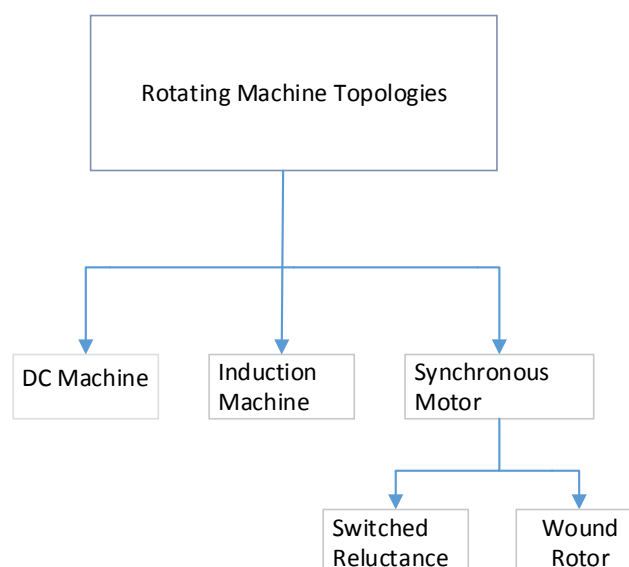
This article is organized as follows. Section 2 highlights the different machine structures either rotary or linear. Section 3 contains the comparison. Finally, the conclusions are drawn in Section 4.

## **2. MACHINE CANDIDATES**

Different topologies within rotary and linear groups could satisfy the requirements of electric drive application either Electric Vehicle (EV)/Hybrid Electric Vehicle (HEV) or HST. The focus here is on the topologies that proved potential and capacity for these applications [1,2,6-9,10-12].

### **2.1. Rotary machine topologies**

The rotary machine topologies are examined in this research according to their application for electric drive either in EV or HEV. However, it is worth to mention that there is less literature regarding the adoption of rotary machine topologies in HST application.



**Figure 1,** Rotary machine topologies for HST application

### **2.1.1. DC Machine**

DC motors may consider suit for electric drive and hence HST, due to match between their torque-speed characteristics and traction requirement. Moreover, the speed control of DC machine is straightforward. However, DC motor drives have cumbersome construction, low efficiency, low reliability and need of maintenance. The DC motor suffers also from a construction limit, commutator and brushed arrangements, which impedes the current transferred to the rotary part. Moreover, the recent advancements in the areas of solid-state devices and control draft the focus to the AC rotary topologies; since they are inherently lighter, efficient and robust [10-12].

### **2.1.2. Induction Machine**

Induction motors have the potential for electric traction applications. This is due to the advantages of induction machines such as: undependability, roughness, low maintenance, low cost, and capability to work in harsh environment [12-15]. Induction machine enjoys inherent fault tolerance capability; as the phase is de-excited under phase short-circuit failure. Moreover, the machine enjoys robustness and less maintenance requirements [10-18]].

The induction machines, however, suffer from drawbacks such as [10,12,15-18]:

1. Sophisticated excitation configurations are required to fulfill machine reactive power requirements such as field oriented control. The volumetric dimensions and proposed location for such excitation system are conflicted.
2. Low efficiency, low power factor, and low inverter utilization factor.
3. The machine in general is low speed machine, which reduces the reliability and efficiency.
4. A fault disable one-phase could diminish the developed torque.
5. For regenerative operation during braking or descending, the costly power electronic converters have to be deployed to reduce field speed to the low that allows regenerative operation.

### **2.1.3. Permanent Magnet Motor (PM Brushless Motor)**

PM brushless motors recently became preferred option for the electric propulsion/drive of Hybrid Electric Vehicle (HEV), due to the salient features of PM machines such as : High power density (High kW per kg) , reduced weight and volumetric dimensions and high efficiency [19-21].

There are different configurations of PM brushless motors. These topologies differ according to the action of the PM. They are surface magnet mounted or covered magnet mounted, the last being more rough. The surface magnet designs may utilize less magnets, while the covered magnet designs may accomplish higher air-gap flux density. Another configuration is the PM hybrid motor, where the air gap magnetic field is obtained via a blend of PM and a field winding. A PM topology incorporate PM and reluctance characteristics are given in [20-24].

PM may suffer from brushless topologies are albeit expensive, however, for HST application the above mentioned advantages could overwhelm the cost penalty [19,21,23,24].

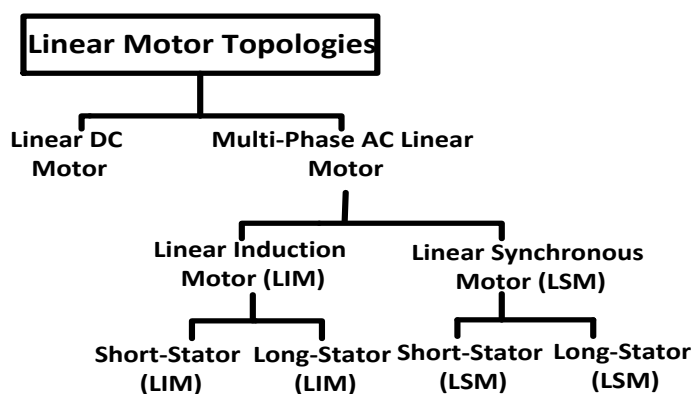
**2.1.4. Switched Reluctance Switched Reluctance Motor (SRM)**

More concern were recently directed to SRM, due to the unequivocal points of interest of straightforward and tough configuration, fault tolerant operation, straightforward control, and exceptional torque-speed characteristics. SRM can inherently run with a great degree long consistent power range [25-28].

SRM has a number of inconveniences, such as acoustic commotion descent, torque ripple, unique converter topology, above the top transport current ripple, electromagnetic interference (EMI) [26-31].

**2.2. Linear Machine Topologies**

Linear machines for HST application are mainly AC type due to the nature of magnetic field required for such area; thus they are divided into broad groups, as shown in Figure 2 [1,2,6,32].

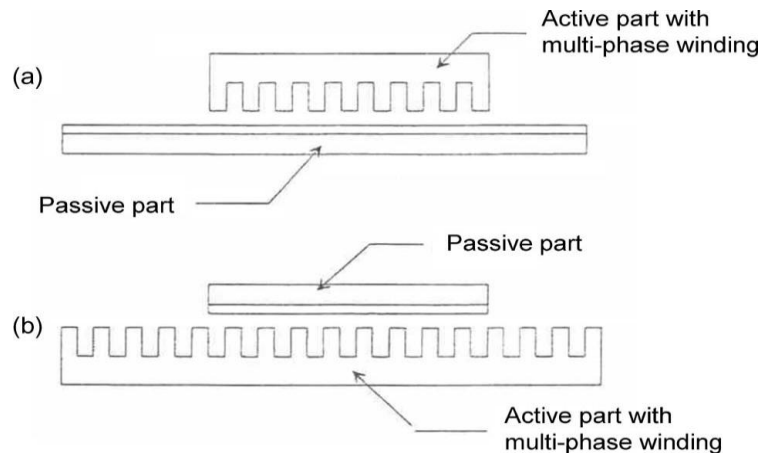


**Figure 2:** Linear machine topologies for HST application

The linear machines as shown in Figure 2 are composed mainly from two configuration irrespective to the topology either induction or synchronous. These configurations are short-stator and long-stator [1,2,32].

In the short-stator configuration, Figure 3, (a) the stator and the frequency converter are fixed on board of the vehicle. Furthermore, the passive part is fitted along the track. Along these lines, the weight of the vehicle increments with the proposed speed, while the cost for the latent part of the machine remains consistent. Likewise, a power transmission framework for bolstering traction energy to the vehicle is important [1,32-33].

For the long-stator straight impetus framework, a multi-phase travelling field winding is field along the track. This winding is energized segment by segment by stationary power converters. Along these lines, the vehicle is the inactive part of the engine and it is not important to transmit traction energy to the vehicle. This is a noteworthy feature of the long-stator linear motor, allowing rates of speed up to more than 500 km/h, Figure 3 (b).



**Figure 3 (a)** Short-stator motor; **(b)** long-stator motor.

### 2.2.1. Linear DC Machine

Linear dc machines are not used for railroad frameworks. Because of the variable polarity in the active part, the brushes between the active and passive part of the motor cause arcing. The terminating of the gatherer brings about a high support prerequisite and the dependability is low [1,32].

### 2.2.2. Linear Synchronous Machine

Linear synchronous motors (LSM) could be dividedly generally into hetero-polar and homo-polar types. LSM resemble rotary synchronous motor in the main principle of

the operation. LSM as other linear machines is also divided into short-stator and long-stator topologies [1,2]. The short-stator is alternatively termed active guide way LSM, with traditional electromagnetic energizing magnets or a superconducting field winding on board of the vehicle. The cross section of active guide way LSM is shown in Figure 4 [33-36].

The long-stator LSM is themed as a passive guide way LSM. The multiphase winding and field winding are incorporated into a single unit. The cost of long-stator LSM is lower than the cost of short-stator LSM. The passive part of long-stator LSM comprises of consecutive shafts. Only part of the field is utilized to deliver a thrust.

The passive guide way LSM is preferred option for transportation frameworks. The dynamic guide way LSM is a heteropolar motor and may have either an iron core or an air core. The iron-center sort have electromagnets or permanent magnets. An ordinary appealing force occurs between the active and passive parts of the iron-center LSM as shown in Figure 5.

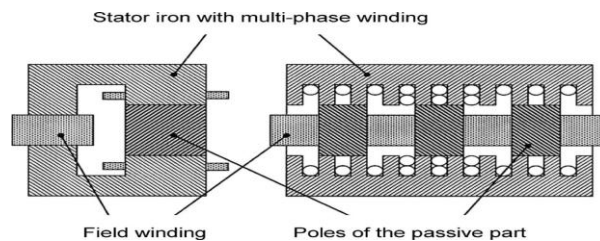


Figure 4. Short-stator linear synchronous homo-polar motor [6].

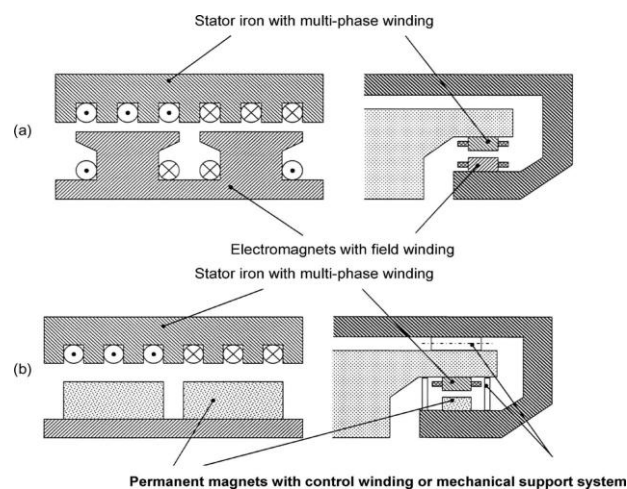


Figure 5. Iron-core long-stator linear synchronous motor. (a) Controllable electromagnetic system. (b) Controllable permanent magnetic system with mechanical support system [6].

### 2.2.3. Linear Induction Machine

Again, the linear induction machine (LIM) and rotary induction machine have the same principles. Also LIM is divided into short-stator and long-stator topologies. In general, the multi-phase winding produce travelling electromagnetic field with synchronous speed. This field produces current in the inactive part and hence flux. The fluxes from field windings and inactive part interact to produce force and hence thrust [1,33-36].

In the short-stator LIM, energy must be transmitted to the vehicle. Therefore, the efficiency of short-stator LIM is lower than long-stator LIM because of the considerable air gap required by tolerances of the driving dynamics. In long-stator LIM, the guide way hardware is extremely basic and cheap. In transportation frameworks, ordinarily short-stator LIM are utilized for low-speed frameworks as shown in Figure 6.

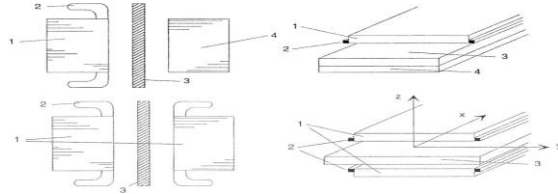


Figure 6. Short-stator linear induction motor: single- and double-stator. 1: Stator iron; 2: multiphase winding; 3: passive part (conductive sheet); 4: solid iron [8].

## 3. COMPARISON ASPECTS

In the following the three promising machine candidates for HST application: Rotary and linear machine topologies are compared regarding reliability, density, robustness and efficiency.

Power density reveals the ratio of the produced power relative to the mass of the machine; it is denoted by Kw/kg. Controllability is the ability to control the system with simple and inexpensive tools. Reliability is the ability to operate under harsh environment with less scheduled and unscheduled maintenance. Fault tolerance is the ability of the motor to continue function after developing sustained fault with a little reduction in output power/torque.

### 3.1. Rotary Machines

Figure 7 shows a comparison between rotary machine for HST applications as underground inter-cities train.



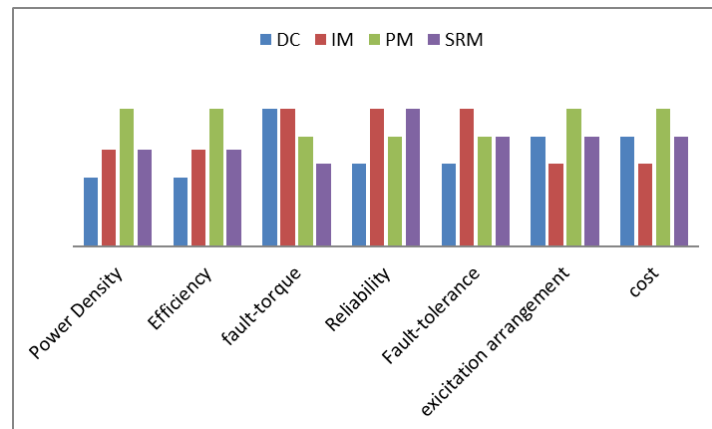


Figure 7. Rotary machine topologies for underground inter-cities HST application

PM enjoys highest power density and efficiency. Moreover, PM has simple excitation arrangement. However, this motor suffer from its elevated cost.

IM is inherently fault-tolerant, as the three-phase short circuit fault at machine terminals result in de-energizing the motor. It is extremely robust machine. Moreover, IM has the lowest cost. However, the IM suffers from low efficiency and power density.

SRM is robust motor with sufficiently high efficiency, reliability and power density. However, SRM requires complicated excitation arrangement. Moreover, SRM has high acoustic noise and torque ripple.

Rotary machines in general could not compete linear topologies in very high speed HST application.

### 3.2. Linear Machines

Figure 8 shows the comparison between linear machine topologies

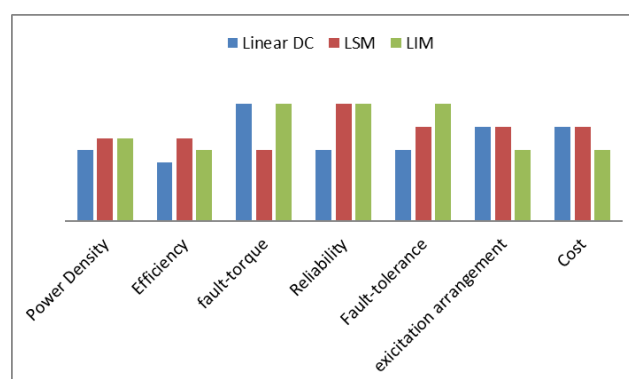


Figure 8. Linear machine topologies for high speed HST

Linear DC motor as mentioned before is not suitable for HST application, due to maintenance and arcing problems.

LIM and LSM are the most preferred options for high speed HST.

#### **4. CONCLUSION**

HST application would improve the compatibility of transportation industry with environment obligations meanwhile reduce fuel consumption. HST has the merits of dependability, reliability and safety. HST yields in mass transportation for the people and product, which boosts the economy.

Different Rotary and linear machine topologies were investigated for HST application. The rotary machine topologies could suit low speed traction applications as EV/HEV. However, this machine type is characterized by low speed, which impede their application for HST area.

The comparison between rotary machine topologies were principally for low speed electric drive applications.

1. The rotary induction machine topology is fault-tolerant, however, they are inherently low speed and efficiency machines.
2. PM is believed to gain the prominent characteristics for this application, as this machine has highest kW/kg ratio. No need for external supply or cumbersome power electronic converters for exciting the machine. However, PM may be not suitable for elevated temperatures. Moreover, the permanent magnet arrangement reduces fault-tolerance capability of the machine.
3. Among other PM and SRM are the most promising topologies. The SRM is inherently fault tolerant. SRM has wide speed range; also, it operates in harsh environment.

The linear machine topologies prove to be the first option for HST application.

1. In Linear machines, the developed powers are directly converted to linear thrust.
2. Linear topologies incorporate easily magnetic levitation, which reduces friction forces allowing extremely high speed to be achieved.
3. The linear machines require less maintenance particularly for magnetic levitation where virtue contact-free drive forced is developed.
4. The linear machines have the capacity to generate wide range power/thrust suitable for various section of the cruise.
5. The long-stator topology is considered to be more favorable in HST application compared with short-stator one, as embedding the drive power framework in the

track reduces the vehicle weight and allows the ability to be coordinated to the track areas.

## **ACKNOWLEDGMENT**

The authors are grateful for Shaqra University and College of Engineering for supporting and encouraging this work in particular Prof. Dr. Abdulaziz S. Alsayyari, dean of Engineering College.

## **REFERENCES.**

- [1] E. Isobe et al., B "Linear metro transport systems for the 21st century" Hitachi Review, vol. 48, no. 3, pp. 30-38, 1999, Japan.
- [2] M. Takahashi, G. Kwok, and K. Kubota, "Marketing strategy of the HSST system", International Conference of Magnetically Levitated Systems, pp. 250-258, Dresden, Germany, 2006.
- [3] Internet homepage of Railway Technical Research Institute RTRI, Japan, 2017. [Online]. Available: [http://www.rtri.or.jp/rd/maglev/html/english/mlx01\\_E.html](http://www.rtri.or.jp/rd/maglev/html/english/mlx01_E.html).
- [4] Internet homepage of Cubu HSST Development Corp., Linimo system, Japan, 2017. [Online]. Available: [http://www.hsst.jp/index\\_e.htm](http://www.hsst.jp/index_e.htm); <http://www.linimo.jp/sonota/index.html>
- [5] Magnet Motion Maglev M3 "Magnet Motion Document UM-1, Version 1, as Part of Federal Administration Project MA-26-7077" Jan. 8, 2003.
- [6] G. Nissen, "Current status of maglev development program" ,International Conference of Magnetically Levitated Syst., Dresden, Germany, 2006.
- [7] Y. Liu, G. Sun, and R. Wei, "The development status and future prospects of maglev technology", International Conference Magnetically Levitated System, Dresden, Germany, 2006.
- [8] R. Thornton, T. Clark, and M. Bottasso, "Maglev personal rapid transit", International Conference Automated People Movers, Vienna, Austria, 2007.
- [9] X. Wu, "Experience in operation and maintenance of shanghai maglev demonstration line and further application of maglev in China", International Conference Magnetically Levitated System, Dresden, Germany, 2006.
- [10] P. Krause; O. Wasynczuk ; S. Sudhoff, and S. Pekarek, " *Analysis of Electric Machinery and Drive Systems*" IEEE press, 3<sup>rd</sup> edition, 2013.
- [11] S. A. Nasar, Handbook of Electric Machines. New York: McGraw-Hill, 1987.

- [12] L. Chang, "Comparison of AC Drives for Electric Vehicles - A Report on Experts' Opinion Survey", IEEE AES Systems Magazine, August 1994.
- [13] M. Schöning, K. Hameyer, "Virtual Product Development for Electrical Motors", Proc. of 6th IEMDC, Antalya, 2007. Antalya, 2007.
- [14] M. Zeraouia, M.E.H. Benbouzid, D. Diallo, "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study", *IEEE Transaction on vehicular technology*, vol.55, issue.6, November 2006.
- [15] D. Fodorean , M. Ruba , L. Szabo and A. Miraoui "Comparison of the main types of fault-tolerant electrical drives used in vehicle applications", *Proc. Int. Symp. Power Electron., Elect. Drives, Autom. Motion*, pp.895 -900 2008
- [16] D. Diallo , M. E. H. Benbouzid and A. Makouf "A fault-tolerant control architecture for induction motor drives in automotive applications", *IEEE Trans. Veh. Technol.*, vol. 53, no. 6, pp.1847 -1855 2004.
- [17] A. M. S. Mendes and A. J. M. Cardoso "Fault-tolerant operating strategies applied to three-phase induction-motor drives", *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp.1807 -1817 2006.
- [18] J. S. Hsu , J. D. Kueck , M. Olszewski , D. A. Casada , P. J. Otaduy and L. M. Tolbert "Comparison of induction motor field efficiency evaluation methods", *IEEE Trans. Ind. Appl.*, vol. 34, no. 1, pp.117 -125 1998
- [19] S. S. Kulkarni and A. Thosar " Mathematical Modeling and Simulation of Permanent Magnet Synchronous Machine" *International Journal of Electronics and Electrical Engineering* , Vol. 1, No. 2, pp. 66-71, June 2013.
- [20] J. E. HILL and S. J. MOUNTAIN 'Control of a variable speed, fault-tolerant permanent magnet generator'. International Conference on Power Electronics, Machines and Drives, PEMD 2002, June 2002, pp. 492–497.
- [21] O. Wallmark , L. Harnefors and O. Carlson "Control algorithms for a fault-tolerant PMSM drive", *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp.1973 -1980 2007
- [22] S. Henneberger, "Design and Development of a Permanent Magnet Synchronous Motor for a Hybrid Electric Vehicle Drive", PhD-thesis, Katholieke Universiteit Leuven, May 1998.
- [23] B.C. MECROW; A. G. JACK; J. A. HAYLOCK and J. COLES 'Fault-tolerant permanent magnet machine drives', *IEE Proceedings on Electrical Power Applications*, 1996, 143, (6), pp. 437–442.
- [24] P.L. CHAPMAN and S. D. SUDHOFF 'Optimal control of permanent magnet ac machine drives with a novel multiple reference frame estimator/regulator'.

- Thirty-fourth IAS Annual Meeting Conference Record of the 1999 IEEE, Industry Applications Conference, 1999, vol. 4, pp. 2567–2573.
- [25] S. Risse and G. Henneberger, “Design and Optimization of a Reluctance Motor for Electric Vehicle Propulsion,” ICEM, Helsinki, August 2000.
- [26] M. Yabumoto, C. Kaido, T. Wakisaka, T. Kubota, N. Suzuki, “Electrical Steel Sheet for Traction Motors of Hybrid/Electrical Vehicles”, Nippon Steel Technical Report, No.87, July 2003.
- [27] ROBERT-DEHAULT E., BENKHORIS M.F., ZAIM M.E.: ‘Control strategy of a five-phase synchronous machine’. Second International Conference on Power Electronics, Machines and Drives, PEMD 04, March–2 April 2004, vol. 1, pp. 114–119.
- [28] A. G. JACK; B. C. MECROW and J. A. HAYLOCK ‘A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications’, *IEEE Transaction on Industrial Applications*, 1996, 32, (4), pp. 889–895.
- [29] LIU K., STIEBLER M.: ‘Voltage control of a switched reluctance generator by means of fuzzy logic approach’. Proceedings Sixth International Conference on Optimization of Electrical and Electronic Equipments, OPTIM’98, May 1998, vol. 2, pp. 443–446.
- [30] M. STIEBLER and K. LIU ‘Closed-loop control of a switched reluctance generator’. *Proceedings of PEMC’96*, September 1996, vol. 3, pp. 229–233.
- [31] M. Ruba and M. Anders "Fault tolerant switched reluctance machine study", Proceeding IEEE International Conference. Electrical Machine, pp.1 -6 2008.
- [32] Linear Motor-Powered Transportation: History, Present Status, and Future Outlook by Rolf Hellinger and Peter Mnich.
- [33] A. Pottharst et al., "Operating point assignment of a linear motor driven vehicle using multi-objective optimization methods" World Congress on Railway Research(WCRR), Cologne, Germany, 2001.
- [34] Y. Nozaki, T. Koseki, and E. Masada, "Analysis of linear induction motors for HSST and linear metro using finite difference method" 5th International Symposium Linear Drives for Industrial application, Kobe, Japan, 2005.
- [35] E. H. Abdelhameed, "Concurrent speed and position tracking of elevator driven by linear induction motor using cascade PI-PI control system," *Eighteenth International Middle East Power Systems Conference (MEPCON)*, pp. 468-473, Cairo, Egypt, 2016.

- [36] ]M. A. M. Cheema; J. E. Fletcher; M. Farshadnia; D. Xiao; M. F. Rahman, "Combined Speed and Direct Thrust Force Control of Linear Permanent Magnet Synchronous Motors with Sensorless Speed Estimation using a Sliding-mode Control with Integral Action," *IEEE Transactions on Industrial Electronics* , vol. PP, issue 99, pp.1-1, 2017