8. Key Considerations in EV Design and Operations

Kiruba Haran

Department of Electrical and Computer Engineering

University of Illinois at Urbana–Champaign
Electric Motors

Kiruba Haran

**Basic Principles of, and Design Considerations in, EV Electric Motors and Generators:** concepts of electromechanical energy conversion – energy, co-energy, force and torque; review of low-frequency electromagnetics (EM) and EM force calculations of shear stress, machine power density and efficiency; generator application requirements on torque–speed curve, constant power speed range; comparative assessment and equivalent circuits of motor types – induction, surface and internal permanent magnet, switched and synchronous reluctance
- Overview
- Requirements
- Technology Options
- Design Considerations
- Control
- Example
Electric Machine Applications

Transportation  Renewable Energy  Industry  Medicine
EV’s

“Loads”
- Aerodynamic drag
- Rolling friction
- Hill climbing
- Acceleration

Voltages
- Voltage
- Current

Electric Motor
- Torque
- Speed

Losses
EV Powertrain

Batteries → Power Converter → Motor → Driveline
Hybrids

Series-HEV

Parallel-HEV

Series-Parallel HEV

Mercedes Citaro bus, MAN-Lions City Hybrid bus, TEMSA Avenue Hybrid bus

Honda insight, Ford Escape Hybrid SUV, Lexus Hybrid SUV, Mercedes Citaro bus, MAN-Lions City Hybrid bus, TEMSA Avenue Hybrid bus

Nissan, Fiat, Toyota Prius
Drivetrain Integration

In-wheel motor assembly - Protean
Electrified Aircraft

Conventional

Turbo-Electric

Parallel Hybrid

Partial Turboelectric

Series Hybrid

Electric

Or hydrogen fuel cells

Boeing

NASA

https://dehavilland.com/

NASA

www.zunum.aero/

Airbus
Distributed Propulsion

Boeing 737

Electric Aircraft Concept (CHEETA)

Electric Bus

PE Converter

Motor

Gearbox

Propeller

Battery
Use EM fields to couple electrical with mechanical

EM fields defined in terms of forces

- Charge in Electric Field
- Current in magnetic field

The force $\mathbf{F}$ acting on a particle of electric charge $q$ with instantaneous velocity $\mathbf{v}$, due to an external electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$,

$$\mathbf{F} = q [\mathbf{E} + \mathbf{v} \times \mathbf{B}]$$

$q\mathbf{E}$ is the ”electric force”

$q\mathbf{v} \times \mathbf{B}$ is the ”magnetic force”
Electric versus magnetic

\[ \sigma_{ij} \equiv \varepsilon_0 \left( E_i E_j - \frac{1}{2} \delta_{ij} E^2 \right) + \frac{1}{\mu_0} \left( B_i B_j - \frac{1}{2} \delta_{ij} B^2 \right). \]

Permittivity of air, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \)
Breakdown in air, \( E_{\text{max}} \approx 3 \times 10^6 \text{ V/m} \)
Force density \( \sim 10^0 \text{ N/m}^2 \)

Permeability in air, \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \approx 1.257 \times 10^{-6} \text{ H/m or N/A}^2 \)
With ferromagnetic steel, practical flux density of \( \sim 1 \text{T} \)
Force density \( \sim 10^5 \text{ N/m}^2 \)
Torque Requirement

\[ F_{\text{wheels}} = F_{\text{accel}} + F_{\text{aero}} + F_{\text{rr}} + F_{g} \]

\[ P_{\text{wheels}} = F_{\text{wheels}} V_{\text{vehicle}} \]

\[ T_{\text{wheels}} = \frac{F_{\text{wheels}} V_{\text{vehicle}}}{2\pi N_{\text{wheel}}/60} \]
Drive cycle

![Graph showing drive cycle with vehicle speed on the vertical axis and time (sec) on the horizontal axis. The graph depicts acceleration/deceleration (m/sec^2) with values ranging from -2 to 2.]
Torque/Power vs speed capability of motors
Speed ratio & Speed–torque profile of a 60 kW electric motor
Losses

- Copper losses
  \[ P_{Cu} = RI^2 \]

- Iron Losses
  \[ P_{Fe} = \left( c_{hyst}f + c_{eddy}f^2 \right)B^2 + c_{excess}(fB)^{1.5} \]

- Mechanical Losses

- Stray losses

Fig. 2. Efficiency map of different electrical machines [19]

Efficiency maps

(a) double layers magnet IPMSM

(b) v-shaped magnets IPMSM

(c) PMa-SynRM.
Traction Motor Requirements

- High torque/power over wide speed range - High torque at low speeds for starting and climbing, as well as high power at high speed for cruising.
- High efficiency over broad speed and torque
- Easy to control
- Light weight and low moment of inertia - high power density.
- Capable of regenerative braking.
- Suppression of electromagnetic interface (EMI) of motor controllers
- High reliability and fault tolerance
- Low noise and vibration
- Low cost
Types of Machines

Electric motor family tree

Many Approaches!

http://www.allaboutcircuits.com/

https://youtu.be/dQKL1apu6LI
General Motors
Permanent Magnet Electric Motor

- Bearing Support Assembly
- Laminated Steel Rotor Core Sections
- Bar Wound Wire
- Steel Plate
- Rotor Hub
- Laminated Steel Stator Core
- Magnets
General Motors Induction Motor

- Rotor Hub
- Bearing Support Assembly
- Bar Wound Wire
- End Ring
- Laminated Steel Rotor Core
- Aluminum Bars
- Laminated Steel Stator Core
Reluctance machines
1. **Ampere’s Law**: a current-carrying conductor produces a magnetic field surrounding it

\[ \oint_c \mathbf{H} \cdot d\mathbf{l} = Ni \]

2. **Faraday’s Law**: the induced voltage in a circuit is proportional to the rate of change over time of the magnetic flux through that circuit

\[ e_{ind} = \frac{d\lambda}{dt} = N \frac{d\phi}{dt} \]

1. A current-carrying conductor in a magnetic field has a force induced on it (due to Lorentz Force)
   - *Basis for motor action*

---

DC Machines
\[ e_a = K_a \phi_d \omega_m \]

\[ e_a i_a = T_e \omega_m \]

\[ T_e = K_a \phi_d i_a = K_a \phi_d \left( v_a - K_a \phi_d \omega_m \right) / R_a \]

\[ \omega_m = \frac{(v_a - i_a R_a)}{K_a \phi_d} = \frac{(v_a - \frac{T_e}{K_a \phi_d} R_a)}{K_a \phi_d} \]
Control

Speed control:
- Flux control or voltage control

\[ E_a = V - I_a R_a = K_a \phi_d \omega \]
\[ \Rightarrow \omega = (V - I_a R_a)/K_a \phi_d \]

Torque Control:
- Armature current (I_a)

\[ P_{\text{mech}} = E_a I_a = K_a \phi_d \omega I_a \]
\[ \Rightarrow \text{Torque} = P_{\text{mech}}/\omega = K_a \phi_d I_a \]