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Performance Comparison of SRM, PMSM & BLDC Motor Drives via Experimentation in Laboratory for EV Application

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Abstract: This paper presents comparative study of three different motor drives using advance speed controllers via experimentation in laboratory for EV application. Advance speed control technique of Switched Reluctance Motor (SRM) drive using Digital Signal Processor (DSP-28335) controller and hardware setup for experimentation is utilized. Permanent Magnet Synchronous Motor (PMSM) drive speed control method used in this paper is Sinusoidal Pulse Width Modulation (SPWM) technology supported inverter and is implemented using DSP (2812) controller hardware setup. Also, advance speed control technique of Brushless DC (BLDC) motor drive by FPGA (Field Programmable Gate Array) controller using hardware setup is adopted. These methods are more preferred in practice. Since there is ever increasing concern on the energy utilization & environmental protection, the development of Electric Vehicle (EV), using particular motor has become a hot research topic. As major part of EV have to offer high efficiency, high torque, easy control, wide speed operating range & maintenance free operations. In recent years, SRM, PMSM & BLDC motors become the best alternative to the conventional motors with all required features & capabilities for EV application. Experiments are conducted in laboratory on SRM, PMSM & BLDC drives by load tests with Digital Storage Oscilloscope (DSO). Test data along with waveform are recorded to calculate efficiency & torque. Comparative study of SRM, PMSM & BLDC drives with better torque & efficiency results for EV application are presented.

Keywords: *SRM; PMSM; BLDC; EV; DSP; FPGA; Experimentation*

1. Introduction

Electric vehicles are important, because contribution that they can make towards improving air quality in towns & cities. Also, no carbon dioxide emissions, this reduces air pollution considerably. It also contributes in reduction in global warming, effective range of EV is completely dependent on battery type & capacity [1, 39]. Today, India is facing a huge energy crisis due to depletion of fossil fuels. EV have their attraction due to air pollution & exhaustion of fossil fuels. These vehicles use motors (SRM, PMSM, Induction motor, DC motor & BLDC motor) to obtain the driving force & for the drive train. There are several advantages of motors along with disadvantages, such as control complexity & manufacturing cost etc. As, conventional vehicle (petrol or diesel-based Internal Combustion engine) increasing level of pollution, therefore EV is the better solution. In early days, EV is driven by brushed dc motor or induction motor. Induction motors have poor efficiency at light load conditions. Brushed dc motor have low efficiency due to friction losses [2-5].

BLDC motor is the better solution compared to dc motor & induction motor for EV application. BLDC motor is more efficient, reliable, less noisy & it has faster operation. It is same as synchronous machine, but permanent magnet is mounted on the rotor. The stator is star connected & its operation is based on magnetic locking between stator and rotor. For magnetic locking, rotor pole position must be known & it can be determined by using hall effect sensor. The signal from hall effect sensor is fed to controller to generate gate pulses for the switches of bridge converter. The switches used in the converter are any power electronic switches (MOSFET or IGBT). The controlling of BLDC motor is by controlling switching of converter & taking speed of motor as feedback. The error between actual & reference value of speed is given to controller. FPGA advance controller with xilinx spartan series is used, for controlling speed of BLDC motor in closed loop operation at different loads. It is a digital platform with high density to support parallel execution of bit

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level operations. BLDC motor has trapezoidal back e.m.f., stator flux position commutation at each 60 degrees. Only two phases ON at the same time, content torque ripple at the commutation. Low order current harmonics in the audible range, high core losses due to harmonic content and less switching losses. Control algorithms are relatively simple, easier to control (six trapezoidal states), better for lower speed and noisy [6-11].

Permanent magnet synchronous motor (PMSM) has high torque & power density, high efficiency, low noise, is considered for study. Brushless ac drives are mostly utilized than dc drives for EV applications. Rotor of PMSM is made using permanent magnet material (NdFeB). Advance DSP (2812) controller with inverter fed SPWM technique is used to control speed of PMSM in closed loop at different loads. PMSM has sinusoidal back e.m.f., continuous Stator flux position variation. Possible to have three phases ON at the same time, content no torque ripple at the commutation. Fewer harmonics due to sinusoidal excitation, less core losses and high switching losses at same switching frequency. Control algorithms are mathematically intensive, more complex control (continuous 3 phase sine wave), higher maximum achievable speed and low noisy [12-20].

Switched reluctance motor (SRM) has simple construction, high fault tolerance capability, reliability, low cost is considered for study. SRM has no winding or permanent magnet on rotor and it works on the principle of reluctance. The different pole configurations of SRM are 6/4, 8/6, 10/8, 12/10 etc. SRM with 8/6 or higher pole configuration gives minimum torque ripple. Advance DSP (28335) controller is utilized to control speed of SRM in closed loop at different loads [21-26].

Comparative analysis & capabilities of SRM, PMSM and BLDC motors are done for EV, EHV (Electric Hybrid Vehicles) applications, and SRM is better applicable than PMSM & BLDC motor [27]. The changes in the residual loss values of low emission vehicles in relation to conventionally powered ICEV (Internal Combustion Engine Vehicle), based on selected expert method are studied [28]. PMSM and SRM are compared with sizing, design equations for application in particular environment, PMSM can be smaller than SRM in the same value of speed and output power [29]. The study of five different types of drive train systems such as, SRM, induction motor, permanent magnet motor, dc motor & axial flux PMBLDC motor for EV application, and authors suggested axial flux PMBLDC motor drives as first choice for EV [30]. Author presented different driving techniques in urban conditions for plug in hybrid vehicles for economical aspects [31]. The dc motor, induction motor, SRM, PMSM and BLDC motors are studied for EV application, more priorities are given to PMSM and BLDC motors [32]. A review on electrical motor drive lines in all electric vehicles studied and authors proposed the adaption of a standardized drive cycle or other standardized methods of efficiency measurement [33]. The control strategies for optimal control of EV batteries during primary frequency regulation, comparing with V2G (vehicle-Grid) approach and battery degradation perspective are addressed [34]. Different electric motors for EV application compared on the basis of efficiency, power density, size and reliability, but effective at present is PMBLDC motor [35]. The characteristics of different motors, cost of controller and their comparison for EV application are discussed [36]. Authors described the current trends, future vehicle strategies and function of power electronic subsystem. The requirement of power electronic components and electric motor drives for successful development of vehicles are elaborated [37]. Authors has made comparative study of electric, hybrid and fuel cell vehicles, also merits of induction, PMSM, SRM and BLDC motor drives are reviewed. Methods for enhancing PM excitation, torque, reluctance torque components, improving torque and power capability are described [38]. A comprehensive study of EV, components, electrical machines, charging technologies, challenges, impacts and future direction of development is suggested [39]. In this paper design and simulation of SRM for EV application using ANSYS software is detailed [40]. Design and simulation of BLDC motor with outer rotor design using ANSYS software is considered for EV (scooter) application [41].

The comparison of two low-cost motors (SRM & induction motor) drive technologies for Asian electric scooter application are studied. Authors proposed the adaption of drive cycle, European urban driving cycle (ECE 15 driving cycle), Bangkok driving cycle, by conducting simulation study. The e-scooter ranges varied from 36 to 109 km depending on driving cycle, with expected driving range of 35 to 55 km in traffic [42]. Authors presented comparison of different motors (SRM, induction motor & interior permanent magnet motor) design drives for hybrid electric vehicles applications [43]. Authors described comparison of induction & PMSM drives for EV application including design examples. The three motors are compared in terms of energy consumption using NEDC (New European Driving Cycle), with interior permanent magnet synchronous motor having better overall performance [44]. Authors presented comparative study of interior permanent magnet synchronous motor, induction motor & SRM drives for EV & EHV applications using FEA (Finite Element Method), to meet performance & efficiency requirement simultaneously [45]. Authors described method to develop a new driving cycle for vehicles traveling on Bangkok's main roads during peak traffic hours & compared with presently used European driving cycle. The obtained driving cycle produce more realistic results of the emissions & fuel consumption assessment tests for vehicles traveling in Bangkok [46]. Author proposed the ARTEMIS (Assessment and Reliability of Transport Emission Models & Inventory System) European driving cycles for measuring car pollutant emissions [47].

The article focusses on applications such as small electric vehicles. The 1 h.p. capacity motors (BLDC at present) for bicycle/tricycle/scooter application are used, since the choice of the most appropriate type of electric motors for an EV is highly dependent on the power rating, constant power speed range and operating conditions of the electric vehicle. The interior permanent magnet motors and wound field motors are also often used in the drive of electric vehicles.

Finally, experimentation is done in laboratory on hardware setup of SRM, PMSM & BLDC motor drives at different loads. Reading data, all waveforms are recorded to find torque and efficiency of three motors & results are compared.

The novelty of the work is, more innovative and new work articulated. All 3 motors (SRM, PMSM & BLDC) with same power capacity i.e. 1 h.p. are tested with full load, efficiency & torque calculated from experimental measurements, using advance speed control technique. This is proper new practical platform for simultaneously implementation of choice of any one out of three motor drives, for EV application (bicycle/tricycle/scooter) in industry manufactures & EV application designers.

2. System Description

Figure 1 shows common block diagram of battery powered EV using PMSM, BLDC motor & SRM. The main components of EV are Battery, PMSM/BLDC motor/SRM and the vehicle. For batteries, the charging circuit is important to charge the battery. Battery output is connected to battery management system, which is further connected to charging input. As a result, the supply given to the controller and controller gives gate signal to the power converter. The controller block is introduced by the drive control signal.

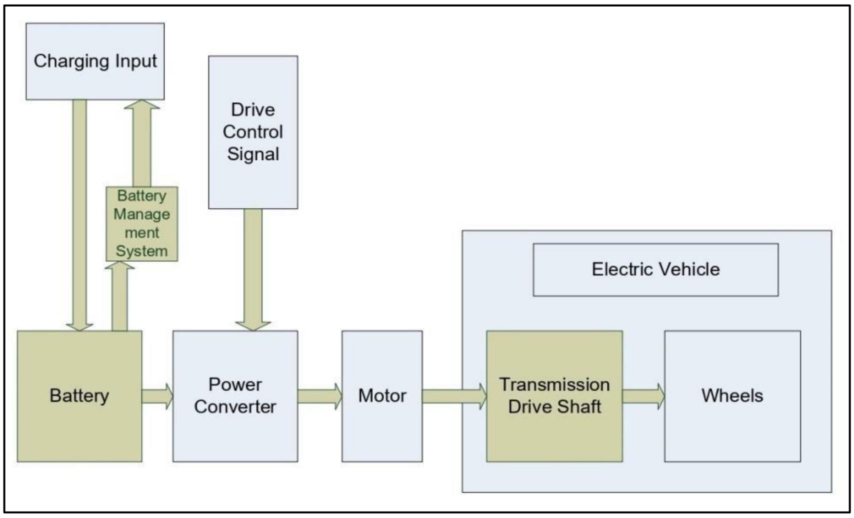

Fig 1. Common block diagram of an EV with Motor (SRM/PMSM/BLDC motor) drive control signal output is distributed to the power converter.

The battery output is also distributed to the power converter. Converter input is supplied to the PMSM/BLDC motor/SRM stator. EV models include drive axles and wheels. It is mechanical arrangement for vehicle. Transmission drive shaft & wheels are connected to the SRM/PMSM/BLDC motor by using chain sprocket. When motor gets energized, it starts to run & due to connection between motor & wheel, vehicle starts to move.

3. Experimental Performance of Motors

The aim of this experimental study is to compare performance of three different drives and motors of same capacity (1 h.p.) for EV application. The primary objective of braking mechanism applied in motors are to provide mechanical loading. Braking used for BLDC motor is prony type and eddy current dynamo for both PMSM & SRM. Also, purpose is solved to load fully upto rated current of all three motors. Motors tested at single speed, because it is in closed loop controlled drive, whatever speed is set (single value), after loading it will reduce, but controller will adjust it automatically to set speed. Hence, we can set any speed value, upto rated speed of that particular motor. Therefore, motors tested at a single speed. The 1 h.p. capacity motors (BLDC at present) for bicycle/tricycle/scooter application are used, since the choice of the most appropriate type of electric motors for an EV is highly dependent on the power rating, constant power speed range and operating conditions of the electric vehicle. The interior permanent magnet motors and wound field motors are also often used in the drive of electric vehicles.

The specifications & ratings for three motors under test are mentioned in table 1. All motor ratings are 1 h.p. power capacity.

The converter power module is utilized for all three motor drives along with feedback sensor QEP (Quadrature encoder pulse). The controller used are DSP 28335, DSP 2812 and FPGA for SRM, PMSM & BLDC motor drives respectively.

Table 1. Specifications of SRM, PMSM & BLDC Motor**.**

Sr.No.	Parameter	SRM	PMSM	BLDC
1	Power	1 H.P.	1 H.P.	1 H.P.
2	Voltage	310 dc Volt	310 dc Volt	310 dc Volt
3	Current	2.6 dc Amp	3.8 ac Amp	4.52 ac Amp
4	Speed	2000 rpm	4600 rpm	4600 rpm
5	Torque	2 N-m	3.4 N-m	2.2 N-m
6	Poles	S/R- 8/6	4	4
7	Type of Loading	Eddy current dynamo	Eddy current dynamo	Prony brake

3.1. PMSM

Figure 2 shows experimental setup of PMSM. It consists of converter power module, which is controlled by DSP-2812 controller. This experimental setup applied eddy current dynamo loading to check the performance of motor. The performance of motor is determined in closed loop system with speed is set at 2700 rpm.

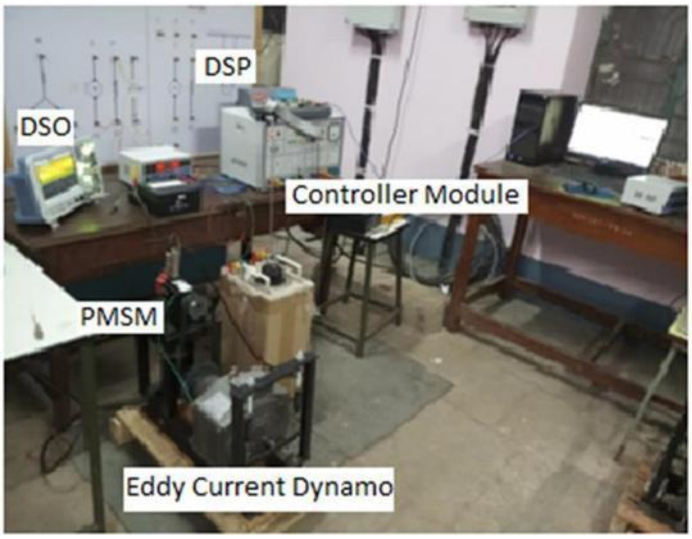

Fig 2. Experimental setup of PMS Motor**.**

The experimental results are mentioned in table 2. The motor torque varies up to 2.54 Nm and the motor current reaches to 3.8 Amp and speed is maintained constant at 2700 rpm. The efficiency of motor is calculated as 85.95 %. Initially, ac voltage is applied using three phase auto transformer to converter power module (cpm), load is minimum i.e. dc voltage and current (battery) zero, connected to eddy current dynamo. DSP controller is switched on to give pulses to power electronics switches (MOSFET) in cpm. Program is run in controller using code composer studio, by selecting closed loop operation mode. Then, load is increased in steps and experimental measurements are noted.

Table 2. PMSM performance results**.**

Sr.No.	Input Voltage		Input Current	Speed	Torque	Input power	Output power	Efficiency
	Volts (dc)	Volts (ac)	Amp (ac)	rpm	Nm	Watt	Watt	percentage
1	300	220	1	2700	0	220	0	0
2	300	220	1.45	2700	0.5651	319	159.69	50.06
3	300	220	2	2700	1.1301	440	319.36	72.58
4	300	220	2.5	2700	1.5539	550	439.13	79.84

5	300	220	3	2700	2.0483	660	578.84	87.70
6	300	220	3.5	2700	2.2602	770	638.73	82.95
7	300	220	3.8	2700	2.5427	836	718.56	85.95

Figure 3 shows, input current, pwm pulses, torque and dc voltage/current waveform recorded in DSO respectively for PMSM. Two DSO probes with 1:10 attenuation are used. In converter power module different output terminals are given for pulses, current, feedback sensor signals, etc. By connecting probes at proper terminal various waveform are captured and stored in DSO. The *x*-axis is time and *y*-axis is voltage. Voltage corresponds to current in current waveform or torque in torque waveform, as time is common in all waveforms.

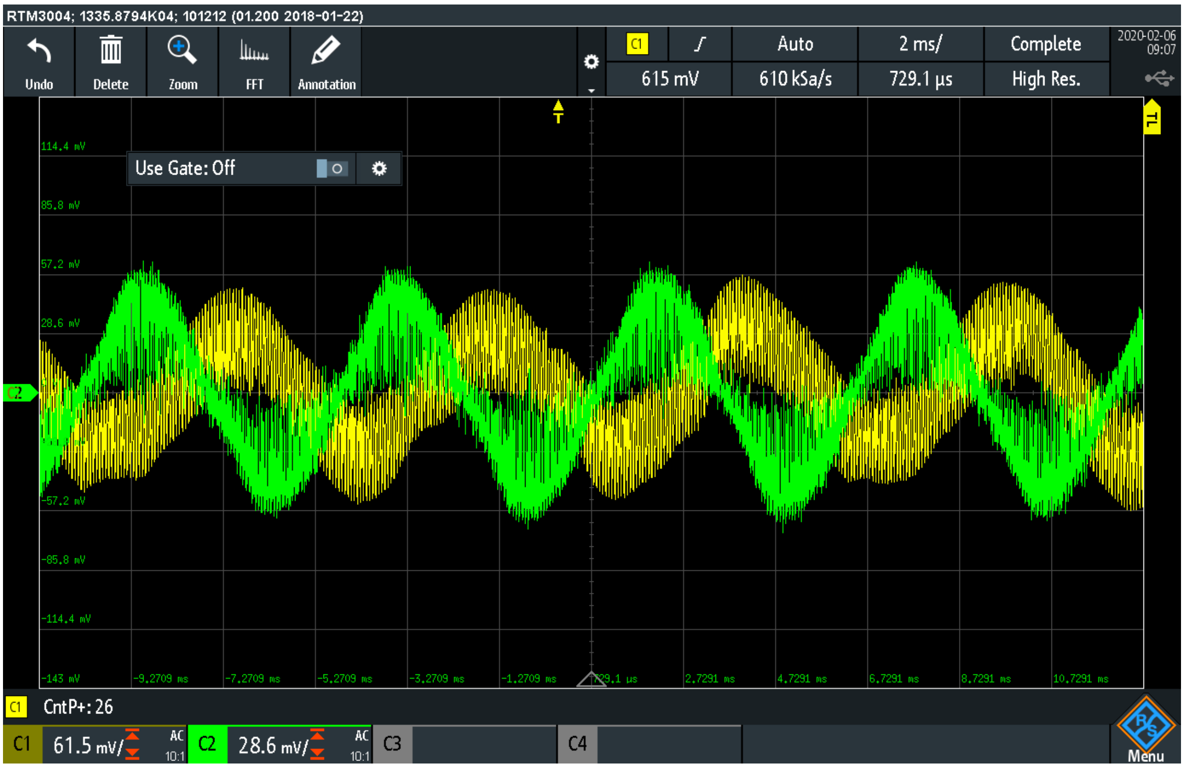

Fig 3. PMSM Experimental Parameters (a) Input Current.

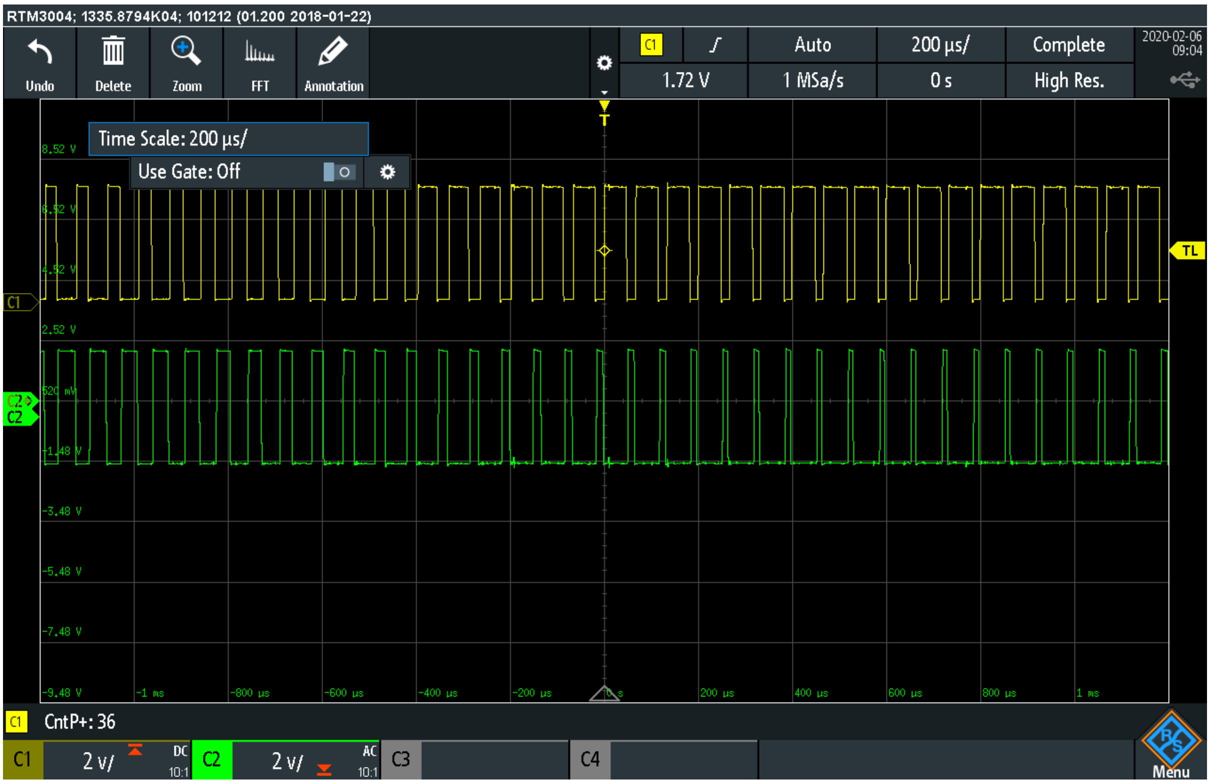

Fig 3. PMSM Experimental Parameters (b) PWM Pulses.

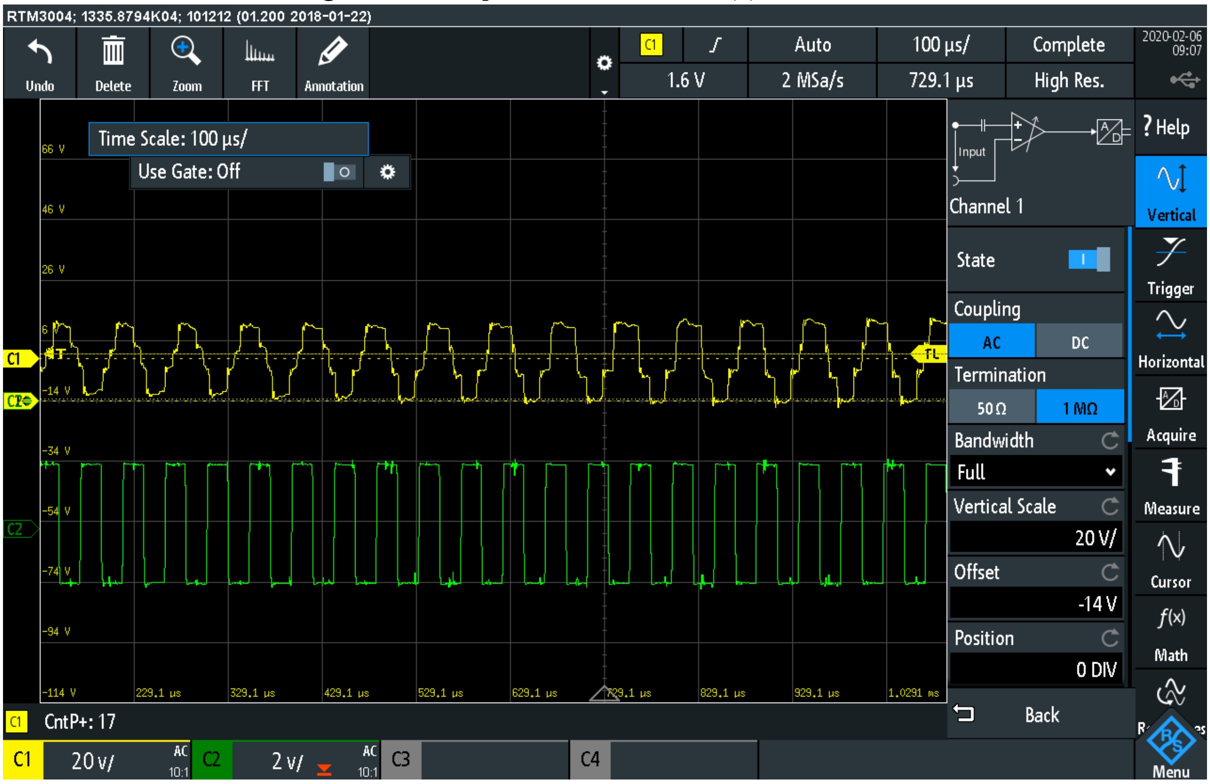

Fig 3. PMSM Experimental Parameters (c) Torque.

Fig 3. PMSM Experimental Parameters (d) V_{dc} & I_{dc} .

3.2. BLDC

Figure 4 shows experimental setup of BLDC. It consists of converter power module, FPGA controller, sensor feedback card. The closed feedback is made through hall sensor card and FPGA controller using field programmable gate array processor. The speed of the motor is fixed at 4000 rpm. The experimental results are mentioned in table 3. The motor torque varies up to 2.015 Nm and the motor current reaches to 4.52 Amp and speed is maintained constant at 4000 rpm. The efficiency of motor is calculated as 82.95%. Initially, ac voltage is applied using three phase auto transformer to converter power module (cpm), load is minimum i.e., in prony brake arrangement pully-belt is free. FPGA controller is switched on to give pulses to power electronics switches (MOSFET) in cpm. Program is run in controller, by selecting closed loop operation mode. Then, load is increased in steps and experimental measurements are noted.

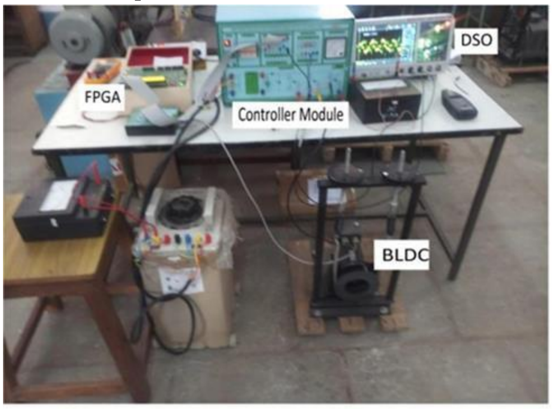

Fig 4. Experimental setup of BLDC Motor.

Table 3. BLDC performance results.

Sr. No.	Input Voltage		Input Current	Speed	Torque	Input power	Output power	Efficiency
	Volts (dc)	Volts (ac)	Amp (ac)	rpm	Nm	Watt	Watt	percentage
1	310	225	0.5	4000	0	112.5	0	0
2	310	225	0.9	4000	0.3099	202.5	129.74	64.06
3	310	225	1.5	4000	0.6199	337.5	259.53	76.89
4	310	225	2.1	4000	0.9299	472.5	389.32	82.39

5	310	225	2.5	4000	1.0849	562.5	454.21	80.75
6	310	225	3.2	4000	1.3949	720	583.99	81.11
7	310	225	4.52	4000	2.0149	1017	843.57	82.95

Figure 5 shows, current waveform, pwm/current, hall sensor/pwm, pwm pulses and dc voltage/current waveform using DSO respectively for BLDC. Two DSO probes with 1:10 attenuation are used. In converter power module different output terminals are given for pulses, current, feedback sensor signals, etc. By connecting probes at proper terminal various waveform are captured and stored in DSO. The *x*-axis is time and *y*-axis is voltage. Voltage corresponds to current in current waveform or torque in torque waveform, as time is common in all waveforms.

Fig 5. BLDC Experimental Parameters (a) Input Current (Ir & Iy) .

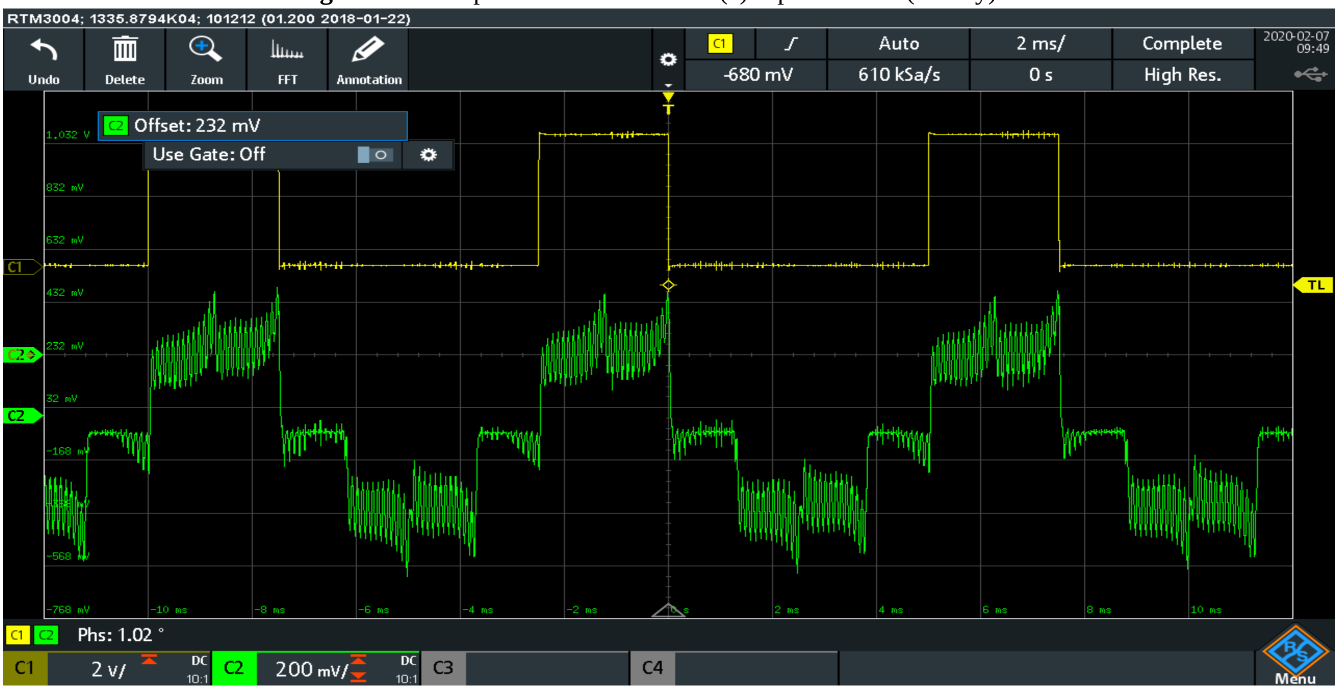

Fig 5. BLDC Experimental Parameters (b) PWM & Ir.

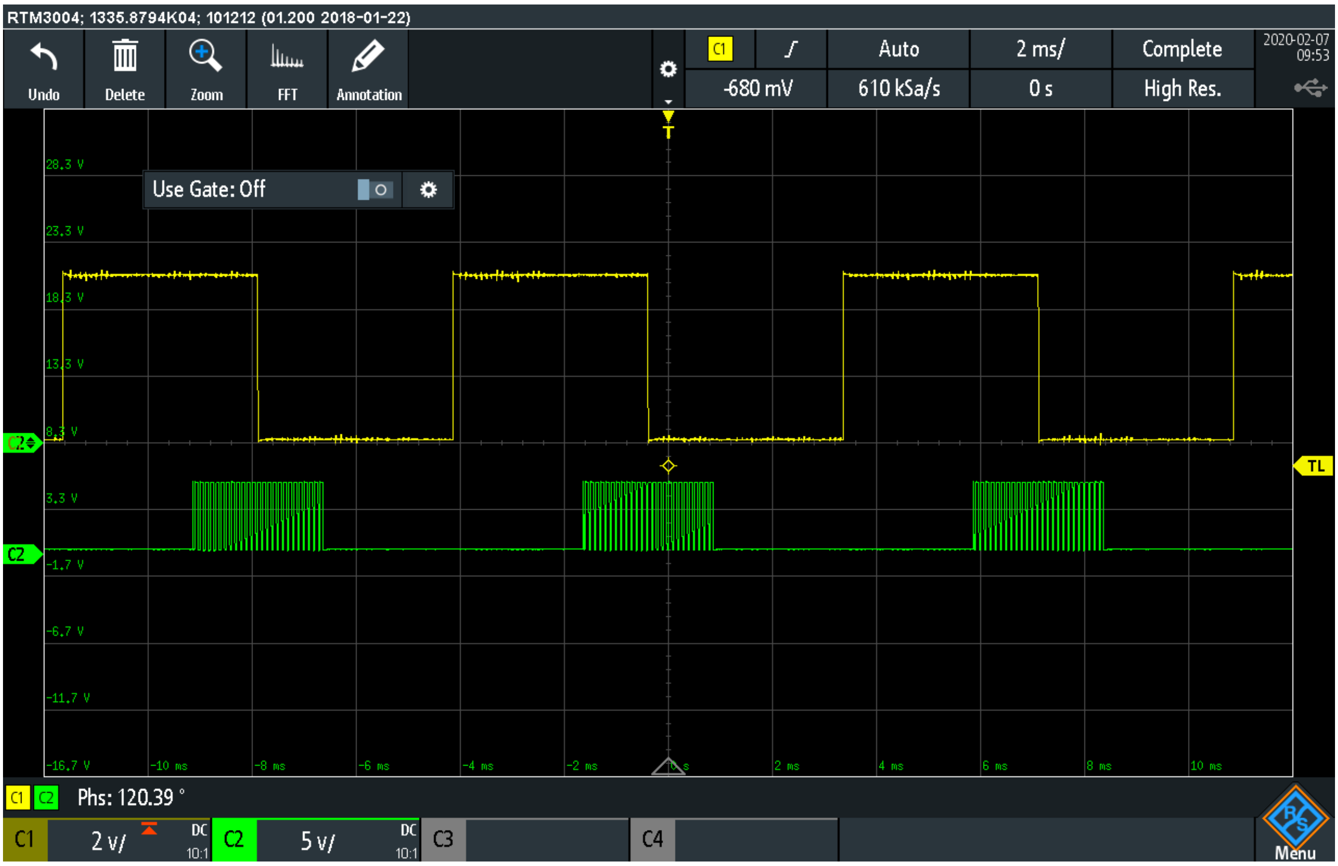

Fig 5. BLDC Experimental Parameters (c) Hall sensor & PWM.

Fig 5. BLDC Experimental Parameters (d) PWM Pulses.

Fig 5. BLDC Experimental Parameters (e) V_{dc} & I_{dc}

3.3. SRM

Figure 6 shows experimental setup of SRM. It consists of converter power module (intelligent power module), DSP-28335 controller, feedback sensor is used. The eddy current dynamo loading is applied. The speed of the motor is fixed at 2000 rpm. The pulses from processor are applied to inverter switches to match set & actual speed. Also, program is run in DSP (28335) controller using computer & code composer studio. The experimental results are mentioned in table 4. The motor torque varies up to 3.28 Nm and the motor current reaches to 2.6 amp and speed is maintained constant at 2000 rpm. The efficiency of motor is calculated as 87.97%. Initially, ac voltage is applied using single phase auto transformer to converter power module (cpm), load is minimum i.e. dc voltage and current (battery) zero, connected to eddy current dynamo. DSP controller is switched on to give pulses to power electronics switches (MOSFET) in cpm. Program is run in controller using code composer studio, by selecting closed loop operation mode. Then, load is increased in steps and experimental measurements are noted.

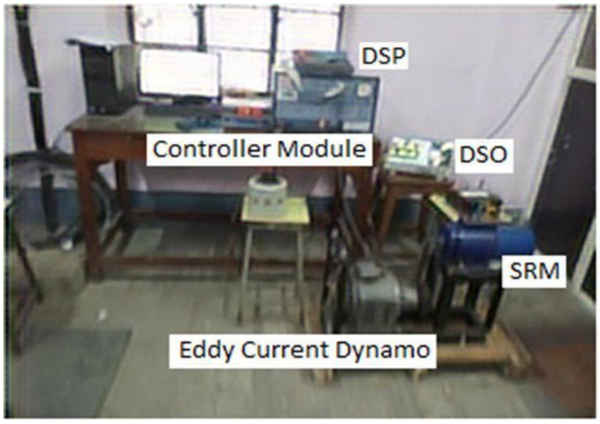

Fig 6. Experimental setup of SR Motor.

Table 4. SRM performance results.

Sr. No.	Input Voltage		Input Current	Speed	Torque	Input power	Output power	Efficiency
	Volts (dc)	Volts (ac)	Amp (dc)	rpm	Nm	Watt	Watt	percentage

1	300	230	1.6	2000	0	480	0	0
2	300	230	1.8	2000	1.1230	540	235.08	43.53
3	300	230	2	2000	1.9007	600	397.88	66.31
4	300	230	2.3	2000	2.8479	690	596.16	86.40
5	300	230	2.6	2000	3.2780	780	686.19	87.97

Figure 7 shows, current, pwm pulses, torque, pwm & id waveform using DSO respectively for SRM. Two DSO probes with 1:10 attenuation are used. In converter power module different output terminals are given for pulses, current, feedback sensor signals, etc. By connecting probes at proper terminal various waveform are captured and stored in DSO. The *x*-axis is time and *y*-axis is voltage. Voltage corresponds to current in current waveform or torque in torque waveform, as time is common in all waveforms.

Fig 7. SRM Experimental Parameters (a) Input Current (Ia & Ib).

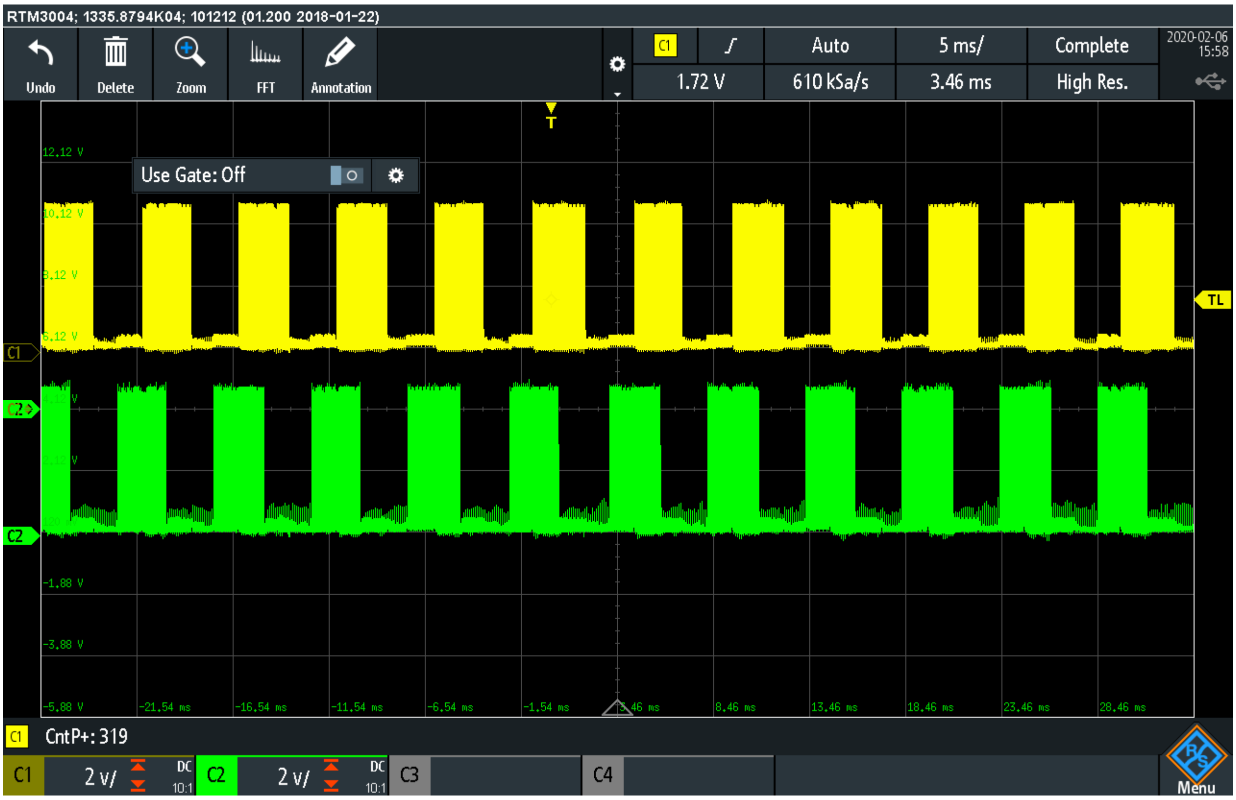

Fig 7. SRM Experimental Parameters (b) PWM pulses.

Fig 7. SRM Experimental Parameters (c) Torque**.**

Fig 7. SRM Experimental Parameters (d) PWM & I_d.

4. Result & Discussion

All three motors are tested in laboratory. Experimental data used to calculate torque & efficiency from no load to full load conditions. Advanced speed control methods are adopted using DSP & FPGA controllers for SRM, PMSM & BLDC drives respectively. Advanced speed control testing results (gate pulses, feedback signals, stator current, torque/speed, all waveform at different loading conditions), of closed loop operation of drives at set speed, obtained are satisfactory. Figure 8 shows performance of all three motors. It is found that, maximum torque of SRM, PMSM & BLDC motor is 3.2780, 2.5427 & 2.0149 Nm respectively at their respective speed 2000 rpm, 2700 rpm & 4000 rpm. The efficiencies of SRM, PMSM & BLDC motor are 87.97 %, 87.70 % & 82.95 % respectively. It is found that SRM have higher efficiency 87.97 % (but higher than PMSM & BLDC motor) & increasing torque with greater speed capability, low maintenance, slightly higher noise compared to PMSM & BLDC motors & good performance at higher speed. Torque of SRM is 3.2780 Nm. It is observed that PMSM have higher efficiency 87.70 % (higher than BLDC motor & lower than SRM) & increasing torque, greater speed capabilities, low maintenance, spark less operation, low noise and good performance at higher speed. Torque of PMSM is 2.5427 Nm. The BLDC motor efficiency also high 82.95 % (lower than SRM &PMSM) & increasing torque, higher performance, greater speed, low noise and low maintenance. Torque of BLDC motor is 2.0149 Nm.

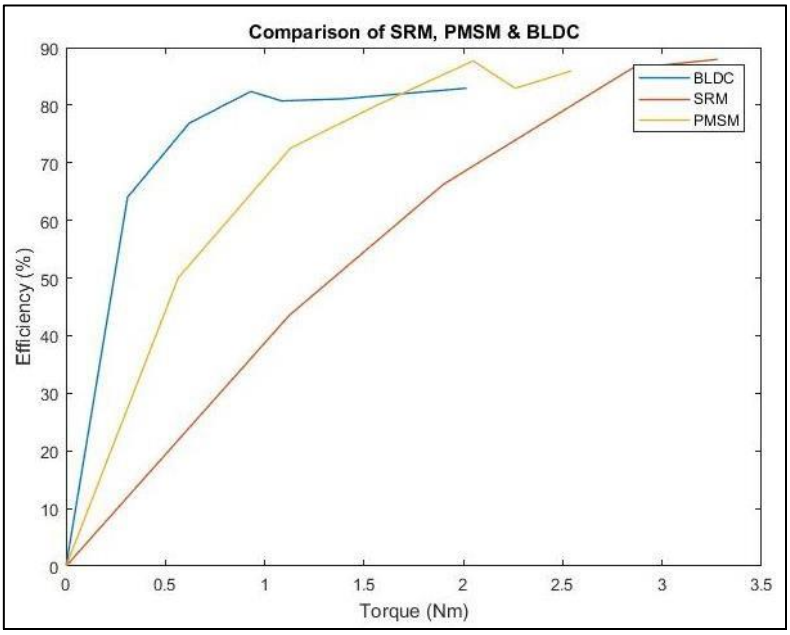

Fig 8. Torque vs. Efficiency for SRM, PMSM & BLDC Motor.

The aim of this experimental study is to compare performance of three different drives and motors of same capacity (1 h.p.) for EV application. The primary objective of braking mechanism applied in motors are to provide mechanical loading. Braking used for BLDC motor is prony type and eddy current dynamo for both PMSM & SRM. Also, purpose is solved to load fully upto rated current of all three motors. Motors tested at single speed, because it is in closed loop controlled drive, whatever speed is set (single value), after loading it will reduce, but controller will adjust it automatically to set speed. Hence, we can set any speed value, upto rated speed of that particular motor. Therefore, motors tested at a single speed. All three motors (SRM, PMSM & BLDC) are of same power capacity i.e. 1 h.p. for performance comparison is considered. The 1 h.p. capacity motors (BLDC at present) for bicycle/tricycle/scooter application are used, since the choice of the most appropriate type of electric motors for an EV is highly dependent on the power rating, constant power speed range and operating conditions of the electric vehicle. The interior permanent magnet motors and wound field motors are also often used in the drive of electric vehicles. Most of the other authors proposed the adaption of drive cycles (European urban driving cycle, ECE 15 driving cycle, Bangkok driving cycle, New European Driving Cycle) to find the performance for EV application.

5. Conclusion

This paper presented comparative study of SRM, PMSM & BLDC motor drives using advance speed controller techniques via experimentation in laboratory for EV application. The torque of all three motors i.e. SRM, PMSM & BLDC motor increasing from no load to full load conditions. BLDC motor has high performance utilization in electric vehicle applications now days. However, PMSM has high power density & high starting torque, because of permanent magnets on rotor and its efficiency is better than BLDC motor. Large size of EV application now prefers the PMSM. SRM can be utilized for very high speed EV. The noise and torque ripple restricted the application but this can be avoided by using the sound proof enclosures. The article focusses on applications such as small electric vehicles. The 1 h.p. capacity motors (BLDC motor at present) for bicycle/tricycle/scooter application are used. There is also scope of SRM & PMSM for small EV application. Thus novelty of the work has been proved and more innovative and new work articulated. This is proper new practical platform for simultaneously implementation of choice of any one out of three motor drives, for EV application (bicycle/tricycle/scooter) in industry manufactures & EV application designers.

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