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Application of Permanent Magnet Synchronous Motor for Electric Vehicle

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Abstract*: The automobile industry is transforming into electrically driven vehicles. Electrical machines have evolved significantly during the past many years with direct current, induction, and synchronous motors of varying designs. In the electric vehicle (EV) automobile industry, some of the motors—induction motors (IM), permanent magnet synchronous motors (PMSM), brushless direct current motors (BLDCM), switched reluctance motors (SRM), and direct current (DC) series, shunt, and compound motors—have proven success. The advantages of PMSM have led to widespread adoption by manufacturers for commercially available electric vehicles. For EV motors, a widely frequency control method is deployed using a PWM input AC supply to the motor. However, controlling poles in conjunction with frequency controls has a potential in EV applications when additional torque is required at low speeds. The need to further improve the power densities of PMSM by utilizing lighter-weight materials and rotor and stator materials with higher magnetic saturation flux densities become a preferable choice for manufacturers when they try to optimize the costs of EVs. Additionally, the thermal efficiencies of motors continue to improve over time, and best practices in thermal management with air and liquid cooling become a significant factor in curbing energy consumption.

***Keywords*: Electric Motor, Energy Density, Lithium-Ion Battery, Permanent Magnet Synchronous Motor**

I. INTRODUCTION

Electric motors have proven successful with applications in various industries. Based on application these are either Direct (DC) or Alternating (AC) powered. AC Induction motors (IM) are known to offer robust design and be cost-effective in many applications. Some car manufacturers have utilized their inherent cost-effectiveness for EV applications. DC motors have been prevalent in traction applications for a long time. They have offered excellent speed controls and higher torque for operation of trains in a smooth manner [1]. Types of motors purposed for traction applications become a foundation for the evolving EV industry. DC motors consist of wound stator and rotor with application of brushes for commutation. The motor types vary based on connection of the field windings (series, shunt, and compound). Compound motors consist of both series and shunt field windings.

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Switched Reluctance Motors (SRM) consists of stator and rotors prepared from laminated steel sheets wherein the stator windings are wound on stator poles and no magnets are provided for rotors. Brushless DC Motors as the name suggests have no brushes for commutation. The stator windings provide alternating poles, and thus, the magnetic field allows the permanent magnet rotor's rotation. Permanent magnets essentially allow reduction of brushes for commutation. Based on the back emf waveforms these motors are classified as trapezoidal and sinusoidal. Permanent magnet synchronous motors are like BLDCM but use sinusoidal input power. Even though with a similar operating procedure wherein the stator windings offer a rotating magnetic field which allows the permanent magnet rotor to allow rotation at synchronous speed, it offers a smoother operation compared to BLDCM. The advantages of PMSM include lighter weight, offers a wide speed control, higher control accuracy, increased service life, and smoother performance [2] [3] [4] [5].

A. PMSM Composition

PMSM contains rotating (rotor) and stationary (stator) parts. The rotor in PMSM is a permanent magnet, whereas the stator has copper windings that are energized by a three-phase AC. With PMSM efficiencies being in the order of 92- 97% [6], it becomes an excellent player for EV applications. Major EV manufacturers such as Tesla and General Motors have launched PMSM-driven EVs on the road. Other types of electric motors used in EV applications are either induction motors (IM), brushless direct current motors (BLDCM), switched reluctance motors (SRM), and DC series motors. BLDCM and PMSM are largely used in the EV industry because of their superior performance at a given cost. In general, a PMSM, when applied for EV application, requires conversion of DC from vehicle battery to three-phase AC. DC from vehicle battery is converted to three phase AC by using an inverter. Basic diagram of PMSM with stator and rotor windings is shown in Fig. 1. The intent for car manufacturers is mainly to find the best fit within the given cost designated for the purchase of electric motors from original equipment provider manufacturers. A compact and more efficient motor under the preferred price range ideally drives the research work for improving PMSMs. Additionally, less power consumption in nature is another aspect wherein the thermal performance of the motor comes into the picture. For example, the resistance of a conductor increases with rising temperature and is given by equation (7). EV battery efficiency drops with rising temperature.

So, the integration of a cooling system to limit the overall heating of EV systems adds to another aspect of research work. Power densities for PMSM typically ranges from 0.3-0.5kW/Kg [7]. For example, a PMSM, Make: Motoenergy ME1717, 4kW, 9.3kg motor offers a rated power-to-weight density of 0.43kW/kg. Similarly, Bogen Electric Bus Motors offered 0.46kW/kg for C170 and 0.45kW/kg for C215. Typical breakdown of PMSM components is shown in Table 1. The Stator, Rotor, and Casing generally contribute to 41%, 20%, and 39% respectively of the overall weight of the motor [8]. Improvement of power density must be focused on by motor manufacturers as reduced car weight reduces the energy required by the motor.

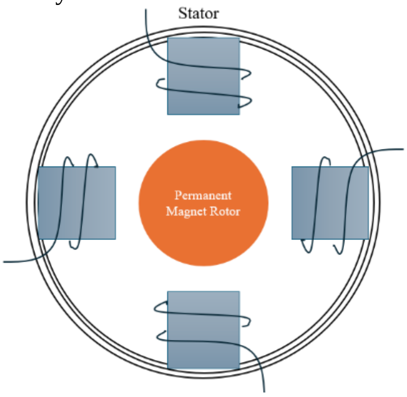

Fig. 1. Stator and Rotor of PMSM

Table 1. Materials by Components of PMSM [9]

Stator	Rotor	Casing, Shaft & Bearings
Electric Steel Sheet	*Pre-magnetized Magnets	Housing Steel/ Aluminum/ Cast Iron
Polyester Foil	Adhesive	Terminal Block
Enameled Copper Wire	Steel Rod	Connectors
Insulating Tape and Tubing	Steel Sheet	Position Sensors
Nylon Thread		Cold/ Hot Rolled Steel
Epoxy Resin		Chrome Steel
Cable Lugs		End Shields
Resolver		Paint
Paint		

**Type of Magnet varies*

B. PMSM Power Density

Using 1J22 (soft magnetic alloy) allows for stator and rotor composition offers higher saturation flux density than silicon steel [10]. Thus, a greater power density is achieved from 1J22 [10]. Using materials with higher saturation flux density for silicon steel, for example, K-MP11 (Tohoku Steel Company Limited) with 2.3T is another option to increase power density with silicon steel material. Other methods include use of low-density materials [7], and switching to double stator type PMSM [11]. Additionally, light-duty battery EV costs are currently high, but utilizing economies of scale and scope will result in decreasing production costs. When the use of lightweight and high saturation flux density materials is leveraged in production, further cost optimization is possible.

II. PMSM MATHEMATICAL MODEL

The mathematical equation of the PMSM in d-q is given by (1) to (3) [3].

$$\frac{d\omega}{dt} = \frac{3P\lambda_m}{2J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} \quad (1)$$

$$\frac{di_q}{dt} = \frac{R}{L} i_q - P\omega i_d - \frac{P\lambda_m}{L}\omega + \frac{1}{L}V_q \quad (2)$$

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + P\omega i_q + \frac{1}{L}V_d \quad (3)$$

Where, ω is angular speed of rotor, P is number of poles pairs, λ_m is rotor magnetic flux, J is rotor inertia, B is friction factor, T_L is load torque, i_q is q-axis current, i_d is d-axis current, V_q is q-axis voltage, V_d is d-axis voltage, R is stator resistance, and L is stator inductance.

In abc model the equation is given by (4) [3].

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = R_s \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} + \frac{dL_{ss}}{dt} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} + \psi_r \frac{d}{d\theta_e} \begin{pmatrix} \cos(\theta_e) \\ \cos(\theta_e - 2\pi/3) \\ \cos(\theta_e + 2\pi/3) \end{pmatrix} \quad (4)$$

V_a, V_b, V_a are stator voltages, I_a, I_b, I_c are stator currents, L_{ss} is stator inductance, ψ_r is the flux linkages, R_s is stator resistance, and θ_e is rotor angle.

Given the above equations, authors have modeled PMSM in Simulink [12]. This paper uses the standard model available in MATLAB Simulink Library. Typical torque vs speed characteristics is given in Fig. 2.

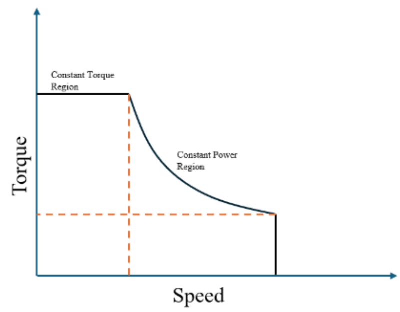

Fig. 2. Torque Vs Speed Characteristics [13]

A. DC to 3-Phase AC Inverter

The key element when implementing PMSM for EV applications is to provide a DC to 3-phase inverter. In general, a universal bridge (with 6 MOSFETs) as shown in Fig. 3 allows conversion of DC from battery bank to 3-phase AC [14]. Here S1 to S6 are used for switching the inverter by generating a PWM which in turn generates a 3-phase sinusoidal output wave. The output wave acts as a speed control when switching S1 to S6 is controlled to obtain desired AC waveform to run the electric motor [15]. A closed loop block diagram for controls is visualized in Fig. 4 and 5.

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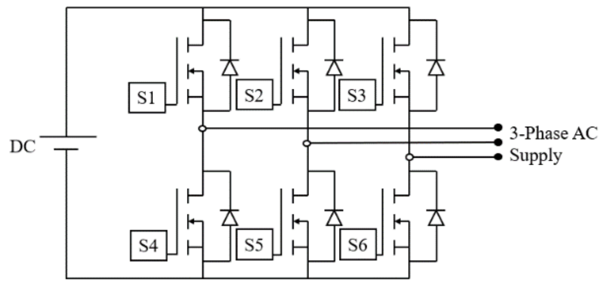

Fig. 3. 3-phase DC Inverter [14]

B. Modeling the Controls

When speed control is deployed using frequency control the synchronous speed is altered depending on the driver's command. Constant pole allows a fixed torque vs speed characteristics which means high torque at lower speed and vice versa. However, torque vs speed characteristics can be improved with higher torque at lower speed by using pole changing method [16]. Poles, when altered at lower speeds, offer better torque control. This is promising for heavy duty vehicles. Motor speed equation is given by (5)

$$N_s = 120\frac{f}{P} \qquad (5)$$

C. Frequency Control

Fig. 4 shows a block diagram of how a frequency control is applied for controlling the speed. Speed control by varying frequency of 3-phase AC power from Inverter by using a controller is shown. A Pulse Width Modulation (PWM) allows varying the frequency of AC supply to the motor. A set of position and speed sensors provide input for comparison with required speed and thus allowing frequency controls.

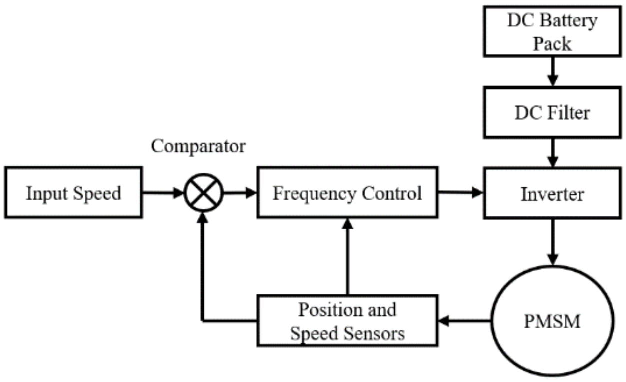

Fig. 4. Frequency Control

D. Frequency and Pole Changing Control

Fig. 5 shows a block diagram of how both frequency and pole-changing are applied for controlling the speed. Here pole changing allows speed controls with close coordination with frequency controls. The exact methodology for the implementation of a joint coordination with frequency control depends on the designer. However, given at lower speeds wherein some motors require more torque for specific applications such as an electric vehicle towing or moving above a steep elevation, the use of pole changing can offer speed controls. Per equation (5), the greater the quantity of pole pairs, the slower the speed, and the reduction of pole pairs results in increased speed.

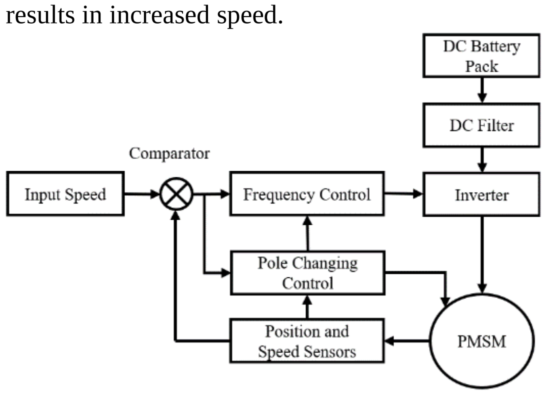

Fig. 5. Frequency and Pole Changing Control

III. PMSM MODELING IN SIMULINK

Using standard blocks for PMSM available in MATLAB Simulink and input parameters from as listed in Table 2, a base model was developed. A simple power system for PMSM in an EV application is shown in Fig 6. Universal bridge converts the DC power from the Battery bank to three-phase AC power to drive the PMSM. The MOSFETs were controlled by a control signal from PWM generator available in MATLAB Sample files. Typical speed vs time is shown in Fig. 7. The speed of the motor stabilizes after 2 seconds of operation.

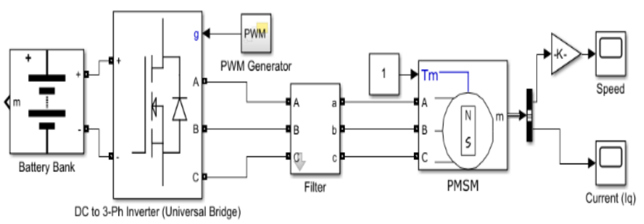

Fig. 6. PMSM Base Model

Although several methods are available to model a PMSM, simple modeling in MATLAB/ Simulink was performed to demonstrate the electrical component (mainly the electric motor) operation in an EV. The exact block diagram for PMSM development in MATLAB/ Simulink involves utilization of the mathematical equations (1) to (4).

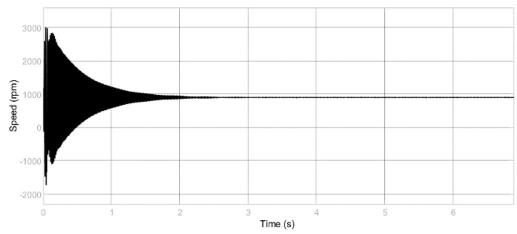

Fig. 7. Speed Vs Time Characteristics

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Table 2. Parameters

Parameter	Value*
Back EMF Waveform	Sinusoidal
Rotor Type	Round
Line to Line Resistance (Ohm)	0.36
Line to Line Inductance (mH)	1.67
Torque Constant (oz.in/Apeak)	60
Inertia (lb.in.s^2)	0.0055
Viscous Damping (oz.in/krpm)	4.25
Pole Pairs	4

*per standard manufacturer's specifications in MATLAB

A. PMSM Speed (Frequency) Control

A speed control was implemented using a PID controller. The q-axis current was used to control the speed. The d-axis current was maintained at zero. The PWM generator in the base model was replaced with an input from PID controllers with a Speed Controller block, as shown in Fig. 8.

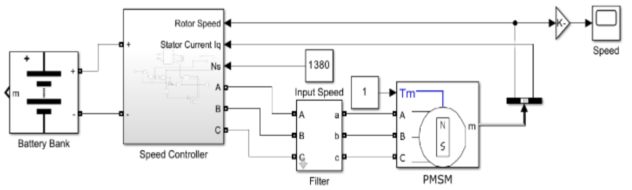

Fig. 8. Implemented Speed Controller

The characteristics curve of speed vs time is shown in Fig. 9. The speed of the motor starts to get closer to the required speed after 1.5 seconds, but additional elements are required to stabilize the speed when implementing the given speed control methodology.

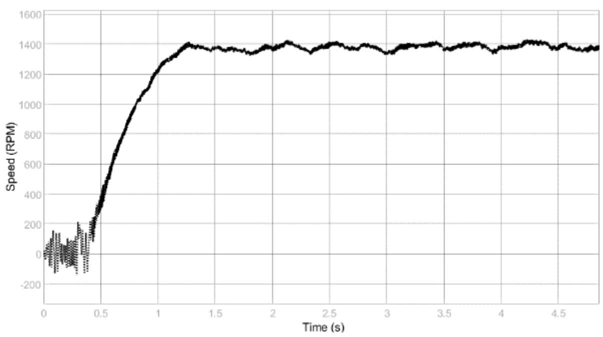

Fig. 9. Speed Vs Time Characteristics

IV. PMSM LOSSES REDUCTION AND EFFICIENCY IMPROVMENT

Generally, the power flow is characterized by given flow: Rectifier-[AC to DC] → Battery-[LI-ion Chemical to DC] → Inverter-[DC to 3-ph AC] → PMSM [3-ph AC to Mechanical] The losses before battery charging are dependent on the source whereas the losses starting from EV battery to the PMSM are under control of the manufacturers. In this paper, mainly the losses at the PMSM level were focused. Mainly, losses are mechanical and electrical. The overall efficiency of the motor is given by (6) [5]:

$$\eta = \frac{P_{mechanical-out}}{P_{mechanical-out} + P_{losses}} \qquad (6)$$

Where, numerator is mechanical output power and denominator is electrical input power. Mechanical losses are due to the frictional losses of the ball bearings and windage losses. Losses in PMSM are categorized as losses in winding, core, and rotor permanent magnet. The winding losses are primarily due to loss of energy due to heat dissipation from the stator winding resistance (refer to equation (7)). The higher the stator resistance greater are winding losses. Moreover, resistance starts to increase with increasing temperature. Operation of the windings with a cooling mechanism offers reduced winding losses. Permanent magnet rotors perform differently based on temperature variation affecting the magnetic properties [17]. Stator windings are designed to minimize skin effects [18].

$$R = R_0(1 + \alpha T) \qquad (7)$$

Where R is the resistance at a given temperature, R_0 is the resistance at zero-degree K, α is the temperature coefficient, and T is the given temperature. The core losses are due to hysteresis and eddy currents in the stator and rotor [19]. Due to changing magnetic fields, rotors and stators are exposed to core losses are developed. The tendency of the magnetization curve to not follow the same characteristics during magnetization and demagnetization results in the two components of losses namely hysteresis and eddy current loss. Minimization of the core losses are possible by changing the design of magnets and slots or by selecting the appropriate number of poles [20]. Losses in permanent magnet due to rotor eddy currents add to overall losses in PMSM.

A. Mitigation of Losses

Air, fan, and liquid cooling are conventional methods for cooling electric motor windings. Liquid assists with not only motor cooling but also the battery. The thermal management systems are dedicated to cooling batteries, electronic equipment, and motors. Although traditional methods of using oil for cooling are applicable for the stator windings, water-glycol offers a heat sink when it flows in a water jacket that surrounds the stator [21] [22]. Authors have presented varying stator slot size potentially improve the efficiency and thermal capabilities [23] [24] [31]. Temperature is a limiting factor for PMSM efficiency [25] [27] [28] [29] [30], thus an improved efficiency by thermal controls of motor is an untapped resource. With advanced tools and techniques available the temperature is accurately predicted for the PMSM [26]. When predictive tools are combined with mitigation techniques, efficiencies are improved.

V. CONCLUSION

This paper described the various types of motors that have a promising application in EV industry. PMSM is a choice considering better performance against torque vs speed, speed control, stability, cheaper design, and costs. A simple model of PMSM powered from a DC battery bank with DC to a three-phase AC inverter was presented.

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Speed controls using the q-axis current for feedback using a PID controller were implemented. The need for adding a pole-changing method in conjunction with the frequency controls was presented. Reduction of losses due heat dissipation and their containment by using thermal management with liquids such as water glycol was presented. Power densities of PMSMs by use of materials offering higher magnetic saturation flux (such as 1J22 and K-MP11) for both stator and rotor, lowers the energy consumption by EVs. The selection of lightweight materials for motor composition forms another basis for design improvement for PMSMs where lowering the energy consumption is concerned.

VI. FUTURE ASPECTS

Electric motors performing a higher efficiency continue to become a subject of interest for the successful application in the EV industry. Cooling technologies for heavy-duty vehicle applications may evolve and promise higher efficiencies. Many manufacturers limit the type of motor selection based on the price point of the given vehicle. Although electric motors have significantly improved over time, the application of EVs continues to become an area of research. The concept that electric motors depend heavily on power supply from the battery bank manufacturers' design considerations includes limiting battery weight to increase the vehicle miles traveled per unit energy consumption. At times, whether to add liquid cooling becomes a question of how much efficiency improvement is offered against the added weight of the cooling system. The hazards posed to large battery banks on board continue to remain a topic of research even when EVs were found generally safer than ICE vehicles when comparing fire hazards. Electric batteries at the most vulnerable point of failure and major cost elements for replacement limit the potential of other high-performance elements, such as PWM controllers, with reduced losses at increased reliability. Varying the type of motors for EV applications is heavily influenced by how leading car manufacturers completed research and development of commercially available EV cars. Some newer concepts of in-wheel motors with radial or axial flux-type become a subject for next-generation EVs. The invention of substitute products for EVs, such as the successful adoption of large-scale fuel-cell-based cars or any other technology, poses a threat to the EV industry. The shift of commute behavior from personal vehicles to ride share or public transport poses a threat to the overall EV market. Additionally, global supply chain issues for parts such as battery packs, and other electronic components are existing limitations. A sooner shift to EVs promises industries to increase production and thus reduce production costs and market prices.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

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