ELECTRIC MOTORS FOR ELECTRIC AND HYBRID VEHICLES

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References

ELECTRIC AND HYBRID VEHICLES

- C.C. Chan and K.T. Chau. « Modern Electric Vehicle Technology » Oxford Science Technology. 2001.
- M. Ehsani, Y. Gao, S. Gay, and A. Amadi. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. Fundamentals, Theory, and Design. CRC Press. 2005.
- I. Husain. Electric and hybrid vehicles. Design fundamentals. Second edition. CRC Press. 2011.
- B. Multon. Motorisation des véhicules électriques. Les techniques de l'ingénieur. Dossier E 3 996.
- Michel Kant. La voiture électrique. Les techniques de l'ingénieur. Dossier D 5 560.
- Le véhicule électrique. Educauto. www.educauto.org

References

ELECTRIC TRACTION OF RAILWAY VEHICLES

 R. Kaller & J.-M. Allenbach. Traction électrique. Presses Polytechniques et Universitaires Romandes. Vol 1 et 2. 1995.

VEHICLE TECHNOLOGIES

 R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)

ELECTRIC MOTORS

T. Wilbi and G. Sybille. Electrotechnique. 4ème édition. De boeck. 2005

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Outline

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Outline

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INTRODUCTION



Introduction

- This lecture introduces electric traction motors and their application to electric and hybrid electric vehicles
- Three main components of electric traction machines:
 - Electric machine itself;
 - The related power electronics: continuous management of voltage, current intensity, frequency of electrical energy supplying the electric machine depending on the driving request;
 - The command itself that is necessary to optimize the operation efficiency.
- The powertrain architecture is treated in a separate lecture.

BASIC PRINCIPLES ACTING IN ELECTRIC MACHINES

Basic principles acting in electric machines

- The torque in electric machine is produced utilizing the basic principles of electromagnetic theory in one or two ways.
 - Mutual interaction of two orthogonal <u>magneto motive forces</u> (mmf) utilizing the Lorentz-Laplace force.
 - Using a <u>varying reluctance path</u> where the rotor moves towards attaining the minimum reluctance position.
- DC, AC synchronous and asynchronous machines, including permanent magnets (PM) machines work on principle 1
- Variable reluctance machines work on principle 2.

Basic principles acting in electric machines

- Electric machines:
 - Convert electrical energy to mechanical energy in motor mode
 - Convert mechanical energy towards electric energy in generators.
- Electric machines are <u>reversible machines</u>.
- Two basic phenomena responsible for energy conversion are acting <u>simultaneously</u> in electric machines:
 - 1/ Voltage is induced when a conductor moves in an electric field.
 - 2/ When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

Motional voltage

- Let a conductor I moving in a uniform magnetic field B at a velocity v.
- There will be a voltage induced in the conductor

$$E = (\vec{v} \times \vec{B}) \cdot \vec{l}$$

- The voltage induced is known as the motional voltage or speed voltage.
- It can also be evaluated using the Lentz Faraday law

$$E = -\frac{d\Phi}{dt} = -N \, \frac{d\phi}{dt}$$

Where N is the total number of turns

Motional voltage

 Let's consider the following situation describing a turn of conductor rotating within an induction field B:



The voltage in the conductor is

$$E = (\vec{v} \times \vec{B}) \cdot l\vec{e}_z = -\omega r B \cos \theta$$

Electro Motive Force (EMF)

- So as soon as the rotor is spinning there is creation of an induced voltage in the armature turns which is called Electro Motive Force (EMF).
- The EMF is proportional to the rotating speed.
- When the machine operates as a motor, the electromotive force is opposite to the applied voltage and the minus sign disappear. We are facing a Back Electro Motive Force (BEMF).

Electro Motive Force (EMF)

• Let's consider a conductor turn rotating between two magnets



$$E = (\vec{v} \times \vec{B}) \cdot L \, \vec{e_z} = -\omega \, r \, B \, L \, \cos \theta$$

The width of the turn is defined as W=2r. Since the turn is made of two conductors which are connected, the total voltage in the turn is:

$$E_T = -2\omega \frac{W}{2} L B \cos \theta$$

Electro Motive Force (EMF)

The result could have been recovered from Faraday's law. The surface offered by the turn in the direction of the field **B**



 $S(\theta) = W L \sin \theta$ $\Phi \ = S(\theta) \ B \ = \ W \ L \ B \ \sin \theta$

Faraday's law yields:

 $E_T = -\frac{d\Phi}{dt} = -W L B \cos \theta \dot{\theta}$

Using the peak flux value

 $\Phi_{MAX} = W L B$

$$E_T = -\omega \, \Phi_{MAX} \, \cos \theta$$

 The simple electric machine will produce sinusoidal voltage when rotated at constant speed in a uniform magnetic field.

$$E_T = -\omega \Phi_{MAX} \cos \theta$$



- The voltage can be rectified into a direct current to have a DC output. This is achieved using a pair of commutators and brushes attached at the end of the external circuit ports.
 - The <u>commutators</u> are attached to the end turns and rotate with the coil.
 - The <u>brushes</u> are positioned perpendicularly to the stator magnets pole. They are stationary and connected to the external circuit.







• Average voltage is also given by

$$\langle E \rangle = \frac{1}{\pi} \int_{\pi/2}^{3\pi/2} (-1)\omega \, \Phi_{MAX} \, \cos \omega t \, d(\omega t)$$
$$= \frac{\omega \, \Phi_{MAX}}{\pi} \, [\sin \omega t]_{\pi/2}^{3\pi/2} = \frac{2 \, \omega \, \Phi_{MAX}}{\pi}$$

ELECTROMAGNETIC FORCE

 Laplace force: a current carrying conductor placed in a magnetic field B experiences a force given by the Lorentz-Laplace equation:

$$\vec{F} = i \, \vec{l} \times \vec{B}$$



 Let's now calculate the forces and torque acting on a simplified electric machine



 $\vec{F}_1 = (i L \vec{e}_z) \times B \vec{e}_x = i L B \vec{e}_y$ $\vec{F}_2 = (-i L \vec{e}_z) \times B \vec{e}_x = i L B \vec{e}_y$

 Let's now calculate the forces and torque acting on a simplified electric machine



Using the maximum flux

$$T = \phi_{MAX} I \, \cos \theta$$

 Let's now calculate the forces and torque acting on a simplified electric machine



 This shows that the torque ripple of a simple electric motor with a single turn



Electric machine with switched reluctance

- In switched reluctance machine, the electromagnetic torque is related to the variation of the self inductance and mutual inductance of the turns as a function of their relative angular positions.
- The torque is given by the variation of the complementary magnetic energy of the system

$$T_{EM} = -\frac{dW_{EM}}{d\theta}$$



Electric machine with switched reluctance



ELECTRIC MOTOR

Principle of operation of DC motors

- A wire carrying a current i placed in a magnetic field B is subject to a force $\vec{F} = i \vec{dl} \times \vec{B}$
- When the wire is shaped into a coil, the magnetic forces produces a torque that tends to align the coil with the flux



 In order to obtain a continuous torque, it is necessary to invert the current direction when passing through mid plan. This is done by the brushes



The magnetic field can be produced by permanent magnets (PM motor) or by a set of winding (wound field motor).



- Depending on the mutual interconnection of the wound-field and armature circuits, one can distinguish 4 different types of DC machines:
 - Separately excited: wound-field is driven by an independent source of current.
 - Shunt DC motor: the wound and armature circuits are connected in parallel to the voltage source
 - Series DC motor: the wound and armature circuits are connected in series to the voltage source
 - Compound motor: the magnetomotive force (mmf) of a series field is a function of the armature current and is in the same direction as the mmf of the shunt field



The behavior of any DC motor is governed by the following equations:

$$E = K_e \Phi \omega_m$$

$$V_a = E + RI_a \qquad \Phi = L I_f$$

$$T = K_e \Phi I_a$$

- E, the electromotive force, V_a the armature voltage, R_a the armature resistance, I_a armature current
- K_e the electromotive constant or the torque constant
- I_f the field current and Φ the inducting flux
- $\omega_{\rm m}$, the rotation speed of the motor

Series DC Motor

- The DC motor is the simplest controller : the motor voltage is adjusted as a function of the current by adjusting the battery voltage or the on/off ratio or chopper frequency by means of a circuit breaker.
- For energy recovery: power controller requires additional components.
- As the armature current and wound current are in series, the drive power drops as the square of the rotation speed when a constant voltage is applied.




Series DC Motor

- Efficiency is moderate (~80%)
- Used mostly in trucks and industrial vehicles because of its moderate cost and of its simplicity
- For these applications, the low maximum speed allows nevertheless using a unique reduction ratio



- The magnetic excitation is regulated by a separate controller. One can reduce the wound field by a field variable resistance with a ratio of 1 to 4.
- Principle of control following two methods:
 - Control of armature current:
 - Constant torque operation
 - Speed is increased with armature voltage
 - Control of induction field (wound current)
 - Speed is increased by reducing wound voltage
 - Constant power operation



- Principle of control following two methods:
 - Control of armature current
 - Control of induction field (wound current)

- Below the base speed (acceleration phase), one restricts the current in the armature.
- The nominal power is obtained by a maximum armature current combined with a maximum motor voltage.
- Above the base speed, the wound current (induction field) is reduced and the motor output power is more or less constant.
- The commutation (brushes) becomes difficult when the inducing field is strongly reduced, the armature current must be reduced also over a the maximum speed and the power drops.



Control scheme of a DC motor with separated excitation



$$T = K_e \Phi I_a$$
$$\omega = \frac{V_a - RI_a}{K_e \Phi}$$

Control of armature voltage

- Reducing (increasing) the armature voltage leads to reducing (increasing) the armature current and so to reducing the torque and also to reducing (increasing) the rotation speed.
- The armature current being restricted and the induction field being fixed, the voltage control can maintain a constant torque
- This voltage control is limited up to the rotation speed corresponding to a point for which one reaches the nominal (max) power. Beyond this one the voltage can not be increased without exceeding the maximum power.



Field control

- Variation of wound voltage while keeping the armature voltage
 - If induction flux is reduced, the counter electromotive force is reduced too, and the armature current is increased. The motor accelerates to reestablish a counter electromotive force and keep the armature current at its maximum value.
- One can modify the rotation speed, while working at constant power
- Rotation speed is proportional to the inverse of the inducting flux and to the inverse of the inducting voltage
- Above the nominal voltage, it is possible to control the speed by playing with the field

- Because commutating poles are required, this design is more complex than that of series-wound motors.
- Because of more complex commutation, the rotation speed is often limited to more or less 7000 rpm
- This leads generally to adopt a multistage gear box to reduce the cost and the weight of the motor
- Regenerative energy during braking is possible without additional components.
- Carbon brushes must be periodically replaced albeit at relatively long intervals.

DC motor: series and separated excitation



DC series motor

DC motor with separated excitation

Moteurs électriques DC



Citroën Berlingo Electrique. courbes caractéristiques du moteur électrique.





- de 1600 à 5500 tr/min, la puissance du moteur est constante pendant que la valeur du couple chute.

AC motor principles



- A rotating magnet creates a rotating magnetic field that goes through a magnetic cylinder
- The sides of cylinder placed in the magnetic field behave like active wires. The driving currents are proportional to the flux variation, and they create forces that give rise to a torque
- One observes that the cylinder follows the magnet rotation with a certain slippage.

- The rotating permanent magnet is replaced by the stator winding fed by 3-phase AC current
- The 3-phase AC winding creates a spatially rotating field
- The rotor is inserted with highly conducting metal rods (copper or aluminum) in closed circuits to drive induction currents
- There are no brushes and no commutations
- Simple concept and simple manufacturing



- With 3 sets of winding arranged with a phase-shift of 120°, one has an AC induction machine adapted to high power and used in electric traction
- Two configurations are possible: star and triangle







Moteur asynchrone triphasé (principe)



- Let's consider a 3-phase current system
- With the spatial shift of stator windings, one creates a rotating magnetic field, with a rotation speed given by external supply voltage frequency
- If the frequency of the 3-phase current system is controlled, one drives the emotor rotation speed.
- The e-motor torque comes from the slippage between the rotation speeds of the stator magnetic field and the rotor ones. (Magnetic friction effect)
- By its nature, the efficiency of the induction motor is less than 100%











- Torque curve of AC asynchronous motor as a function of the slippage rotation speed
- Modification of torque curve of AC asynchronous motor when working at constant stator flux but variable frequency

- As for the separated excitation DC motors, the AC induction machines exhibit two regimes:
 - Constant max torque with a limitation of current
 - Constant power with reducing flux



Power electronic and control of AC machines



Working principle of an inverter



Fig-1.4 Torque-speed curves at variable voltage and variable frequency up to field-weakening region

Constant

torque

Torque



Moteur asynchrone triphasé (principe)



Montage étoile



Stator current Base speed

Constant

power

High

speed

Stator voltage

Torque-speed AC asynchronous motors

- Advantages
 - Cost is lower (no permanent magnetic in the rotor)
 - Robustness (the swirl cage is mechanically robust, no brushes)
 - Specific power (kW/kg) is high
 - Thermal management can be made by external system (air or water cooled to reduced the rotor losses)
 - High rotation speed (15.000 to 18.000 rpm)
 - Excellent reliability and low maintenance effort
- Drawbacks
 - Efficiency is around 90% but lower than permanent magnets emotors
 - Vector field command (I,V,f) is complex and costly



- AC induction machines are the simplest and the less expensive electric motor
- They are smaller and lighter than DC motors
- HOWEVER, the electronic control systems of 3-phase AC induction machines are much more complex
- As separated excitation DC machine, AC induction machine can work with reduced fields but also with variable frequency commutation
- As there is no mechanical commutation, the strong squirrel cage allows operating at rotation speeds up to 20.000 rpm
- One single gear ratio is often necessary.

- The conversion efficiency of induction machines is superior (~95%) than DC machines (~80%) but similar or less than AC synchronous machines with permanent magnets
- Energy recovery during braking is possible with a high efficiency





- The curve and the numbered points in this figure are explained as follows:
- (1) to (4) Speed range of the motor. Point (1) can be zero speed.
- (3) Base rating point for 100% base speed and voltage.
- (2) to (3) Constant torque range. Inverter provides constant volts per Hertz to ensure a constant level of motor air-gap magnetic field.
- (1) Torque at minimum speed, based on temperature consideration and voltage boost from (2) to (1) to compensate for stator winding IR drop.
- (3) to (4) Constant horsepower range, constant voltage.
- (4) Maximum operating speed.

- Historically AC synchronous machines were used as generators
- More recently, synchronous machines have shown as the rising star of electric traction drives for passenger cars
- Their command control laws are rather complex requiring a sophisticated power electronics
- Synchronous machines are also based on the principle of a rotating magnetic field generated by stator windings
- Induction field at the rotor level can be created using two main principles
 - Winding like in DC motors with commutation
 - Permanent magnets
- Rotor spins at the same rotation speed as the external stator magnetic field





Generation of a rotor magnetic field

- Winding (synchronous machine with wound rotor)
 - Modulation of rotor field using a chopper (like a DC machine)
 - Enable the optimized control at high speed
 - Electric commutation with the brushes and the chopper
 - Extra cost and lower reliability



Generation of a rotor magnetic field

- Permanent magnets (Synchronous machine with permanent magnets)
 - High conversion efficiency
 - High energy density (3kW/kg) and volumetric energy
 - Reliability and maintenance operation similar to induction machine





Generation of a rotor magnetic field

- Permanent magnets (Synchronous machine with permanent magnets)
 - Control is delicate: acceleration from rest, shocks at low rotation speed
 - It is possible to loose the permanent field in high flux operation and high temperature operations
 - Permanent magnets \rightarrow rare earth: raw materials?
 - Examples:
 - Neodymium Fer Bore (NdFeB)
 - Samarium Cobalt (SmCo)
 - Aluminium, Nickel, Cobalt (AlNiCo)

Permanent magnets materials







PM e-motors by UQM

- Synchronous AC motors make use of permanent magnets made of rare earth (e.g. CoSm) to create the rotor flux.
- Synchronous permanent magnets are characterised by a very high conversion efficiency even at part load (> 90%)
- Permanent magnets made of rare earth give rise to solutions combining a high specific power to a large torque per unit of mass.
- However resorting to permanent magnets increases the cost over induction machines.





PowerPhase[®] 125



AC motors: induction vs synchronous



AC induction motor
- For synchronous motor, it is not possible to work with reduced induction field as they are produced by permanent magnets
- One can nonetheless obtain a similar effect to reduce the effective torque components by increasing reactive current in the stator
- Generally one can use multiple gear reduction ratio because of small x= base speed / max speed ~2
- Example: THS2 motor of Toyota Prius 2

• Example: THS2 motor of Toyota Prius 2







AC motors: induction vs synchronous



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Comparison of electric motors



Courbes d'efficacité

- a/ Moteur DC à excitation séparée
- b/ Moteur AC synchrone à aimants permanants

Comparison of electric motors



Couple et puissance en fonction de la vitesse

a/ Moteur DC série b/ Moteur DC avec excitation indépendantes c/ Moteurs asynchrone triphasé d/ Moteur AC synchrone à aimants permanents

Comparison of electric motors



Comparison of electric motors and controllers

Parameters	DC motor	AC induction motor
Rotation speed control	voltage, flux	Voltage, frequency
Torque control	Current, flux	Current, slippage frequency
Speed range	4	2
Max speed	2	5
Specific power	2	3
Volume	4	5
Efficiency	4	5
Energy recovery	4	2
Manufacturing	2	5 ₈₁

5 = excellent 1 = bad

Comparison of electric motors and controllers

Parameters	DC motor	AC induction motor
Cooling	2	3
Robustness	2	5
Noise	5	5
Control simplicity	3	2
Price	1	2
Pollution	5	5
Maintenance	4	5
TOTAL (/70)	44	54

Remark: score of ICE : 21

Switched Reluctance e-Motors





Switched Reluctance e-Motors

SR motor basics (Only simplified cross-sections shown) Stator pole (6) Potor pole (4) Phase current Stator. Coil windings flaminated steel) Shaft Torque ø Rotor. (laminated) Independent. phase currents. steel-no-A. B. C not shown permanent macnets). (a) 1-phase SR motor (b) 3-phase SR motor (6/4 pole structure)

Source: Environ Motor Co., SRDnives division and Control Engineering

Switched Reluctance e-Motors



Power electronics



Working principle of a chopper

- The electronic converter called CHOPPER aims at modifying the voltage at the armature or at the wound circuit, and so to regulate the speed of the flux.
- The chopper chops the input voltage into a high frequency rectangular signal. When filtered the continuous component of this signal has linearly decreasing value with on/off frequency
- The converter works by modifying the working frequency
- Modifying the ratio T1(on)/T2(on+off) modulates the mean output voltage
- For separated excited DC motors, one needs two choppers, one for the armature and one for the wound field



- The resulting device is simple and economical
- Control of chopper is based a microprocessor.
- The command is generally realized in PWM: Pulse Width Modulation
- One major constraint is the restriction on motor and batteries temperature







PWM control of a DC motor



Four quadrants DC chopper: direct and reverse drive Motor and generator work



Figure 15 - Moteurs à courant continu à collecteur et à excitation séparée



Working principle of current inverter

- For electric traction, the inverter is an electronic converter from DC current (battery current) to 3-phase currents
- The output is a set of equilibrated 3-phase currents with a phase shift of de 2π/3 (120°) and variable frequency from 0 to 50 Hz.
- The type of converter is able to modify the frequency of the 3phase current and so to modify the rotation speed.
- This process allows a high power and a high conversion efficiency for a wide range of regimes.
- The frequency controls the rotation speed, while the voltage regulates the torque.





- This technology allows adapting eventually industrial AC motors (robust and less expensive) to electric traction applications.
- Inverters make possible to skip the gear box.
- One can also introduce in-wheel motors.
- Monitoring of the temperature is generally available as an extended functionality.



Electric motor performance curves



- At low speed: constant torque
 - Voltage supply increases with rotation speed through electronic converter while flux is kept constant
- At high speed: constant power
 - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed
- Base speed: transition speed from constant torque to constant power regime 100



- Independently from the motor technology, the global performance of the combined motor and its power electronic system offer three regimes
 - In low regimes, the current is limited and the torque is kept constant
 - Then, power remains constant, which means that the maximum torque is reduced as P/N
 - At very high speed: the max power regime can not be maintained and power drops. Generally this part is not considered in the EV design.



- Speed ratio x = ratio between the maximum rotation speed to base speed
 - X ~ 2 Permanent Magnet motors
 - X ~ 4 Induction Motors (IM)
 - X ~ 6 Switched Reluctance motors

For a given power, a long constant power region (large x) gives rise to an important constant torque, and so high vehicle acceleration and large gradeability. Thus the transmission can be simplified.

Continuous and discontinuous regimes

- One fundamental difference in the sizing of electric motor and ICE is the distinction of discontinuous regime and continuous regime.
- The discontinuous or temporary regime relates to performance during a short period. It is dominated by the maximum power that can be handled by the controller.
- The continuous regime is defined as the output of the system when working at least during half an hour for road vehicles. The limitation comes from the heating of the motor and by the maximum working temperature.

Continuous and discontinuous regimes

- Depending on the type of motor, electric motor can be overcharged by a factor 2 to 4.
- The power is ruled by the admissible power for the controller (thermal characteristics of controller, motor and batteries).
- The difference between short and long term is also coming into the measure of performances: for instance, the maximum speed: one distinguish maximum speed over a distance of 2*1 km and a maximum speed over a period of 30 minutes.



- Traction electric motors are able to sustain overcharging during a short period of time, typically 1 to 2 minutes.
- Overcharging factor depends on the electric motor technology but it can be as high as 2 to 4.
- Thus, one has also to distinguish the continuous power from the peak power (which is much higher)
- One can admit as a basic approximation that both regimes can be deduced from each other by constant scaling factor

Continuous and discontinuous regimes



 Electric machine efficiency of transformation of the electric power to mechanical power is dependent on the torque speed operating conditions

$$\eta_{e-M} = \frac{\mathcal{P}_{\text{MECA}}}{\mathcal{P}_{\text{ELEC}}}$$

- It can be mapped on the torque/power-speed space
- The efficiency mapping can be different when working as a motor (generally lower) than as a generator (often better)

