CHAPTER 4. DRIVES

Overview of power electronic drives for electric vehicles

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Abstract

With ever increasing concerns on energy efficiency, energy diversification, and environmental protection, the development of electric vehicle (EV) technology has taken on an accelerated pace. The dream of having commercially viable EVs is becoming a reality. This paper identifies the uniqueness of EV drives, and hence provides an overview on the development of power electronic drives for EVs. Researches on various EV motors and EV power converters are particularly addressed.

1 Introduction

In 1801, Richard Trevithick built a steam-powered carriage, opening the era of horseless transportation. After tolerating over thirty years of noise and dirtiness due to steam engines, the first battery-powered electric vehicle (EV) was built in 1834. Over fifty years later, the first gasoline-powered internal combustion engine vehicle (ICEV) was built in 1885. So, EVs are not new and already over 170 years old. With the drastic improvement in combustion engine technology, ICEVs showed much better performance and EVs were out of use from the 1930s to the 1950s. The rekindling of

interests in EVs started at the outbreak of energy crisis and oil shortage in the 1970s. The actual revival of EVs is due to the ever increasing concerns on energy conservation and environmental protection throughout the world as summarized below:

- EVs offer high energy efficiency. In general, the overall energy conversion efficiencies from crude oil to vehicle motion for EVs and ICEVs are 18% and 13%, respectively. Moreover, EVs can perform efficient braking by converting the kinetic energy back to electricity, virtually boosting up the energy efficiency by at most 25%.

- EVs allow energy diversification. Electricity can be generated not only from thermal power using fossil fuels - coal, natural gas and oil, but also from hydropower, wind power, geothermal power, nuclear power, tidal power, wave power, solar power, chemical power and biomass power.

- EVs enable load equalization of power system. By recharging EVs at night, non-stockable energy at non-peak hours and hence the power generation facilities can be effectively utilized, contributing to energy saving and stabilization of power cost.

- EVs show zero local exhaust emissions. Even globally, the emissions due to the generation of electricity for EVs are only 2% in carbon monoxide, 76% in carbon dioxide, 56% in nitrogen oxides and 9% in hydrocarbons exhausted by ICEVs. Increasingly, the emissions generated by power plants can be further minimized by dedicated filtering, and even recycled such as the use of carbon dioxide recycling for electricity generation.

- EVs operate quietly and almost vibration-free, whereas ICEVs are inherently noisy and with sensible vibration. Thus, EVs are welcomed by drivers and appreciated by local residents.

Nowadays, many governments actively promote the use of EVs by providing incentives such as financial subsidies and tax reduction, as well as enforcing stricter regulations such as zero-emission zones and ultralow-emission vehicles. Response to this governmental promotion is sure to be a major issue among automobile manufacturers around the world.

EV technologies are multidisciplinary - involving electrical engineering, mechanical engineering, and chemical engineering [1]. Among them, the technology of power electronic drives plays an important role in electrical

engineering. The purpose of this paper is to identify the uniqueness of EV drives, and hence to provide an overview on the current status of power electronic drives for EVs. Recent research trends on EV motors and EV power converters will also be discussed.

2 EV systems and subsystems

The conventional ICEV employs a combustion engine for propulsion. Its energy source is gasoline or diesel fuel. In contrast, the EV employs an electric motor and the corresponding energy sources are batteries, fuel cells, capacitors and/or flywheels [2]. Notice that the presently achievable specific energy of capacitors and flywheels precludes them from being the sole energy sources for EVs. The key difference between the ICEV and EV is the device for propulsion (combustion engine versus electric motor). Currently, there are three categories of EV systems:

- The battery EV (BEV) utilizes batteries as the sole energy source, and electric motors as the propulsion device. This BEV has been commercially available though not yet under mass production, and is mainly designed for commuter operation with the driving range of about 100 km per charge.

- The hybrid EV (HEV) incorporates both of the combustion engine and electric motor as the propulsion device. It adopts gasoline or diesel fuel as the main energy source, and utilizes batteries as the auxiliary energy source [3]. The HEV can offer the same driving range as the ICEV (over 500 km per refuel), while produces much lower emissions than those of the ICEV. This HEV has been commercially available and under mass production.

- The fuel cell EV (FCEV) adopts fuel cells as the main energy source, and the electric motor as the propulsion device. Since fuel cells can not accept regenerative energy, batteries are generally adopted as the auxiliary energy source [4]. Being fuelled by hydrogen or methanol, the FCEV can provide a driving range comparable with the ICEV. Because of its high initial cost, this FCEV is not yet commercially available.
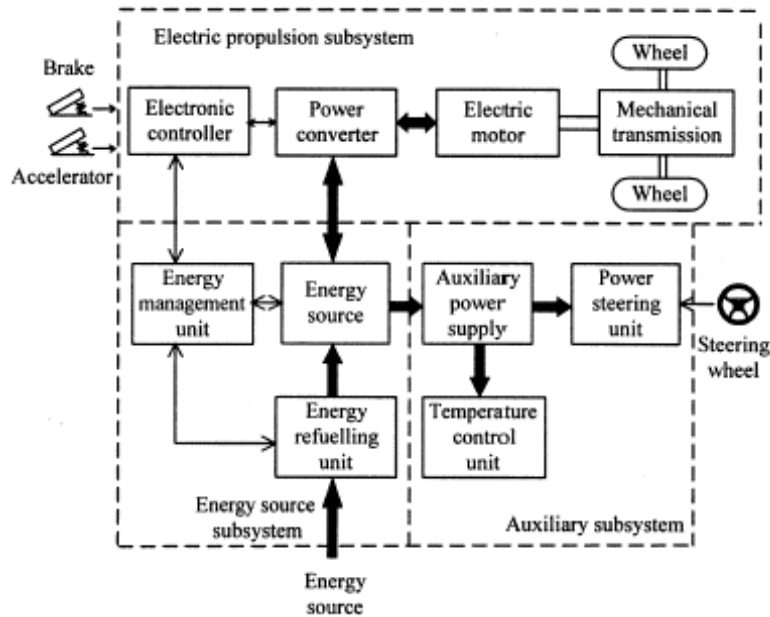
Figure 1: General electrical configuration of EVs.

Fig. 1 shows the general electrical configuration of EVs, including the BEV, HEV and FCEV. It consists of three major subsystems – electric propulsion, energy source, and auxiliary. The electric propulsion subsystem comprises the electronic controller, power converter, electric motor, mechanical transmission, and driving wheels. The energy source subsystem involves the energy source, energy management unit, and energy refuelling unit. The auxiliary subsystem consists of the power steering unit, temperature control unit, and auxiliary power supply. In the figure, a mechanical link is represented by a double line, an electrical link by a thick line and a control link by a thin line. The arrow on each line denotes the direction of electrical power flow or control information communication. Based on the control inputs from the brake and accelerator pedals, the electronic controller provides proper control signals to switch on or off the power devices of the power converter which functions to regulate power flow between the electric motor and energy source. The backward power flow is due to regenerative braking of the EV and this regenerative energy can be stored provided that the energy source is receptive. Notice that most available EV batteries as well as capacitors and flywheels readily accept regenerative energy. The en-

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ergy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery. It also works with the energy refuelling unit to control refuelling and to monitor usability of the energy source. The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units. Besides the brake and accelerator, the steering wheel is another key control input of the EV. Based on its angular position, the power steering unit can determine how sharply the vehicle should turn.

3   Concept of EV drives

Some engineers and even researchers may consider EV drives kindred or similar to industrial drives. However, EV drives usually require frequent start/stop, high rate of acceleration/deceleration, high-torque low-speed hill climbing, low-torque high-speed cruising and very wide-speed range of operation, whereas industrial drives are generally optimized at rated conditions. Thus, EV drives are so unique that they are deserved to form an individual class. Their major differences in load requirement, performance specification and operating environment are summarized as follows:

- EV drives need to offer four to five times the maximum torque for temporary acceleration and hill-climbing, while industrial drives generally offer twice the maximum torque for overload operation.

- EV drives need to achieve four to five times the base speed for highway cruising, while industrial drives generally achieve up to twice the base speed for constant-power operation.

- EV drives should be designed according to the vehicle driving profiles and drivers' habits, while industrial drives are usually based on a particular working mode.

- EV drives demand both high power density and good efficiency map (high efficiency over wide speed and torque ranges) for the reduction of total vehicle weight and the extension of driving range, while industrial drives generally need a compromise between power density, efficiency and cost with the efficiency optimized at a particular operating point.

- EV drives desire high controllability, high steady-state accuracy and good dynamic performance for multiple-motor coordination, while industrial drives seldom desire such coordination.

- EV drives need to be installed in mobile vehicles with harsh operating conditions such as high temperature, bad weather, and frequent vibration, while industrial drives are generally located in fixed places.

4 EV motors

As shown in Fig. 1, electric motors are the key element of EV propulsion. There are many types of motors that have been developed for EVs. A classification of these EV motors is shown in Fig. 2, where there are two main groups, namely the commutator motors and the commutatorless motors. Since the AC commutator motors have already been obsolete for EV propulsion, the DC commutator motors are loosely termed the commutator motors or simply the DC motors. The commutatorless motors can be further classified as two subgroups, namely the AC motors and the switched DC motors. The AC motors include the induction motors, permanent magnet synchronous (PMS) motors, PM brushless DC (PMBDC) motors, and PM hybrid (PMH) motors, fed by sinusoidal, pulse-width modulated (PWM) or rectangular AC waveforms. The switched DC motors are mainly the switched reluctance (SR) motors which are fed by PWM or rectangular DC waveforms. Notice that the motor types encircled by round-corner boxes in Fig. 2 have ever been used in EVs. Table 1 also illustrates their applications to flagship EVs.
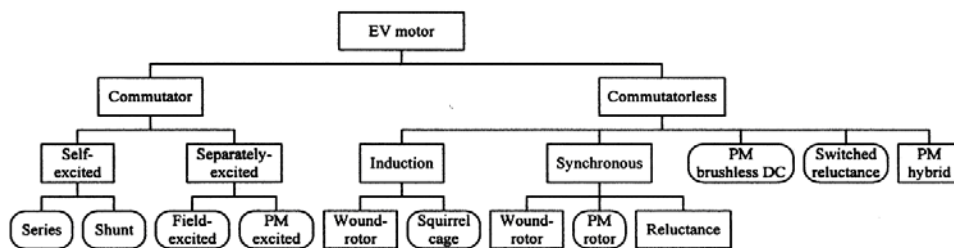

Figure 2: Classification of EV motors.

4.1 DC motors

Traditionally, DC commutator motors have been loosely named as DC motors. Their control principle is simple because of the orthogonal disposition of field and armature MMFs. By replacing the field winding of DC motors

with PMs, PM DC motors permit a considerable reduction in stator diameter due to the efficient use of radial space. Owing to the low permeability of PMs, armature reaction is usually reduced and commutation is improved. However, the principle problem of DC motors, due to their commutators and brushes, makes them less reliable and unsuitable for maintenance-free operation. Nevertheless, because of mature technology and simple control, DC motors have ever been prominent in electric propulsion. As shown in Table 1, all types of DC motors, including series, shunt, separately excited, and PM excited, have ever been adopted by EVs.

EV models	EV motors
Fiat Panda Elettra	Series DC motor
Mazda Bongo	Shunt DC motor
Conceptor G-Van	Separately excited DC motor
Suzuki Senior Tricycle	PM DC motor
Fiat Seicento Elettra	Induction motor
Ford Th!nk City	Induction motor
GM EV1	Induction motor
Honda EV Plus	PMS motor
Nissan Altra	PMS motor
Toyota RAV4	PMS motor
Chloride Lucas	SR motor

Table 1. Applications of EV motors.

4.2   Induction motors

Induction motors are a widely accepted commutatorless motor type for EV propulsion because of their low cost, high reliability and no compulsory maintenance. However, conventional control of induction motors, such as variable-voltage variable-frequency (VVVF), cannot provide the desired performance. One major reason is due to the nonlinearity of their dynamic model. With the advent of microcomputer era, the principle of field-oriented control (FOC) of induction motors has been accepted to overcome their control complexity due to the nonlinearity. Notice that FOC is also known as vector control or decoupling control. Nevertheless, these EV induction motors employing FOC still suffer from low efficiency at light loads and limited constant-power operating region. By adopting an on-line efficiency-optimizing control scheme [5], those vector controlled EV induction motors

can reduce the consumed energy by about 10% and increase the regenerative energy by about 4%, leading to extend the driving range of EVs by more than 14%. On the other hand, by adopting an electrically pole-changing scheme [6], EV induction motors can significantly extend the constant-power operating region to over four times the base speed.

4.3   PM synchronous motors

By replacing the field winding of conventional synchronous motors with PMs, PMS motors can eliminate conventional brushes, slip-rings, and field copper losses. Actually, these PMS motors are also called as PM brushless AC motors or sinusoidal-fed PM brushless motors because of their sinusoidal AC waveform and brushless configuration. As these motors are essentially synchronous motors, they can run from a sinusoidal or PWM supply without electronic commutation. When PMs are mounted on the rotor surface, they behave as non-salient synchronous motors because the permeability of PMs is similar to that of air. By burying those PMs inside the magnetic circuit of the rotor, the saliency causes an additional reluctance torque which leads to facilitate a wider speed range at constant-power operation. On the other hand, by abandoning the field winding or PMs while purposely making use of the rotor saliency, synchronous reluctance motors are generated. These motors are generally simple and cheap, but with relatively low output power. Similar to induction motors, those PMS motors usually employ FOC for high-performance applications. Because of their inherent high power density and high efficiency, they have been accepted to have great potential to compete with induction motors for EV propulsion. In recent years, the corresponding efficiency has been further increased by applying self-tuning control to achieve optimal efficiency throughout the operating region [7], and the controllability has been significantly improved by applying phase-decoupling technique to eliminate the mutual inductances between phases [8].

4.4   PM brushless DC motors

By virtually inverting the stator and rotor of PM DC motors, PMBDC motors are generated. Notice that the name containing the 'DC' term may be misleading, since it does not refer to a DC motor. Actually, these motors are fed by rectangular AC waveform, hence also called as rectangular-fed PM brushless motors. The most obvious advantage of these motors is the removal of brushes, leading to eliminate many problems associated with

brushes. Another advantage is the ability to produce a larger torque because of the rectangular interaction between current and flux. Moreover, the brushless configuration allows more cross-sectional area for the armature winding. Since the conduction of heat through the frame is improved, an increase in electric loading causes higher power density. Different from PMS motors, these PMBDC motors generally operate with shaft position sensors. Because of their inherent high power density and high efficiency, PMBDC motors have promising applications for EV propulsion. In recent years, the corresponding developments have been very active. In [9], a phase-decoupling PMBDC motor has been developed for EVs, which offers the merits of outstanding power density, no cogging torque, and excellent dynamic performance. Also, it can adopt advanced conduction angle control to extend greatly the constant-power operating range. In [10], by adopting self-tuning control, this PMBDC motor can further achieve optimal-efficiency constant-power operation.

4.5 SR motors

SR motors are direct derivatives of single-stack variable-reluctance stepping motors. They have the definite advantages of simple construction and low manufacturing cost. Although they possess the simplicity in construction, it does not imply any simplicity of their design and control. Because of the heavy saturation of pole tips and the fringe effect of poles and slots, their design and control are difficult and subtle. Also, they usually exhibit acoustic noise problems. In recent years, research activities on SR motors have been quite limited. Nevertheless, an optimum design approach to SR motors has been developed [11], which employs finite element analysis to minimize the total motor losses while taking into account the constraints of pole arc, height, and maximum flux density. Also, fuzzy sliding mode control has been developed for those SR motors so as to handle the motor nonlinearities and minimize the control chattering [12].

4.6 PM hybrid motors

Recently, a new research direction has been identified in the development of PMH motors for EV propulsion. In principle, there are many PM hybrids with three of them having been actively investigated, namely the PM and reluctance hybrid, the PM and field-winding hybrid, and the PM and hysteresis hybrid.

Firstly, the PM and reluctance hybrid has been developed in two direc-

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tions. By burying PMs inside the magnetic circuit of rotor, the PMS motor or PMBDC motor can readily be extended to the PMH motor which incorporates both PM torque and synchronous reluctance torque. In [13], by adopting a surface-inset PM rotor and specially controlled stator currents, the surface-inset PMH motor can offer the characteristics of both the conventional PMBDC motor and DC series motor. In [14], by further adopting a polygonal stator winding, the PMH can offer simple and versatile flux weakening, hence enhancing the capability of constant-power operation for EV cruising. On the other hand, by incorporating PMs into the SR structure, another PM and reluctance hybrid is generated which is so-called the doubly salient PM (DSPM) motor [15]. Recent development of this DSPM motor has shown that it is of high efficiency and high power density [16]. By adopting a split-winding arrangement, the DSPM motor can provide flux-weakening operation for EV cruising [17].

Secondly, the PM and field winding hybrid has been implemented in two ways. By incorporating an additional DC field winding in the inner stator of a claw-type PMS motor, the resulting PMH motor has the air-gap flux produced by both the PMs and field winding which are magnetically shunt in nature [18]. With the control of DC field current, the air-gap flux can be flexibly adjusted, hence the torque-speed characteristics of this PMH motor can be easily shaped to meet the special requirements for EV propulsion. Similarly, by inserting an additional DC field winding in the stator of the DSPM motor, this doubly-fed DSPM not only inherits the advantages of the DSPM motor, but also offers very flexible torque-speed characteristics for EV operation [19].

Thirdly, another PMH motor, incorporating both PM torque and hysteresis torque, has been introduced [20]. By inserting PMs into the slots at the inner surface of the hysteresis ring, this PM hysteresis hybrid motor can offer unique advantages such as high starting torque as well as smooth and quiet operation for EV applications.

4.7   Evaluation of EV motors

In order to evaluate the aforementioned EV motors, a point grading system is adopted. The grading system consists of six major characteristics and each of them is graded from 1 to 5 points. As listed in Table 2, the induction motors and PMS motors are most acceptable. When the cost and maturity of the PMBDC motors and PMH motors have significant improvements, these motors will be most attractive. Both the DC motors and SR motors seem to be losing their competitive edges for modern EVs, although the DC

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motors can still play a role in the low-cost EV market.

5 EV power converters

In the past decades, power device technology has made a tremendous progress. These power devices have grown in power rating and performance by an evolutionary process. Among existing power devices, including the thyristor, gate turn-off thyristor (GTO), power bipolar-junction transistor (BJT), power metal-oxide field-effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT), static-induction transistor (SIT), static-induction thyristor (SITH), MOS-controlled thyristor (MCT), and MOS turn-off thyristor (MTO), the IGBT is almost exclusively used for modern EVs. Nevertheless, the power MOSFET has also been accepted for those low-voltage low-power EVs.

	DC motor	Induction motor	PMS motor	PMBDC motor	SR motor	PMH motor
Power density	2	3	5	5	3	4
Efficiency	2	3	5	5	3	5
Controllability	5	3	4	4	3	5
Reliability	3	5	4	4	5	4
Maturity	5	5	4	3	3	2
Cost	3	5	2	2	4	2
Total	**20**	**24**	**24**	**23**	**21**	**22**

Table 2. Evaluation of EV motors.

The evolution of power converter topologies normally follows that of power devices, aiming to achieve high power density, high efficiency, high controllability, and high reliability. The power converter topologies depend on the motors to be driven. The selection criteria of motor drives (including the motors and their power converters) for EVs can be divided into the mandatory requirements and the preferable requirements. The mandatory ones are that the motor drive can offer the torque-speed requirements of the EV driving profile without involving variable gearing or gearbox, and the motor drive can provide the capability of bidirectional power flow to recover the regenerative braking energy. In general, the DC, AC or SR motor drives can offer the desired torque-speed requirements under proper motor design.

The preferable requirements of EV motor drives are low cost, high efficiency, high power density, high controllability and maintenance-free operation.

5.1 Power converters for DC motor drives

DC motor drives take the advantages of mature technology and simple control. However, their commutators and brushes make them less reliable and unsuitable for maintenance-free operation. Thus, the DC motor drives are mainly applied to low-cost EVs, such as motorcycles and mini EVs. The corresponding DC-link voltage and power ratings are 24-48 V and 1-3 kW, respectively.

The power converters for DC motor drives are traditionally based on hard-switching which results in pulsating currents and voltages, thus imposing high voltage and current stresses on power devices and contributing to electromagnetic interference (EMI). Although there have been many soft-switching DC-DC converters developed for switched-mode power supplies, these converters cannot be directly applied to DC motor drives for EV propulsion. Apart from suffering excessive voltage and current stresses, they cannot handle backward power flow during regenerative braking. It should be noted that the capability of regenerative braking is very essential for EVs as it can extend the vehicle driving range by up to 25%.
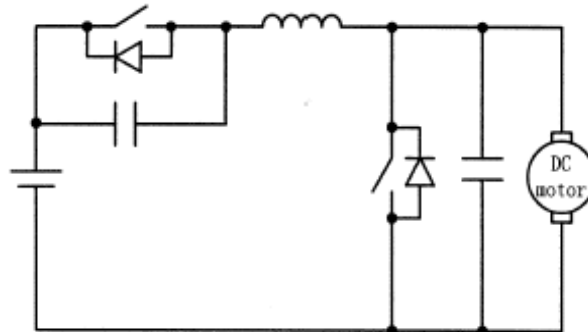
Figure 3: 2Q-ZVS-MR converter for DC motor drives.

In recent years, some soft-switching DC-DC converters have been specially developed for EV propulsion, which offers the capability of bidirectional power flow for motoring and regenerative braking. As shown in Fig. 3, a two-quadrant zero-voltage-switching multi-resonant (2Q-ZVS-MR) converter has been applied to DC motor drives [21]. The major advantages of

this converter are ZVS operation of both power switches, full ranges of both voltage conversion-ratio and load, constant-frequency operation, capability of short-circuit operation, and absorption of all major parasitics. However, the high circulating energy and hence the conduction losses are significantly increased, resulting the power devices and other circuit components to be rated for higher VA ratings, as compared with their PWM counterpart.
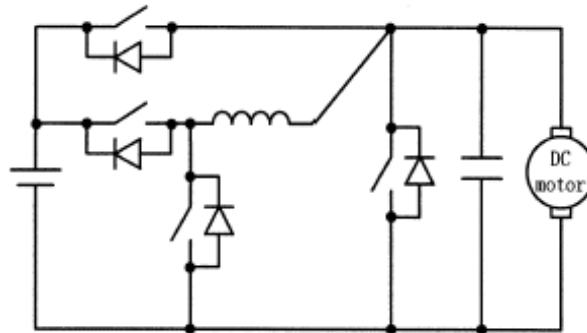

Figure 4: 2Q-ZVT converter for DC motor drives.

Consequently, as shown in Fig. 4, a two-quadrant zero-voltage-transition (2Q-ZVT) converter has been specially developed for DC motor drives [22]. It possesses the advantages that both the main switches and diodes can switch with ZVS and unity device stresses during both the motoring and regenerating modes of operation. It also offers a simple circuit topology and low cost, leading to achieve high switching frequency, high power density, and high efficiency. Other key features are the use of the same resonant tank for both forward and backward power flows and the full utilization of all built-in diodes of the power switches, thus minimizing the overall hardware count and cost. This 2Q-ZVT converter is particularly useful for those power MOSFET-based DC motor drive applications, which generally suffer from severe capacitive turn-on switching losses. On the other hand, a 2Q-ZVS isolated converter has been proposed for DC motor drives [23]. As shown in Fig. 5, this converter adopts a dual half-bridge topology which can offer ZVS with neither a voltage-clamping circuit nor additional switching devices and resonant components, leading to a reduced number of devices and hence compact packaging. As an extension from the 2Q-ZVT converter, a two-quadrant zero-current-transition (2Q-ZCT) converter has also been proposed for DC motor drives [24]. As shown in Fig. 6, this 2Q-ZCT

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converter possesses the advantages that both the main and auxiliary switches can operate with zero-current switching (ZCS) during both the motoring and regenerating modes. It takes the role to be particularly useful for those IGBT-based DC motor drive applications, which generally suffer from severe inductive turn-off switching losses.
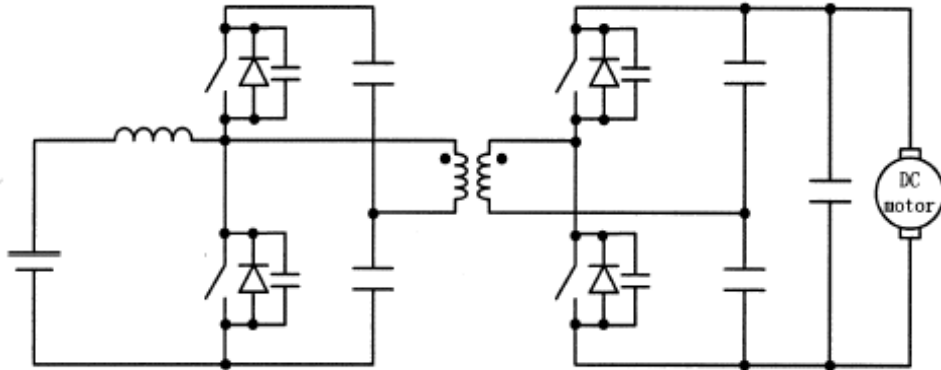

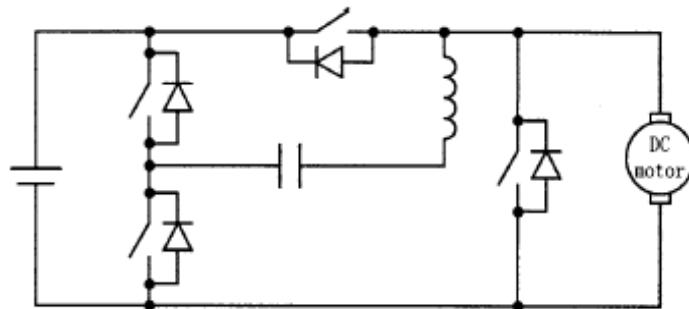Figure 5: 2Q-ZVS isolated converter for DC motor drives.

Figure 6: 2Q-ZCT converter for DC motor drives.

At present, most commercially available electric motorcycles and mini EVs utilize DC motor drives for propulsion, and all of them adopt hard-switching DC-DC converters. Since motorcycles and mini vehicles are widely accepted in densely populated cities such as Tokyo, Beijing and Taipei, the development of soft-switching DC-DC converters for electric motorcycles and mini EVs has a definite market value. The major challenges are to

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elevate the power level of those soft-switching converters up to 3 kW, and to cater at least 2Q but preferably four-quadrant (4Q) operation.

5.2 Power converters for AC motor drives

AC motor drives take the advantages of high efficiency, high power density and maintenance-free operation, as well as the inherent capability of backward power flow. Their major disadvantage is the control complexity. Thus, they have superseded the DC motors for electric propulsion in high-performance EVs, especially passenger cars and buses. The corresponding DC-link voltage and power levels are 240-480 V and 10-80 kW, respectively.

The development of power converters (usually called inverters) for AC motor drives has become one of the key research areas in electric propulsion. The wish list of those inverters inclused efficiency over 95%, power density over 3.5 W/cm^3, switching frequency over 10 kHz, dv/dt below 1000 V/μs, zero EMI, zero failure before the end of the vehicle life, and redundance with limp-home mode. In order to achieve this wish list, there are two major research directions, namely the soft-switching inverters and the multilevel inverters.
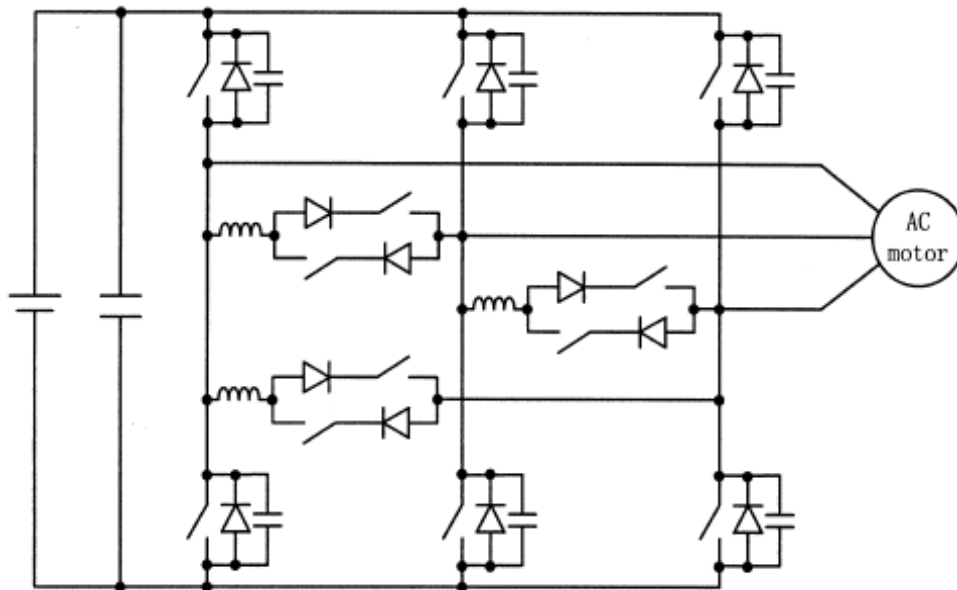

Figure 7: Delta-configured ARS inverter for AC motor drives.

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The development of soft-switching inverters for AC motor drives has been conducted for about two decades. Basically, the soft-switching inverters can be categorized as the resonant DC-link types and the resonant AC-pole types. The milestone of those resonant DC-link types is the well-known resonant DC-link inverter [25]. Subsequently, many improved soft-switching topologies have been proposed [26-31], such as the quasi-resonant DC-link inverter, series resonant DC-link inverter, parallel resonant DC-link inverter, and synchronized resonant DC-link inverter. On the other hand, the resonant AC-pole types include the resonant pole inverter, auxiliary resonant commutated pole inverter, auxiliary resonant snubber (ARS) inverter, zero voltage transition (ZVT) inverter, and zero current transition (ZCT) inverter [32-40]. Among them, the ARS inverter has been actively developed for electric propulsion. By using auxiliary switches and resonant inductors along with resonant snubber capacitors to achieve the soft-switching condition, the delta-configured ARS inverter is shown in Fig. 7 [37]. This inverter offers the merits that all main power devices can operate at the ZVS condition, while all auxiliary power switches also operate at the ZCS condition. Moreover, the parasitic inductance and stray capacitance are utilized as a part of the resonant components. With the use of soft-switching vector control [38], the power loss of the corresponding auxiliary circuit can be further reduced. On the other hand, the ZCT inverter has also been actively developed for electric propulsion.
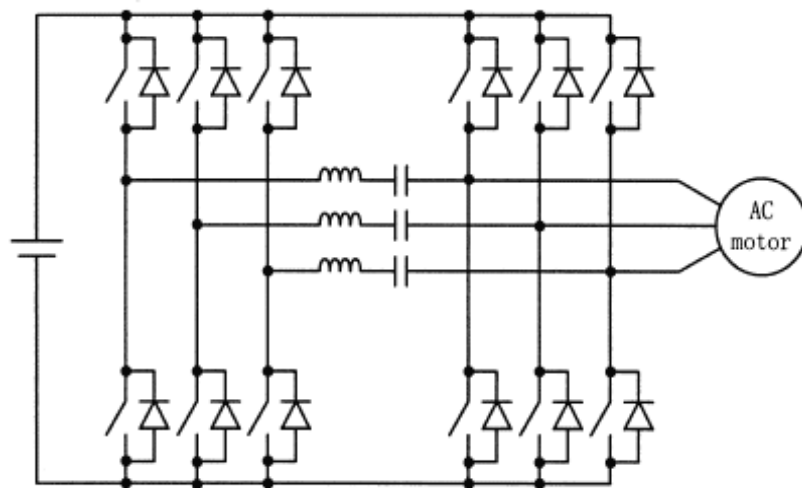

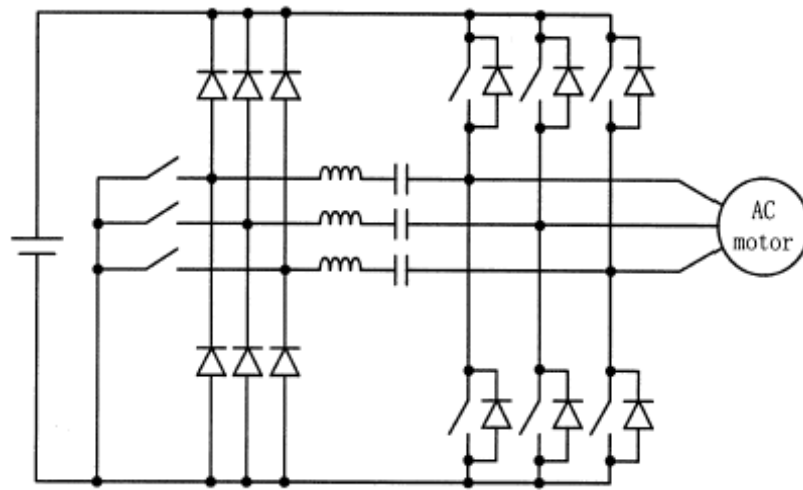Figure 8: 6-switch ZCT inverter for AC motor drives.

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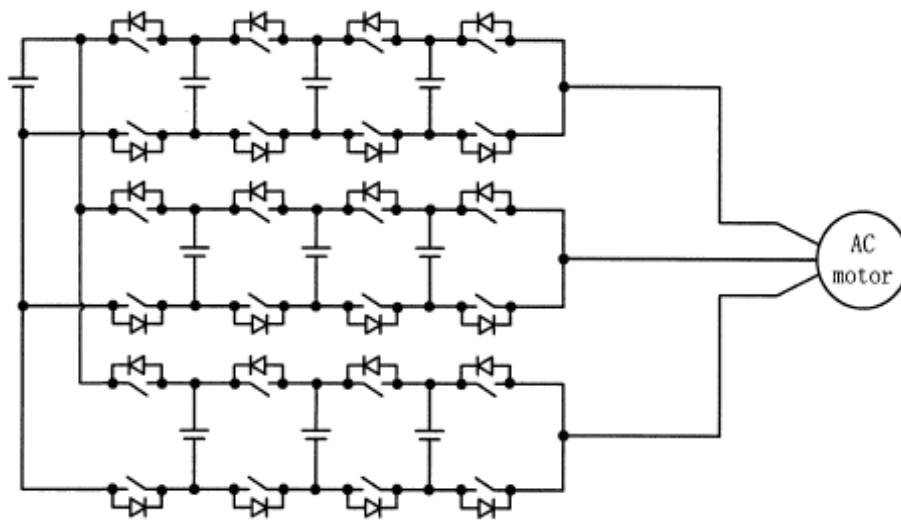Figure 9: 3-switch ZCT inverter for AC motor drives.

Figure 10: 4-cell floating source multilevel inverter for AC motor drives.

Fig. 8 shows the 6-switch ZCT inverter in which ZCS is achieved by using a bidirectional resonant current to divert the currents from the main switches to the auxiliary circuit [36]. It takes the definite advantage that

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each main switch has its own auxiliary switch for ZCS, hence offering flexible PWM. In order to save the number of auxiliary switches, the 3-switch ZCT inverter has been proposed as shown in Fig. 9 in which one auxiliary switch serves for one phase, rather than one main switch [40].
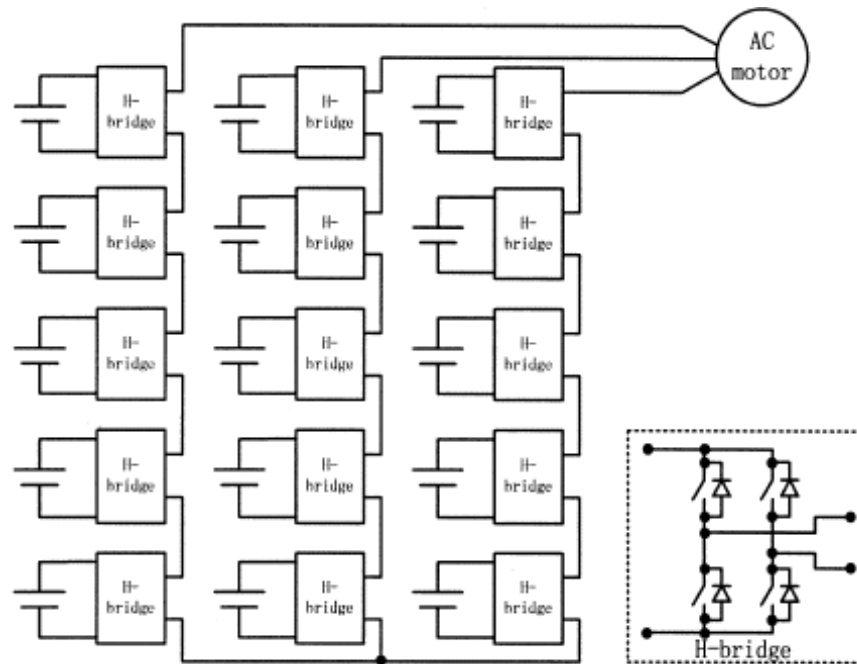

Figure 11: Cascaded H-bridge multilevel inverter for AC motor drives.

The development of multilevel inverters for AC motors has lagged behind that of soft-switching inverters [41-48]. Nevertheless, the multilevel inverters can offer some unique advantages that are particularly beneficial to EVs. Namely, they can generate near-sinusoidal voltages with only fundamental frequency switching, produce almost no EMI, are suitable for high-power motor drives, and fit well with BEVs where floating DC sources are naturally available. Thus, the development of multilevel inverters for EVs takes an accelerated pace. There are three main types of multilevel inverters, namely the diode-clamped type, the flying-capacitor (floating-source) type, and the cascade type. Fig. 10 shows the commonly adopted 4-cell floating-source multilevel inverter. By employing the full binary combination schema [48], the number of voltage levels and thus the power quality of this inverter

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can be further increased. On the other hand, Fig. 11 shows a cascaded H-bridge multilevel inverter which consists of 4 floating DC sources per phase [44]. This inverter not only takes the unique advantages of multilevel inverters, but also the use of identical H-bridge inverter units, thus enhancing modularity and manufacturability.

At present, all commercially available electric passenger cars and electric buses utilize AC motor drives for propulsion, and all of them adopt hard-switching inverters. Although there are many types of soft-switching inverters or multilevel inverters that are claimed to be advantageous and very suitable for EVs, their realistic applications to EVs are still controversial [49,50]. Particularly, the EV manufacturers are not willing to adopt either of them. The major reasons are due to their high complexity and hence the anticipated low reliability. Since the potential market size of EVs and hence the market value of EV inverters is huge, the development of advanced inverters for electric propulsion is promising. The major challenges are to decouple the increased complexity of those advanced inverters from their reliability, and to maintain high reliability at high-power EV operation under harsh temperature or humid environment. For instance, the capability of fault tolerance will play an important role in the development of EV inverters.
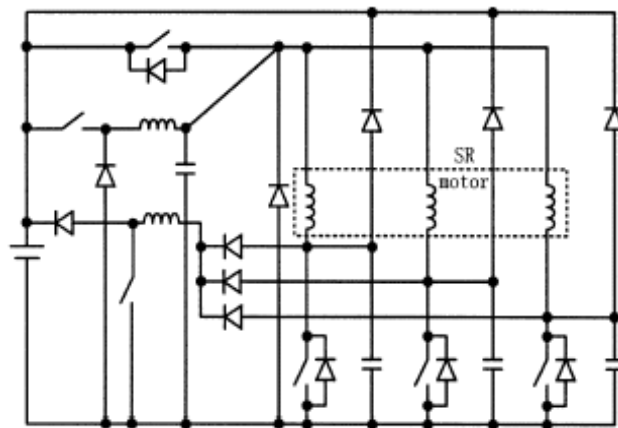

Figure 12: ZVT converter for SR motor drives.

5.3 Power converters for SR motor drives

SR motor drives take the advantages of simple construction and low man-ufacturing cost, as well as the inherent capability of backward power flow. However, they suffer from the difficulty in motor design and control, and the acoustic noise problems. The corresponding DC-link voltage and power levels are the same as those of AC motor drives.

Compared with the development of soft-switching inverters for AC motor drives, the relevant development for SR motor drives has been quite limited [51-57]. Fig. 12 shows the ZVT converter for SR motor drives [54]. It possesses the advantages that the main switches and diodes can operate with ZVS, unity device voltage and current stresses. As a counterpart, Fig. 13 shows the ZCT converter for SR motor drives [55]. It possesses the advantages that both the main and auxiliary switches are operating with ZCS, as well as minimum current and voltage stresses. On the other hand, Figs. 14 and 15 show other soft-switching converters for SR motor drives, namely the actively clamped resonant DC-link (ACRDCL) converter [56] and the 4-switch soft-switching converter [57]. The latter one takes the definite advantage of the minimum number of power switches.
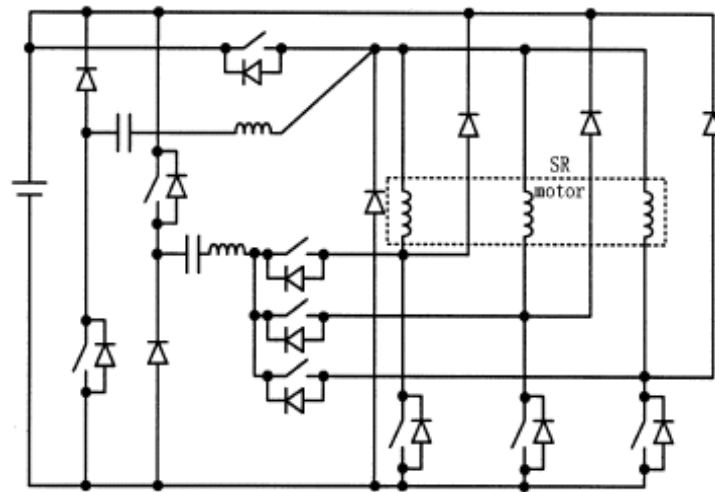

Figure 13: ZCT converter for SR motor drives.

The SR motor drives need to compete with the AC motor drives for EVs with the same DC-link voltage and power levels. Since the advantages of SR motor drives seem to be unable to outweigh their shortcomings as compared

with the AC motor drives, they have suffered from little research activities in recent years. In fact, the EV manufacturers have no activities to further develop the SR motors or their power converters.
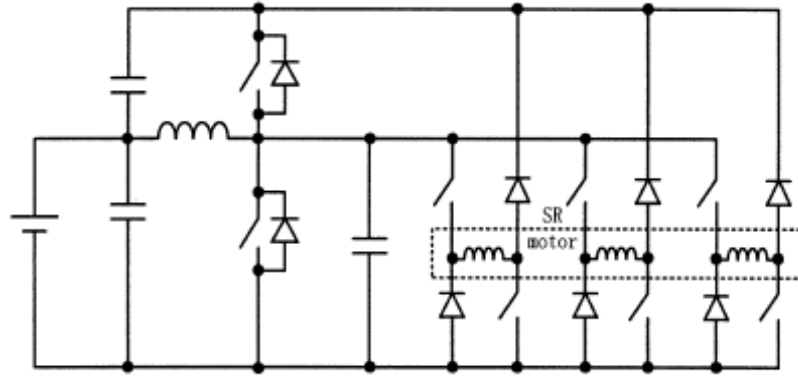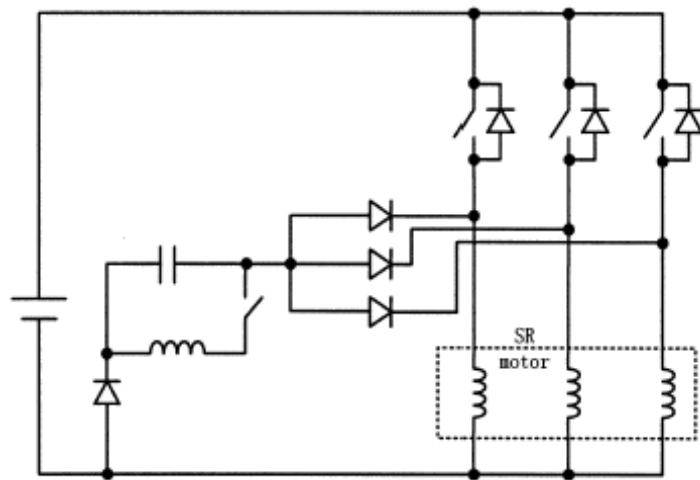

Figure 14: ACRDCL converter for SR motor drives.

Figure 15: 4-switch soft-switching converter for SR motor drives.

6　Conclusions

In this paper, the uniqueness of EV drives has been identified, and an overview on the development of power electronic drives for EV propulsion has been given. Recent research on EV motors and EV power converters have also been discussed, with emphasis on the soft-switching converters for DC motor drives, soft-switching inverters and multilevel inverters for AC motor drives, as well as soft-switching converters for SR motor drives.

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