

A Review of Electric Motor Drives for Applications in Electric and Hybrid Vehicles Abstract – This paper reviews several types of electric motor drives and their features in applications for electric vehicles (EV) and hybrid electric vehicles (HEV). Their major advantages include 1) reduced overall weight and volume for given output power (high power density) due to the highly energized magnetic field from PM; 2) inherently higher efficiency owing to the absence of the rotor windings (hence the associated copper loss); 3) more efficient heat dissipation since it is mainly generated by the stator; 4) high reliability due to their immunity to overheating issue or mechanical damage by PM excitation. Currently, with rapid development of power electronic devices and improved material quality, high performance electric machines employing induction motor (IM), permanent magnet (PM) motor, switched reluctance motor (SRM) or other novel motor design have been intensively researched. In the succeeding sections of the paper, five types of electric motors for EV/HEV application are introduced and analyzed, namely, the DC motors, the induction motors (IM), PM brushless motors, switched reluctance motors (SRM), and synchronous reluctance motors (SynRM). IM motor drives are regarded as one of the most competent candidates as electric propulsion system for EVs and HEVs because of their robust construction, reliability, ruggedness, low maintenance demand, low cost and excellent peak torque capability. Section III to Section VII analyze and compare five major types of motor drives, namely, DC motor drives, induction motor (IM) drives, permanent magnet (PM) motor drives, switched reluctance motor (SRM) drives, and synchronous reluctance motor drives (SynRM). Due to some salient features such as zero or low emission and high-power efficiency, Electric vehicles (EV) are gaining increased research efforts and booming dramatically in global automobile market. On the other hand, DC motors also suffer from several disadvantages such as bulky dimension, low efficiency, low maximum speed, low reliability and high demand for maintenance, especially for motors with mechanical commutators and brushes.

PERMANENT MAGNET BRUSHLESS MOTOR DRIVES The PM motors is capable of utilizing both reluctance torque and magnetic torque to improve its efficiency and torque density. The surface magnet designs usually produce only the magnetic torque (round rotor structure) and require less magnet, while interior magnet motor design yields both reluctance and magnetic torque with obtaining higher air-gap flux density. Various HEV/EVs have already been manufactured incorporating these motors to compete the conventional internal combustion engine (ICE) vehicles in the automotive market. Some major requirements for the EV motor drive include high instant power, high initial torque for accelerating and high power for cruising, fast torque response, high power density, wide constant torque and constant power regions, high efficiency over wide speed range, high reliability and reasonable cost.

DC MOTOR DRIVES DC motors are regarded as options for EV/HEV applications owing to their capability of achieving high torque at low speed. A novel type of IM drives with such feature are the vector controlled doubly fed induction motors (DFIM) [9–10], which can achieve field weakening range of 3–5 times the base speed. Even though such technique may extend the constant power operation of IM motors, the breakdown torque (maximum torque requirement) is increased thus results in the over-sizing issue for the motor. However, this type of motors has relatively short constant power range due to their limited fieldweakening capability, which is mainly resulted from the presence of strong field flux produced by the PM, as shown in Fig. It can be seen that in high-speed region, due to significant back EMF the

stator current is reduced hence the torque is inversely proportional to square of the motor speed. The main driving forces for researching and producing EVs and HEVs are fast depletion of fossil fuels and deteriorating atmospheric conditions. The major challenges in this advanced propulsion system include design of powertrain component, energy storage and power management, hybrid control theory and control optimization, and selection of the optimal electric machine topologies. This feature allows for diverse operating modes, especially the unique multi propulsion power operating mode by joint action of the ICE and two motors. The motor rated power P_m can be expressed by the following equation:

$$P_m = \frac{m}{2t_f} (v_{rm}^2 + v_{rv}^2)$$

Where m is the mass of the vehicle, v_{rm} is the electric motor rated speed. Both shunt and series DC motor have only one voltage source hence the controls of flux and torque are simultaneously. On the other hand, the separately excited DC motors are intrinsically capable for field weakening operation since the torque and flux controls are decoupled. Due to these drawbacks, brushless DC motor is more generally used with improved efficiency and reduced size, as shown in Fig. Despite of aforementioned disadvantages, the DC motor drives are preferred in low power conditions, and they are more than the alternatives in automotive industry especially for HEV applications. Then the discussion of diverse types of electric motors including DC, IM, PM, SRM, and SynRM machines is presented. Section VIII provides the concluding remarks for the paper and discusses the future trend of EV vehicles and electric machine design.

CONFIGURATIONS AND SYSTEM CHARACTERISTICS OF EV & HEV

The typical system schematic of EVs is demonstrated in Fig. However, the significance of this theoretical discussion is evident: it reveals that the required motor power can be reduced by extending the constant power region. As mentioned above, the electric propulsion system is the heart of EVs and HEVs, while the motor drives, consisting of electric motor, power converters, and electronic controller, is the core part of such system. Compared with conventional brushed DC motor, BLDC motors do not contain brushes. One possible method to increase the maximum speed range and improve the efficiency is controlling the conduction angle of the power converter at above the base speed (Fig. Nonetheless, at very high-speed range, the efficiency may drop drastically due to the fact that the PM may suffer from demagnetization caused by significant back EMF and possible fault occurrence. Based on the placement of PM, they can be categorized into two types: surface magnet mounted (SPM) and interior magnet mounted (IPM). An example of such motor is the permanent reluctance motor (PRM) developed by TOSHIBA for HEV and EV motors [11], which is shown in Fig. In this design, by changing the magnet position and magnetic circuit design, the motor employs more portion of reluctance torque. The benefits of Increasing of reluctance torque lie in reducing required PM amounts and smaller back EMF. Hence, the motor can achieve a large variable speed range over 1:5, smaller flux weakening current and higher efficiency at high-speed operation region. As indicated in Fig. 1, the annual worldwide sales of Plug-in Electric Vehicles (PEV) are growing remarkably from 50,000 in 2011 to above 550,000 in 2015 [1]. Within the U.S., California is the largest domestic market with 52% of the total PEV sales (shown in Table I. According to the prediction in [1], with the annual growth rate of 8.6%, the EV sales in 2026 will reach 263,000 and the cumulative sales will be over 2.5 million. II. Compared to conventional ICE vehicles, electric motor drives are the core parts in the propulsion system with batteries, ultracapacitors, and fuel cells serving as the energy source. In addition,

plenty of electrical components are incorporated in EV such as power converters, electric machines, microcontrollers and sensors. The electronic controller switches on and off the power devices in the power converter depending on the control from the brake and accelerator of the vehicle. It has several advantages such as reduced number of propulsion devices and smaller sizes of motor and ICE required for desired performance. In series-parallel hybrid, it combines the features of both series and parallel configurations due to the addition of an extra mechanical link between ICE and transmission devices. Generally, three major aspects are involved in vehicle operation: 1) the initial acceleration; 2) cruising at vehicle maximum speed; and 3) cruising at the rated vehicle speed. The commutation process is performed electrically by the electronic drive to excite the stator windings. Without commutator and brush, the IM motors are free from brush friction hence the maximum speed limit is increased. In order to gain independent controls of the torque and the field flux, field orientation control (FOC) can be adopted, which is similar to the case of separately excited DC machine. Typically, permanent magnet brushless motor drives have better performance compared to IM drives as candidates for the electric propulsion system. Considering the above advantages, PM motors are the prior choice for most of the HEVs and EVs manufacturers. A modified type is the PM hybrid motor, in which both PM and field winding are used to produce the air-gap magnetic field. In general, there are three major types of EVs: battery electric vehicles (BEV), hybrid electric vehicles (HEV) and fuel-cell electric vehicles (FCEV) [2]. Section II presents the introduction of typical EV/HEV configurations and system characteristics. Different from EVs, HEVs incorporate both electric motor and internal combustion engine (ICE) as the energy sources. Generally, four kinds of HEVs are classified, namely, the series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid, as shown in Fig. For the complex hybrid, it is very similar to series-parallel type, but the key distinction lies in the bidirectional power flow of the electric motor in this topology and unidirectional power flow of the electric motor in the series-parallel hybrid. The fundamental design constraints are generally set by these three conditions for the EV and HEV drivetrain. Therefore, if the motor is accelerating from 0 to v_{rv} in t_f seconds in constant power region alone, the minimum power is achieved. However, if the motor operates entirely in the constant torque region during this period, then $v_{rm} = v_{rv}$. Based on different topologies, DC Motors can be categorized into three types: series excited, shunt excited, and separately excited machine. By changing the frequency of the excited voltage, speed variation of the IM motor is achieved. In general, IM drives suffers from several drawbacks such as high copper loss, low efficiency, low power factor, and limited constant power range. Various configurations of PM brushless motor drives are commercially available. It may also include the motor whose topology is characterized by features of both PM motor and reluctance motor. Moreover, future trend of EVs as well as electric machine developments are also envisaged. It is essentially an ICE-assisted EV because the ICE supplies power directly to the generator, which either drives the motor or charges the battery. Once meeting these constraints, a drivetrain will usually function adequately in other possible operational regimes. The condition for minimum motor power can be found by differentiating P_m with respect to v_{rm} and setting it to 0, which results in: $v_{rm}=0$. This condition sets the theoretical limit for minimum motor power. Their torque speed characteristics is fitting for traction requirement [4–5]. Even without the DC-AC inverters, they can operate directly from an alternating

current (AC) voltage supply. This paper presents a review of electric motor drives for applications in electric and hybrid vehicles. It is composed of three subsystems – energy source, electric propulsion, and auxiliary. The series hybrid is the simplest type of HEVs, and its only driving force comes from the electric motor. Inherently, it is an electric-assisted ICEV.2 [3].3.5.8.13