Impacts of Interior Permanent Magnet Machine Technology for Electric Vehicles

M. A. Rahman[1], *Life Fellow, IEEE*, M.A. Masrur[2], *Fellow IEEE*, and M. Nasir Uddin[3], *Senior Member IEEE*

1. Memorial University of Newfoundland
   St. John's, Newfoundland,
   Canada, A1B 3X5
   E-mail: arhaman@mun.ca

2. US Army RDECOM-TARDEC
   6501E 11 Mile Road, Warren,
   MI 48397-5000, USA
   E-mail: m.a.masrur.civ@mail.mil

3. Lakehead University
   Thunder Bay, ON
   Canada, A1B 3X5
   E-mail: muddin@lakeheadu.ca

Abstract — The past twenty years have been an exciting period with tremendous advances in the development of interior permanent magnet (IPM) electrical machines. Over this period, the interior permanent magnet synchronous machines (IPMSM) have expanded their presence in the automotive marketplace of high-efficiency electric traction drives for the latest generation of electric vehicles (EV) and hybrid-electric vehicles (HEV). Closer examination reveals that several different knowledge-based technological advancements and market forces have combined to accelerate the development of the impressive IPMSM drives technology. The purpose of this paper is to provide a brief statement on impacts of the various factors that lead to the current state-of-the-art IPM motor technology, and to illustrate its application success in the automotive industry. Particularly, the impact of IPM machines on cost and reliability for EV and HEV applications is highlighted in the paper.

I. INTRODUCTION

Electric power system forms the backbone of modern society. Electricity and its accessibility is one of the major engineering achievements. In order to maintain and develop the energy consuming technologies, availability of sustainable energy sources and their effective uses through efficiency improvements are of paramount importance. Power electronics based ac drive, which regulates the speed of the motor by controlling the frequency, can significantly reduce the energy consumption, and particularly in traction drive of electric and hybrid electric vehicles [1, 4, 10]. Thus improvements in efficiency of the electric motor drive systems are the most effective measures to reduce primary energy consumption.

The objective of this invited paper is to provide a brief introduction to the recent emergence of high efficiency and high performance interior permanent magnet (IPM) synchronous motors. Highlights of IPM motor drives include wide spread application in both electric and hybrid electric vehicles, which are just few of many items of ac motor drive in passenger automobile to save precious electric energy technology, and to illustrate its application success in the automotive industry. The impact of interior permanent magnet synchronous motor (IPMSM) on cost and reliability for EV and HEV applications is highlighted. The application of intelligent controllers for IPMSM drives and its prospect for EV and HEV application are also discussed in the paper.

II. ANALYSIS

The principle of operation of any rotating electric motor is derived from Lorenz force. A current carrying conductor placed in a magnetic field is acted upon by a force by way of the *BLI* rule. A line-start interior permanent magnet (IPM) motor is an induction-start but synchronously-run high efficiency motor. An IPM motor behaves like a permanent magnet excited salient-pole synchronous machine without physical variation of air gaps like in a conventional salient synchronous machine. It must overcome the magnet brake torque at line starting. The IPM motor can also be started by direct control of stator magnetic field, so as to react with the permanent magnet [24] and produce torque via position sensor or sensorless means [28].

However, there are many challenges to overcome in the design stage as well as for its successful applications in electric and hybrid electric vehicles. Some of these are as follows:

(a) Create variation of d-q axis inductances without varying air gap of the IPM motor.
(b) Varying and control of permanent excitation of rotor of IPM motor.
(c) Optimum variation of PM torque and reluctance torque for specific applications.
(d) Reduction of cost, weight and size of IPM motor.
(e) Intelligent ac-dc converter and dc-ac inverter for IPM motor drive.

The steady state developed power P_d in a 2-pole 3-phase IPM synchronous motor can be given as;

$$P_d = \frac{3V_pE_0}{X_d}\sin\delta + \frac{3V_p^2(X_d - X_q)}{2X_dX_q}\sin 2\delta \qquad (1)$$

where, P_d is the developed power, V_p is terminal voltage/per phase, E_o is excitation voltage/per phase; X_d and X_q are d-q axis reactances per phase respectively, and δ is phase angle between V_p and E_o.

The first expression of equation (1) is called the electric power due to permanent magnet excitation and the second expression of equation (1) is called the reluctance power due to reluctance variation at the airgap. The contribution of each power component to the total power P_d is significant for the optimum design of a non-visible salient-pole like IPM motor. For fixed parameter values it is obvious that the first term of equation (1) is maximum

Report Documentation Page

1. REPORT DATE **06 AUG 2012**	2. REPORT TYPE **Journal Article**	3. DATES COVERED **06-08-2012 to 06-08-2012**	
4. TITLE AND SUBTITLE **Impacts of Interior Permanent Magnet Machine Technology for Electric Vehicles**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) **Abul Masrur**		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC ,6501 E.11 Mile Rd,Warren,MI,48397-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER **#22598**	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000**		10. SPONSOR/MONITOR'S ACRONYM(S) **TARDEC**	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) **#22598**	

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted to IEEE IEVC-2012

14. ABSTRACT
The past twenty years have been an exciting period with tremendous advances in the development of interior permanent magnet (IPM) electrical machines. Over this period the interior permanent magnet synchronous machines (IPMSM) have expanded their presence in the automotive marketplace of high-efficiency electric traction drives for the latest generation of electric vehicles (EV) and hybrid-electric vehicles (HEV). Closer examination reveals that several different knowledge-based technological advancements and market forces have combined to accelerate the development of the impressive IPMSM drives technology. The purpose of this paper is to provide a brief statement on impacts of the various factors that lead to the current state-of-the-art IPM motor technology, and to illustrate its application success in the automotive industry. Particularly the impact of IPM machines on cost and reliability for EV and HEV applications is highlighted in the paper.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

when δ is 90^0, and the second term of Eq. (1) is maximum for $\delta = 45^0$. The IPM synchronous motor develops more stable power for a given excitation level, because the total developed power P_d is always greater than each of its components individually.

The challenge for designers of an IPM motor is to create reluctance variation of the motor by keeping airgap length constant. This has been done by inserting permanent magnets in various arrangements and magnet polarity orientations below the conduction cage of the IPM rotor such that the machine reluctance variations are made possible but keeping the airgap length uniformly constant [1]. For some specific applications, the squirrel/conduction cages can be dispensed with for new IPM rotors for electric and hybrid electric vehicles.

The developed torque T_d is obtained by dividing equation (1) by angular synchronous speed. An IPM motor develops its driving torque due to both the permanent magnet excitation and reluctance variation in rotor.

The history of development of IPM motors is linked to the advancement of high-energy permanent magnet (PM) materials over the past 60 years [2]. In the 1950s the most promising material was the Aluminum Nickel Cobalt magnet with (BH) $_{max}$ at around 5 MG Oe. Next, Barium Ferrite magnets came by 1960s, and Samarium Cobalt magnets appeared in the 1970s with (BH) $_{max}$ at about 4 and 6 MG Oe., respectively. The latest quantum jump occurred in early 1980s, when Neodymium Boron Iron (NdBFe) magnets with (BH)$_{max.}$ at 14 MG Oe. became commercially available. Nowadays, NdBFe magnets with (BH)$_{max}$ at 60 MG Oe. are manufactured in sintered process, and marketed by various manufacturers in the world. The critical properties of permanent magnets for IPM motors are very high coercive force H_c, high residual magnetic flux density B_r, and highest (BH)$_{max}$ energy product. All PM materials except NdBFe magnets are found not quite suitable for high efficiency IPM motor drives. Merrill introduced an earlier IPM motor using Alnico-5 in 1955. Binn, Barnard, and Jabbar presented a series of flux focused IPM motor using ferrite PM materials in 1978. Rahman designed and built the first large 45 kW high efficiency IPM motor utilizing NdBFe magnets in 1982 [3]. Rahman and Slemon provided analytical models for IPM in 1985. Jahns incorporated the flux-weakening regime in 1987. Sebastian and Slemon presented inverter driven IPM drives in 1987. Fratta, Vagati and Villata provided design criteria of IPM for field weakening operation in 1990. Zhou and Rahman presented the finite element analysis of IPM motor incorporating field and circuit coupling in 1994. Sustained and extensive research, development, analysis, control and application of IPM motors are progressing in leaps and bounds for the past two decades, perhaps even exceeding Merrill's dream [2] and Alger's expectation.

III. DESIGN REQUIREMENTS

The key requirements of IPM motors and generators for successful traction applications in electric and hybrid electric vehicles are:

- Large torque and higher power density
- High torque at low speeds for starting and uphill climb
- High power at high cruising speeds
- Maximum efficiency over wide speed and torque ranges
- Wide speed range with constant power mode, exceeding 2- 4 times the base speed
- Optimum compromise between motor peak torque and inverter volt-ampere ratings
- Short term overload capability, typically twice the rated torque over short duration
- Low cogging torque, low ripple and low acoustic noise
- Optimum stator winding design
- Rotor design with magnets orientation for optimum d-q reactances
- Reduction of magnetic saturation due to cross-coupling limits to open circuit voltage and total harmonic contents
- Low copper and iron losses at high speeds
- High reliability for all operating conditions
- Minimum weight and smallest size
- Low fuel consumption rate (litre/km)
- New ICE engine technology with hybrid gasoline/diesel
- Homogenous charge-compression ignition (HCCI)
- Clean and environmentally benign
- Quiet, smooth and comfortable ride
- Better battery power and self-charging
- Smart sensors and interfaces
- Least magnet flux leakage
- Magnet demagnetization withstand to armature reaction
- Temperature and surface corrosion constraints of magnets
- Minimum gear and more direct drive
- Regenerative braking and short charging cycle of batteries
- Impulse charging of batteries
- Plug-in during off peak periods
- No plug-in and hybrid transmission
- Gas generator and plug-in charging
- Solar panel body and hybrid transmission
- Seamless transfer between engine and electric traction
- Minimum maintenance and high efficiency
- Lowest initial and operating costs.

IV. MOTOR TORQUE

The developed torque T_d for an IPM motor can also be expressed for synchronously revolving d-q axis reference frame as

$$T_d = \frac{3p}{2}\left[\lambda_m i_q + (L_q - L_d)i_d i_q\right] \qquad (2)$$

where, λ_m is flux linkage due to permanent magnet excitation, L_d and L_q are d-q axis inductances, respectively; i_d and i_q are d-q axis currents, respectively and p is number of pole pairs. It is also to be noted that the torque equation (2) is quite non-linear, because λ_m, L_d, L_q, i_d and i_q are not usually constants. All these five quantities

vary during dynamic and field weakening modes of operation.

It is to be noted that the first term of equation (2) is identical to the separately excited PM dc motor. The second term is the reluctance torque and is important for indirect vector control of an IPM motor. Efficient utilization of this reluctance torque component of equation (2) is most critical for intensive flux weakening modes of operation and efficiency improvements in electric and hybrid vehicles.

V. STEADY STATE OPERATING MODE

The operation of an IPM synchronous motor can be explained by using the Thevenin's per phase equivalent circuit model. The applied phase voltage V_p and the excitation voltage E_o at the airgap due to permanent magnet excitation in the rotor of the motor is connected by series reactance X, neglecting stator resistance drop. The phasor voltage triangle is governed by the Kirchoff's voltage law. For the sake of better insight of the equivalent dc field current due to PM excitation in its rotor, the Thevenin's equivalent can be replaced by its dual Norton's equivalent circuit model.

Fig.1 shows the Norton's equivalent circuit per phase of an IPM motor. The phasor current triangle of the Norton's equivalent circuit of a synchronous motor is governed by the Kirchoff's current law of $I_f + I_s = I_m$. Note that I_s is the stator current per phase, I_m is the magnetising current per phase and I_f is the phasor current arising out of the rotor permanent magnet excitation. It is quite well known that a conventional synchronous motor can be operated at variable power factor modes by regulating its dc field current in the rotor field winding. This is not possible for IPM synchronous motors, because I_f is constant.
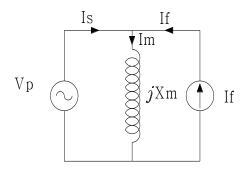
Fig 1. Norton's equivalent circuit of IPM Motor.

VI. ROTOR DESIGN FOR IPM MOTOR

The modern design of the rotor for IPM motors using NdBFe magnets with high B_r and very large H_c lead the trend for IPM rotor designs. Fig.2 shows the rotor for an IPM motor with line start. The left hand figure depicts the IPM rotor, and the right hand figure details the dimensions and permanent magnet orientations over one quadrant of a 4 pole IPM rotor [25].
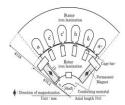
Fig.2: IPM Rotors for Line Start Motor [25].

VII. CURRENT APPLICATIONS OF IPMSM

The IPM motors with intelligent power electronics module are now used for traction drives in electric (EV) and hybrid electric vehicles (HEV). IPM motors are now increasingly used for energy saving applications in electric and hybrid electric vehicles. The key requirements of IPM propulsion motors for both EV and HEV applications include the following criteria:

High torque and power density, high torque at low speeds for starting and uphill climb but high power at high cruising speeds, maximum efficiency over wide speed and torque ranges including at low torques, wide speed range with constant power mode, exceeding 2-4 times the base speed, optimum compromise between motor peak torque and inverter volt-ampere ratings, short term overload capability, typically twice the rated torque over short duration, low acoustic noise, low cogging torques, low torque ripples, optimized stator distributed/concentric winding with minimum total harmonic distortion factor, innovative rotor design topology with magnets orientation for maximum variation of d-q axis inductances, reduction of cross-coupling magnetic saturation, least magnet flux leakage, magnet demagnetization withstand with respect to armature reaction, temperature and surface corrosion constraints of NdBFe, excessive open circuit back emf, load and no load stator iron losses at high speeds, high reliability, and robustness for various operating conditions, minimum weight and smallest size, low fuel consumption rate (litre/km), clean, quiet, smooth, powerful, efficient and affordable low cost. It is obvious that many of the above mentioned design requirements are complex, some times conflicting and interlinked for specific EV and HEV applications. Furthermore, these design criteria cannot be isolated from their control strategy including power electronic converter and battery.

The sophisticated and intelligent control in electric and hybrid electric vehicle forms the key to successful utilization of IPM traction motors. Smart power electronic modules as well as new lithium ion and nickel metal hydride batteries are the enabling technology for these vehicles. The design of hybrid system includes gasoline engine, gasoline/diesel hybrid, plug-in/gas generator, new transmission system, IPM traction motor, converter/inverter module, battery and control units. The innovative transmission is geared to achieve maximum fuel efficiency and a high degree of driving comfort of IPM traction drive motors, which are crucial for fulfilling the power characteristics required for high performance passenger automobiles [26].

VIII. Intelligent Controllers For Ipm Drive

Due to the recent developments in sophisticated control algorithms, power semiconductor switches, digital signal processors, and magnetic materials modern ac motor drives can achieve high efficiency and high performance requirements in the industrial sector. Fast and accurate speed response, quick recovery of speed from any disturbances and insensitivity to parameter variations are some of the important criteria of the high performance drive systems used in electric and hybrid electric vehicles. In order to achieve high performance, the closed loop vector control technique is employed for IPM drives. However, the controller design of such system plays crucial role in the system performance. The decoupling characteristics of vector controlled IPM are adversely affected by the parameter changes. Over the years, the conventional PI controller and other controllers have been widely utilized as speed controllers in the IPM drive. However, the difficulties of obtaining the exact d-q axis reactance parameters of the IPM motor leads to cumbersome design approach for these controllers. Moreover, the conventional fixed gain PI controller is very sensitive to uncertainties [12]. Again, precise speed control of an IPM drive becomes a complex issue due to nonlinear coupling among its winding currents and the rotor speed as well as the nonlinearity present in the electromagnetic developed torque due to magnetic saturation of the rotor core of IPM drives [13]. Therefore, there exists a need to apply intelligent control algorithms to ensure optimum drive performance over a wide range of operating conditions. The main advantages of intelligent controllers are: (a) their designs do not need accurate system mathematical model, (b) they can handle any nonlinearity of arbitrary complexity [14, 27].

Recently, researchers have reported some works on the application of fuzzy logic, neural network, neurofuzzy, genetic, brain emotional leaning based intelligent control techniques for IPM drives [12,14-16,23-32]. A novel fuzzy logic controller (FLC) is used to control both torque and flux of the IPMSM so that the motor can operate in flux weakening region for constant power operation [12]. This control could be suitable candidate for high speed application of EV motor drives. In [14] authors applied a genetic algorithm based neuro-fuzzy control technique to tune the PI controller parameters for IPMSM drive. All the intelligent controllers showed promising performances of the IPM drive such as no overshoot/undershoot quick transient response and insensitivity to disturbances. However, most of the intelligent algorithms suffer from high computational burden, which requires high speed and expensive digital signal processor (DSP) to implement these algorithms. Thus, the conventional intelligent controllers may not suitable for real-time application of EV motor drives in order to keep the cost of the vehicle at low level. Uddin et. al. developed a novel low computational FLC, which could be a suitable candidate for IPM drive in EV applications [16]. Currently, the FLC can be found in limited applications such as, antilock braking system (ABS) of the vehicles. Considering the performance enhancement and reliability of the motor control system, the cost could be justified to employ intelligent controllers for high end luxury electric and hybrid electric vehicles.

IX. Impact Of Ipm Machines On Cost, Packaging, And Reliability In ev And Hev Applications

In practical applications of any electrical machine based propulsion for electric and hybrid electric vehicles, industry is extremely sensitive to the issue of cost, size/packaging, and reliability. While the size/packaging is more directly connected to manufacturer's perspective, the other ones, i.e. cost and reliability, are extremely important from the point of view of both the manufacturer and the customer. Reliability in particular, has impact in terms of warranty and also safety of operation. It will, therefore, be instructive to look specifically to the above items and how those are affected by the introduction of IPM, and in which respects.

One advantage of IPM is that the permanent magnets (PM) are buried inside the rotor and is better protected from demagnetization due to stator currents, as opposed to its surface mounted counterpart (SPM) for the same thickness of the magnets in both. IPM also provides better overload capability [6]. IPM motors, due to its synchronous torque and the reluctance torque contributing to the total load demand, has higher specific torque compared to its SPM counterpart [7], contributing to better packaging. These are of significant important in propulsion motors in EV and HEV.

In addition to ground vehicle applications, IPM is nowadays finding importance in naval applications as well [8], which can be effective in pod propulsion based systems. In such applications, with hundreds of kilowatts of power, IPM has an edge over SPM [8]. Under certain operating conditions the temperature of the magnets can go well over 100^0 C and SPM cannot rely solely on adhesives to bind the magnets to the rotor, which can complicate the manufacturing, cost, and other problems. IPM also is better protected against corrosion and hence proves to be more robust.

Ref. [9] has made a very interesting comparison between SPM and IPM under the following conditions for both: power – 50 kw continuous, 12000 rpm, 173% overload, liquid cooled, rated phase voltage – 173 volt. Ref. [9] also noted that the particular IPM design needed 40% more PM material compared to SPM, but it also indicated that this is not a general rule and depends on specific designs. In addition [9] indicates and that in the motors cited, the IPM was not optimized from the perspective of magnetic material usage. Ref. [8], however, specifically indicates that under same power rating and same level of demagnetization, magnetic material needs in IPM is smaller. It appears therefore, that in general the magnetic material needs in IPM is lesser, leading to better cost advantage.

As noted before, IPM allows better overload capability. It also has higher CPSR (constant power speed region) [10] which is better (in terms of vehicular load demand) for vehicular applications at higher motor speeds. These aspects are superior to SPM, and very important in EV and HEV applications. This also implies the motor can be

sized smaller compared to SPM, based on this consideration.

Other observations on this topic are as follows. In general, SPM is better at low speed in terms of losses, compared to IPM, and IPM is better at high speeds compared to SPM. It should be noted, however, that for applications in very high power ranges, like those in mining vehicles, involving several megawatts of power, and also in applications like passenger buses, which undergo very high duty cycles, induction motors are considered to be a better choice. This is, notwithstanding the fact that size of the induction motor will be somewhat larger. But in these special applications under very harsh operating conditions, robustness and long durability provides a better edge to the induction machines [11].

X. CONCLUSIONS

This paper gives a brief introduction to the emergence of high efficiency interior permanent magnet (IPM) traction motors. Simple expressions for developed power and torque are given. Rotor design features and operation for specific applications are briefly covered. The specification requirements for EV and HEV application are listed. Impacts of IPM motor technology on EV and HEV for passenger automobiles are implied. This paper opens up the debate on plug-in EV, parallel/series HEV, gasoline/diesel/gas hybrid, solar and auto-charged smart hybrid electric vehicles.

REFERENCES

[1] M.A. Rahman, "Combination Hysteresis, Reluctance, Permanent Magnet Motor", US Patent No.5, 187,401; 1993.

[2] F.W. Merrill, "Permanent Magnet Excited Synchronous Motors", AIEE Transactions, vol.74, 1955, pp 1754-1760

[3] M.A. Rahman, NSERC-PRAI-CGE Project on IPM, 1982.

[4] M.A. Rahman, "Permanent Magnet Synchronous Machine", McGraw-Hill Yearbook of Science and Technology, 2011, pp.242-245

[5] M.A. Rahman, "Permanent Magnet Synchronous Motor - A Review of the Design Art", Proceedings of International Conference of Electrical Machines-ICEM'80, Athens, Greece, Sept. 15-17, 1980, pp. 312-319.

[6] M. Barcaro, N. Bianchi, and F. Magnussen, "PM Motors for Hybrid Electric Vehicles", The Open Fuels and Energy Science Journal, 2009, Bentham Open 2009, 2, pp. 135-141.

[7] J. S. Hsu, C. W. Ayers, C. L. Coomer, R. H. Wiles, S. L. Campbell, K. T. Lowe, and R. T. Michelhaugh, "Report On Toyota/Prius Motor Torque Capability, Torque Property, No-Load Back Emf, And Mechanical Losses", Oak Ridge National Laboratory Report # ORNL/TM-2004/185, Oak Ridge Institute for Science and Education.

[8] B. Ružojčić, D. Žarko,D. Ban, "Interior Permanent-Magnet Motor for Ship Propulsion, Design and Testing", EPE 2009 – Barcelona, 2009, pp. 1-10.

[9] G. Pellegrino, A. Vagati, P. Guglielmi, and B. Boazzo, "Performance Comparison Between Surface-Mounted and Interior PM Motor Drives For Electric Vehicle Application", IEEE Transactions on Industrial Electronics, Vol. 59, No. 2, February 2012, pp. 803-811.

[10] M. Olszewski, "Final Report on Assessment of Motor Technologies for Traction Drives of Hybrid and Electric Vehicles", Subcontract No. 4000080341, Oak Ridge National Laboratory, March 2011.

[11] C. Mi, M. A. Masrur, and W. Gao, "Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives", Publisher - John Wiley (UK), 2011.

[12] M. Nasir Uddin and M. I. Chy, "A Novel Fuzzy Logic Controller Based Torque and Flux Controls of IPM Synchronous Motor", IEEE Trans. on Ind. Applications, vol. 46, no.3, May/June 2010, pp. 1220-1229.

[13] M. A. Rahman and Ping Zhou, "Field circuit analysis of brushless permanent magnet synchronous motors", IEEE Trans. on Industrial Electronics., vol.43, No.2, April 1996, pp. 256-267.

[14] M. N. Uddin, M. A. Abido and M. A. Rahman, "Development and Implementation of a Hybrid Intelligent Controller for Interior Permanent Magnet Synchronous Motor Drive" IEEE Trans. on Industry Applications, vol. 40, No. 1, Jan./Feb. 2004, pp. 68-76.

[15] Yang Yi, Mahinda Vilathgamuwa, "Implementation of an Artificial-Neural-Network-Based Real-Time Adaptive Controller for an Interior Permanent-Magnet Motor Drive" IEEE Trans. on Industry Applications, vol. 40, No. 1, Jan./Feb. 2004, pp. 68-76.

[16] M. N. Uddin and M. A. Rahman, "High Speed Control of IPMSM Drives Using Improved Fuzzy Logic Algorithms", IEEE Trans. on Industrial Electronics, vol. 54, No. 1, Feb. 2007, pp. 190-199.

[17] K.J. Binn, W.R. Barnard and M.A. Jabbar, " Hybrid Permanent Magnet Synchronous Motors", IEE Proc., Pt.B, vol.125, No.3, 1978, pp203-208

[18] .A. Rahman, T.A. Little and G.R Slemon, "Analytical Models for Interior-Type Permanent Magnet Synchronous Motors", IEEE Trans. on Magnetics, vol. MAG-21, No.5, 1985, pp. 1741-1743.

[19] T.M. Jahns, " Flux-weakening Regime Operation of an Permanent Synchronous Motor Drive", IEEE Transactions on Industry Applications, vol.23, No.4, 1987, pp. 681-689.

[20] T. Sebastian and G.R. Slemon, "Operating Limits of InverterDriven Permanent Magnet Synchronous Motor Drives", IEEE Trans. on Industry Applications, vol.23, No.2, 1987, pp. 327-333.

[21] A. Fratta, A. Vagati and F. Villata, "Design Criteria of an IPMMachine Suitable for Field-weakening Operation", Proceedings, ICEM, MIT Cambridge, 1990, pp. 1059-1065.

[22] M. A. Rahman and Ping Zhou, "Field Based Analysis of Permanent Magnet Motors", IEEE Transactions on Magnetics, vol. 30, No.4, 1994, pp. 3664-3667

[23] Y.Honda, T. Nakamura, T. Higaki and Y. Takeda, " Motor Design Consideration and Test results of an Interior Permanent Magnet Motor for Electric Vehicles", IEEE–IAS Annual Meeting, New Orleans, vol. 1, 1997, pp.75-82.

[24] L Zhong, M.F. Rahman, W.Y.Hu, K.W. Lim and M.A. Rahman, "A Direct Torque Controller for Permanent Magnet Synchronous Motor Drive", IEEE Transactions on Energy Conversion, vol.14, No.3, December 1999, pp.637-642.

[25] K. Kurihara and M.A. Rahman, "High Efficiency Line-Start Interior Permanent Magnet Synchronous Motors", IEEE Transactions on Industry Applications, vol. 40, No.3, 2004, pp. 789-796.

[26] M. Kamiya, "Development of Traction Drive Motors for the Toyota Hybrid System", Proc. IPEC-2005, Niigata, April 4-8,2005, Paper S43-2

[27] M.A. Rahman, T.S. Radwan, R.M. Milasi, C. Lucas and .N.Arrabi, "Implementation of Emotional Controller for Internal Permanent Magnet Synchronous Motor Drive", IEEE Trans. on Industry Applications, vol. 44, No.5, Sept./ Oct. 2008, pp.1466-1476

[28] Yu-seok Jeong, R.D. Lorenz, T.M. Jahns and S.K. Sul, "InitialPosition Estimation of an IPM Synchronous Machine using Carrier frequency Injection Methods", IEEE Transactions on Industry Applications, vol.41, No.1, 2005, pp. 38-4.

[29] M. A. S. Khan and M.A. Rahman, "Implementation of Wavelet based Controller for Battery of Hybrid Electric Vehicles" , IEEE Transactions on Industry Applications, vol. 47, No.6, 2011, pp. 2241- 2249.

[30] C.C. Chan, "The State of the Art of Electric and Hybrid Vehicles", Proc. IEEE, vol.90, No. 2, 2002, pp. 247-275.

[31] J.M Miller, "Propulsion Systems for Hybrid Vehicles", IET Press, UK, 2008 Edition,

[32] J. Voelcker, "A New Mercedes", IEEE Spectrum, December 2008, pp.38-41