Design of a High Speed 18/12 Switched Reluctance Motor Drive with an Asymmetrical Bridge Converter for Electric Vehicles

Abid Ali Shah Bukhari
School of Engineering and Applied Sciences
Aston University
Aston Triangle, Birmingham, United Kingdom
*bukhars2@aston.ac.uk

Shahid Hussain Shaikh
Department of Electrical Engineering
Quaid-e-Awam University College
Larkana-Sindh Pakistan
*shaikhshahid@quest.edu.pk

Toufique Ahmed Soomro
School of computing and mathematics
Charles Sturt University Australia
tsoomro@csu.edu.au

Zhengyu Lin
School of Engineering and Applied Sciences
Aston University, Birmingham UK
z.lin5@aston.ac.uk

Safdar Ali
Department of Electrical Engineering
Sukkur IBA University Sindh-Pakistan
safdar.abro@iba-suk.edu.pk

Wenping Cao
School of Engineering and Applied Sciences
Aston University
Aston Triangle, Birmingham, United Kingdom
w.p.cao@aston.ac.uk

Abstract: The application of permanent magnet free motors have gained a huge attention for pure electric and hybrid electric vehicles. This paper proposed the design of 20-kW switched reluctance motor having 18 stator poles and 12 rotor poles by using finite element analysis machine design software Infolytica magnet and the main focus is to achieve the high speed, torque with adequate performance for electric vehicles. The asymmetric bridge converter has been used and the series of varying the excitation voltage, slot fill factor with respect to the number of turns and stranded area of the conductor has been analysed. Additionally, in order to the electromagnetic force vector, the switching sequence is examined. The simulation results show the great potential of the suggested motor and can provide a good starting torque with high speed and can be suitable to achieve the freedom Car 2020 electric vehicle target.

Key words: Electric vehicle, Energy saving, freedom car 2020, hybrid electric vehicle, machine design, slot fill factor, 18/12 switched reluctance motor drive, Torque Improvement.

1. Introduction

Currently, the global research for decreasing the usage of fossil fuel has been increased therefore electric vehicles (EVs) have achieved the huge interest in the automotive industry. The world-wide organisation of motor vehicle makers expressed that, in 2011, 80 million vehicles were manufactured all over the world which has been further massively increased in 2015 as depicted in figure 1, [1]. Would these completely converted into electrified at that time undoubtedly this classification of electrical machine production will take on huge importance.

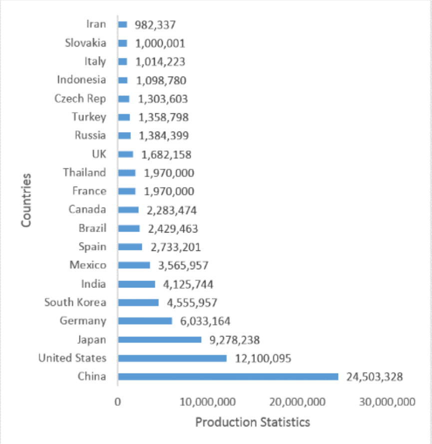


Fig. 1. Top 20 motor vehicle producing countries 2015 [1]

Fig. 2. 2017 Audi A3 Sportback e-tron revealed [2]

The mass adoption of electric vehicle will be beneficial and will have number of impacts including the ability to assist in the integration of renewable energy into existing electrical grids [3]. There are many reasons why people should move to electric vehicles (EVs) to get them to the places they need to be. This includes the following points as under.

1. The dependence of oil will be reduced in transportation.
2. EVs are great to drive because they are fast and smooth.
3. Many studies show that the emissions from burning fossil fuels such as gasoline produce harmful greenhouse gases. EV's produce no smelly fumes or harmful greenhouse gases.
4. EVs are innovative and cool.
5. The EVs only cost approximately $360 in a year to operate as compare to $3600 for an internal combustion engine (ICE) vehicles [4].
6. It is the long term solution for the future technology in vehicle industry.
7. EVs are a smart and convenient choice.

Further the number of positive features can be anticipated from EVs, including overall cost and the ability to contribute and support to the power quality of the grid if the proper planning in infrastructure is adopted, the 2017 Audi A3 sportback e-tron model is shown in figure 2.

The literature reveals that the switched reluctance motor (SRM) drive offers outstanding mechanical reliability and integrity, which is extremely required for EVs propulsion system [5, 6]. Different SR motors have been compared in [7] with the observation of increased number of turns and stator taper angle. In order to achieve the good torque density, speed and efficiency 18/12 SRM has been designed in [5, 8] with different material point of view and stator and rotor structure. A 30kW cooling design with thermal performance of Switched reluctance motor has been analysed in [9]. In [10, 11], a profile of novel current has been proposed to analyse the radial forces for decreasing the acoustic noise and vibration. An In-wheel 18/12 switched reluctance motor has been designed in [12] with attention to electrical and dimensional parameters. The author observed that there is a potential gap in the paper to consider the effect of slot fill factor with the change of number of turns and stranded area of the conductor while changing the excitation voltage and switching sequence of the SRM. This paper has been organized as follows. Section 1, discussed the detail introduction and background of the research with respect to energy scenario issues and the current data of electrical vehicles. The type of motor drive technologies used in electric vehicle including its essential qualifications and associated main problems, challenges and importance of electric vehicles have been reviewed in Section 2. The modelling of switched reluctance motor and their related advantages and the diverse analysis has been done on 18/12 SRM by varying the slot fill factor, switching sequence and excitation voltage to achieve the freedom car 2020 target while using the simulation software Infolytica Magnet in Section 3. The simulation results have been described in section 4. And the brief application and research methodologies with future prospective trends are presented in conclusion section 5.

2. Motor drives for EV

In the machine design the main challenge and limiting factor is thermal constrain due to winding on stator and rotor [13]. There is a great interest in machines with reduce mass of magnet or having no magnet, in general for current technologies the switched reluctance machines have pushed the boundaries for traction motor drives applications due to simple and robust construction, absence of demagnetization, no copper winding on the rotor with the main focus on cost, robustness and high temperature environment applications [14]. The main advantage of SRM is a very extensive field weakening area, up to 10 time has been appealed. The goal has been set to achieve the target sets by the US department of energy for freedom car 2020 [16]. In order to propel the driving wheels the major part of the electrical vehicle is electrical motor so that's why the research and discussion

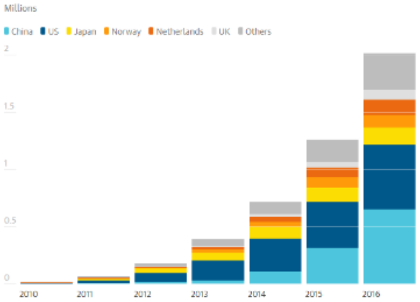
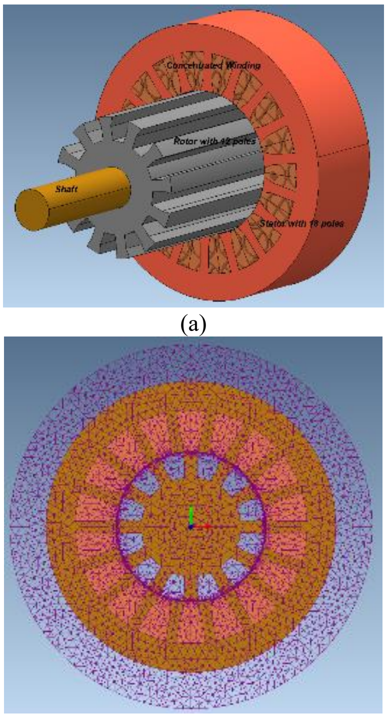


Fig. 3. The Chart of electric car accelerate past 2m mark globally [15]



(a)

(b)

Fig. 4. (a) 18/12 SRM model (b) Mesh view

about rotating electrical machines has been increased. The exchange to greener technologies and skills has directed to promote and growth in demand for innovative, new efficient classes of electrical machines. Organisations such as the United States Department of Energy [17] and European Union [18] have announced rules which necessitates the enhancements in the efficient productivity of industrial electrical machines. Similarly the progress in energy generation from renewable technologies has driven the enlargement of new types of electrical machines, for example to generate the energy from wind and wave. On the other hand, plea for electrical machines in the subsequent span is possibly to be motivated through the progression in demand for electrical motors for automotive applications. The chart of availability of electric car by different countries up to 2016, is shown in figure, 3. It is expected in [19] that by 2020 there will be yearly production of 9 million electric and hybrid electric vehicles, collectively demanding to a great extent of high torque dense electrical machines.

The increasing requirement for unpolluted and plentiful source of energy has directed to a growing curiosity in transportation electrification. Even though the major part of the expansions has been on areas for example power electronics, controlling, switching and energy storage systems, there is a rising demand for novel and innovative traction motors so as to run into the required performance keys of an electrically powered powertrain at an estimated and lower cost. The investigation in advanced traction motors essentially emphasis on necessities such as greater efficiency, higher power density, superior specific torque, lesser noise and cost. Additionally, there are numerous further applications associated constraints. The essential qualifications for the best traction electric machine (EM) can be shortened as under [20]:

1. high efficiency in excess of a wide range of speed particularly for regenerative braking;
2. high power and torque density;
3. high torque at lower speeds for starting, hill climbing and acceleration;
4. high power for cruising at high speeds;
5. extensive constant power speed range (CPSR);
6. fast active response;
7. operation in challenging environments as frequent start/stop;
8. operation in harsh conditions for example dust, cold, water, and hot temperatures;
9. Proficient in intermittent overload capability (two times the rated power);
10. low- maintenance and service requirement;
11. must be rugged and robust;
12. fault tolerance capability and safety;
13. comfort (proper sound quality);
14. Low cost.

There are mainly two configurations to drive the EV wheel. (1) Single motor to propel the driving wheels (2) multi motors independent drive to propel individual wheel. After the invention of power electronics technology, the interior permanent magnet motors are being widely used in hybrid and electric vehicles and it provides peak power capability with good starting torque, but still a problem for mass production due to the price of the rare earth magnets and the flux weakening capability to apply negative current which originates huge copper and iron losses and in reality contribute to increase the flux harmonics in the machine [21]. The induction motor also has extraordinary flux saturation and high operational frequency therefore the secondary winding losses are considerably greater than typical values and huge eddy current losses are generated, hence the conventional induction motor is not good enough to be used for EV application as stated in literature [22-25].

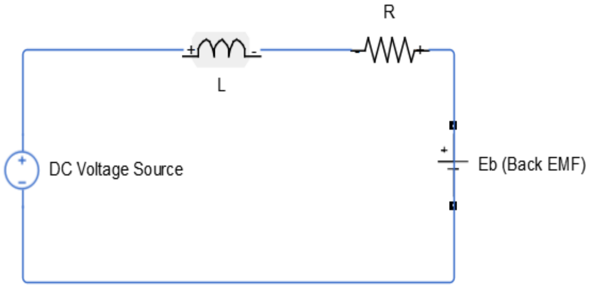


Fig. 5. Equivalent circuit of one phase of SRM

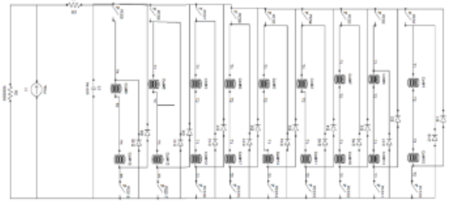


Table I

Design Specifications of the 18/12 SRM

Parameter	Symbol	Value	Units
Stator diameter	*ds*	200	mm
Rotor diameter	*dr*	102.9	mm
Air-gap	*g*	0.65	mm
Machine length	*l*	200	mm
Number of stator poles	*Ns*	18	-
Number of rotor poles	*Nr*	12	-
Stator pole arc	*βs*	12	o
Rotor pole arc	*βr*	14	o
Number of phases	*m*	3	-
Peak speed	*nN*	12418	rpm
Average speed	*Av:N*	5770	rpm
Phase Voltage	*Vdc*	200	V
Number of turns	*Np*	7	turns
Shaft diameter	*dsh*	30	mm
Rotor yoke thickness	*yr*	38	mm
Stator yoke thickness	*ys*	38	mm
Rotor pole length	*lr*	34.23	mm
Stator pole length	*ls*	57	mm
Rotor pole width	*tr*	25	mm
Stator pole width	*ts*	23	mm
Average torque		35.5	Nm

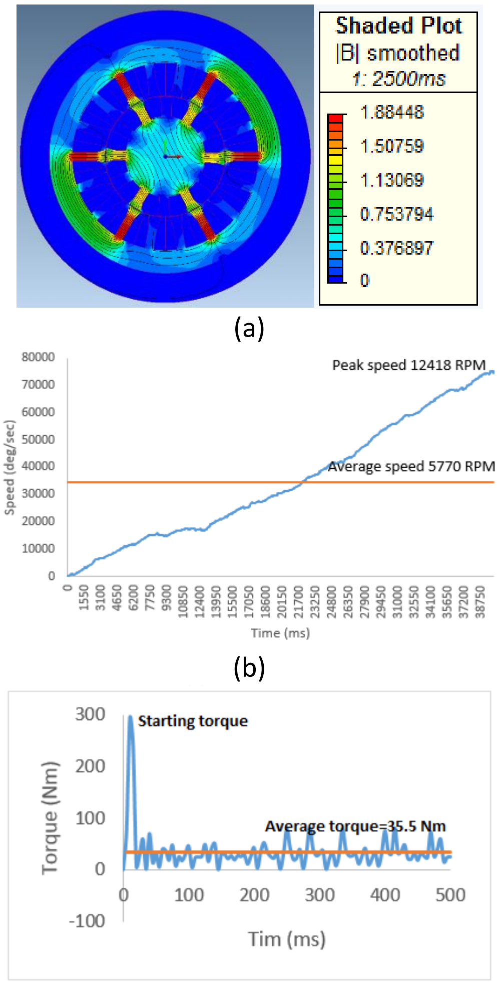
Fig. 5, Asymmetric bridge converter topology for driving 18/12 SR motor

In order to meet the demand, now a days there is more attention in the low cost switched reluctance motor drive system because of several advantage such as robust construction, normally cheap, design simplicity, no winding on rotor and absence of demagnetization which

is the most suitable for electric and hybrid electric vehicle [14, 22, 26-30].

3. Modelling and Design of Switched Reluctance machine

The equivalent circuit of the one phase of the SRM is shown in Figure, 5 whereas dc voltage source are provided to excite the winding and the components L and R shows the winding inductance and resistance of the SRM and Eb is the corresponding back EMF.



(a)

(b)

(c)

Fig. 6, (a) shows the flux function view with 1.8 (tesla) magnetic flux density (b) speed vs time graph and (c) shows the average and starting torque produced by the 18/12 SRM

The 18/12 SRM used in this paper is shown in figure, 4(a) with the initial model has rather coarse general mesh with global element sizing setting of 2mm, as 2D mesh view is shown in figure 4(b). From the figure, 5 (SRM equivalent circuit) the equation can be developed as follows.

$$V_{dc} = R_a I_a + L\frac{d_i}{d_t} + Eb \tag{1}$$

The relationship between the source voltage, flux linkage (Ψ) and the rotor position angle (θ) is:

$$V_{dc} = R_a I_a + L_a \frac{dia}{dt} + \frac{\partial \Psi a}{d\theta}\frac{d\theta}{dt} \tag{2}$$

TABLE II
Comparison of Current, Voltage, Starting and Average Torque with Speed at 40, 50 and 60% Slot Fill Factor

Fill factor	**Turns**	**Area**	**I_{ave}**	**V_{ave}**	**T_{start}**	**T_{ave}**	**Speed**
40%	200	1.74	2.88	14.9	239	24.9	164
	150	2.32	5.03	2.95	285	27.9	234
	100	3.49	8.31	11.5	420	45.7	254
	50	6.98	26	23.3	775	224	866
50%	200	2.18	3.07	18.7	245	25	160
	150	2.90	4	16.1	290	32.8	215
	100	4.36	8.2	11.1	425	45	257
	50	8.72	32	24.8	329	211	874
60%	200	2.61	3.49	16.1	255	27	151
	150	3.49	4.03	14.3	295	35	215
	100	5.23	10.7	5.68	430	43.8	243
	50	10.4	40.3	4.92	400	217	889

TABLE III
Performance Comparison at 40, 50 and 60% Slot Sill Factor.

Fill Factor	**Turns**	**Energy**		**Flux Linkage**
		Instantaneous Energy	***Co-energy***	
40%	200	11.85J	17.385J	0.238 Wb
	150	12.866J	20.64J	0.228Wb
	100	20.37J	36.6J	0.179Wb
	50	55.24	156.2J	0.070Wb
50%	200	13.26	20.50	0.25
	150	14.14	20.16	0.199
	100	20.38	36.99	0.176
	50	55.8	161.64	0.098
60%	200	15.52	24.572	0.289
	150	14.47	21.09	0.192
	100	23.6	44.79	0.237
	50	60.84	185.86	0.1089

TABLE IV
18/12 SR Machine Core and Copper Losses

Fill factor	**Shaft**	**Rotor**	**Stator**	**I^2R Losses**
40%	0.497	25.6	46.2	8.601
	0.492	32.3	52.1	12.314
	1.07	54.3	86.6	16.089
	0.987	63.1	92.3	186
50%	0.598	29.7	55.5	8.22
	0.609	35.3	66.9	7.43
	1.05	54.6	85.9	13.34
	1.11	62.9	93.9	157.5
60%	0.678	33.1	62.3	8.194
	0.643	35.1	62.3	6.58
	0.813	59	83.4	13.25
	1.22	67.8	109	161.46

*all the above are average values in table II, III and IV

Since ψa= L_a I_a

$$V_{dc} = R_a I_a + L_a \frac{dia}{dt} + \frac{\partial La}{\partial \theta}\frac{d\theta}{dt} \qquad (3)$$

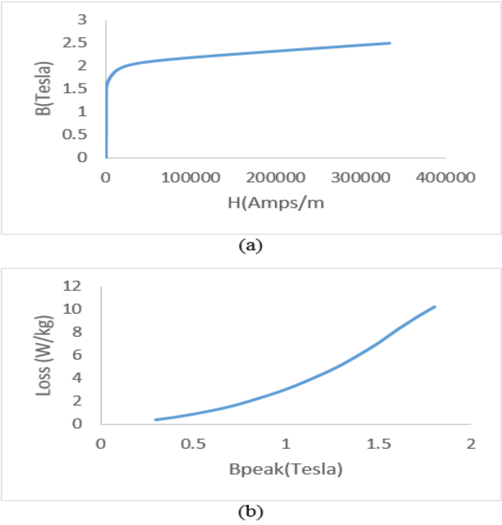
The instantaneous electromagnetic torque produces by (Ta) of the switched reluctance machine by one phase:

$$T = \frac{1}{2}\, i^2 \frac{\partial La}{\partial \theta} \qquad (4)$$

and

$$T - T_L = J\frac{d\omega}{dt} + B\omega \qquad (5)$$

whereas T represents the electromagnetic torque of the motor and T_L is the torque produced by the load, and $\omega = \frac{d\theta}{dt}$ is the speed of the motor. The above equations are used to model the SRM.

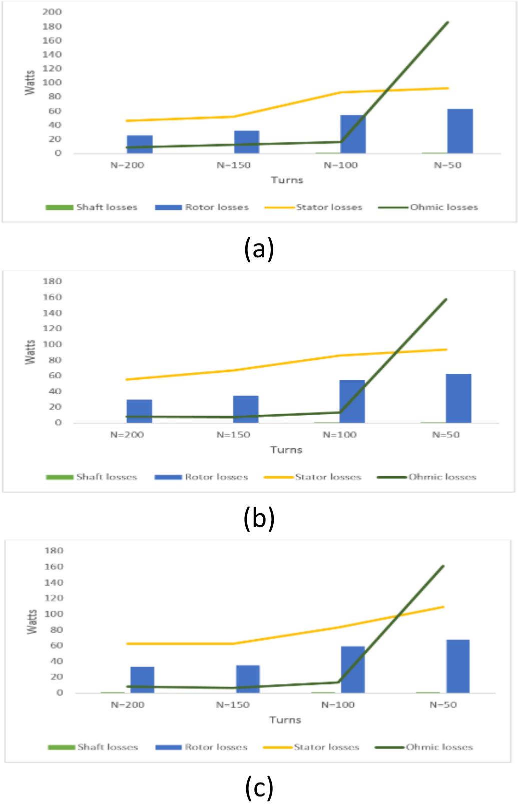


Figure, 7 shows (a) the graph of magnetic permeability of New Core (1000/65) material with (b) losses of the same at 20 degree C with respect to (0.2 to 1.9) peak tesla

4. Results and discussion

The 18/12 switched reluctance motor has been simulated with the specifications shown in table, I. Initially the same design of SR motor, single switch with single diode per phase converter topology was applied but the results were not satisfactory and motor was producing oscillating effect in between (0 to 500 RPM) which is not desirable for the electric vehicle application. Then further the author of this paper tried another configuration and asymmetric bridge converter topology has been used to drive the proposed motor, it has two switches per phase with two diodes which is the main advantages due independent and flexible controlling and favourable for high speed machine operation thus overlap between adjacent current is possible however compromise is made between costs due to extra switches and diode per phase. In order to control the current magnitude the current source of piecewise liner (PWL) as an input source for excitation winding has been provided which is shown in figure 5.

The stack length of 200mm have been maintained to get the sensibly-proportioned machine and the basic switching pattern for high speed has been adopted which energises the phase-1 at 0, and open at 10 degrees, when overlaps ceases. This pattern repeats after every 30 degrees. So a periodic sequence to is is ON-0-OFF-10-ON-30 has been adopted throughout the simulation. The other switches follow the same pattern in sequence with the delay by 10 degrees at each time successively. The magnetic flux density of 1.8 Tesla with speed results and electromagnetic torque developed is shown is figure. 6, (a to c).



Figure, 8 shows the losses of 18/12 SRM at (a) 40%, (b) 50% and (c) 60% slot filling factor

The transient simulation with the number of turns and cross sectional area of turn to get the sensible results of 200, 150, 100 and 50 turns with (1.74 to 10.4) mm^2 which is intended to represent 40, 50 and 60% slot filling factor (packing) in the slot area as depicted in table II, III and IV respectively and the nonlinear lamination material Newcore 1000/65 selected for the core the graph of magnetic permeability of Newcore (1000/65) and the losses are shown in figure, 7 (a and b). The load-driven transient simulation carried out at 500 milliseconds, it can be noted that the machine has good starting torque up to 300 N-m but rapidly falls off. The reason is the inductive leg effect when switches are turned ON and OFF, and the motor provide the effective torque of 35.5 N-m respectively. The graph of core and ohmic losses produced by the proposed machine at 40 to 60% filling factor are shown in figure, 8 (a to c). The shaft losses are very negligible, so that's why author has ignored in this work with the graph of losses of 12/8 SRM.

It can be seen that the core losses at 40% filling factor are less as compare other filling factors whereas copper losses are much higher up to 186 watts with the simulation time 500 ms of the proposed machine. In comparison with the 50% filling factor, the iron and copper losses are less as compare to 60%, which is good for the insulation and efficiency enhancement in the machine in addition to easiness in the manufacturing and prototype development.

5. Conclusion

The 18/12 SR motor has been designed which include finite element analysis. An asymmetrical bridge converter used for the driving circuit and providing switching circuit. Different slot filling factor of the proposed machine have been analysed by varying the number of turns and conductor area and comparative results have been shown in table II, III and IV in addition to the graph of core and conductor losses. It has been analysed that 50% slot filling factor having 50 number of turns with 8.72 stranded conductor area has the best results in terms of speed, torque performance. The data will be beneficial while designing for enhancement in the performance of SR motor to achieve the required parameters of freedom car 2020 and can be used effectively for the application of various designs of electric machines.

Reference

[1] J. D. Widmer, R. Martin, and M. Kimiabeigi, "Electric vehicle traction motors without rare earth magnets," *Sustainable Materials and Technologies,* vol. 3, pp. 7-13, 2015.

[2] R. Gibson. (2017, Spetember 22, 2017). *EV Review: 2017 Audi A3 Sportback E-Tron. https://www.fleetcarma.com/ev-review-2017-audi-e-tron/?utm_campaign=Newsletter&utm_source*.

[3] D. B. Richardson, "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration," *Renewable and Sustainable Energy Reviews,* vol. 19, pp. 247-254, 2013.

[4] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews,* vol. 20, pp. 82-102, 2013.

[5] A. Chiba, Y. Takano, M. Takeno, T. Imakawa, N. Hoshi, M. Takemoto, *et al.*, "Torque Density and Efficiency Improvements of a Switched Reluctance Motor Without Rare-Earth Material for Hybrid Vehicles," *IEEE Transactions on Industry Applications,* vol. 47, pp. 1240-1246, 2011.

[6] Y. Hori, "Looking at cars 100 years in the future," in *Mechatronics (ICM), 2013 IEEE International Conference on*, 2013, pp. 31-35.

[7] Y. Takano, M. Takeno, N. Hoshi, A. Chiba, M. Takemoto, S. Ogasawara, *et al.*, "Design and analysis of a switched reluctance motor for next generation hybrid vehicle without PM materials," in *Power Electronics Conference (IPEC), 2010 International*, 2010, pp. 1801-1806.

[8] K. Kiyota and A. Chiba, "Design of switched reluctance motor competitive to 60-kW IPMSM in third-generation hybrid electric vehicle," *IEEE Transactions on Industry Applications,* vol. 48, pp. 2303-2309, 2012.

[9] H.-C. Chiu, J.-H. Jang, W.-M. Yan, and R.-B. Shiao, "Thermal performance analysis of a 30 kW switched reluctance motor," *International Journal of Heat and Mass Transfer,* vol. 114, pp. 145-154, 2017.

[10] M. Kawa, K. Kiyota, J. Furqani, and A. Chiba, "Acoustic noise reduction of a high efficiency switched reluctance motor for hybrid electric vehicles with novel current waveform," in *Electric Machines and Drives Conference (IEMDC), 2017 IEEE International*, 2017, pp. 1-6.

[11] J. Furqani, M. Kawa, K. Kiyota, and A. Chiba, "Comparison of current waveforms for noise reduction in switched reluctance motors," in *Energy Conversion Congress and Exposition (ECCE), 2017 IEEE*, 2017, pp. 752-759.

[12] Z. Omaç, M. Polat, E. Öksüztepe, M. Yıldırım, O. Yakut, H. Eren, *et al.*, "Design, analysis, and control of in-wheel switched reluctance motor for electric vehicles," *Electrical Engineering,* pp. 1-12, 2017.

[13] A. Walker, M. Galea, D. Gerada, C. Gerada, A. Mebarki, and N. Brown, "Development and design of a high performance traction machine for the FreedomCar 2020 traction machine targets," in *Electrical Machines (ICEM), 2016 XXII International Conference on*, 2016, pp. 1611-1617.

[14] B. Burkhart, A. Klein-Hessling, I. Ralev, C. P. Weiss, and R. W. De Doncker, "Technology, research and applications of switched reluctance drives," *CPSS Transactions on Power Electronics and Applications,* vol. 2, pp. 12-27, 2017.

[15] A. industry. (2017). *Electric cars accelerate past 2m mark globally. https://www.theguardian.com/environment/2017/jun/07/electric-cars-sales-2-million-worldwide-global-sales*

[16] A. Walker, M. Galea, C. Gerada, A. Mebarki, and D. Gerada, "A topology selection consideration of electrical machines for traction applications: towards the FreedomCar 2020 targets," in *Ecological Vehicles and Renewable Energies (EVER), 2015 Tenth International Conference on*, 2015, pp. 1-10.

[17] R. K. Dixon, E. McGowan, G. Onysko, and R. M. Scheer, "US energy conservation and efficiency policies: Challenges and opportunities," *Energy Policy,* vol. 38, pp. 6398-6408, 2010.

[18] E. Union, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC," *Official Journal of the European Union,* vol. 5, p. 2009, 2009.

[19] Z. Živanović and Z. Nikolic, *The application of electric drive technologies in city buses*: INTECH Open Access Publisher, 2012.

[20] E. Bostanci, M. Moallem, A. Parsapour, and B. Fahimi, "Opportunities and Challenges of Switched Reluctance Motor Drives for Electric Propulsion: A Comparative Study," *IEEE Transactions on Transportation Electrification,* vol. 3, pp. 58-75, 2017.

[21] A. Athavale, K. Sasaki, B. S. Gagas, T. Kato, and R. D. Lorenz, "Variable flux permanent magnet synchronous machine (VF-PMSM) design to meet electric vehicle traction requirements with reduced losses," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016, pp. 1-8.

[22] S. Abid Ali Shah Bukhari, Wenping Cao, Kamran Ahmed Samo, Zheng Liu and Shahzeb Ansari, "Electrical Motor Drive Technologies for Green Electric Vehicle: A Review," *Engineering Science and Technology International Research Journal,* vol. 1, pp. 1-10, 2017.

[23] H. Li and K. W. Klontz, "Rotor design to reduce secondary winding harmonic loss for induction motor in hybrid electric vehicle application," in *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, 2016, pp. 1-6.

[24] N. Kunihiro, K. Nishihama, M. Iizuka, K. Sugimoto, and M. Sawahata, "Investigation into Loss Reduced Rotor Slot Structure by Analyzing Local Behaviors of Harmonic Magnetic Fluxes in Inverter-fed Induction Motor," *IEEE Transactions on Industry Applications,* 2016.

[25] W. Li, J. Cao, and X. Zhang, "Electrothermal analysis of induction motor with compound cage rotor used for PHEV," *IEEE Transactions on industrial electronics,* vol. 57, pp. 660-668, 2010.

[26] Z. Zhou, X. Sun, L. Chen, Z. Yang, S. Han, K. Li, *et al.*, "A segmented rotor type switched reluctance machine for BSGs of hybrid electric vehicles: Concept, design and analysis," in *Electrical Machines and Systems (ICEMS), 2017 20th International Conference on*, 2017, pp. 1-4.

[27] Syed Abid ali Shah Bukhari, WenPing Cao, Tiejiang Yuan, and Kamran Ahmed Samo, "DESIGN AND COMPARATIVE INVESTIGATION OF A 12/8 AND A 6/4 SWITCHED RELUCTANCE MACHINES FOR ELECTRIC VEHICLES," *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY,* vol. 6, p. 13, 25-8-2017 2017.

[28] T. Jahns, "Getting Rare-Earth Magnets Out of EV Traction Machines: A review of the many approaches being pursued to minimize or eliminate rare-earth magnets from future EV drivetrains," *IEEE Electrification Magazine,* vol. 5, pp. 6-18, 2017.

[29] O. Argiolas, E. Nazeraj, O. Hegazy, J. De Backer, A. Mohammadi, and J. Van Mierlo, "Design optimization of a 12/8 Switched Reluctance Motor for electric and hybrid vehicles," in *Ecological Vehicles and Renewable Energies (EVER), 2017 Twelfth International Conference on*, 2017, pp. 1-10.

[30] W. Uddin, T. Husain, Y. Sozer, and I. Husain, "Design Methodology of a Switched Reluctance Machine for Off-Road Vehicle Applications," *IEEE Transactions on Industry Applications,* vol. 52, pp. 2138-2147, 2016.