Electrical Motor Drive Technologies for Green Electric Vehicle: A Review

ISSN (e) 2520-7393
ISSN (P) 2521-5027
Received on 27th April, 2017
Revised on 26th May, 2017
www.estirj.com

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Abstract: The environmental concerns, thermal comfort, Energy security and economic problems are motivating aspects for improvement of research on decreasing energy consumption and the associated greenhouse gas emissions in every section of the world's economy, so that's why the choice of the correct electric traction drive is essential phase while planning and design with intention to have good performance optimization, as the application of electric vehicle demands wide speed range, high power density, and low cost of machine. Since the recent trends and interest by manufacturers, engineers and researchers in rare earth free machines application due to unstable cost of rare earth metal and fault tolerant issues, shows the major breakthrough in switched reluctance machine technology. This paper presents the review of cost effective and performance based study of switched Reluctance machine drive technologies in addition to induction and permanent magnet machines used for electric vehicle applications with respect to target set by US department of energy (DoE) for freedom Car 2020 and will be linked to the guidance of new technologies for electric motors, which can play pivotal role in the selection of suitable EV machine. The research and analysis prove that, SRM could be the best alternative and can be preferred due to wide speed range operation capability and low cost with minimum losses in EV application.

Keywords: *CO_2 Emission, Electric Machine Drive, Electric Vehicle, Hybrid Electric Vehicle, Switched Reluctance Motor.*

1. Introduction

The most part of transport sector in the technologically advanced world is run mainly by liquid fuels refined from petroleum crude oil fuel. For example, approximately 97% of transport is powered by petroleum in the United States [1, 2]. Currently, the major cause of atmospheric environmental problem such as global warming and smoke is the tailpipe emissions of gasoline vehicles. Recently, the proportion of air contaminants from vehicle emissions and radiations are rising with speedy growth of vehicle number in many cities in developing countries, The electric cars' carbon emissions is shown in Figure. 1[3].To address these problems and to clarify the environmental impacts the emergence of electric vehicles in the place of conventional gasoline vehicles is a favourable and encouraging latest approach to diminish metropolitan air toxic waste and greenhouse gases in many countries such as America, Europe, China, U.K and the Japan.

A vehicle is deliberated Green when it is further environmentally friendly than the old-fashioned petroleum combustion engine [4]. The BEVs (Battery electric vehicles) are set up to bring an enhanced substitute for the most of sustainability impression classifications. Whereas around the benefits for instance support to employment and CO_2, SOX and NOX emission reduction potential of BEVs come to be greater toward 2050, other sustainability gauges together with vehicle ownership cost and social and humanoid health impacts of BEVs are higher than the other vehicle types on 2010s and 2020s [5].

We aim to develop in this study, a more expanded and broadened approach of electrical machines from a choice and design perspective in order to provide an in-depth sustainability impact assessment of alternative machines in vehicle technologies. The projected motor is skilful of catching economic, social, and environmental effects. A comprehensive literature review is presented in the following subsections.

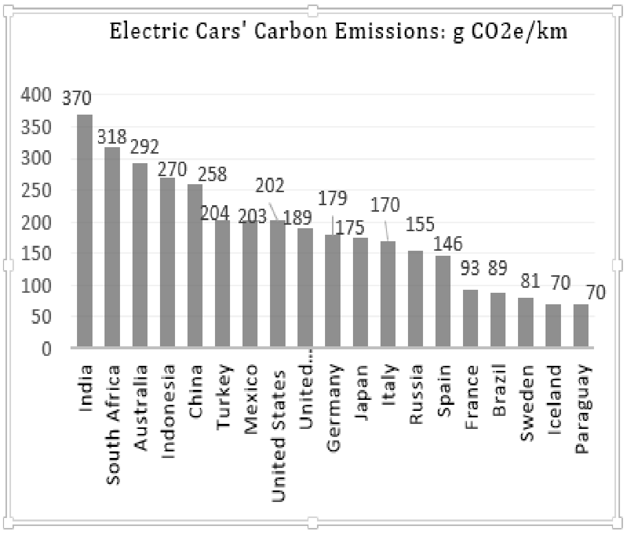

Figure. 1 Electric cars' carbon emissions [4]

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2. Electric Vehicle Development

The EV was well thought-out among the first vehicle and earlier of internal combustion engine (ICE). It ruled the vehicle registering with 3:1 relating to petrol vehicles in the early 1920s to 1930s and believed best of the land automobile performance record in initial 1900s. It was considered as a most important transportation means and commonly used in the public for resident transportation better from horse carriages [6, 7]. The control system from simple non-rechargeable to modern state of art and the development of EV can certainly be classified into three stages: Early Starting years, Midterm years and present.

3. Early Stage of Development

The electric machine propelled taking after Michael Faraday's invented work in 1821. The principal commutator current electric engine skilful of wheel rotation was made by the British researcher William Sturgeon in 1832. The essential electric train was made in 1837 by the scientific expert Robert Davidson, and was run by non-rechargeable batteries. Davidson later designed a bigger train which was shown at the Royal Scottish Society of Arts Exhibition in 1841. The primary utilization principle line was on a 4 mile (6.4 km) extend of the Baltimore Belt Line in the USA in 1895. The time to time advancement of EV is shown in Fig. 2 [5].

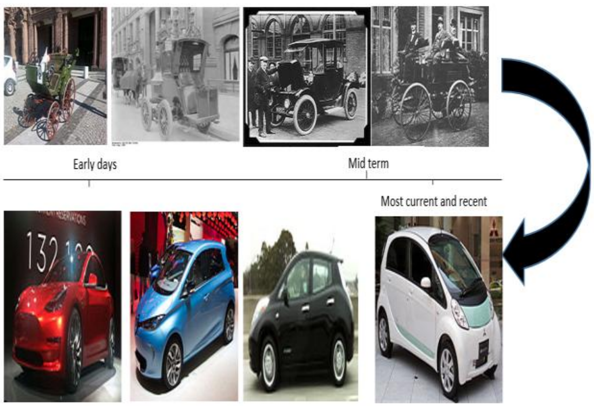

Figure.2. Development of EV [4]

Electric cable cars or trolley autos were first tentatively fitted in St Petersburg, Russia, in 1880. The principal deliberate electric cable car benefit, the Gross-Lichterfelde Tramway, went into administration in Lichterfelde, a suburb of Berlin, Germany, and was framed by Siemens and Halske AG, in May 1881. The underlying electric parkway tramway in Britain, the Blackpool Tramway, was discharged on 29 September 1885. By the begin of the First World War cable cars were utilized as a part of different urban areas all through the world. The trolleybus goes back to 29 April 1882, when Dr. Ernst Werner ran his transport in a Berlin suburb. In 1901 the world's first explorer conveying trolleybus worked at Bielathal, close Dresden, in Germany. In Britain, trolleybuses were first put into administration in Leeds and Bradford in 1911, [9]. The development of fuel vehicle could be mass created at a sensible cost. With this large scale manufacturing vehicle turned out to be all the more rapidly accessible to the overall population and continue to enhance the standard of life. By considering both the execution and cost perspective gas vehicle assumed control as the pioneer and outperform electric vehicle. The change in the infrastructure and request of between city travels required a more extended travel remove that was never ever ready to exploit by the electric vehicle. The absence of charge infrastructure advancement, appropriate and dependable transmission of power and constrained travel separately. The electric vehicle not suited for the request and the desire of the consumer and lost the edge to consistent fuel vehicle. The significant reason for restricted and no legitimate electric framework augment credibly the renunciation.

2.1. Midterm Development (1930s-1980s)

In 1935 the ignition engine assumed control over the place as in the individual transportation the generation and improvement of Electric Vehicle stopped. Political affectability amid the 1970s the need for vitality autonomy was made by OPEC (Organization of Petroleum Exporting Countries). In that period harder fuel productive standard for the business was reintroduced by the Government of the United States a board enthusiasm for an electric vehicle. Amid the early emergency of vitality in the 1970s driven the postal administration of United States put in a substantial request as a test armada of 350 electric vehicles. It was being considered as a most elevated hub of midterm improvement.

2.2. Modern Development

The Modern electric vehicle improvement was ruled by EV1 who delivered by GM (General Motors) for Armada application. This program was supported by the accompanying Bureau of vitality, Ford advancement EV Ranger pickup truck. Honda had an EV accessible and it was given by Toyota Rav4 EV and in addition during the late 1990s and mid-2000s. The current electric vehicles have appeared in Table 1.

Table. 1 Recent EV list

Model	Maker	Max Distance
EV1	GM	100 miles
Ranger	Ford	75 miles
Rav4	Toyota	100 miles
Car	Honda	100 miles

Tragically as a result of confounded governmental issues, instruction, monetary and innovation that incorporated the vehicle generation security concerns and cost issues, this short surge of electric vehicle accessibility did not understand the business creation. EV1, Ranger, Rav4 and Honda EV were aiming for the main armada test. Furthermore, at last, every one of the vehicles was ceased, wrecked and reused, however just the modest bunch of EV were made due under the hands of electric vehicles devotees.

2.3. Modern HEV Development

American cross breed electric vehicle, Escape SUV HEV (Sports utility vehicle or suburban utility vehicle), which opened the new period of competition in US among HEVs.

By The time of 2008, the offers of hybrid electric vehicles were over 2.5% for aggregate deal volume [5].

The short time later era of HEV from Toyota, Honda, and Ford have brought into 2009 with further upgrade along latest innovation with enhanced fuel proficiency. Toyota is a clear pioneer in the HEV field base on volume and scope of models with it. "Cooperative Energy Drive System" basically called Hybrid Synergy Drive HSD. In fact it is a brand name of Toyota for hybrid auto drive prepare innovation. The HSD innovation creates a full mixture vehicle which enables the auto to keep running on the electric motor just, as a contrast with most other brand hybrids which can't, and are considered as a mild hybrid.

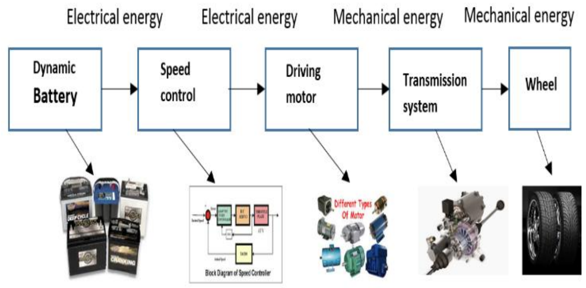

Figure.3. The power transport process of EV [8]

2.4. Future Development

As the cost of fuel is expanding quickly, joined with ecological concern, people, in general, restores the interest for social commitment. EV and AFV (Alternative fuel vehicle) rapidly grown well known once more. After the declaration of Chevy Volt module idea couple of years back and full electric vehicle from Nissan, another round of EV improvement has limited into unique hardware maker's cycle arrange in the up and coming years. By contrasting with past EV advancement, there are a couple variables that will guarantee the start to be effective later on [5]. The vehicle administrators are the immediate target clients of creating an electric vehicle. The power transport procedure of EV is depicted in Fig.3 [10]. Starting innovation and natural adopter will the essential pioneers and clients. They are quick to encourage and can impact the achievement. Additionally different instruction projects and electric vehicle genius change general comprehension of fuel productive vehicles and their benefits. Wholehearted acknowledgment of electric vehicle is high in the coming years. Collaboration in charging station and framework advancement has expanded consideration at various levels. A few plans of action are being investigated. The business and government are guaranteed that last technique will reach before the mass dispatch of the electric vehicle.

3. Energy in Driving Car

The schematic arrangement of EV and its internal structure is shown in Figure.4 [9], and the energies affecting on road car is shown in

Figure. **6**. When car runs on the road its weight and size really does the matter speeding up then slowing down using the brakes;

Air resistance;

Rolling resistance;

Heat – 70% of the energy lost as heat

Rate of energy used = Kinetic energy /time between braking events

$$=(\mathbf{1/2\ mv^2})/\ (d/\mathbf{v}) =(\mathbf{1/2\ mv^3})/d \qquad (1)$$

As the car travels it effectively moves a mass of air dependent upon the area A and speed

Air mass= $\rho A v t$ *where* ρ is the air density and t time.

$$\text{Energy used} = \mathbf{1/2\ \rho} \boldsymbol{A}\mathbf{vtv}^2/t = \mathbf{1/2\ \rho}\boldsymbol{Av}^3 \qquad (2)$$

$$\text{Hence total energy used} = (\mathbf{1/2\ mv^3})/d + \mathbf{1/2\ \rho}\boldsymbol{Av}^3 \qquad (3)$$

Mass dominates in urban driving i.e. whilst effective area dominates on motorways

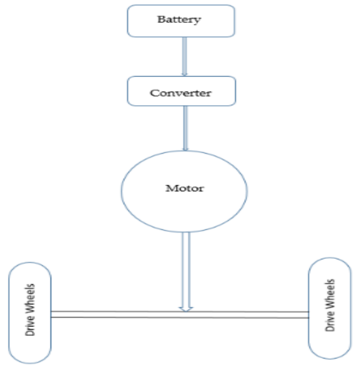

Figure.4.(a) Schematic arrangement of EV [9]

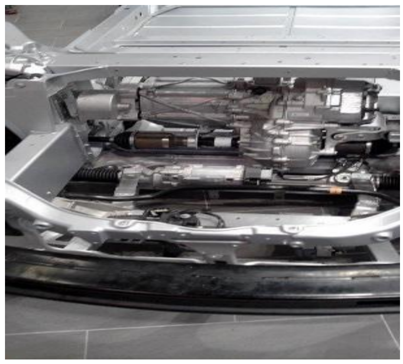

Figure. 5 (b) internal structure of Tesla Model X [9]

Figure. 6. Energies affecting on road vehicle [12]

3.1. Main Challenges for Electric Vehicle

In order to propel the wheels from the stored energy in a battery, electric motor is used in Battery Electric Vehicle (BEV) and Hybrid electric vehicle.

Tabl . 2 Current and future target for EPS technology

Characteristics	**Research and development status 2010**	**Target**	
		2015	**2020**
Cost ($/kW)	<19	<12	<8
Power density (kW/L)	>1.06	>1.2	>1.4
Specific power (kW/kg)	>2.6	>13.5	4.0
Efficiency	90	93	95

The choice and type of electric motor, mechanism for controlling the circuit hardware and to match it with the battery bank supply decides the functional requirements and the performance of the entire electric vehicle. At present the main challenge in electrical vehicle is design and implementation of electrical machine with suitable power electronic converter. The current status and future target for electrical propulsion system is presented in Tabl . **2** [10].

Table.3. Specifications set for freedom car [11]

Rated Power	30kW
Peak Power	55kW for 18 sec.
Peak Torque	200Nm for 18 sec.
Rated speed	2800rpm
Maximum Speed	14000rpm
Back EMF at maximum speed	600V
Maximum Machine Diameter	250mm

Recently the US department of energy (DoE) has set the targets for freedom Car especially for the electric motors used for the traction application is shown in Table.3. In order to achieve the above mentioned targets, the following comparison of different machine derive technologies are as under.

4. Electric Drive

The electric drive technology have grown and matured notable in the last two decades. The electric dive systems, which consist of electric machine and power electronics are a key enabling technology for advance vehicle propulsion system. Its function is to convert electrical energy into mechanical energy and is one of the most important part in the EV, In order to have substantial outcome, electric drive equipment essentially be economical in terms of cost, weight, and size while meeting reliability and performance anticipations [12, 13]. So the dynamism and energy saving motor drive technology has developed one of the intentional points to electrical vehicles commercialization, which requires electric drive to improve efficiency and reduce emissions [14].The classification of electric drive is shown in

Figure.7 [9].

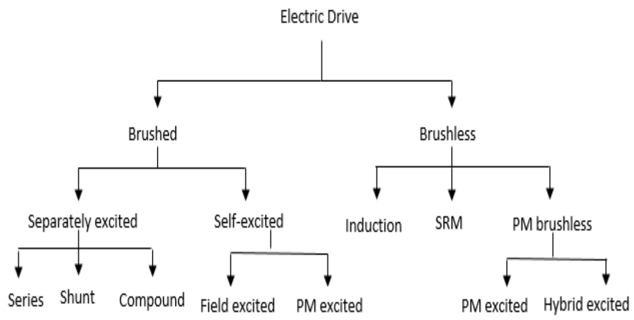

Figure.7. Classification of electric drive

The literature reveals that, a lot of work has already been done in the area of electrical vehicle machines and its drive. As the electric vehicle has enormous advantages and is also called zero emission vehicle, and it is green due to environment friendliness, In spite of the above advantages EV are not being widely used due to their short range and high price explained by famous authors C.C Chan and K.T Chau in [6]. The motors mostly used in drive application for electric vehicle are Permanent magnet motors (PMM), Induction motor (IM), and Switched reluctance motors (SRM), which are described as under.

4.1. Permanent Magnet Motor

The permanent magnet synchronous machines with enhanced coercive force are very commonly used for EV applications and its magnet provides peak power capability and high torque. Due to attractive features of interior permanent magnet synchronous motors (IPMSM), it is popular for commercialization in vehicle technology. Although there are undisputed performance benefits of permanent magnet such as high efficiency, wide speed range and high power density, but, the strategy of flux weakening capability to apply negative current causes great copper and iron losses which contribute to increase the flux harmonics in the machine [15] and due to increase in annual demand, the cost of light rare earth magnet Neodymium Iron Boron (NdFeB) and heavy rare earth magnet Dysprosium (D_y), Neodymium (N_d) is very huge in last 8 years, which is instigating government, engineering industry and academia to explore substitutes to the use of these materials in electric machines for traction application [16]. Also it is the general concept that whatever the price may be, if the rare earth magnet is removed from electrical machines, there will be massive decrease in price of electrical machines.

It has also been reported in the literature [17, 18] that, it is potentially a damaging process in the environment to extract or refine the rare earth oxides. Now it is clear that, although rare earth magnetic materials facilitate electric motors by great torque densities, their replacement compromises attractions in terms of motor cost, environmentally friendly footprint and even some other performance features. It is therefore meaningful and advisable to think through the substitutes to the usage of rare earth permanent magnets, whether these aim to decrease the volume of rare earth material or replace it entirely.

4.2. Induction Motor

Due to the robustness, low cost and self-starting capability, the Induction motor is the best used electrically powered machine for industrialized use [19, 20]. Besides IM has a lot of other advantages and in industrial automation, it is very common but rarely used for automotive purpose. Since it is essential to have higher power density for EV, moreover IM also has extraordinary flux saturation and high operational frequency consequently the secondary winding losses are significantly greater than typical values and huge eddy current losses are generated, therefore the conventional induction motor is not good enough to be used for EV application as stated in literature [21-23], However copper rotor cage induction machine has been used by the Tesla Motor Corporation, Renault and Toyota (RAV4 EV SUV) in their automotive vehicles as reported in literature [24, 25], but research has shown that some authors A. Arkkio and T. Jokinen argued that the induction machines suffer huge losses in their rotor conductors, which effects in total rotor losses usually two to three times higher than in a permanent magnet based motor [26]. Therefore S. S. Kalsi pointed out and W. M. Su, S. H. Mao supported that extraordinary rotor losses are not anticipated as the rotating rotor is much more challenging to cool than the stationary stator [27, 28]. Then Thomas Finken and Matthias Felden did the comparison of different types of machines to investigate and find out the suitability in electric machines for hybrid electric vehicle in [29]. Further explaining the same James D. Widmer in his research provided the comparison of different motors with respect to material used as depicted in figure 7, [24].

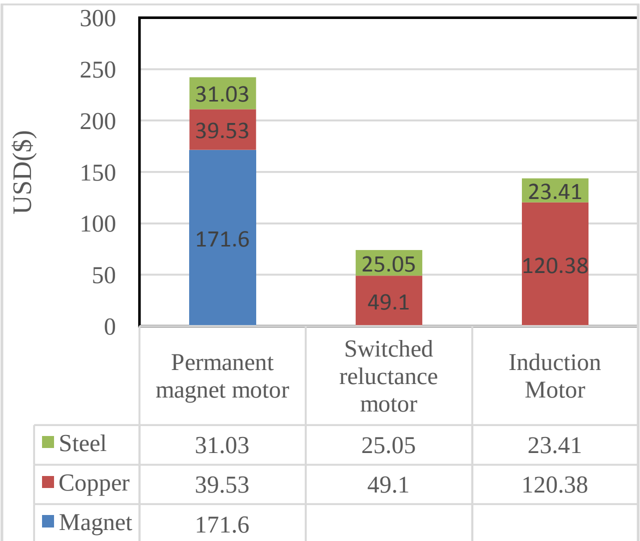

Figure.8. Materials cost of different motors at 30kW rating

From the Fig.7, it is clear that from cost point of view switched reluctance motor is very low in price as compare to induction and permanent magnet motor.

4.3. Switched Reluctance Motor

Switched Reluctance Motor (SRM) having concentrated winding on the stator side and no winding on the rotor. The two different design configurations and structure of SRM machine is shown in Fig.8. It is widely used in industry because of its low cost and it has the biggest advantage is lack of permanent magnet. An additional benefit of switched reluctance motors is that has an ability to be driven over a wide range of speed, torque and less complex control structure for the reason that this machines is very useful for electric vehicle and can be used to enhance fuel efficiency and reduced CO2 emission for electrical propulsion. It has also been endorsed by A. Chiba, Y. Takano in The New Energy and Industrial Technology Development Organization (NEDO), a public management organization in Japan, that switched reluctance motor is the potential solution [30].

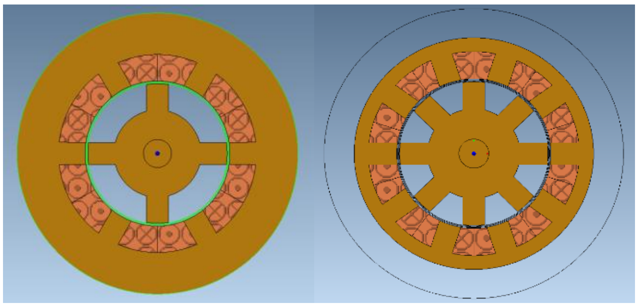

Figure.9. Solid Model Internal Structure 6/4 and 10/8 SRM

Table. 4. Performance comparison of IM, PM and SRM of

Motor-Items	IM	PM	SRM
System efficiency	Lower	Higher	Higher
Starting Torque	Lower	Higher	Highest
Power Density	Lower	Highest	Higher
Workmanship	simple	complicated	simplest
Reliability	higher	lower	highest
Life	longer	short	longest
Manufacturing cost	lower	highest	lowest

4.4. SRM and its Effectiveness

As the Switched reluctance machine has been prominent as a most important substitute in several applications due to their low cost, good mechanical reliability, high torque-volume ratio, simple and robust construction, Absence of demagnetization, ability of fault Tolerant, simple rotor design, operating temperature can be increased and high rotational speed is possible as documented in literature [31-37]. The comparison of different machine is shown in Table. 4.Recently jaguar has also released a concept which uses the SRM for hybrid electric vehicle [38]. Further Bilgin et al. evaluated the comparative analysis of 8/6 and 10/6 switched reluctance machine for HEV traction application in [39]. This shows that Switched reluctance motors (SRM) are one and only alternative candidates.

5. Results and Discussions

The specifications of two different configuration 6/4 is given bellow.

Table .5 Design specification of 6/4 and 10/8 SRM and 10/8 switched reluctance machine

Outer Stator radius	100mm
Rotor radius	49.639mm
Shaft radius	10mm
Stator and rotor pole arc	18 deg
Stator pole height	19mm
Stator pole width	15.98mm
Rotor pole width	15.89mm
Rotor pole height	19mm
Winding coil material	Copper
Stator and Rotor material	Newcor 1000/65
Air-gap	2mm
Rotor air box radius	50mm
Rotor remesh radius	50.5mm
Stator remesh radius	51mm
Stator air box	100mm

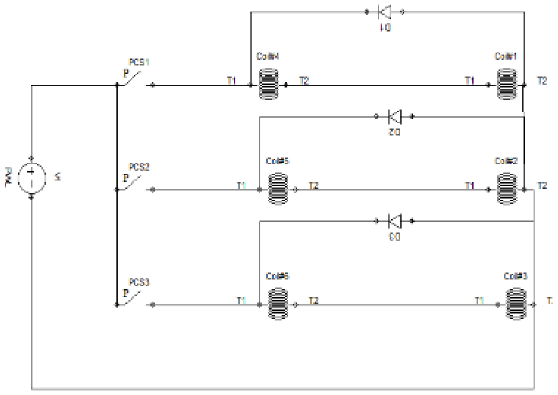

Figure. 9. (a) Energizing circuit of 6/4 and 10/8 SRM

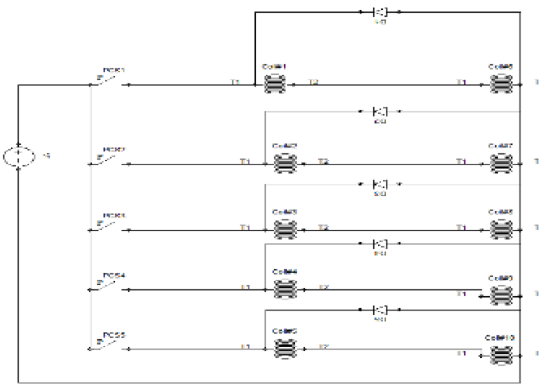

Figure. 9. (b) Energizing circuit of 10/8 SRM

5.1. Driving circuit for 6/4 and 10/8 SRM

In order to drive the SR motor three and five position control switches have been connected in a separate circuit window. The rotor alignment and un-alignment positions at different degree of 6/4 SRM and 10/8 SRM is shown in Fig.9 and 10.

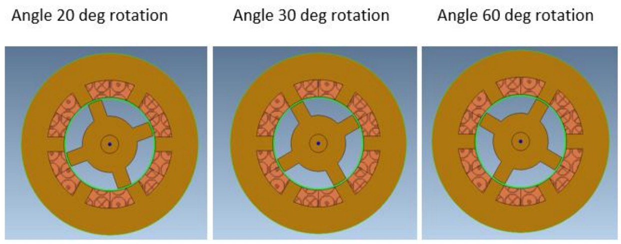

Figure. 10. Rotor alignment and un-alignment positions at different degrees 6/4 SRM

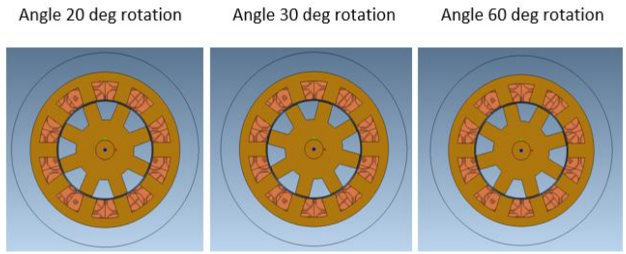

Figure. 11. Rotor alignment and un-alignment positions st different degrees 10/8 SRM

The voltage source of piecewise liner have been used to provide the excitation to the coils. Different switching patterns were provided to each switch so that during alignment position the next switch can be energized which has higher inductance and near to adjacent stator poles. For the 6/4 SR motor, initially PCS3 switch was turn on with (ON=0, OFF=30 and ON=90) degrees switching sequence of rotor rotation then in the next step PCS1 was energized with sequence of (ON=30, OFF=60, ON=120) degree rotation, then further PCS2 switch was given the sequence of (ON=60, OFF=90, ON=150) degree rotation. The freewheeling diode have been provided across the coils to absorb the electromagnetic energies during turn off time with the value 0.0001Ω and OFF resistance of 100*106Ω respectively.

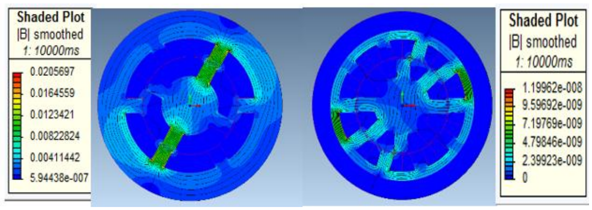

Figure. 12. The flux function view of 6/4 and 10/8 SRM

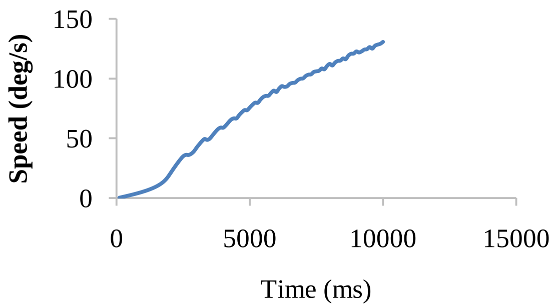

Figure. 13. Speed graph of 6/4 SRM

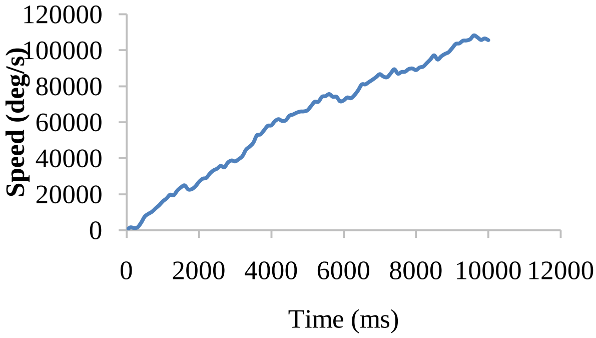

Figure.14. Speed graph of 10/8 SRM

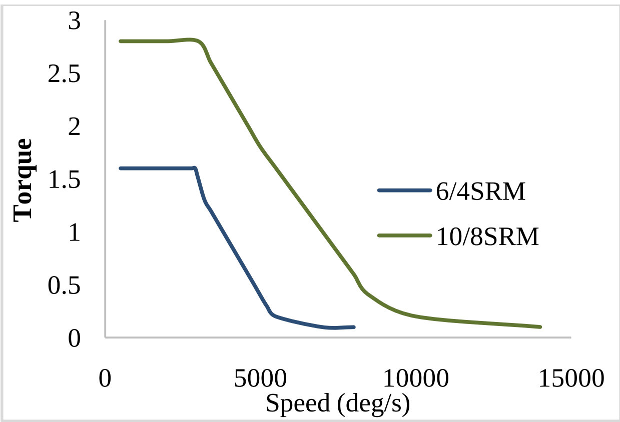

Figure .15. Torque speed envelop of 6/4 and 10/8 SRM

When the switch PCS3 is turn on the winding coil 3 and 6 are energized and produces magnetic flux path in this way nearest rotor poles are attracted by the energised stator poles in order to achieve the minimum reluctance path. The switching pattern suitable for 10/8 SRM was given initially PCS5 turn ON at 0, and open again at 15 degrees, this pattern repeats every 45 degrees. So a periodic sequence to use in ON-0-OFF-15-45. By inspection, the other switched follow in sequence PCS1, PCS2, PCS3 and PCS4, delayed by 9 degrees each time, so PCS1 is ON-9-OFF-24-ON-54 and the others follow accordingly. The flux function view of both the machine is shown in Fig.12, which produces the magnet flux density of 0.0205and 1.199 Tesla respectively.

From the above design, the speed graphs of both the machine 6/4 and 10/8 is shown in Fig.13 and 14 and 14000rpmfrom 10/8 SRM have been achieved and it is within the target required for the freedom Car. The torque speed envelop produced by 6/4 and 10/8 design is shown in Fig.15. The simulation results is aimed to show the performance of two different configurations of SR motor at different operating conditions and characteristics, which can be further improved by design optimization, excitation and other configurations of the SR motor. Further work is going on to extend the research and to investigate the other design.

5.2. Challenges and Opportunities in Switched Reluctance Motor Design.

There are also certain disadvantages in in the SRM like: (i) low efficiency (ii) low torque density (iii) unique inverter circuit (iii) high torque ripple (iv) high noises and vibration. The efficiency has been improved by K.Kiyota in literature [40-43]. To improve further SRM performance, diverse investigation and research have been reported in the literature [44-50].

From the design point of view In-wheel drive has been developed in [51] by GEMCO truck and the same configuration of SRM design performance with similar specifications were achieved by K Boynov, A Kechroud showed the extended torque-speed envelop in SRM which is shown in figure 16 [31].

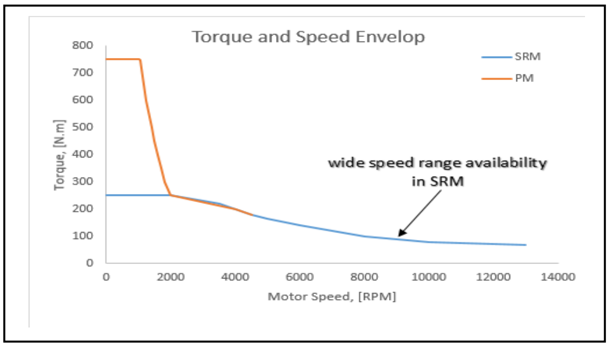

Figure.6. Extended Torque-speed envelop [51]

From the Fig.16, which shows high torque region and high speed range of the SRM and the performance can be further upgraded through optimal excitation with magnetic design as the enhancement in the power density considerably alters the situation and opens the opportunity to deliberate SRM for high performance applications for electric vehicle [52]. The Recent research in [53-58] has shown that, with proper design optimization and with novel design approach SRM can attain high torque and power density and could be the alternative of interior permanent magnet motor.

5. Conclusion

In this study we have mainly focused on the target set by US department of energy for the freedom Car for 2020, as the past three eras have realized a prominent growth in the research and improvement of switched reluctance motor (SRM) drives. Because of the emerging trend in eco-friendly limitations and rare earth free motors, new developing usages in the area of electrified vehicles necessitates the standard of high-efficient, wide speed range, high-speed and high-reliability electrical motor drives. Due to these requirements, advance machine design and power converter topologies are facing technical challenges and a unified drive system needs to be considered with upgraded thermal performance. High consistency can be achieved with better machine and control design.

This work which is based on analytical method, actually focuses on the overview and development of machine design and control strategies used for electric vehicle, with the comparative study of permanent magnet, induction and switched reluctance machine drives. As the rare earth free machines becoming a trendy new amenity that can offer to attract researchers and engineers to make them stay a bit longer but what kinds of machine can benefit? SRM could be likely candidate out of these machines, and considered as the ongoing and growing contestant for upcoming electric vehicles.

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