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DESIGN AND COMPARATIVE INVESTIGATION OF A 12/8 AND A 6/4 SWITCHED RELUCTANCE MACHINES FOR ELECTRIC VEHICLES

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ABSTRACT

Currently, it is widely accepted that CO_2 emissions are required to reduce significantly in order to keep global warming under control. This has led to rapid development of renewable energy and sustainable technologies. In automotive industry, hybrid and pure electric vehicles are most popular for the customer vehicles. The main part of these vehicles is traction drive. An electric machines with reduced magnet mass or with no magnets are of extremely attractive. Due to the development in power electronics, the switched reluctance motors (SRM) have gained popularity as a good candidate for the application of electric vehicle. In this paper, the performance comparison a 3-phase 12/8 and a 6/4 switched reluctance machines have been studied through finite element analysis by using Infolytica Magnet software. The simulation results shows that, as the higher number of stator and rotor poles the smaller change in geometry of the stator and rotor lead to improved magnetic characteristics and the energy efficient in torque production. The SRMs are proven to be able to replace the permanent magnet synchronous machine (PMSM for hybrid and pure electric vehicles.

KEYWORDS: Electric vehicle, Machine design, Switched reluctance motor, Torque ripple.

1. INTRODUCTION.

The growing interest in electric and hybrid electric vehicle due to increasing concern on environments, which has led government, car manufacturers to improve the performance of electric drive system, batteries and other components [1]. The electrical machines are one of the supreme major technology sustaining the progress of the modern society. Currently approximately entire electrical energy [2], globally some 15,000 TWh yearly, is generated by electrical generators; 45% of this generated energy is then all over again altered into mechanical power by means of electrical machines [3, 4]. The trade to greener advances and aptitudes has coordinated to advance and development popular for creative, new effective classes of electrical machines. Associations, for example, the United States Department of Energy [5] and the European Union [6] have declared standards which require the improvements in the proficient profitability of modern electrical machines. Essentially the advance in vitality era from inexhaustible innovations has driven the broadening of new sorts of electrical machines, for instance, to create of vitality from wind and wave. Then again, request for electrical machines in the ensuing range is conceivable to be persuaded through the increased demand for electric motors for E applications. Till 2013 in UK there were 405,000 cars were sold [7] and it is predicted in [8] that, till 2020 there will be a yearly generation of 9 million hybrid and pure electric vehicles in the world, the overall demand is to produce high torque density electrical machines. The extensive organizations of Motor Vehicle Makers disclosed that, in 2011, 80 million vehicles were made everywhere throughout the world. Would these totally changed over into an electric vehicle around then without a doubt this arrangement of electrical machine creation will go up against gigantic significance. When the car run then different types of energies affect directly on the car which is shown in fugure-1. At the same time the machine which is installed within the car must have sufficient power and load carrying capability, the interior permanent magnet motors are very famous in electric vehicle technology due to high efficiency and great power density , but because of increasing demand of NdFeb has increased the price of

permanent magnet machines and there are a lot of environmental concerns due to waste products generated while in the process of exploration and refinement of these material [9, 10].
Mainly the common materials used in machines are NdFeB Magnet, copper, aluminium, steel, and polyethylene as per available properties, these materials are used for difference purposes like for producing magnetic field, as good conductor of electricity and for electric and heat insulation. Among these material the NdFeB has serious environmental effects. The Fig. 1 shows the chart of Life cycle assessment of the material which are commonly used in electrical machines, this actually shows the environment impact of NdFeB compared with copper, aluminium, steel and polyethylene. Because of this reason the switched reluctance machine has become the strong candidate for the electric and hybrid electric vehicle due to cheap in cost, simple in construction, very robust, absence of demagnetization and can be operated smoothly at excessive high temperature. In most of the paper the SRM is point out as a real drive for electric car [11-14].
When a vehicle runs then different types of energies effect on it and electric motor has to carry all that load, so the motor which provides driving force to vehicle should be capable to withstand the load, fig. 2 shows the impact of energies on road vehicle.

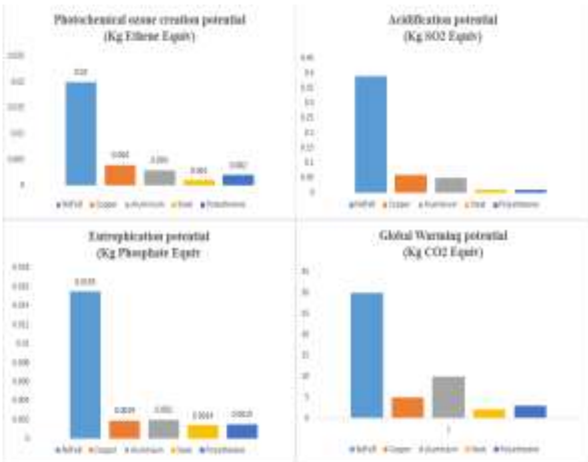

Figure. 1 Life cycle assessment of the material which are commonly used in electrical machines, shows the environment impact of NdFeB compared with copper, aluminium, steel and polyethylene [3].

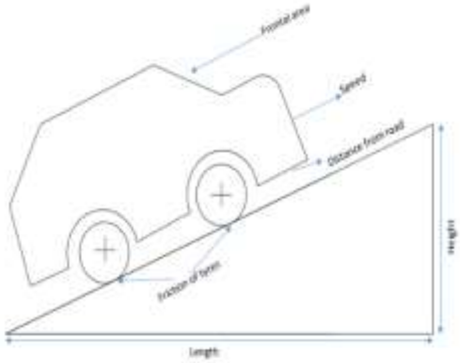

Figure. 2 the impact of different energies on road vehicles

1.1 Current Situation

In this paper while designing the SRM, the author has kept main attention on the 12/8 SRM and improvement in the peak torque and efficiency in terms of low ohmic losses. In [15] number of winding turns and geometrical shape of winding slots of 12/8 toothed SRM has optimized. A comparison of SRM with switched with permanent magnet motors for the vehicle application has been described in [16], A design strategy of 12/8 SRM for small electric vehicles is proposed in [17], A dynamic simulation for EV application of 12/8 SRM is presented which actually based on flux linkage and characteristics of torque in which fix angle chopping is adopted in literature [18], A 40kW SRM is presented in [19] with the EV driving force torque vs speed characteristics. Another 12/8 modular stator with hybrid excitation SRM is presented in [20], The novel 6/5 SRM segmental type rotor with additional application of cooling fan construction is described in [21], The double stator SRM is introduced as an alternative contestant for the electric vehicle propulsion system and the adjustable drives have been compared in [22], A new voltage PWM rectifier simulation in 12/8 SRM drive which can easily obtained the regenerative braking system is presented in [23], A segmental rotor pole with hybrid stator poles body structure with improved torque density and reduced motor core losses is presented in [24]. Among all of the above research paper the authors has found the research gap in the comparison between 6/4 and 12/8 with slight design changing in rotor and stator pole shape and their impact on switched reluctance motor performance in terms of torque, flux linkage, instantaneous magnetic energy, current voltage and ohmic losses of the machine. This paper has been organized as follows. Section 1, discussed the detail introduction and background of the research with respect to energy scenario issues related to electric and hybrid electric vehicles with current situation available in literature. The working principal of switched reluctance machine including its essential components and associated main issues, challenges have been reviewed in Section 2. The modelling and comparison between 6/4 and 12/8 SR machine is presented in result and discussion section 3. The diverse performance comparison analysis has been done in section 4 including design issues with various aspects of modelling and characterization. The brief application and future prospective trend, research methodologies are present in conclusion section 5.

2 SWITCHED RELUCTANCE MOTORS

The Switched Reluctance Machine is the category of distinct electrical machine, it is really advanced version of steeper motor. A steeper motor is usually made for discreet rotational based on the sequential pulse than it will produced the discreet rotation. Here the identical construction but in switched reluctance machine we obtain a constant rotation. The construction is, it is a double silent machine, the opposed poles are attached together to form a phase. The windings are employed in a stator only, and there is no any rotor windings or magnet and it is simple material made of silicon steel stampings so the inertia of the rotor is very less that is the major future of the SRM machine. It is required to energize the phase windings in a consecutive manner with the help of switching pattern, to achieve a reluctance torque. First of all what is reluctance torque?

$$T = \frac{1}{2}\, i^2 \frac{dl}{d\theta} \tag{1}$$

Why the name switched reluctance machine. Actually reluctance is the property of magnet that compete with magnetic flux as the resistance competes against electricity. The switching stroke will be managed through the power electronics converters, so through the switching actions we energize the machine windings. The rotor poles starts rotation, it continuously vary the inductance. The different alignment positions of the SRM are shown in fig. 3, and basic SR motor is shown in fig. 4.

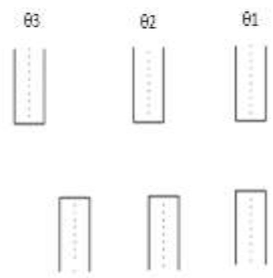

Figure. 3 Alignment of SRM

$\theta 3$=Unaligned Position
$\theta 2$=Intermediate Position
θ_1=aligned Position

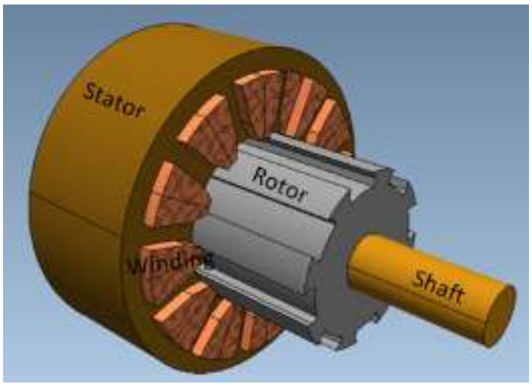

Figure. 4 Basic SR motor stator, rotor, shaft and winding

In aligned position the airgap between rotor and stator poles is very less. As soon as the energization will occur in the stator poles the rotor will attract the stator poles, so it starts the rotation and θ_2 denotes the rotor moment during intermediate state from unaligned to aligned position. The rotor will start the movement and that position will generate the torque. Based on the variation in the reluctance, θ_1 position is called as an aligned position, in that position mutually stator and rotor are in aligned so the airgap will be least compare to $\theta_{3,}$ so at all times rotor try to appeal towards the minimum reluctance position that is the idea of switched reluctance machine.

$$T = \frac{1}{2}\, i^2 \frac{dl}{d\theta}$$

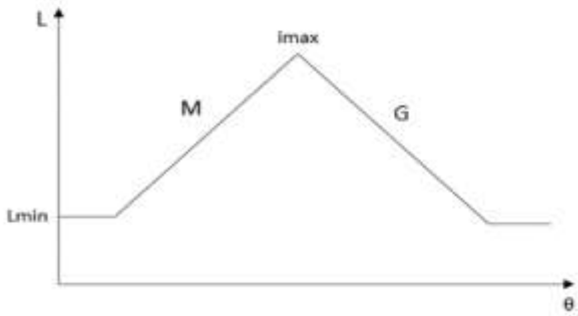

Figure. 5 inductance vs torque profile

Once the inductance varied from $L_{min,}$ that is lowest inductance value to highest inductance value we try to change in inductance with respect θ, so the torque is depend upon two major factors, one is current and another one is change in inductance. So machine designer decides the variable inductance with respect to (θ) movement and this (i^2) current will be deliberated by power electronic converter circuit the magnitude of the current, so the torque proportional to half $i^2 \frac{dl}{d\theta}$. And torque is achieved through excitation the current and $\frac{dl}{d\theta}$. So when we apply generating action means, we have energized the machine in a falling inductance profile that means maximum inductance to minimum inductance $\frac{dl}{d\theta}(-ve)$ that is representing G, which means generating action. The inductance versus torque profile is shown in fig. 5. So the prime mover we run the machine in the falling inductance profile we obtain as a generator. Consequently this machine appropriate for both motoring as well as generating applications.

As wind turbine needs to start the prime mover, as a motor SRM drives the wind turbine and in a car it needs starter motor after that ones the starting process has happened, later it will be converter as a generator and it works as a generator. So this SRM is suitable for dual mode application because simply we converted this from motor to generator action, this is the major merit of switched reluctance machine. The working principal is through the power electronic converter, we obtain an excitation based on the position signal and torque is obtained, so ease of action, the mechanical design is very simple and we have to switch in an appropriate period based on the position information. This machine is currently very useful in research area to obtained required outputs. The major drawbacks are Torque Ripple and Acoustic Noise.

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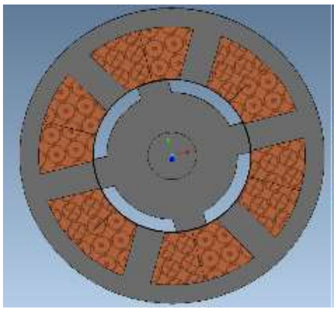
The torque ripple can be removed from phase overlapping scheme and acoustic noise are removed by default as the torque ripple removal. So the major drawbacks can be removed by good machine design approaches. So SRM is the major machine drive which will be used in future. As this machine replaces all the industrial requirements surely. It is a very attractive machine compare to all the conventional and special machines like: BLDC and synchronous machines, those machines have permanent magnets and it has the problem of long term running and demagnetized issues and these are major problem. But SRM does not have any windings or permanent magnets in the rotor part and is energized in the stator part alone that is why this is highly preferable machine in future.

Table. 1 specifications of the switched reluctance machine [25]

Parameter	Symbol	Value	Units
Stator diameter	*ds*	250	mm
Rotor diameter	*dr*	132.5	mm
Air-gap	*g*	0.65	mm
Number of stator poles	*Ns*	6 and 12	-
Number of rotor poles	*Nr*	4 and 8	-
Stator pole arc	*βs*	21	o
Stator pole arc	*βr*	23	o
Number of phases	*m*	3	-
Rated speed	*nN*	10,000	rpm
Phase Voltage	*Vdc*	25	V
Number of turns	*Np*	250	turns
Shaft diameter	*dsh*	40	mm
Rotor yoke thickness	*yr*	15.35	mm
Stator yoke thickness	*ys*	14.18	mm
Rotor pole length	*lr*	10.9	mm
Stator pole length	*ls*	44.72	mm
Rotor pole width	*tr*	23.08	mm
Stator pole width	*ts*	21.82	mm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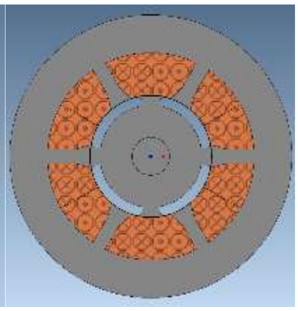
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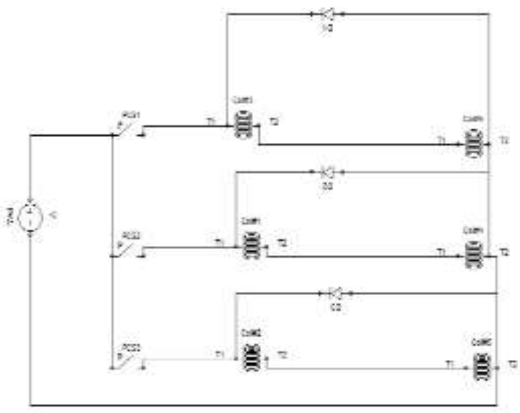

(c)

Figure: 6 (a) solid view conventional 6/4 SRM (b) taper rotor and stator poles 6/4 SRM (c) excitation circuit

The SRM is widely used in industry because of its low cost and it has the biggest advantage is non-existence and lack of permanent magnet [26]. 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 CO_2 emission for electric propulsion [27]. Furthermore the development in power electronics lets SRM to be used as drives in many industrial applications [28]. It has also been endorsed in The New Energy and Industrial Technology Development Organization (NEDO), a public management organization in Japan, that switched reluctance motor is the potential solution [29, 30]. Two diesel-electric hybrid construction loaders were introduced equipped with switched-reluctance motors and generators. At electrical vehicle Japan in January 2012, Nidec presented switched reluctance automobile traction motor which could consume the lowest cost for achieving the performance close to IPM machine. Numerous other companies are correspondingly in the process of using EV based on switched reluctance motor for propulsion system [29].

3 RESULTS AND DISCUSSION

In this section two SRM design have been presented and their performance is investigated. Our actual goal is to achieve the high and stable torque with low ripples. The example of design which are shown here have the same rotor and stator diameter, stack length and excitation voltage here we start with 6/4 SRM design.

3.1 Design of the 6/4 SRM

The specifications of 6/4 SRM are shown in table-1. Author has examined here the effect of changing the small tip of rotor and stator poles

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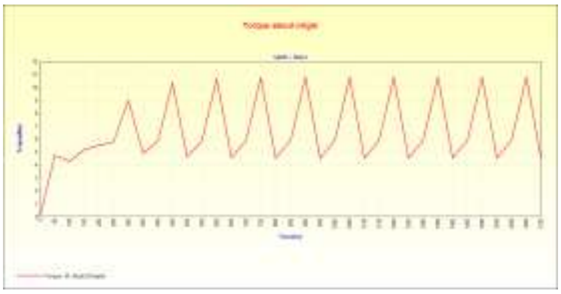
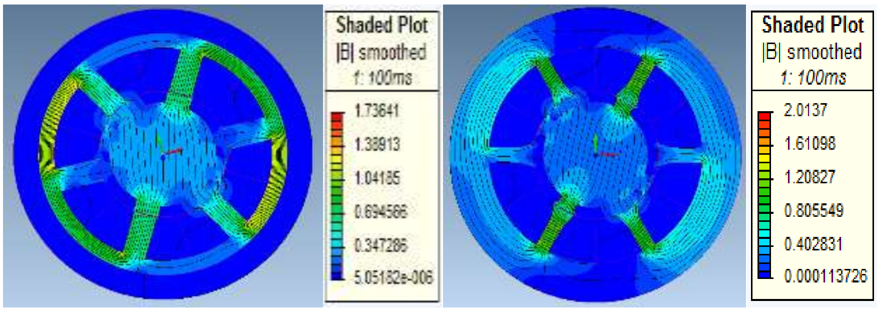


(b)

Figure. 7 (a) Graph of torque produced by conventional 6/4 SRM (b) Torque produced by taper rotor and stator poles 6/4 SRM



(a) (b)

Figure. 8 Magnetic flux density of 6/4 SRM design (a) and (b)

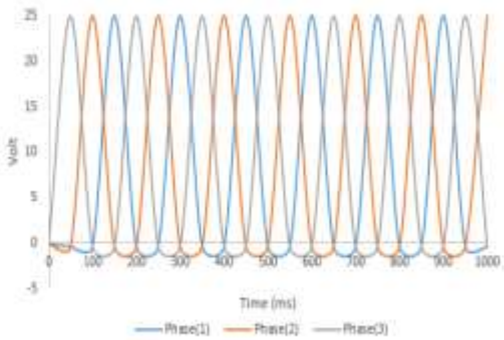


Figure. 9, 3-Phase voltage of 6/4 SRM

design and their performance. The solid view of 6/4 SRM and its excitation circuit is shown in fig. 6. Initially the machine was design in AutoCAD software then was imported into Infolytica magnet software to make the solid model of the design. The instantaneous energy produced in the design (a) is 35.5 Joules where design (b) produce 44 Joules and the torque developed by design (a) is higher than design (b), during starting time the torque reaches up to 10.9 N-m then in conventional 6/4 SRM is 11.2 N-m and the torque ripple is 62%. In the design (b) the torque ripple is 55% and it is shown in fig. 7. Whereas the flux density is low of design (a) which is 1.736T as compare to design (b) and it is 2.013T as shown in fig 8. In order to energize the winding, 50V excitation voltage were provided. The voltages are stable throughout the running in both the design (a) and (b) machine as depicted in fig 9. However the current is slightly different in machine (b) which is 19A and in design (a) it is 17.5A, as it shown in fig 10.

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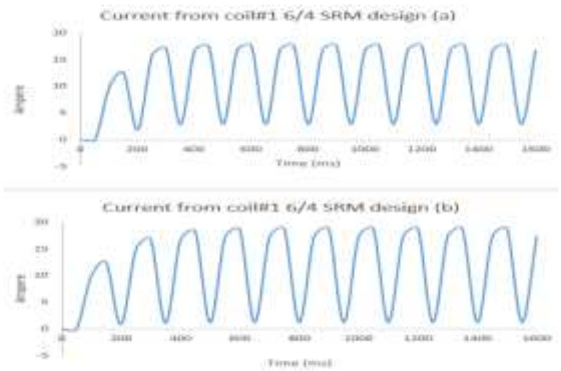
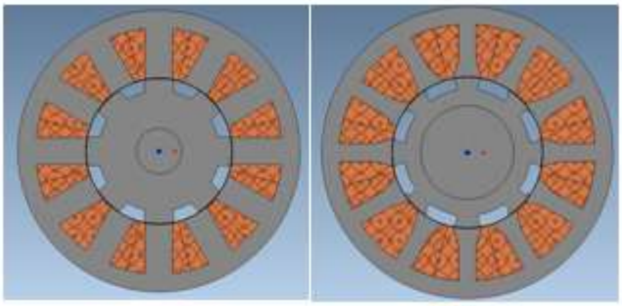
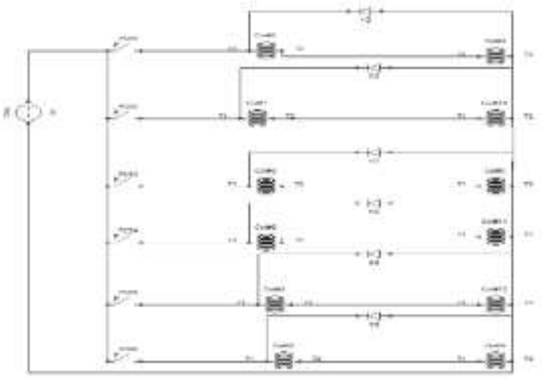


Figure. 10 Current from coil#1 in 6/4 SRM design 9a) and (b)



(a) (b)

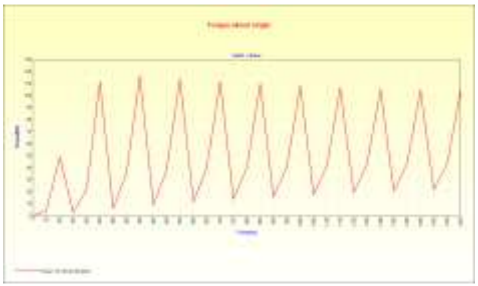


(c)

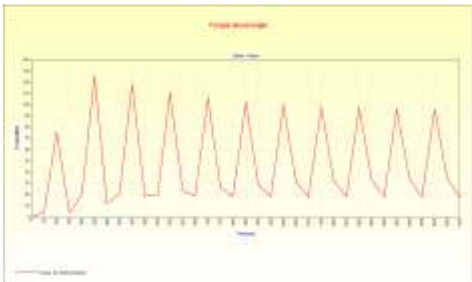
Figure. 11 (a) solid view conventional 12/8 SRM (b) taper rotor and stator poles 12/8 SRM (c) excitation circuit

3.2 Design of the 12/8 SRM

The specifications of 12/8 SRM are the same as 6/4 SRM and can be referred in table. Author has changed the number of stator and rotor poles to examine the effect as compare to 6/4 SRM. The solid view of both (a-b) 12/8 SRM and its excitation circuit is shown in fig. 11. The design procedure adopted was the same as during the design of 6/4 SRM. The instantaneous energy produced in the design (a) is 205 Joules where design (b) produce 183 Joules and the torque developed by design (a) is, during starting time the torque reaches up to 118 N-m then in slightly decreases up to 103 N-m, the torque production by 12/8 SRM design (b) is, initially it peaks up to 130 N-m and then decreases at 95 N-m. In the design (b) and is shown in fig. 12. Whereas the flux density is low of design (a) which is 1.56T as compare to design (b) and it is 1.657T as shown in fig 13. In order to energize the winding, 50V excitation voltage were provided. The voltages phase 1 is slightly unstable during starting time and then stable throughout the running in both the design (a) and (b) machine as depicted in fig. 14. However the current is slightly different in machine (b) which is 56A and in design (a) it is 58, as it shown in fig. 15.

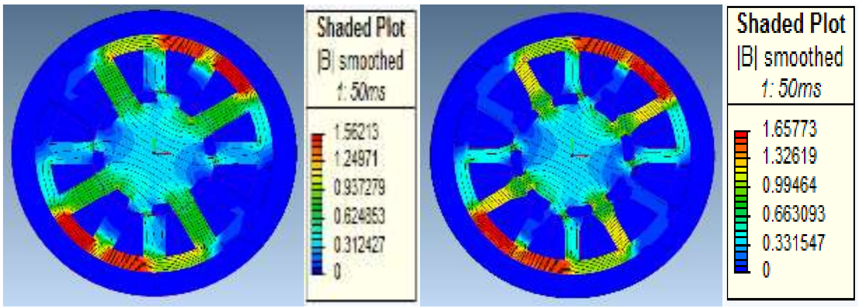


(a)



(b)

Figure. 12 Torque produced by 12/8 SRM design (a) and (b).



(a) (b)

Figure. 13 Magnetic flux density of 12/8 SRM design (a) and (b)

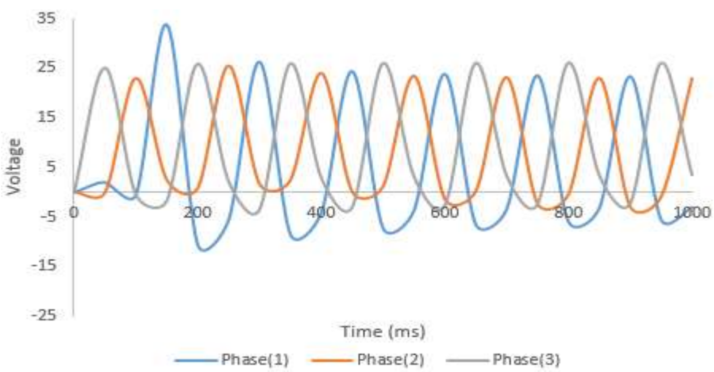


Figure. 14, 3-Phase voltage of 12/8 SRM

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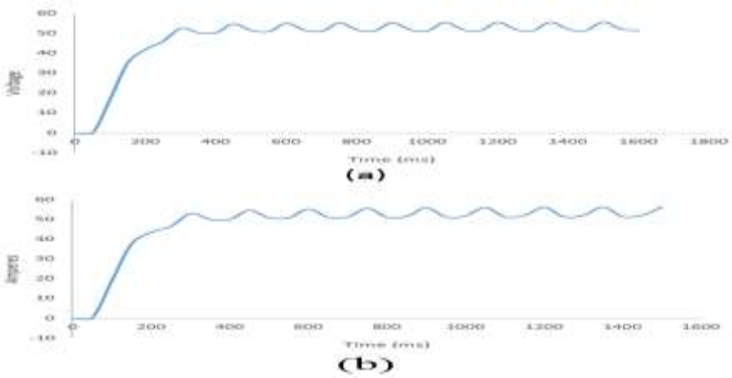


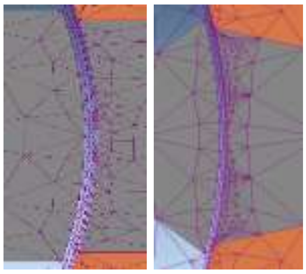
Figure. 15 Current from coil#1 in 12/8 SRM design (a) and (b)

Table. 2 comparison between results of 6/4 and 12/8 SRM designs.

	6/4 SRM		12/8 SRM	
	Design (a)	**Design (b)**	**Design (a)**	**Design (b)**
Magnetic energy (Joules)	35.5	44	2.5	183
Torque (N-m)	11.2 N-m	10.9 N-m	118	130
Flux density (Tesla)	1.73	2.013	1.56	1.65
Flux Linkage (web)	1.08	1.2	1.7	1.39
Average Hysteresis losses				
Shaft	0.00145	0.00135	0.0079	0.0374
Rotor	0.0936	0.143	0.565	0.476
Stator	0.148	0.128	0.366	0.389
Average eddy current losses				
Shaft	0.0000134	0.000014	0.0000000898	0.000438
Rotor	0.00126	0.00213	0.0108	0.00947
Stator	0.00221	0.00183	0.00561	0.00637

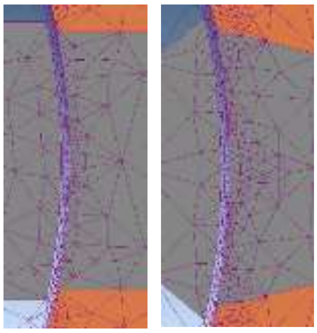
4 PERFORMANCE COMPARISON

The transition performance of 6/4 and 12/8 SRM was simulated and compared with the results as shown in table. 2. There is also effect due to change in design on flux linkage. The flux linkage decreased in 6/4 SRM and increased in 12/8 SRM, the initial 2d mesh is shown in fig. 16 and 17. The switching pattern of both the machines was same and produce working switching sequence in the excitation circuit shown in fig. 6 and 11, a periodic sequence is used while switches ON-0-OFF-15-ON-45, by continuing the pattern the other switches follow in sequence PCS1, PCS2 and PCS3 and PCS4, successively delayed by 9 degrees each time, so PCS2 is ON-15-OFF-30-ON-60 and all the other switched follow accordingly. However as there are more number of stator and rotor poles so 12/8 SRM has 6 switches connected in the circuit, from the results it can be analysed the by changing the small rotor and stator pole tip the performance of the machine also changes. There is some effect on magnetic energy and almost negligible effect on torque in 6/4 SRM design. Due to taper design the average hysteresis losses and eddy current losses are very low in 12/8 design (b).



(a) (b)

Figure. 16 initial 2D Mesh of 6/4 SRM design (a) and (b)



(a) (b)

Figure. 17 initial 2D Mesh of 12/8 SRM design (a) and (b)

5 CONCLUSION

The comparison between 6/4 and 12/8 SRMs has been presented in this research paper. Two different SRM topologies have been designed by the FEM method using Infolytica magnet software. The simulation results shows that small change in rotor and stator design can affect the performance of switched reluctance machines, for higher number of stator and rotor poles there is a small change in geometry of the stator and rotor, this can enhance the magnetic characteristics and there is improvement in torque, Instantaneous magnetic energy with reduced, moment of inertia, hysteresis and eddy current losses. This investigation will be helpful in further design and performance of other 4/6, 8/6 10/8, 8/14, 18/12 and 36/24 SRM topologies.

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