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Technology and Key Strategy of IE4 Permanent Magnet Brushless DC Motor Drive for Electric Vehicle Application

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ABSTRACT: Environmental protection and energy conservations are the main concern of 21st century Asia Pacific developing countries. This concern has compelled to design and develop zero pollution road transportation Electric Vehicles (EVs). The EV system consist of energy storage devices such as battery, fuel cell, ultra-capacitors along with electric propulsion, body of the vehicle and energy management system with the diversified technology of electrical, electronics, mechanical, automotive and chemical engineering. The objective of electric vehicle is to produce commercial viable range, efficient performance, and comfort with safety and reliable operations at cheaper price than its counterpart the Internal Combustion Engine Vehicle (ICEV). The PMBLDC motors are the present choice of automobile industries and researchers because of its high power density, compact size, reliability, with noise free and minimum maintenance requirements. The present state of art Permanent Magnet Brushless DC (PMBLDC) Motor drive for the electric vehicle application is studied / reviewed in this paper.. In addition the study also reveals the advancement of the Power Processing Unit (PPU) which consists of Microelectronics and Controls (Me and C) to produce the super-premium efficiency PMBLDC drive system for EV applications.
Keywords: PMBLDC motor drive; Fuel cell; Power Processing Unit, Microelectronics and control.

I. INTRODUCTION

For the Asia Pacific developing countries 21st century is an environmental protection century. Electric Vehicles were available in the 19th century till about 1918 [1-10]. Since then, because of the development and viable of ICE, the use electric vehicle for transportation was reduced to nil. But, present factors like environmental pollution problems, shortage of petroleum products and its sharp rise in cost along with energy independence has encouraged to reorganize the electric vehicles as an alternative mode of transportation. In the past decades Direct Current (DC) and Alternating Current (AC) variable speed drives were commonly used for electric vehicle applications. But in this 21st century because of the availability of high quality rare earth permanent magnet materials like samarium cobalt (Sm-Co) and Neodymium-Iron-Boron (Nd-Fe-B), the development of PMBLDC motor drives has become highly attractive for EV applications. In addition because of the advancement of microelectronics and control systems the PMBLDC drives has become has more reliable and categorized in to IE4 efficiency (super premium efficiency) classification.

II. GENERAL SURVEY

Asia pacific environment: The current Asia Pacific environment related to Electric Vehicle (EV) development can be summarized as below [11]:

- Swift trade and industry development
- Plentiful natural resources
- Low-priced labor
- Less industry
- Practical performance requirement
- Less constraints for new infrastructure
- Major electricity comes from relatively clean sources

Hence, EVs also provide additional new transportation system along with replacement of conventional ICE vehicles [12-17]. From environment aspect, EV provide zero emission transportation and from energy point of view it is ecofriendly and efficient because it offers secure, comprehensive and energy balance spectrum. From transportation point of view, EVs provide intelligent transportation system that will improve road utilization and safety. The motor required for Electric scooter applications should be compact, small axial length, less weight with high efficiency. The aerodynamic drag, tractive force of the load, i.e. the road should be overcome by the torque developed by PMBLDC motor propulsion. Higher motor driving current is the major limitation of the PMBLDC motor.

International Energy (IE) Standard:

The increase in electric motor efficiency contributes to the worldwide energy savings. To make this possible International Electrotechnical Commission (IEC) has made International Energy (IE) to develop the standards and performance of the motor drives [18-19]. The main concern of IE standards is efficiency which can be categorized as

- IE 1 (standard efficiency)
- IE 2 (high efficiency)
- IE 3 (premium efficiency)
- IE 4 (super premium efficiency)
- IE 5 (ultra-premium efficiency)

Currently this classification run from IE 1 to IE 4, but at present stage IE 3 is made mandatory in some countries so that performance can be increased. IE 4 standard is still not legally applied, but the regulation and specification are defined. The manufacturers use IE 4 as the readiness for implementation. The IE standards are already designed for the motor ranging from 0.75kW to 375 kW, within which the motor of 7.5kW to 375kW mandatory rule for some application is made to follow from 2015 and for low power from 0.75kW is 2017. With the up gradation to IE 4 standards efficiency can be brought up for the machines of 120W to 500kW.

Comparison between electric vehicle and conventional vehicle [20]:

TABLE I: Comparison between electric vehicle and conventional vehicle

Feature	Electric vehicle	IC Engine vehicle
Prime mover	Electric motor	IC Engine
Powered Source	Charged battery, Ultra capacitor Fuel Cell	Diesel, Petrol
Self-weight	High	Low
Transmission system	Both electrical as well as mechanical	Mechanical
Braking system	Regenerative braking	Friction braking
Efficiency	Low	High
Eco friendly	Yes	No
Initial cost	High	Average
Running cost	Low	Very high

The IC engine efficiency is low because of heat loss also its cooling system is of intricate. On the other hand electrical machines have higher efficiency than ICE.

III. CLASSIFICATION OF ELECTRIC VEHICLE

A. Electric Vehicle
1 Battery operated electric vehicle
2 Battery and ultra-capacitor operated electric vehicle
3 Solar operated electric vehicle
B. Hybrid Electric Vehicle
1 Fuel cell operated electric vehicle
2 Hybrid electric vehicle

IV. VEHICLE ARCHITECTURE

Electric vehicle is a complicated assembly dealing with various fields like Mechanical, Electrical, Control, Magnetic, Electrochemical, Thermal, Chemical etc [21-24]. The fuel tank of the conventional vehicle is replaced by the battery bank. Power AC mains supply or fuel cell is used charge the batteries. The arrangement is provided to charge these batteries either by regular power chargers or by fast chargers which varies on the type of chargers. The power controller is provided to control the power supply to the motor. To supply the power to auxiliaries and peripheral devices a separate 12V battery is provided.

The heart of an electric vehicle is combination of the electric motor, controller and the batteries. The batteries deliver the power to the controller and thus to the motor. The accelerator knob is coupled to a pair of potentiometers (variable resistors) which provides the signal to the controller estimating the power to be delivered for the particular load condition. The controller can deliver zero power (when vehicle is at rest),full power(when accelerator nob is raised to full speed),or any power level in between. The variable power could be delivered by the application of very large thyristers that rapidly turn the batteries voltage on and off [25-29]. The signal from the potentiometers decides the power to be delivered to the electric motor.

Motor Drive:

Usually the electric motors are used where it is run for long time, constant speed, slightly variable loads etc,. But for electric vehicle application the motor needs to start, stop frequently, periodic acceleration and deceleration which cannot be compared with industrial electric motors. In order to suit the motor for electric vehicle application some of the key features have to be satisfied to operate at good performance and efficiency. The motor for electric vehicle should have high torque for starting and uphill propulsion, higher power density for acceleration and speeding, capacity to bear over load for certain interval of time, reliable, efficient and cost affordable. The speed torque characteristics of the motor decide the suitability of the motor. Figure I and Figure II shows the speed- torque characteristics of the desired electric vehicle motor [30] and standard electric motor [31].

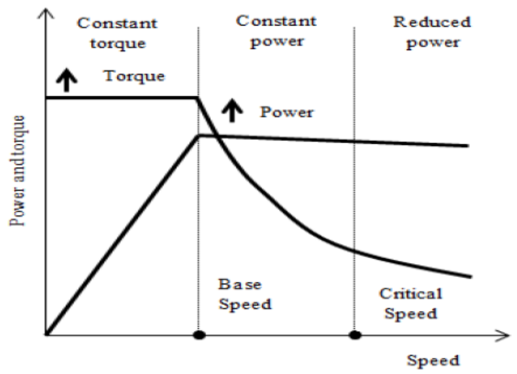

Figure I: Speed- torque characteristics of desired electric vehicle motor

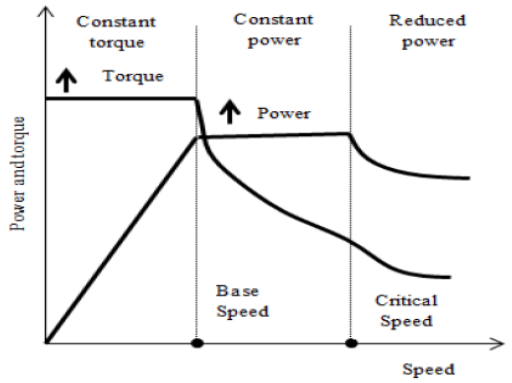

Figure II: Speed- torque characteristics of standard electric motor

TABLE II: Comparison between different types of DC and AC machines used for EV applications

Features	BLDC Motor	Brushed DC motor	AC Induction Motor
Speed Vs Torque Characteristics	Linear. Hence operation at all speeds with rated load is possible.	Moderately flat. Approximately linear. Torque developed is decreased at high speeds due to friction of the brushes	Non-Linear. At low speeds developed torque is less.
Commutation	Electronic	Brushed	
Rating/size	High	low	Moderate / low
Efficiency	High	Moderate	Low
Maintenance	Less	frequent	frequent
Speed range	high	low	high
Electric Noise	Low	High	moderate
control	Complex and expensive	Simple and inexpensive	Simple and inexpensive
Life	Longer	Short	moderate
Slip	No slip	No slip	Present
Starting Current	rated		5-7 times rated current

The DC motors characteristics are suitable for EVs. But its limitations are the commutator and brushes. However the Power Processing Unit (PPU) used for DC motor is economically cheaper than used for three phase induction motor [32-38]. The purpose of commutator and brushes are now implemented by means semiconductor devices. As a result zero maintenance motors were developed which are known as brush less dc motors. Since, these PMBLDC motors are without commutator and brushes their maintenance is very low also there is increase in efficiency and power-to-weight ratio. Hence, present trend is to use PMBLDC motor drive for electric vehicles. The cost of PMBLDC motor drive has two main components, namely motor and the controller. The ease of control of the motor has made the researchers to take up the motor to work at efficiency and cost reduction and commercialize the application of the motor. Due to these features PMBLDC motor drives finds the wide application in low power drives and automotive. PMBLDC motors are well known for less maintenance, long life, low EMI and quiet operation. The output power of these motors produce more output power per frame than other motors.

TABLE III: Required scooter parameters

Sl. No	Parameter	Values	Unit
1	Total mass of vehicle, people	200	Kg
2	Maximum acceleration	0.65	m/s^2
3	Coefficient of normal type rolling resistance	0.013	
4	Density of air	1.23	Kg/m^3
5	Drag coefficient	0.6	
6	Frontal area	0.8	m^3
7	Angle of slope	12	degree

These values are necessary to calculate torque, power and speed of the PMBLDC motor drive. The electric motor for this application should be small in size, light weight and higher efficiency. In order to fit the motor into the scooter it should have a short axial length. Sufficient torque has to be generated to overcome the rolling resistance, drag, tractive force against gravitation during locomotion. The other constraints such as the size of the motor, size of the tyre, driving current and output power are to be taken into consideration. Hence, the feasibility of PMBLDC motor drive is studied from the technical specifications as mentioned in Table IV

TABLE IV: Technical specification of the motor drive

Sl. No	Parameter	Values	Unit
1	Rated voltage	48	Volts (DC)
2	Rated power	500	Watts
3	Rated torque	1.27	Nm
4	Rated speed	3000	Rpm
5	Rated current	11.4	Amps
6	Peak current	34.2	Amps
7	Peak torque	3.81	Nm
8	Resistance	0.94	Ohms
9	Inductance	1.19	mH
10	Electrical time constant	1.26	ms
11	Mechanical time constant	4.91	ms
12	Voltage constant	10.1	v/krpm
13	Torque constant	0.128	Nm/A
14	Rotor moment of inertia	0.51	Kg.cm^2
15	Motor length	130	Mm
16	Motor weight	1.6	Kg

Storage Technologies for Electric vehicle:
A. Batteries in electric vehicle:

Lead acid battery: The spongy lead acts as negative active material of the battery, lead oxide is the positive active material and dilute sulfuric acid is the electrolyte. For discharging, both materials are transformed into lead sulphate [39-41]. These are sealed batteries which provide maintenance free operation and long-term application is possible.

Lithium-ion battery: The positive electrode is composed of an oxidized cobalt material, the negative is of carbon material and lithium salt in an organic solvent is the electrolyte. These are lighter in weight and good efficiency and energy density. These have good self-discharge rate.

Sodium sulphate battery: These batteries bear very high energy density and wide application for low power drives.

Nickel based battery: The aqueous, room temperature batteries such as nickel iron (Ni-Fi), Nickel Cadmium (Ni- Cd) and Nickel-metal hydride (Ni-MH) finds higher advantages due to high peak power and higher energy density. Also these batteries are safe materials and totally sealed for maintenance free operation. Ni-MH batteries eliminates Cadmium from the negative electrode and finally from entire cell. In Ni-MH battery positive electrode is made up of nickel hydroxide, negative is made of an alloy of vanadium, titanium, nickel and other metals. Ni-Cd batteries have the greater advantage on the range of operating temperature [42].

B. Fuel Cell:

The electric vehicle using fuel cell instead of battery is called fuel cell electric vehicle in which electricity to power the wheels of vehicle is supplied by fuel cell. But a battery must be recharged once all the fuel is reacted; a fuel cell is a refillable battery. The fuel cell generates power from the fuel on the anode and oxidant on the cathode and the reaction takes place in the presence of electrolyte. The reactants flows into the cell during the process of generation mean while the products flows out, the generation continues as far as the process is maintained. The major advantage of fuel cell is higher efficiency in conversion, quit operation, fuel flexibility, durability and reliability.

Various combinations of fuel and oxidant is possible, hydrogen is a non-polluting fuel for fuel cell that after reaction it liberates water and it has the highest energy density. Other fuels are hydro-carbons and alcohols and oxidants being chlorine and chlorine oxide. The efficiency of the fuel cell depends on the power drawn, higher the power drawn, lower is the efficiency. Losses occur due to the voltage drop on the internal resistance and the fuel cells have relatively longer response time [43-45]. Also, fuel cells are more expensive than the other batteries.

C. Flywheel:

Flywheel is a device that stores and delivers the energy in the mechanical motion due to size and weight problem, the use is being reduced in electrical vehicle application as these require minimal size and weight. Flywheel energy storage takes place when flywheel is accelerated to high speed and rotational energy is maintained. As and when the energy in the flywheel is extracted, the rotational speed reduces as a consequence of principle of conservation of energy. The energy storage in flywheel is directly proportional to its mass and square proportional to velocity from supply and delivers to the load as per the requirement. Sl. No Parameter Values Unit 1 Rated voltage 48 Volts (DC) 2 Rated power 500 Watts 3 Rated torque 1.27 Nm 4 Rated speed 3000 Rpm 5 Rated current 11.4 Amps 6 Peak current 34.2 Amps 7 Peak torque 3.81 Nm 8 Resistance 0.94 Ohms 9 Inductance 1.19 mH 10 Electrical time constant

1.26 ms 11 Mechanical time constant 4.91 ms 12 Voltage constant 10.1 v/krpm 13 Torque constant 0.128 Nm/A 14 Rotor moment of inertia 0.51 Kg.cm2 15 Motor length 130 Mm 16 Motor weight 1.6 Kg Due to the advancement in bearing, carbon-fiber composite materials, micro-electronics and controls has made the wide application of flywheel [46-48]. As a result of these improvements numerous advantages are added to this category i.e, efficiency, reliability, high speed at lower weight and size, thus made the storage system more suitable for electric vehicular propulsion system. The recent flywheels can store more power and energy when compared to the conventional batteries. These are independent of indepth discharge thus does not alter the life cycle of the system.

D. Hybrid Energy System:

The battery and fuel energy systems have high specific energy but less specific power when compared to flywheel. It can be said that apart from energy density, voltage and current characteristics of the different energy storage system are different. Combination of the energy system with proper calculation and placing can improve the performance of the system [49-50]. This condition is called hybrid energy system. The combination depends on the type of vehicle and the required output. With the combination of storage system, both energy density and power density could be enhanced. The application of only system for higher power density like flywheel increases the cost, weight and size but with combination, the problem could be solved. The overall efficiency, reliability, durability can be improved with this storage system and also concern the cost and weight.

V. COMMERCIAL ASPECTS TO POPULATE THE ELECTRIC VEHICLE IN RURAL AREA:

There is a lot of scope for battery operated electric and hybrid vehicles in rural areas in Udupi as the people are aware of the crisis of energy and increasing fuel cost. But small mandatory changes in the Government and local authorities will help in reaching the people more affectively on road and upgrade the efficiency to IE 3 standards and further to IE 4. For small rural and urban works people used to travel in two wheelers with two seats, within which 90% of the riders travel alone with another seat empty. But two wheeler one seat is not so much commercialized as those are used in some industries and in some executive office works. For one person ride the vehicle need not have that higher torque and high speed when compared to two. Thus for these one person ride two wheeler, single seat is more suitable and electric scooter suits the case well. As the commercial vehicles are IC engine powered these have high speed, thus battery operated low speed vehicles are now considered as the alternative for cycles. The main factors of low speed, limited range and high initial cost are main hurdles in popularizing the two wheelers. The replacement to present vehicle to electric vehicle can be effectively achieved by implementation of electric vehicle in the form of three wheelers at the initial stage and then commercialize the two wheelers, thus contribute to the crisis.

Safety: The industries dealing with chemical, explosive, petroleum where there are dangers of fire hazards, battery operated electric vehicles can be utilized for such applications.

Air Pollution: The factories like food products, pharma industries where the process has to be carried in air conditioned premises and gas emissions are not allowed.

Sound Pollution: Holiday resorts, wildlife sanctuaries, hospitals are main systems where people expect peace and calm, battery operated electric vehicles can be used so that there will not be any delay in the transportation.

VI. BENEFITS OF ELECTRIC VEHICLE

- The battaries for the Electric vehicle will be charged in off-peak hours, this condition helps in ulilizing the base load plant, hence the generated power can be used for the development of renewable energy sources.
- Electric Vehicle works at higher efficiency compared to conventional IC engine vehicle, that hardly it works at 35% efficiency.
- Reduces air pollution and Global warming problems
- Reduction in the use of depleting fossil fuels.

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