UNIT-3
EV PROPULSIONS AND DYNAMICS

EV considerations

The choice of electric propulsion systems:

The choice of electric propulsion systems for EVs mainly depends on three factors-**driver expectation, vehicle constraint and energy source**. The driver expectation is defined by a driving profile which includes the acceleration, maximum speed, climbing capability, braking and range. The vehicle constraint depends on the vehicle type, vehicle weight and payload. The energy source relates with batteries, fuel cells, capacitors, flywheels and various hybrid sources. Thus, the process of identifying the preferred features and packaging options for electric propulsion has to be carried out at the system level. The interactions between subsystems and those likely impacts of system trade-offs must be examined. The development of electric propulsion systems has been based on the growth of various technologies, especially electric motors, power electronics, microelectronics and control strategies

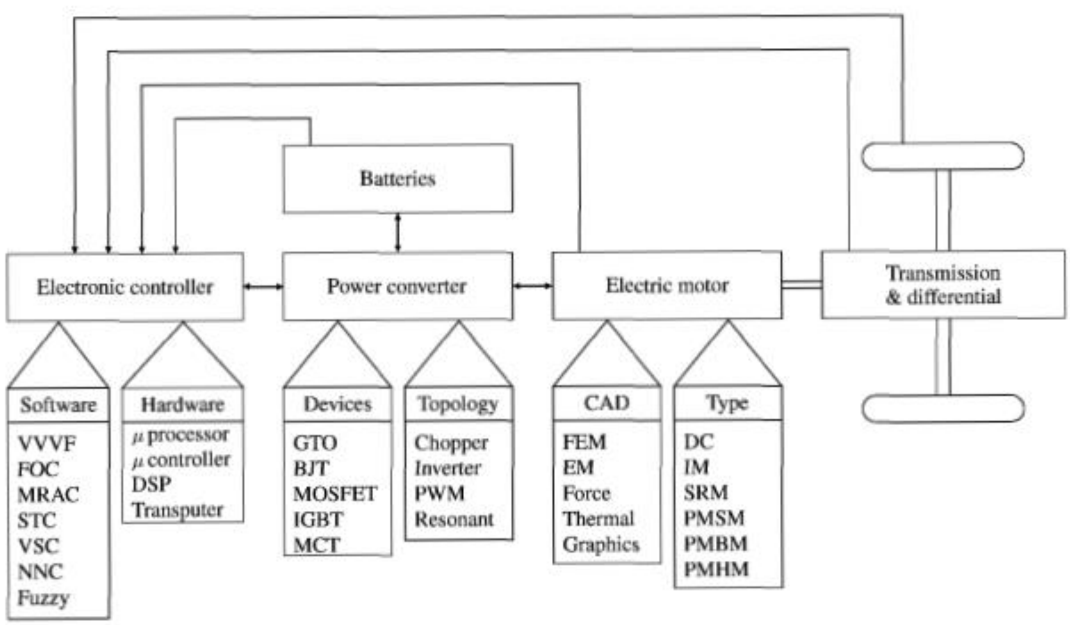

Fig. 5.1. Functional block diagram of an EV propulsion system.

Concept of EV motors

Some engineers and even researchers may consider EV motors kindred or similar to industrial motors. However, EV motors 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 motors are generally optimized at rated conditions. Thus, EV motors 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 motors need to offer the maximum torque that is four to five times of the rated torque for temporary acceleration and hill-climbing, while industrial motors generally offer the maximum torque that is twice of the rated torque for overload operation.
- EV motors need to achieve four to five times the base speed for highway cruising, while industrial motors generally achieve up to twice the base speed for constant-power operation.
- EV motors should be designed according to the vehicle driving profiles and drivers' habits, while industrial motors are usually based on a typical working mode.
- EV motors 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 motors generally need a compromise among power density, efficiency and cost with the efficiency optimized at a rated operating point.
- EV motors desire high controllability, high steady-state accuracy and good dynamic performance for multiple-motor coordination, while only special purpose industrial motors desire such performance.
- EV motors need to be installed in mobile vehicles with harsh operating conditions such as high temperature, bad weather and frequent vibration, while industrial motors are generally located in fixed places. Apart from satisfying the aforementioned special requirements, the design of EV motors also depends on the system technology of EVs. From the technological point of view, the following key issues should be considered:

(1) Single- or multiple-motor configurations-

One adopts a single motor to propel the driving wheels, while another uses multiple motors permanently coupled to individual driving wheels. The single-motor configuration has the merit of using only one motor which can minimize the corresponding size, weight and cost.

On the other hand, the multiple-motor configuration takes the advantages to reduce the current/power ratings of individual motors and evenly distribute the total motor size and weight. Also, the multiple-motor one needs additional precaution to allow for fault tolerance during the electronic differential action.

For instance, each motor may have its own controller which is controlled by a master controller. The functional block diagrams of single- and dual-motor configurations are shown in Fig. 5.2, while their comparison is listed in Table 5.1. Since these two configurations have their individual merits, both of them have been employed by modern EVs. For examples, the single-motor configuration has been adopted in the GM EV1 while the dual-motor configuration has been adopted in the NIES Luciole. Nevertheless, the use of single-motor configuration is still the majority today.

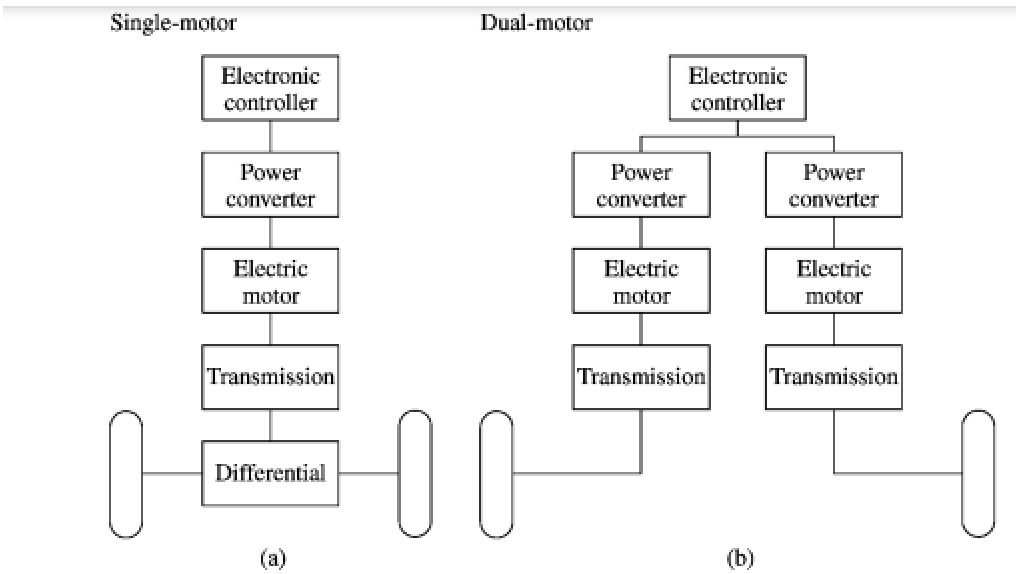

Fig. 5.2. Single- and multiple-motor configurations.

Table 5.1 Comparison of single- and dual-motor configurations

	Single-motor	Dual-motor
Cost	Lower	Higher
Size	Lumped	Distributed
Weight	Lumped	Distributed
Efficiency	Lower	Higher
Differential	Mechanical	Electronic

(2) Fixed- or variable-gearing transmissions-

It is also classified as single-speed and multiple-speed transmissions. The former adopts single-speed fixed gearing, while the latter uses multiple-speed variable gearing together with the gearbox and clutch.

Based on fixed-gearing transmission, the motor should be so designed that it can provide both high instantaneous torque (3 to 5 times the rated value) in the constant-torque region and high operating speed (3 to 5 times the base speed) in the constant-power region.

On the other hand, the variable gearing transmission provides the advantage of using conventional motors to achieve high starting torque at low gear and high cruising speed at high gear.

However, there are many drawbacks on the use of variable gearing such as the heavy weight, bulky size, high cost, less reliable and more complex. Table 5.2 gives a comparison of fixed-gearing and variable-gearing transmissions. Actually, almost all the modern EVs adopt fixed-gearing transmission

Table 5.2 Comparison of fixed- and variable-gearing transmissions

	Fixed-gearing	Variable-gearing
Motor rating	Higher	Lower
Inverter rating	Higher	Lower
Cost	Lower	Higher
Size	Smaller	Larger
Weight	Lower	Higher
Efficiency	Higher	Lower
Reliability	Higher	Lower

Geared or gearless-(geared and gearless in-wheel motor configurations)

The use of fixed-speed gearing with a high gear ratio allows EV motors to be designed for high-speed operation, resulting high power density.

The maximum speed is limited by the friction and windage losses as well as transaxle tolerance. On the other hand, EV motors can directly drive the transmission axles or adopt the in-wheel drive without using any gearing (gearless operation).

However, it results the use of low-speed outer-rotor motors which generally suffer from relatively low power density.

The breakeven point is whether this increase in motor size and weight can be outweighed by the reduction of gearing. Otherwise, the additional size and weight will cause suspension problems in EVs. Both of them have been employed by modern EVs.

The functional block diagrams of geared and gearless in-wheel motor configurations are shown in Fig. 5.3. For examples, the high-speed geared inner-rotor in-wheel motor has been adopted in the NIES Luciole while the low-speed gearless out-rotor in-wheel motor was adopted in the TEPCO IZA.

Nevertheless, with the advent of compact planetary gearing, the use of high-speed planetary-geared in-wheel motors is becoming more attractive than the use of low-speed gearless in-wheel motors.

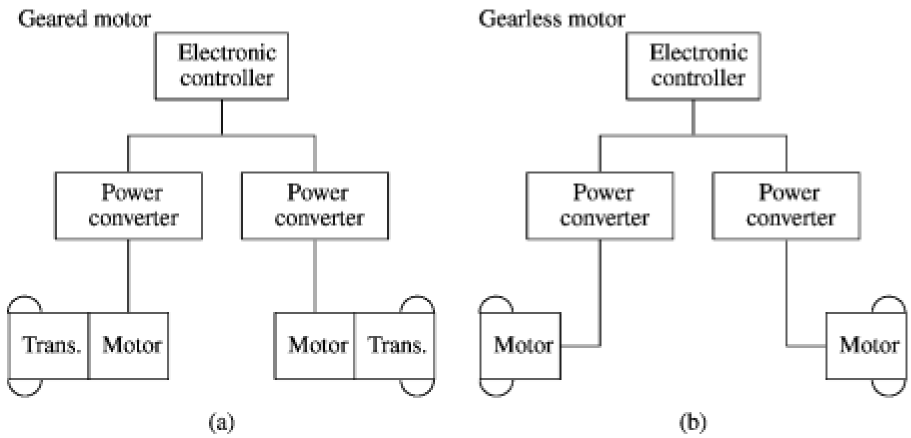

Fig. 5.3. In-wheel motor configurations.

Classification of EV 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 relatively slow.

Nevertheless, the development of motors is continually fueled by new materials, sophisticated topologies, powerful computer-aided design (CAD) as well as modern power electronics and microelectronics.

As illustrated in Fig. 5.4, those motors applicable to electric propulsion can be classified as two main groups, namely the commutator motors and commutatorless motors.

The former simply denote that they generally consist of the commutator, while the latter have no commutator.

Moreover, the shaded motor types indicate that they have ever been adopted by recent EVs. Table 5.3 also illustrates their recent applications to flagship EVs.

To keep up with the stringent requirement and fast changing motor topologies, the design of motors have turned to CAD. Basically, there are two major design approaches-circuit and field.

In essence, the circuit approach is based on equivalent circuit analysis while the field approach depends on electromagnetic field analysis. The field approach takes the advantages of more accurate results, greater knowledge of the critical areas as well as capabilities of handling complicated machine geometry and nonlinear materials. Recently, the finite element method (FEM) has been regarded as one of the most powerful tools for electromagnetic field analysis of EV motors.

The FEM outranks other numerical methods because of its flexibility and applicability in stress and thermal field analyses. Moreover, with the use of computer graphics, the analysis can be carried out visually and interactively.

The basic consideration of motor design includes magnetic loading-the peak of fundamental component of radial flux density in the air-gap of the motor, electric loading-the total r.m.s. current per unit length of periphery of the motor or ampere-turns per unit periphery, power per unit volume and weight, torque per unit volume and weight, flux density at each part of the magnetic circuit, speed, torque and power, losses and efficiency, and thermal design and cooling.

The corresponding key issues are better utilization of steel, magnet and copper, better electromagnetic coupling, better geometry and topology, better thermal design and cooling, understanding the limits on the motor performance, and understanding the relationship among geometry, dimensions, parameters and performance, thus to achieve higher power per unit weight, higher torque per unit weight and better performance.

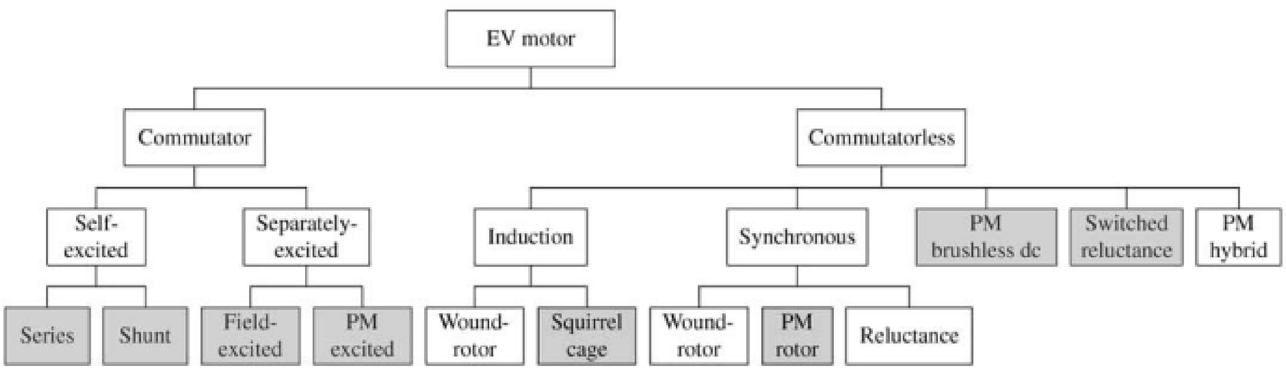

Fig. 5.4. Classification of EV motors.

Table 5.3 Applications of EV motors

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	PM synchronous motor
Nissan Altra	PM synchronous motor
Toyota RAV4	PM synchronous motor
Chloride Lucas	Switched reluctance motor

Recent EV 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. Actually, various types of dc motors, including series, shunt, separately excited and PM excited, have ever been adopted by recent EVs.

Recently, technological developments have pushed commutatorless motors to a new era, leading to take the advantages of higher efficiency, higher power density, lower operating cost, more reliable and maintenance-free over dc commutator motors.

As high reliability and maintenance-free operation are prime considerations for electric propulsion in EVs, commutatorless motors are becoming attractive. Induction motors are a widely accepted commutatorless motor type for EV propulsion because of their low cost, high reliability and free from maintenance.

However, conventional control of induction motors such as variable-voltage variable-frequency (WVF) 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.

Recently, an on-line efficiency-optimizing control scheme has been developed for these EV induction motors which 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, an electrically pole changing scheme has been developed for EV induction motors,which can significantly extend the constant-power operating region to over four times the base speed. By replacing the field winding of conventional synchronous motors with PMs, PM synchronous motors can eliminate conventional brushes, slip-rings and field copper losses.

Actually, these PM synchronous motors are also called as PM brushless ac motors or sinusoidal-fed PM brushless motors because of their sinusoidal ac current 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 PM synchronous 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 applications. Recently, a self-tuning control has been developed for PM synchronous motors which can enable them to achieve optimal efficiency throughout the operating region.

By virtually inverting the stator and rotor of PM dc motors, PM brushless dc motors are generated. Notice that the name containing the ‘dc’ term may be misleading, since it does not refer to a dc current motor.

Actually, these motors are fed by rectangular ac current, 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 PM synchronous motors, these PM brushless dc motors generally operate with shaft position sensors. Recently, a phased ecoupling PM brushless dc 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 greatly extend the constant-power operating range.

SR motors have been recognized to have considerable potential for EV applications. Basically, they are direct derivatives of single-stack variable-reluctance stepping motors.

SR motors have the definite advantages of simple construction, low manufacturing cost and outstanding torque-speed characteristics for EV propulsion. 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. Recently, an optimum design approach to SR motors has been developed 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 EV SR motors

so as to handle the motor non-linearity's and minimize the control chattering. Recently, a new research direction has been identified on the development of PM hybrid motors for EV applications.

In principle, there are many PM hybrids in which three of them have been actively investigated, namely the PM and reluctance hybrid, the PM and hysteresis hybrid, and the PM and field-winding hybrid. Firstly, by burying PMs inside the magnetic circuit of rotor, the PM synchronous motor can easily incorporate both PM torque and synchronous reluctance torque.

Table 5.4 Evaluation of EV motors

	Dc motor	Induction motor	PM brushless motor	SR motor	PM hybrid motor
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	22	26	25	23	23

In order to evaluate the aforementioned EV motor types, 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 5.4, this evaluation indicates that induction motors are relatively most acceptable. When the cost and maturity of PM brushless (including ac or dc) motors have significant improvements, these motors will be most attractive.

Conventional dc motors seem to be losing their competitive edges, whereas both SR and PM hybrid motors have increasing potentials for EV propulsion.

VEHICLE LOAD FACTORS

- Load factor i.e. how much of the capacity of the truck is used.
- For cars, buses and coaches, we use the term 'occupancy' while for vans and trucks we use 'load factor'.

- A high occupancy rate in passenger cars, buses and coaches has relatively little impact on overall vehicle weight. For freight, the relationship is more complex, as a higher load factor is likely to result in a significant increase in vehicle weight and therefore in more energy use and emissions.

Passenger vehicles occupancy:

- The occupancy of cars, buses and coaches can be indicated by the absolute values of passengers being transported by each vehicle type (e.g. average number of passengers) or the occupancy rate.
- Occupancy rates = passenger-kilometres / vehiclekilometres.

Load factor for goods transport:

- The load factor is the ratio of the average load to total freight capacity in tonnes.
- The load factor = the number of tonne-km / the number of vehiclekm

Example: Specifically, the load factor is the dimensionless ratio of passenger-kilometers travelled to seat-kilometers available. For example, say that on a particular day an airline makes 5 scheduled flights, each of which travels 200 kilometers and has 100 seats, and sells 60 tickets for each flight. To calculate its load factor:

$$\frac{(5 \text{ flights})(200 \text{ km/flight})(60 \text{ passengers})}{(5 \text{ flights})(200 \text{ km/flight})(100 \text{ seats})} = \frac{60,000 \text{ passenger} \cdot \text{km}}{100,000 \text{ seat} \cdot \text{km}} = 0.6 = 60\%$$

Thus, during that day the airline flew 60,000 passenger-kilometers and 100,000 seat-kilometers, for an overall load factor of 60% (0.6).

Vehicle Acceleration:

A car's acceleration is calculated when the car is not in motion (0 mph), until the amount of time it takes to reach a velocity of 60 miles per hour. This means that the initial velocity is zero and the final velocity is 60 miles per hour.

Acceleration Force:

If the velocity of the vehicle is changing, then clearly a force will need to be applied in addition to the forces. This force will provide the linear acceleration of the vehicle, and is given by the well-known equation derived from Newton's third law,

$$F_{la} = ma \qquad (8.4)$$

However, for a more accurate picture of the force needed to accelerate the vehicle we should also consider the force needed to make the rotating parts turn faster. In other

words, we need to consider rotational acceleration as well as linear acceleration. The main issue here is the electric motor – not necessarily because of its particularly high moment of inertia, but because of the higher angular speeds.

Referring to Figure 8.2, clearly the axle torque equals $F_{te}r$, where r is the radius of the tyre and Fte is the tractive effort delivered by the powertrain. If G is the gear ratio of the system connecting the motor to the axle and T is the motor torque, then we can say that

$$T = \frac{F_{te}r}{G} \quad \text{and} \quad F_{te} = \frac{G}{r}T \tag{8.5}$$

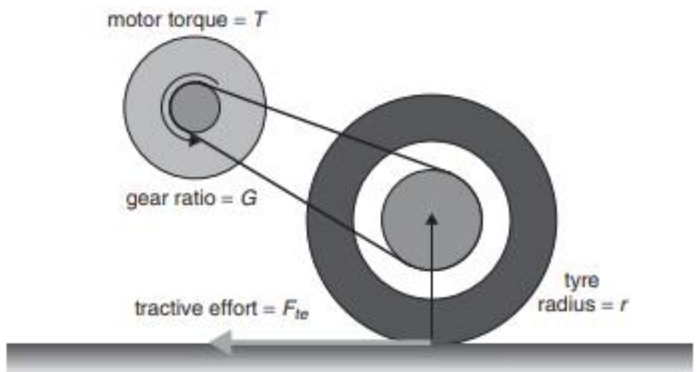

Figure 8.2 A simple arrangement for connecting a motor to a drive wheel

We will use this equation again when we develop final equations for vehicle performance. We should also note axle angular speed equals v/r radians per second, so motor angular speed is

$$\omega = G\frac{v}{r} \text{rad s}^{-1} \tag{8.6}$$

and, similarly, motor angular acceleration is

$$\dot{\omega} = G\frac{a}{r} \text{rad s}^{-2}$$

The torque required for this angular acceleration is

$$T = I \times G\frac{a}{r}$$

where I is the moment of inertia of the rotor of the motor. The force at the wheels needed to provide the angular acceleration ($F_{\omega a}$) is found by combining this equation with Equation (8.5), giving

$$F_{\omega a} = \frac{G}{r} \times I \times G\frac{a}{r} \quad \text{or} \quad F_{\omega a} = I\frac{G^2}{r^2}a \tag{8.7}$$