An Overview of Electric Vehicles - Challenges and Opportunities

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Abstract — In response to concerns about energy cost, energy dependence and environmental damage, a rekindling of interest in electric vehicles (EVs) has been obvious. Based on the 'California rules' on zero emission vehicles in the United States as well as similar tightened air pollution regulation in Europe, Asia and much of the rest of the world, the market size of EVs will be enormous. Thus, the development of power electronics technology for EVs will take an accelerated pace to fulfil the market needs. This paper is to review the current status of multidisciplinary technologies in EVs. Various challenges of power electronics technology for EV propulsion, battery charging and power accessories are explored.

I. MULTIDISCIPLINARY TECHNOLOGIES

The technologies involved in EVs are diversified, which include electrical and electronics engineering, mechanical and automotive engineering, and chemical engineering. Specialists in these disciplines of engineering must work together and pool their knowledge in the main areas that must be integrated: body design, batteries, electric propulsion, and intelligent energy management.

A. Body Design

There are two basic methods for producing EVs - either convert or build for purpose. For the conversion method, the engine and associated equipment of an existing vehicle are replaced by the electric motor, controller and batteries. This offers some economy, because the whole vehicle is already there, and the purchase price is quite low. However, in most conversions, the resulting EV has a greater curb weight, and may have a higher center of gravity and/or other weight distribution differences that can affect handling. Purpose-built or ground-up EVs have more advantages than conversions. In designing an EV from the ground up, the engineers can freely integrate various components so that they work most efficiently together. Now, manufacturers are investing in design of EVs from the ground up, such as the GM Impact 4, Nissan FEV, BMW E1/E2.

There are some design concepts which are particularly important for purpose-built EVs. These concepts include the consistent weight-saving design, optimum safety concept, low drag coefficient body design, and low rolling resistance concept. As shown in Table I, the curb weight, drag coefficient and tire rolling resistance coefficient of latest EVs are given. The top speed, acceleration and range of these EVs are also given. It should be noted that the drag coefficient of 0.185 is almost the lowest figure among present EVs, and the tire rolling resistance coefficient of 0.005 is about 40% that of conventional tires.

B. Batteries

Because the specific energy and specific power of electrochemical batteries are generally much smaller than those of gasoline, a large number of batteries are required to assure a desired level of power performance. However, mounting a vehicle with a large number of batteries suffers from several shortcomings: the reduction of interior and luggage spaces, the increase in vehicle weight and cost, and the degradation of vehicle performances. Thus, the development of battery technology has been accelerated, in which a set of criteria including the specific energy, specific power, energy efficiency, charging rate, cycle life, operating environment, cost, safety and recycling must be considered.

Until now, the most mature battery suitable for EVs has been lead-acid (Pb-Ac). Among various advanced batteries, nickel-based batteries, such as nickel-iron (Ni-Fe), nickel-cadmium (Ni-Cd), and nickel-metal hydride (Ni-MH), have received heightened interest. Whereas, zinc-halogen batteries, such as zinc-bromine (Zn-Br), and high-temperature batteries, such as sodium-sulfur (Na-S), are also attractive. Recent commercially available batteries for EVs are listed in Table II, where the specific power is recorded at 80% depth-of-discharge (DOD), and the cycle life is at 100% DOD.

The battery type, weight, voltage level and energy capacity of latest EVs are also given in Table I. Until now, Pb-Ac batteries are most popular in EVs, such as the GM Impact 4, EPRI/GM G-Van, Mazda Bongo, Suzuki Cervo, Daihatsu Hijet, Mitsubishi Mini-Cab, and Nissan EV Guide II. Ni-Cd batteries are also commonly used in EVs, such as the Nissan FEV, U2001, Renault Zoom, and Tepco IZA. Na-S batteries are used in the BMW E1/E2, Ford Ecostar, and LADWP/SCE LA301. Ni-Fe batteries are used in the EPRI/Chrysler TEVan, and Nissan March EV-II. Zn-Br batteries are used in the Toyota EV-40.

Many researchers are excited by the idea of coupling electrochemical batteries with electric flywheels or ultracapacitors, which can deliver surges of power. Recently, an ultrahigh-speed flywheel has been reported to deliver a whooping 5000-10000 W/kg, which is orders of magnitude higher than anything achievable by an electrochemical battery or even an internal combustion engine.

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TABLE I
COMPARISON OF LATEST EV TECHNOLOGIES

	GM Impact 4	Nissan FEV	BMW E1/E2	HKU U2001
C. w. (kg)	1348	900	915	1973
Drag coef.	0.185	0.19	0.32	0.34
Roll coef.	0.0048	0.005	0.008	0.0044
Top km/h	128	130	120 *	110
Acc. (km/h, s)	0 - 96, 8.5	0 - 40, 3.6	0 - 50, 6 *	0 - 48, 6.3
km @ km/h	193 @ 89 †	160 @ 72	155 @ 80 *	176 @ 88
Batt. type	Pb-Ac	Ni-Cd	Na-S	Ni-Cd
B. w.(kg)	395 †	200	265	792
Volt. (V)	312	280	180	264
kWh	16.8	11.6	28.8	37
Motor	IM	IMs	PMBLM	PMBLM
Trans. gear	Planetary	Planetary	Planetary	Planetary
Converter	IGBT	IGBT	IGBT	IGBT

† Old version of GM Impact, * BMW E1

TABLE II
COMPARISON OF LATEST EV BATTERIES

	Manu.	kg	Ah	Wh/kg	W/kg	Cycle
Pb-Ac	Johnson	18.6	37	24	120	500
Pb-Ac	Sonnen.	30.2	150	29	80-100	700
Pb-Ac	Horizon	27	112	50	>300	900
Ni-Cd	SAFT	23.2	136	45	260	2000
Na-S	ABB	253	238	81	152	600
Na-S	Silent P.	29.2	292	79	90	800
Ni-MH	Ovonics	17.1	100	80	245	1000
Ni-Fe	Eagle-P.	25	203	51	99	920
Zn-Br	SEA	81	126	79	40	350

C. Electric Propulsion

Electric propulsion is to interface electric supply with vehicle wheels, transferring energy in either direction as required, with high efficiency, under control of the driver at all times. It plays a very important role in EVs and will be discussed in details.

D. Intelligent Energy Management

Maximizing energy usage and monitoring energy capacity are critical to attaining acceptable performance in EVs. As shown in Fig. 1, the energy management system (EMS) making use of sensory inputs from sub-systems of the vehicle predicts range for standardized driving profiles, controls the energy usage of vehicle sub-systems, suggests more energy efficient driving behavior, directs regenerated energy to batteries, and selects battery charging algorithm based on battery state-of-charge and cycle life history.

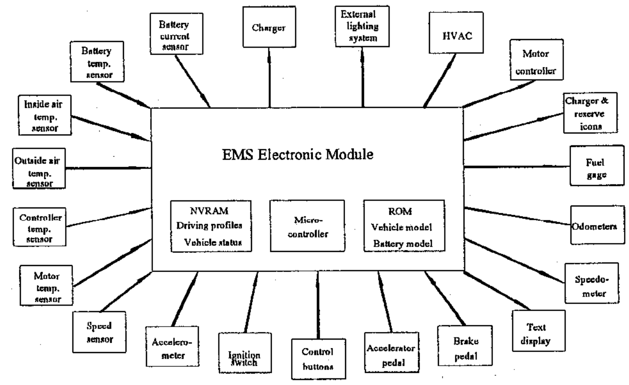

Fig. 1 Energy management system

II. EV PROPULSION

Fig. 2 illustrates the functional block diagram of a typical EV propulsion system. Instead of using a single motor, the use of multiple motors has also been used. Fig. 3 illustrates the single- and dual-motor configurations. The major feature of the dual one is the elimination of mechanical transaxle differentials while the differential action is carried out electronically. Since these two have their individual merits, they have been employed by modern EVs. As in Table I, the GM Impact 4, BMW E1/E2 and U2001 employ the single-motor one, while the Nissan FEV adopts the dual-motor one.

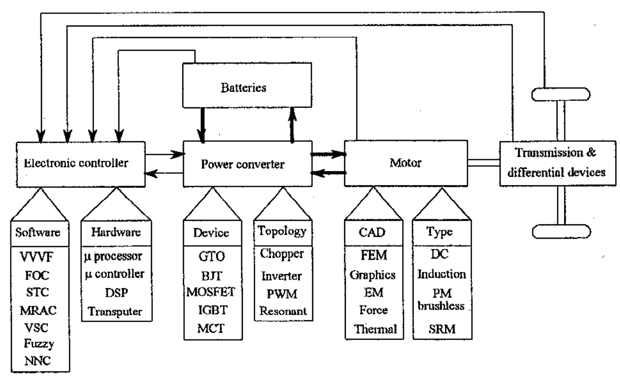

Fig. 2 EV propulsion system

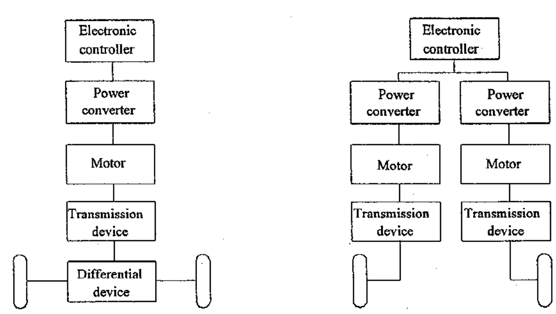

Fig. 3 Single- & dual-motor configurations

A. Motors

Electric motors have been available for over a century. The evolution of motors, unlike that of electronics and computer science, has been long and slow. Nevertheless, the development of motors is continually fueled by high-energy permanent magnets (PMs), sophisticated motor topologies, and powerful computer-aided design (CAD) techniques.

Traditional DC commutator motors, loosely named as DC motors, have been prominent in EV propulsion. Their control principle is simple. By replacing the field winding and pole structure with high-energy PMs, PM DC motors permit a reduction in stator diameter. However, the principle problem of DC motors arises from their commutators and brushes, which makes them less reliable and unsuitable for maintenance-free operation.

Recent technological developments have pushed AC motors to a new era, leading to take definite advantages over DC motors: higher efficiency, higher power density, lower cost, more reliable, and almost maintenance free. As high reliability and maintenance-free operation are prime considerations in EV propulsion, AC induction motors are becoming attractive. However, conventional control of induction motors such as variable-voltage variable-frequency (VVVF) can not provide the desired performance of EVs. With the advent of microcomputer era, the principle of field-oriented control (FOC) becoming attractive.

By replacing the field winding with high-energy PMs, PM synchronous motors can eliminate conventional brushes, slip-rings, and field copper losses. As these motors are essentially traditional AC synchronous motors with sinusoidal-distributed windings, they can run from a sinusoidal or PWM supply without electronic commutation. By inverting the stator and rotor of PM DC motors, rectangular-fed AC motors, so-called PM brushless DC motors, are generated. 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 at the same peak current and voltage, because of the interaction between rectangular current and rectangular magnetic field. Although their configurations are very similar to those of PM synchronous motors, there is a distinct difference that PM brushless DC motors are fed by rectangular AC wave, while PM synchronous motors by sinusoidal or PWM AC wave.

Switched reluctance motors, though the principle of which has been known for over a century, have seen a revival of interest in recent years. Basically, they are direct derivatives of single-stack variable-reluctance stepper motors, in which the current pulses are phased relative to the rotor position to optimize operation in the continuous rotation mode. Similar to PM brushless DC motors, they usually require shaft position sensors. However, switched reluctance motors suffer from the same excitation penalty as induction motors, and can not attain the efficiency or power density of PM AC motors.

To keep up with the more stringent motor requirements, the design of EV propulsion motors turns to CAD. The finite element method (FEM) outranks other numerical methods, because of its applicability in electromagnetic, force and thermal analyses.

A typical classification of EV propulsion motors is illustrated in Fig. 4, where the shaded motor types have been accepted for modern EVs. As given in Table I, both the GM Impact 4 and Nissan FEV employ the induction motor, while both the BMW E1/E2 and U2001 use the PM brushless DC motor. Fig. 5 shows the dual induction motors in the Nissan FEV with a rated output of 20 kW and starting torque of 95.5 Nm, as well as the Unique Mobility PM brushless DC motor in the BMW E1 with 32 kW and 150 Nm. On the other hand, the other motor types are also employed in EVs, such as the PM synchronous motor in the Ford/GE ETX-II, the switched reluctance motor in the Chloride Lucas, the DC series motor in the Daihatsu Hijet, the DC shunt motor in the Mazda Bongo, the DC separately excited motor in the Fiat 900E/E2, and the PM DC motor in the Suzuki Senior Tricycle.

The use of conventional gearing as the transmission device can no longer satisfy the needs of EVs. Recently, planetary gearing has been accepted as the transmission device of latest EVs, such as the GM Impact 4, Nissan FEV, BMW E1/E2 and U2001, because it offers high gear ratio and high transmission efficiency. The planetary gear set of the Nissan FEV is 12 to 1, while the ratio of the U2001 is 11 to 1. By using planetary gearing, the concept of motorized wheels can be easily realized. On the other hand, by abandoning the transmission device or gearing, these motorized wheels can be realized directly using outer-rotor wheel motors. Recently, the Tepco IZA has employed four gearless motorized wheels, where each of them is an outer-rotor PM brushless DC motor of 6.8 kW at 288 rpm.

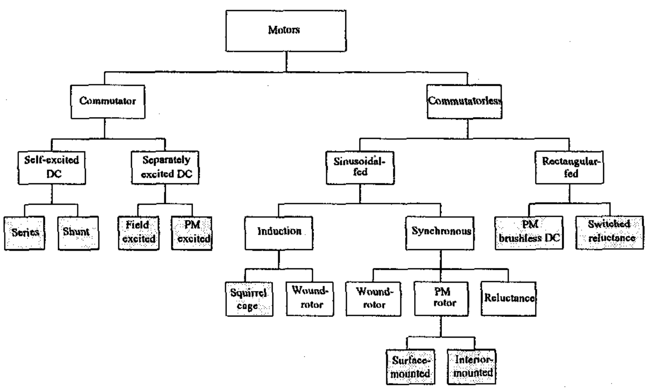

Fig. 4 Classificaton of EV motors

B. Power Converters

In the past few years, power device technology has made tremendous progress. The selection of power devices for EV propulsion is generally based on the requirements of the voltage rating, current rating, switching frequency, power loss, and dynamic characteristic. The voltage rating depends on the battery nominal voltage, maximum voltage during charging, and maximum voltage during regenerative braking. The current rating depends on the motor peak power rating, and number of devices connected in parallel. The switching frequency should be high enough to reduce the acoustic noise, size of filters, and EMI problem. But, higher switching frequencies increase the switching loss. Since an extra 1% efficiency in EV propulsion can enable additional few miles in EV driving range, the power loss including both switching and conduction losses should be minimum. The dynamic characteristic should be good enough to allow for high dv/dt capability, high di/dt capability, simple driving, and easy paralleling. The device protection, packaging, reliability and cost should also be considered.

Among the available power devices, the GTO, BJT, MOSFET, IGBT and MCT are particularly suitable for EV propulsion. Some of their operating characteristics are given in Table III. At present, the IGBT is most attractive because it possesses high input impedance and high speed characteristics of a MOSFET with conductivity characteristic of a BJT. In near future, the MCT will be a good candidate for EV propulsion because it combines high switching speed, high power handling capability, superior dynamic characteristic, and high reliability. An advanced IGBT-based inverter is tested in the Nissan FEV with a maximum output of 60 kVA and switching frequency of 10 kHz. Also, a MCT-based inverter with 87.3 kVA and 5 kHz has been tested by the Ford/GE ETX-II. This MCT-based inverter is only 45% of the BJT-based inverter volume and weighs 28% less than the BJT-based inverter.

The evolution of power converter topologies normally follows that of power devices, aiming to achieve high power density, high efficiency and robust power converters. One of the latest inverter topologies for battery-fed applications is so-called resonant DC-link inverters, either a parallel or series resonant circuit, thus providing either zero-voltage-switching (ZVS) or zero-current-switching (ZCS) condition. Outweighing the additional cost due to the resonant tank and increased control complexity, they have the advantages of zero switching loss, low heat sinking requirement, snubberless operation, high power density, less severe EMI problem, very small acoustic noise, and improved reliability. Because of these merits, resonant DC-link inverters have promising applications to EV propulsion.

In addition to converter topologies, another important aspect of power converters is switching schemes. Starting from the last decade, numerous PWM switching schemes have been developed for battery-fed inverters, focusing on harmonic suppression, better utilization of DC-link voltage, suitability for real-time and microcontroller-based implementation, and tolerance of DC-link voltage fluctuation.

TABLE III
COMPARISON OF LATEST POWER DEVICES FOR EVS

	Power (kV, kA)	Driv.	Gat.	Cond. drop	Drop. sensi. °C	Freq. (kHz)
GTO	5, 3	Trig.	I	Mid	Neg	Low
BJT	1.4, 0.8	Lin.	I	Low	Neg	Mid
MOSFET	1, 1	Lin.	V	High	Pos	V. high
IGBT	1.2, 0.4	Lin.	V	Mid	Neg ‡	High
MCT	0.9, 0.15	Trig.	V	Low	Neg	High

‡ Positive at high current

C. Electronic Controllers

Conventional linear control such as PID can no longer satisfy the stringent requirements placed on high-performance EVs. In recent years, many modern control strategies, such as model-referencing adaptive control (MRAC), self-tuning control (STC), variable structure control (VSC), fuzzy control and neural network control (NNC), have been proposed. Both MRAC and STC have been applied to EV propulsion. Using sliding mode, VSC has also been applied to motor drives. By employing emerging technologies of fuzzy logic and neural networks to realize the concept of intelligent controllers, fuzzy control and NNC have promising applications to EV propulsion.

In order to implement the aforementioned modern control strategies, powerful microelectronic devices are necessary. Modern microelectronic devices include microprocessors, microcontrollers, digital signal processors (DSPs), and transputers. Microprocessors are usually used to recognize the milestone of the development of microelectronics, such as the 8086, 80186, 80286, 80386, 80486, and Pentium. Unlike microprocessors, which are the CPU of microcomputer systems, microcontrollers include all resources to serve as stand-alone single-chip controllers. Thus, microcontroller-based EV propulsion systems possess definite advantages of minimum hardware. The state-of-the-art microcontrollers are the 8096, 80196, and 80960. DSPs, such as the TMS32030, TMS32040 and i860, possess the capability of high-speed floating-point computation, which are very useful to implement sophisticated control algorithms for high-performance EV propulsion systems. Transputers, such as the T400, T800 and T9000, are particularly designed for parallel processing applications. By employing multiple chips of transputers, any sophisticated control algorithms can be implemented.

III. BATTERY CHARGING

The challenge of transforming EVs from concept to reality is to make it safe, convenient and easy for consumers to charge batteries. In order to improve convenience and increase charging efficiency, a number of charging schemes have been proposed: home charge, regenerative charge, solar charge, park-and-charge (PAC), and move-and-charge (MAC). Fig. 5 shows a typical multiple charging system which aims to charge batteries using various charging schemes simultaneously.

As an EV is usually parked at home or a storage site at night, the battery charger in the vehicle can be connected into the domestic single-phase AC plug for slow night-time charging. Depending on the battery capacity and depth of discharge, the charging time takes about 6-8 h, and the charging current is usually limited to 15 A. This on-board charger should be less than 5 kg. Thus, inexpensive, light-weight and compact on-board battery chargers are essential for home charge. This requirement stimulates the development of regulated AC-DC converters (controlled rectifiers) with high power density and high efficiency. As the electricity demand at night is relatively low, this home charging scheme can facilitate the load level control of power utilities.

During deceleration or down-hill, the EV propulsion motor is operated as a generator to charge batteries through regenerative braking, so-called regenerative charge. Thus, multi-quadrant DC choppers and full-bridge inverters are generally used for DC and AC propulsion systems, respectively. In the GM Impact 4, the regenerative braking system can extend the driving range by up to 25%. In order to further enhance the use of energy, batteries can also be charged by solar energy using solar cells embedded in the vehicle roof. Typically, the solar cells are of the single-crystal silicon type and insulated from the vehicle cabin by using plastic. In the Nissan FEV, the 300 V solar cells provide conversion efficiency of 16%, and are capable of fully charging up batteries in five weeks of fine weather.

When an EV is parked at a charging station, a microprocessor-controlled three-phase off-board battery charger initiates the power and effects its transfer to the vehicle. When an amount of parking time selected is insufficient to supply an amount of power selected using a normal charging scheme, the intelligent off-board charger allows for quick charge by adjusting continually the charging rate to match the ability of batteries to accept charge. During quick charge, the charging current is generally over 100 A so that the charging time is about 20 min to attain 80% state-of-charge. This off-board charger weighs about 60 kg. Thus, efficient three-phase AC-DC converters with high current capability are essential for this PAC system. The super-quick off-board charger for the Nissan FEV provides a charging current of 140 A to charge 40% of the battery capacity in 6 min, and a full charge in as little as 15 min. It should be noted that from the power utility point of view, quick charge may not be desirable because it causes high peak power demand. An incentive-based electricity billing system may be employed to encourage people to charge batteries during off-peak periods, while quick charge is encouraged only for emergency purposes at dedicated charging stations.

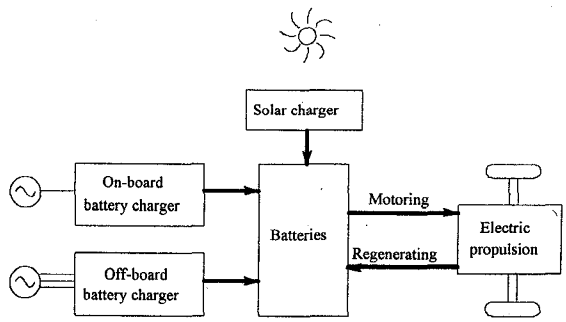

Fig. 5 Multiple charging system

Instead of using plugging type power transfer, an inductive power transfer system has recently been developed for charging EV batteries. The vehicle is equipped with a charging port that also incorporates a coil. When the paddle is inserted into the charging port, the corresponding magnetic fields intermingle to complete the circuit. The incoming power is then converted by an AC-DC converter to charge batteries. This inductive charging system is inherently safe under all-weather operation - tolerant of water, snow, ice, dirt, and dust particles. In order to have a light-weight and compact inductive charging port, low mass magnetic cores and high-frequency AC-DC converter are necessary. Typically, this system can handle power levels from 1.5 to 25 kW with overall efficiency of better than 90%, while the power transfer frequency is 40-350 kHz.

The most ideal situation for charging EV batteries is to perform charge while the vehicle is cruising on the road - so-called MAC. Thus, the driver does not need to find a charging station, park the vehicle, and spend relatively long time to charge up batteries. This MAC system is embedded on the surface of a section of highway, the charging zone, and does not need any additional space. Both contact and inductive types of MAC can be implemented. For the contact type MAC system, an on-board contact arch is mounted on the bottom of the EV body. By physically contacting the charging elements which have been embedded on the road surface, the arch picks up instantaneous high current. Since the EV is cruising through the charging zone, the charging process is so-called pulse charge. For the inductive type MAC system, the on-board contact arch is replaced by inductive coils, and the charging elements are replaced by high current coils which produce strong magnetic field.

IV. POWER ACCESSORIES

Because EVs do not have an alternator, many auxiliary systems must depend on EV batteries to supply the necessary power. Air conditioning, power steering, lamps and radios are just some of the accessories of an EV which have to rely on power converters to provide power from batteries.

A. Temperature Control Unit

The rotary-compressor air-conditioning unit in EVs is powered directly by a dedicated variable-speed motor. This air conditioning unit is of the heating/cooling type as it incorporates a heat pump to provide the heating function. The major features of this unit include the inverter drive, quiet operation assured by effective vibration control, and energy savings achieved through the use of thermal insulated glass that reduces the load on the air-conditioning unit. To minimize penalties to EV driving range and performance, the power consumption and weight of the unit must be low. Thus, efficient and low-weight inverter drives of several kW with low acoustic noise are desirable.

Recently having been used in the U2001, the thermoelectric variable temperature seat (VTS) is a highly energy-efficient means of providing vehicle occupant heating and cooling. A typical energy requirement for the VTS is 100 W per occupant compared with 1-4 kW per vehicle for a standard automotive air-conditioning unit. Since the energy requirement of an existing air-conditioning unit may reduce the driving range of an EV by 20-30%, this energy-efficient VTS is particularly suitable for an EV. The high energy efficiency of the VTS is achieved by using heating and cooling energy to directly heat and cool the occupant rather than to heat and cool the surrounding space and interior vehicle surfaces. The temperature effect is produced by a combination of conduction to the occupant through the seat rest and back rest, and through convection of conditioned air escaping through the surface of the seat. Since heating and cooling are provided by a thermoelectric heat pump and blower contained within the seat, it contains no refrigerants - environmental friendliness. This new idea stimulates the development of efficient, low-weight and compact thermoelectric heat pumps and blowers.

B. Power Steering

In order for power steering to be feasible in EVs, extremely efficient high-power controllers are necessary to provide needed performance without sapping precious battery reserves. Recently, an adaptable inverter fitting most 3-phase AC induction motors has been developed for power steering. A DSP is employed to perform VVVF control. The input power of this unit is about 900 W.

C. Auxiliary Power Converter Unit

An auxiliary power converter (APC) unit is used to convert battery power into regulated power for all vehicle accessories. These power accessories include power seats, power windows, power antenna, power door locks, brake vacuum pumps, radios, windshield defoggers, de-icers, headlamps, air bags, CRT display, and the EMS. Although most of them are operated at DC 12 V, some accessories require DC 47 V of power. This is usually accomplished by using a full-bridge PWM DC-DC converter. In order to reduce heat sinking requirement and improve operating performance, the converter is operated at high frequency and under ZVS condition. Typically, the output power of this unit is about 1.6 kW.

V. SYSTEM INTEGRATION

Due to the multidisciplinary nature of EVs, the process of identifying the preferred features and packaging options for system integration should be carried out at the system level. Fig. 6 illustrates typical sub-system interactions in EVs. The impact of these sub-system interactions affects the vehicle cost, performance, and safety.

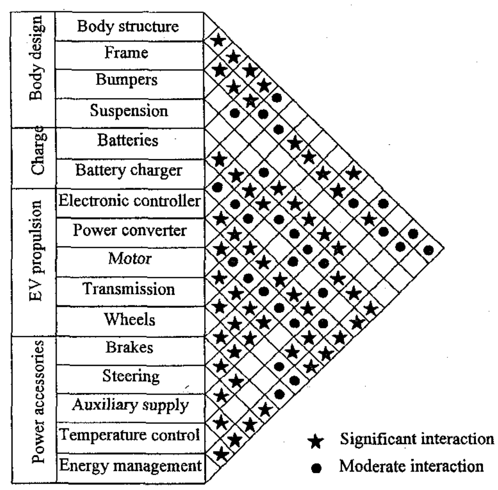

Fig. 6 EV sub-system interactions

VI. CONCLUSIONS

This paper has reviewed the current status of multidisciplinary technologies in EVs, with emphasis on power electronics for EV propulsion, battery charging, and power accessories. It indicates that power electronics technology plays a very important role in the development of EVs. As the EV market will be expanding dramatically in the coming years, research activities on power electronics technology for EVs must be highly attractive.