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Efficiency Improvement of Electric Vehicles by Using Winding-Less Rotor-Based DC Motor

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Abstract: **In electric vehicles (EVs), efficient energy consumption is very important. Based on demand, the manufacturers employ different electric motor technologies and are still evolving. The major drawback of the motors includes power losses in the armature windings that reduce the overall efficiency and run per charge of EV due to additional power consumption from the battery pack. To overcome these losses, the authors have proposed winding-less rotor-based DC motor in EVs application that is more efficient as the windings from the rotor have been replaced by permanent magnets. Therefore, the power losses in armature windings have been eliminated and reduced the power consumption of the motor from the battery pack. The run per charge and the overall efficiency of EV have been increased to 90% by the proposed motor as depicted in the results section of the paper. Moreover, the authors also assessed the electric motors utilized in electric vehicles by the different manufacturer such as DC motor, AC induction motor, Brushless DC (BLDC) motor, permanent magnet synchronous motor (PMSM), switched reluctance motor (SRM), and permanent magnet synchronous reluctance motor (PM-SynRM). The benefits and drawbacks linked to traction motors are pointed out. Finally, conclusions have been made on the traction motors used in the proposed EV model.**

Keywords: **battery pack, efficiency, electric vehicles, electric motors.**

I. INTRODUCTION

Electric Vehicles (EVs) use electric traction motors and are powered up using the electrical energy stored in the battery pack. In EVs, the traction motor gets power from the battery and converts it into mechanical power that drives the wheels through an appropriate transmission system [1]. EVs do not relay on fossil fuels and have battery storages systems. EVs are environmentally friendly and eliminate the need for high-cost fuels such as petrol, and diesel [2]. EVs use AC or DC motors depend on their demand and requirement and are made consistently. Scientists are, however, to deal with their enhancements [3]. Different types of EVs are available in the market such as Hybrid Electric Vehicles (HEVs) and Battery Electric vehicles (BEVs). These EVs use different types of electric motors including Brushless DC motors (BLDC), AC induction motors, and Permanent Magnet Synchronous Motors (PMSM) [4] and have benefits and drawbacks. EVs have been re-energized over the last decades while the motor drive technologies are still in the process of evolution, and their repairing and testing are currently more complex. EV applications require superior efficiency, high torque density, high consistency, and extensive speed range while reducing weight, complexity, total costs, and environmental impact [5]. Many researchers are still working on the enhancement of motor drive technologies used in EVs. To unwind a suitable relationship among all the motors used in electric vehicles, research on this field is indicated again and again. In [6], the authors concluded that manufacturers widely used permanent magnet motors for the traction of electric vehicles and have a high-power density and high specific power. They suggested that in the future the Switched Reluctance, Synchronous Reluctant, and Permanent Magnet motors have been preferred. Later, based on the properties of the traction motors used in EVs, the authors in [7], revealed their calculations by concluding that in the absence of PMSMs, induction motors would be preferred, while induction motors have high dynamic efficiency than that of PMSMs. In [8], the authors investigated BLDC motors due to its extensive operating life, improved torque-speed, high efficiencies, and faster dynamic response. A comparison was made based on electromagnetic performances between the Interior Permanent Magnet Synchronous Motor (PMSM) and Permanent Magnet Assisted Synchronous Reluctance Motor (PMASynRM). The PMASynRM has a high efficiency at high-speed operations, while IPMSM dominates at low-speed operations for the urban drive cycle. However, in perspective of temperature factor, interior PMSM has advantages over the performance of PMASynRM due to its limited range [9].

Depending on the requirements, different EVs use various numbers of motors such as the Toyota Prius used two while Acura NSX used three motors, the choice depends on the function that an EVs are supposed to provide [10]. EVs demand high torque, high power density, high efficiency, reliability, cost effective, less noise, and small size [11]. These requirements are being met by different motors which include DC motors, AC induction motors, and BLDC, although when it comes to the power electronics and control system, interior PMSM and PMASynRM are being most preferred due to superior dynamic performance, low torque ripple, and high power density [12]. Depending upon the type of EV DC motors such as shunt and series, PMSMs, BLDC motors and Squirrel Cage Induction Motors are utilized. While considering other types of motors the Reluctance Motors have been studied for commercial accessibility [13]. A general description of all these motors used by the manufacturer is discussed in Table I. From published literature on the kinds of motors employed in EVs, the authors examined that all the motors have unique specification that make them appropriate for traction purposes however, despite these benefits, motors

TABLE I. DESCRIPTIONS OF MOTORS USED BY DIFFERENT MANUFACTURERS

Ref	**Manufactures**	**Models**	**DC Motor (Brushed)**	**AC Induction Motor**	**DC (Brushless) Motor**	**PMSynRM**	**PMSM**
[14]	Toyota	Prius			✓		✓
		RAV4		✓			
[15]	Tesla	Model S		✓			✓
		Model X		✓			
		Model 3		✓		✓	
		Model Y		✓		✓	
[16]	Nissan	Nissan Leaf					✓
[17]	Porsche	Taycan					✓
[18]	Audi	E-tron		✓			
[19]	BMW	I3		✓		✓	
		Mini E		✓			
[20]	General Motors	GM EV1		✓			
[21]	Fiat Panda	Elettra	✓				
[22]	Kia	Soul EV					✓
		Nitro EV					✓
	Ather Energy	Ather 450X			✓		

possess some key and serious concerns that make the manufacturer think about them before installing the motor in the EVs. Some of the major concerns noticed in motors include copper losses, more power dissipation, volume and weight issues, smooth torque issues, constant speed and power characteristics issues, maintenance cost, and control ability issues.

In this paper, the authors proposed an EVs electric motor system model that is more efficient in comparison with existing models, as the windings from the rotor have been replaced by permanent magnets. Therefore, the power losses in armature windings have been eliminated and reduced the power consumption of the motor from the battery pack. The run per charge and the overall efficiency of EV have been increased to 90% by the proposed system as presented in the results section of the paper. Moreover, motor switching circuit has been designed that switch the magnet poles resulting in rotor conductors interlocking with the stator conductor and refusing to move. The stator has two phase windings, each of which creates an alternative polarity on both sides of the stator, and the rotor starts to rotate. The authors also discussed different types of electric motors utilized in EVs. Besides, this paper also give a quick look at the efficiencies of various motors, battery packs utilized in EVs, and the efficiencies of the battery packs run per charge. The proposed model provides an assessment of electrical motor drive innovations utilized in EV applications and their characteristics.

II. SYSTEM MODEL AND WORKING

The block diagram of the proposed system is presented in Fig. 1. The model consists of dc source, switching circuit, stator, relay, and permanent magnet rotor. The authors have designed a 12V 4-pole Winding-less rotor-based DC motor whose stator has field winding same as simple DC motor, while rotor is based on permanent magnets that is placed inside the stator. When 12V are applied to the motor, the stator winding get energized and generates a magnetic field correspond to magnetic field generated by North and South poles. The magnetic field generated in the stator interacts with the field of the rotor and generates a torque that creates a force. During this control, the rotor's magnetic poles get stuck with the stator winding poles. In typical motors this problem is solved by using commutators. However, in proposed work, the rotor has PMs therefore, the permanent poles are created by the permanent magnetic field and did not change. For the smooth operation of the motor, the magnetic field of stator needs to be changed, which is done by switching circuit using an Arduino and a relay control mechanism. The entire switching architecture of the proposed system is shown in Fig. 2.

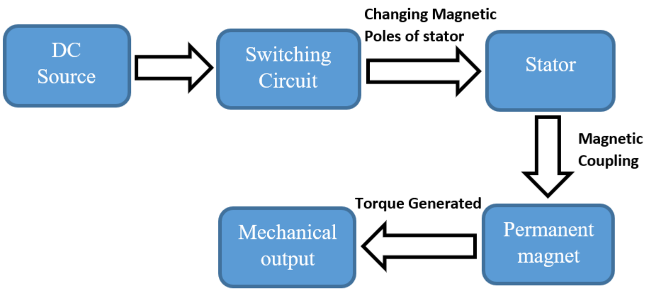

Fig. 1. Block Diagram of Proposed System

The stator is designed with 2 and 4 poles windings. In 4 pole winding, 26-gauge dc wire is used. The stator body is built of iron sheets. The stator consists of 24 slots with a distinction of 4 and 2. In slot change 4, 190 number of turns of coil passing across the slot. While in slot difference 2, the passing number of turns of coil is 180. Fig. 3 displays the 4-pole winding stator. The surface permanent magnetic (SPM)

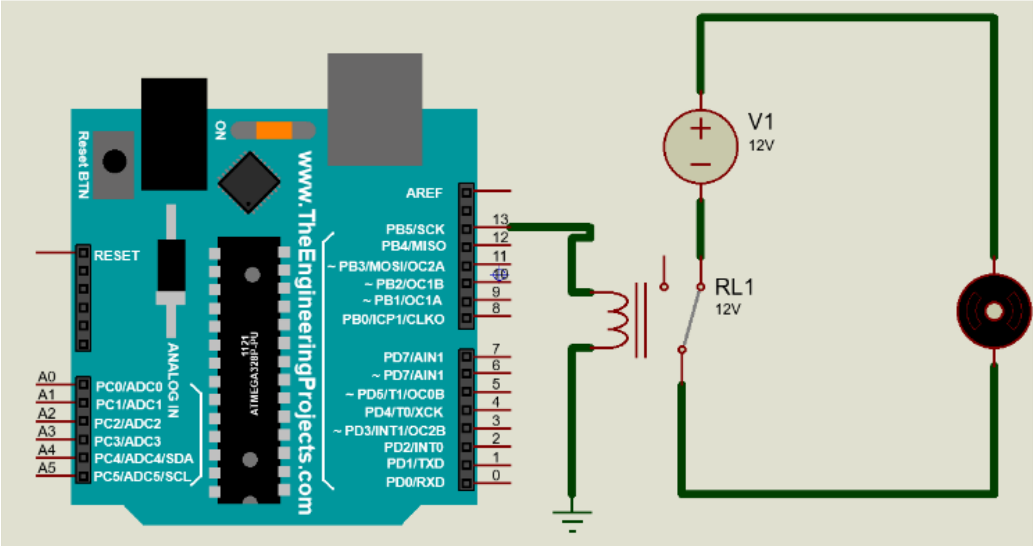

Fig. 2. Switching architecture of proposed system

motor is utilized in which the permanent magnet is equipped over the rotor. The permanent magnet area of one piece is 6cm. The length and diameter of the rotor is 6.5cm and 4cm, respectively. The rotor diameter is 5.2cm after mounting the permanent magnet. While permanent magnet thickness is 1.7cm. Fig. 4 illustrates the permanent magnet rotor.

Fig. 3. 4-pole winding stator

Fig. 4.Permanent magnet-based rotor

The designed system model winding-less rotor-based DC motor is powered up by the battery pack installed on the electric vehicle and needs to be charged and discharged continuously depending upon the time it runs. The charging and discharging cycles play a fundamental role in determining the efficiency of a battery [23], as lower the charge and discharge rates, the better is the efficiency [24]. There are several battery models used for powering purposes, although the Lithium-ion battery shows optimum performance due to its high energy density, more lifetime, and efficiency. The charging and discharging equation of battery pack along with state of charge (SOC) are given below [25]

$$E_{charge} = E_o - K\frac{Q}{Q-I_t}I_t - K\frac{Q}{Q-I_t}I^* + A.e^{(-B.I_t)} \quad (1)$$

$$E_{dischar} = E_o - K\frac{Q}{0.1Q+I_t}I_t - K\frac{Q}{Q-I_t}I^* + A.e^{(-B.I_t)} \quad (2)$$

$$SOC = \frac{Q(t)}{Q_{Max}}100 \quad (3)$$

$$Q(t) = Q(0) - \int_0^t \eta_b I_b d_t \quad (4)$$

Where E_o, K, Q, I_t, A, B, I^*, I_b, η_b, E_{charge}, $E_{dischar}$ represents the constant voltage, polarization constant, extracted capacity, maximum current capacity, exponential zone voltage, exponential zone time constant, low frequency current, battery current, battery efficiency, battery charging, and battery discharging, respectively.

III. RESULTS AND DISCUSSIONS

In this part, the proposed EV system is discussed theoretically and practically. DC series and shunt motors are mostly used in EVs and contain armature windings along with field winding that results in huge power losses. However, the proposed motor design does not have armature winding, no power losses, and is more effective.

A. Theoretically

Fig. 5 and Fig. 6 show the circuit diagrams of DC series and DC shunt motors [26], respectively. For the series DC motor, the armature winding circuit and power equations are given by (5), (6), and (7) [27]

$$V = E + I_a(R_a + R_s) \quad (5)$$

$$P_{out} = P_{in} - P_{losses} \quad (6)$$

$$P_{out} = VI - I^2 R_a - I^2 R_s \quad (7)$$

For the shunt DC motor, the armature winding circuit and power equations are given by (8), (9), and (10) [28]

$$V = E + I_a R_a \quad (8)$$

$$P_{out} = P_{in} - P_{losses} \quad (9)$$

$$P_{out} = VI - I_a^2 R_a - I_{sh}^2 R_{sh} \quad (10)$$

Eq. (7) and (10) shows the output power of the DC motor, comprised of input power with the subtraction of power losses appear in armature and the field winding of DC motor. Where V, I, I_a, I_{sh}, R_s, R_{sh} represents supply voltage and current, armature current, shunt field current, series resistance, and shunt field resistance, respectively. In both equations, the armature losses contribute to the total power losses and decrease the output power and therefore, decreases the efficiency of motor. In the proposed motor design, the rotor is made up of permanent magnets having no armature winding, which results in zero power losses occurring in the armature, therefore I^2R_a losses are eliminated, therefore (7) and (10) can be rewritten as [29]

$$P_{out} = VI - I^2 R_s \quad (11)$$

$$P_{out} = VI - I_{sh}^2 R_{sh} \quad (12)$$

This result clearly shows that the output power of the proposed designed electric motor is greater than the typical DC motor in terms of maximum efficiency.

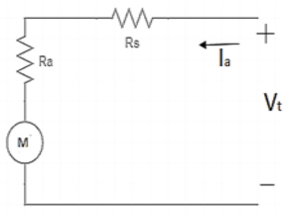

Fig. 5. Series Motor Equivalent Circuit

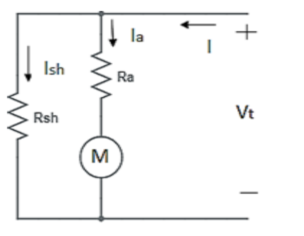

Fig. 6. Shunt Motor Equivalent Circuit

B. MATLAB Simulation

In this section, the graphical representations of the results taken by running MATLAB code are discussed. The shunt DC motor parameters are listed in Table II. Fig. 7 presents the relationship between the armature current and total losses. With the increase in armature current, armature losses are increases that cause a heating effect in the winding of the motor and reduce the motor life and a chance to burn. While Fig. 8 presents the relationship between the armature current and efficiency. The increase in armature current decreases the overall efficiency of a typical DC motor up to 92%, raises the armature losses, and decreases the output of the motor making motor less efficient.

TABLE II. DC SHUNT MOTOR LOSSES AND EFFICIENCY

Symbols	Parameters	Values
V_t	Applied Voltage	240V
R_{sh}	Shunt Field Resistance	100Ω
R_a	Armature Resistance	10Ω

In the proposed motor design, the permanent magnets are used instead of winding, therefore armature winding is negligible, and R_a equals 0ohms, while other parameters remain the same. Fig. 9 implies with the increase in armature current, the losses become constant because of its better constant shunt field resistance. While the load current and the armature current are varying. An increase in armature current increases the output power, therefore the constant losses lead to the maximum output. The efficiency corresponds to the armature current is shown in Fig. 10. The specifications of the proposed motor are listed in Table V.

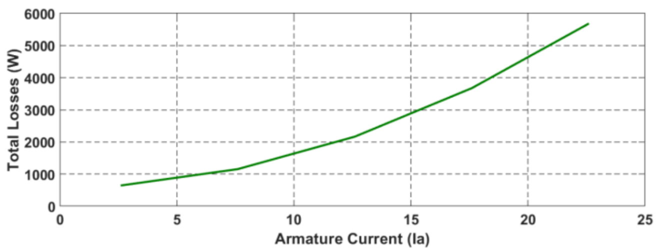

Fig. 7. Typical DC Motor Armature Current Vs Losses

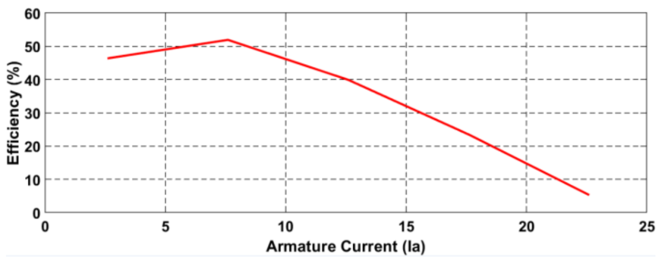

Fig. 8. Typical DC Motor Armature Current Vs Efficiency

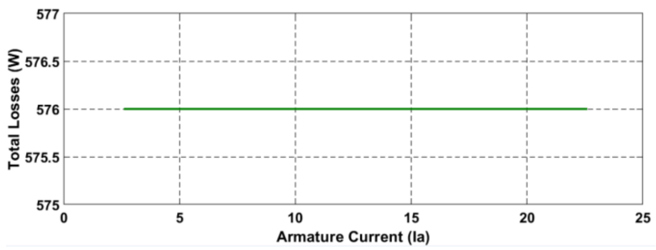

Fig. 9. Proposed DC Motor Armature Current Vs Losses

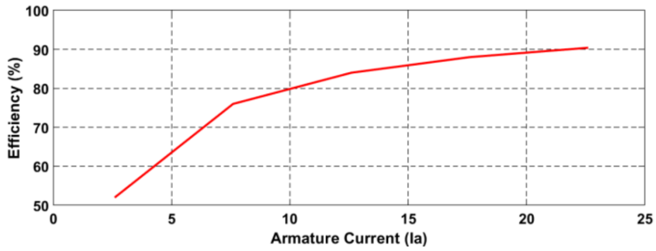

Fig. 10. Proposed DC Motor Armature Current Vs Efficiency

TABLE III. DC SHUNT MOTOR LOSSES AND EFFICIENCY

Resistances (Ω)		Rated Voltages (V)		Currents (A)		Losses (W)		Input Output Power (W)		Efficiency (%)
R_{sh}	R_a	V_t	I_t	I_{sh}	I_a	S_{FL}	A_L	P_{in}	P_{out}	
40	10	88	5	2.2	2.8	193.6	78.4	440	168	38.18
40	10	88	7	2.2	4.8	193.6	230.4	616	192	31.16
40	10	88	9	2.2	6.8	193.6	468.4	792	130	16.4
40	10	88	10	2.2	7.8	193.6	608.4	880	78.4	8.9

TABLE IV. PROPOSED MOTOR LOSSES AND EFFICIENCY

Resistances (Ω)		Rated Voltages (V)		Currents (A)		Losses (W)		Input Output Power (W)		Efficiency (%)
R_{sh}	R_a	V_t	I_t	I_{sh}	I_a	S_{FL}	A_L	P_{in}	P_{out}	
40	0	88	5	2.2	2.8	193.6	0	440	247	56.13
40	0	88	7	2.2	4.8	193.6	0	616	423	68.8
40	0	88	9	2.2	6.8	193.6	0	792	599	75.5
40	0	88	10	2.2	7.8	193.6	0	880	678	77.0
40	0	88	12	2.2	9.8	193.6	0	1056	862.4	81.7

C. Hardware Implementation

To verify the claim of efficiency improvement using winding less rotor-based DC motor, the authors implemented both designed as well as typical DC motor. The authors run the EV on both motors independently and calculate the time taken by the motors to consume a fully charged DC battery. The proposed motor consumed less power in real time as compared to a typical DC motor can be seen in Table IV, therefore the battery life of the battery pack in the electric vehicle has been increased. The designed motor has permanent magnets on rotor instead of winding, and solved the issues regarding magnet slots, magnet placements and switching circuits.

TABLE V. SPECIFICATIONS OF DESIGNED MOTOR

Parameters	Values
Rated Voltage	88V
Rated Current	2.2A
Resistance	38.4 Ω
Speed	1200 RPM
Power	200W
kV Rating	341kV
No Load Torque	28.046(nNM/A)

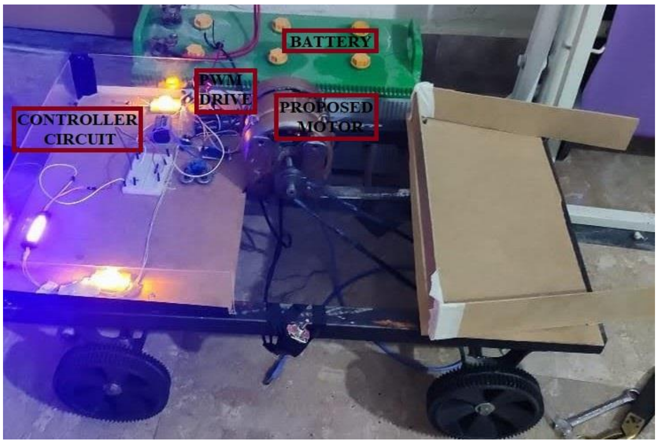

Fig. 9. Practical Hardware Design of Proposed Model

Fig. 9 reveals the practical hardware design of the proposed motor in EVs application. The proposed model is realized using a 12V battery power to the motor. The proposed motor run on 1200 rpm, and the motor terminals have connected with the battery and the driving circuit. The driving circuit is based on the PWM technique that generates the alternate poles on the stator of the motor that result in rotation of the rotor. The authors calculated the losses that occur in the armature winding of a typical DC motor and compared it with proposed winding-less rotor-based DC motor. The assessment of losses and efficiency has been made based on the motor's equation, and the findings are demonstrated in Table III and Table IV, respectively.

IV. CONCLUSION

In this paper, the authors have proposed a winding-less rotor-based DC motor in EVs application that is more efficient as the windings from the rotor have been replaced by permanent magnets. The existing motors used by the manufacturers such as DC motor, BLDC, AC induction motor, PMSM, SRM, and PM-SynRM have some common problem of power loss that reduces the overall efficiency of the EVs. In the proposed motor, by employing the permanent magnets on the rotor, the armature power losses are reduced, and the overall efficiency of EVs is increased to 90% as compared to a typical DC motor. As a result, less power consumption by the motor from the battery pack increases the run per charge of the EVs. Moreover, the lifetime of the permanent magnet is far higher, and it does not require any maintenance that makes them cost-efficient as well. The authors compared the proposed motor with an existing typical DC motor in terms of losses and efficiency verified by mathematical real-time estimations, MATLAB simulation, and hardware validation. The results show that the EV efficiency was improved, and the armature losses were minimized by using the proposed winding-less rotor-based DC motor. For future applications, EVs manufacturers could use the proposed EV system for real-time verification purposes.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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