DEDICATION CEREMONY – MILESTONE PACINOTTI
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Evolution of the species: from the Pacinotti’s machine to the modern brushless motor drives

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Outline

- Pacinotti’s DC machine
- **1st Evolution Step:** Removing Mechanical Commutator
  - *Principle of Electronic Commutator*
- **2nd Evolution Step:** Reversing machine structure
  - *Early DC Machines with Electronic Commutator*
- **3rd Evolution Step:** Electronic commutator improvement
- **4th Evolution Step:** Converter-fed DC Motors with electronic commutator
- **5th Evolution Step:** Brushless DC Motor Drives
  - Advanced issues and applications
- **6th Evolution Step:** Brushless AC Motor Drives
  - Motivations, Advanced issues and applications
- Conclusions
Pacinotti’s DC machine


Brushed DC Machines based on this principle have been produced widely in the years and diffused all over the world. And they are still used!
1st Evolution Step

Removing Mechanical Commutator

The 1st step of the evolution was triggered by the arrival of the first power electronic switches, about 50 years ago. The replacement of the mechanical commutator with an electronic commutator was immediately envisaged.
Switch-based commutator

Two sets of switches (one connected to a positive ring and the other to the negative) may replace the brush-plates system (the mechanical commutator).
Scheme of Electronic Commutator

From:
Luigi Malesani et al, «DC Machine with Electronic Commmutator», Internal Report 68/08, Institute of Electrotechnical and Electronic Engineering, University of Padova, November 1968. (one century after the publication of Pacinotti’s paper)
2nd Evolution Step

Reversing machine structure

For feasibility reasons, armature winding and power switches have to be placed on the stator while the excitation winding is moved to the rotor.
Scheme of the prototyped machine

From:
Experimental Results

Measured voltage across two adjacent winding terminals (voltage across a winding section (i.e. a phase), almost trapezoidal)

Measured voltage across two opposite winding terminals
3rd Evolution Step

Electronic commutator improvement

From a practical point of view, it is preferable to reduce the number of “commutator plates”, that is the number of switches of electronic commutator. In addition, for a better exploitation of the switches, the closed winding typical of the DC machines can be transformed to an equivalent star connected winding.
From closed winding to star winding

Terminal current (Power switch current)

Winding current

Short conduction time
High current

Longer conduction time
Lower current

Only one positive and one negative switch conduct at a time

More positive and negative switches conduct simultaneously

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Converter-fed DC motor with electronic commutator

A DC motor with electronic commutator can be combined with a power converter (as an example a DC/DC converter) to control the armature voltage.
Converter-fed DC Motors with electronic Commutator

Full-bridge DC/DC converter

DC Motor with electronic commutator

PWM control

Commutation logic

Rotor Position
Converter-fed DC Motors with electronic Commutator

Full-bridge DC/DC converter

DC Motor with electronic commutator

A positive voltage is applied to the DC motor armature
Converter-fed DC Motors with electronic Commutator

Full-bridge DC/DC converter

DC Motor with electronic commutator

A voltage is applied to the DC motor armature

PWM control

Commutation logic

Phase off

Rotor Position

EDLab
Brushless DC (BLDC) Motor Drives

DC/DC converter and electronic commutator can be merged in a single power electronic converter (usually called “inverter”). The resulting system is the well-known Brushless DC Motor Drive (also BLDC Motor Drive)
Brushless DC Motor Drives

A positive voltage is applied to the DC motor

Brushless DC Motor Drive

Inverter

PWM Control & Commutation Logic

Phase off

Rotor Position

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A negative voltage is applied to the DC motor.

- Brushless DC Motor Drives
  - PWM Control & Commutation Logic
  - Phase off
  - Rotor Position

Inverter
Brushless DC Motor Drives

Zero crossing of the BEMF occurs while current is zero: \( \Rightarrow \) measurable for sensorless position detection.

\[ P = e_1i_1 + e_2i_2 + e_3i_3 = \text{constant} \]

\( \Rightarrow \) the torque is constant (*)

(*) Actual current/bemf waveforms cause torque ripple, which is mitigated by proper current profiles and/or rotor pole shaping.
Brushless DC Motor Drives

Excitation is normally done by Permanent Magnets (PM)

Applications are in the small and medium power range
- Pumps
- Ventilation
- Small home appliances
- Low power vehicles
- Portable tools
- etc

This is a special case of rotor that has interior PM and poles shaped in order to minimize torque ripple.
Brushless DC Motor Drives

Wheel motor

PM Outer rotor configuration

OUTER ROTOR INNER ROTOR
Alternative motor design for increasing power density

Inner stator

PM Outer rotor
6th Evolution Step

Brushless AC (BLAC) Motor Drives

Advances in three-phase current control, microprocessor capability together with increased demand in performance and power ratings have suggested machines with sinusoidal bemf and sinusoidal currents: Brushless AC Motors (also BLAC Motors). They can be also classified as Synchronous Motors and are used in the Synchronous Motor Drives.
Brushless AC Motor Drives

\[ P = e_1 i_1 + e_2 i_2 + e_3 i_3 = \text{constant} \]

\[ \implies \text{the torque is constant} \]

Back EMF

BLAC motor drives are not affected by torque ripple due to current commutation as the phase currents are continuous (sinusoidal) waveforms, synchronised with the sinusoidal bemf to get a constant three-phase power and torque. Position sensorless operations is a more challenging issue in this case.
Different rotor configurations are possible. They are intensively studied and continuously improved.

PM cost, torque density (Nm/m$^3$), efficiency, sensorless and flux-weakening capability are the figures normally chosen to be optimized.
Advance in BLAC Motor Drives

BLAC Motors with

IPM rotors (left and up)
and
Reluctance rotor (right)
Advances in BLAC Motor Drives

BLAC Motor Drives cover the full power range of the Variable speed applications

- Robotics
- Machine tools
- Automotive
- Aircraft
- Ship propulsion
- Energy (Wind, Hydro)

Tooth-wound stator for highest efficiency

Advanced control issues in BLAC motor drives

- Full speed range sensorless position detection by HF voltage injection and state observers.
- Predictive Control of torque/speed...
Conclusions

• Pacinotti’s machine has evolved over time by exploiting
  – Technological advancements,
  – High performance power electronic components,
  – Powerful digital processors,
  – High energy PM materials,
  – New Control engineering knowledge,
  – …..

….. to get to the actual BLDC and BLAC Motor Drives that are the cutting-edge solution for high efficiency, high performance home and industrial applications.

THANK YOU FOR YOUR ATTENTION!