HIGH-PERFORMANCE FULL-DIGITAL DRIVE
SYSTEM FOR HYBRID STEPPER MOTORS

PROF. AGGR. ROBERTO PETRELLA
roberto.petrella@uniud.it
OUTLINE OF THE PRESENTATION

- PRESENTATION OF THE EDLabUD
- OBJECTIVES AND MOTIVATION OF THE PROJECT
- HYBRID STEPPER MOTORS: STRUCTURE, OPERATION AND CONTROL
- HYBRID STEPPER MOTOR DYNAMIC MODEL
- FIELD-ORIENTED CONTROL OF HYBRID STEPPER MOTORS
- PWM STRATEGIES
- TECHNOLOGY DESCRIPTION
- EXPERIMENTAL RESULTS AND COMPARISON WITH CONVENTIONAL SYSTEMS
- FUTURE DEVELOPMENTS
OBJECTIVES AND MOTIVATION OF THE PROJECT
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OBJECTIVES:
development of a high-performance full-digital drive system for hybrid stepper motors

CHARACTERISTICS:
✓ power rating in excess of 500W with extremely compact design;
✓ full digital control by last generation digital signal controller;
✓ optimized and state-of-the-art power converter;
✓ standard half and microstepping or field oriented current control;
✓ standard incremental encoder feedback with FOC;
✓ magnetic encoder option with innovative automatic calibration algorithm;
✓ integration of PLC functions in the drive;
✓ full remote control via CANOpen communication bus;
✓ sensor-less control (in development).

ADVANTAGES:
✓ reduced noise and vibration with respect to standard stepper motor drives;
✓ higher torque-to-current ratio, wider torque-speed area, better dynamics;
✓ higher efficiency thanks to FOC control and closed-loop current/speed/position control;
✓ performance are comparable to those obtained with PM synchronous motor drives;
✓ increased reliability and flexibility;
✓ reduced costs and weight.
THEORY OF HYBRID STEPPER MOTOR: STRUCTURE, OPERATION AND CONTROL
Hybrid stepper motors combine the operating principles of **variable reluctance** with **permanent-magnet** stepper motors.

**ADVANTAGES:**
- rugged and simple construction;
- little maintenance;
- high torque at low speed;
- theoretically no need for position; or velocity feedback devices (200 steps/rev. typical);
- simple electronic driving solutions.

**DISADVANTAGES:**
- diminished torque at high speeds;
- resonance and noise;
- high consumption of current (even at standstill);
- relevant cogging torque (by construction);
- relatively low maximum operating speeds (about 1500 rpm).

Almost all can be attenuated by proper controller design.
Stator stack is normally **laminated** and wound with **bifilar windings** on each tooth.

Windings configurations is **chosen by the user** or **hard-wired** by the manufacturer.

**Multiple secondary teeth** are present on each stator tooth to increase the accuracy of positioning.

Ratio between number stator phases, rotor teeth and stator secondary teeth are chosen to obtain the required accuracy and torque/speed characteristics.
HYBRID STEPPER MOTOR: STATOR STRUCTURE

The 8 poles on the stator are displaced by 45 degrees.

Each pole face has 5 teeth spaced at 7.2 degrees intervals.
The hybrid rotor has **2 sets (stacks)** of laminations separated by a **permanent magnet**, with **axial flux**.

Each set of laminations has **50 teeth** and are offset from each other by **1/2 tooth pitch**.

This gives the rotor **50 north** and **50 south** poles at the rotor outer diameter.
HYBRID STEPPER MOTOR: TORQUE PRODUCTION

REAR STACK

FRONT STACK
**HYBRID STEPPER MOTOR:**

**MAIN PARAMETERS AND CHARACTERISTICS**

**HOLDING TORQUE:** the maximum steady torque that can be applied to the shaft of an energized motor without causing rotation.

**DETENT TORQUE:** the maximum torque that can be applied to the shaft of a non-energized motor without causing rotation.

**TORQUE/SPEED CHARACTERISTICS:** the torque/speed characteristics of a stepping motor are a function of the drive circuit, excitation method and load inertia.
**Hybrid Stepper Motor: Main Parameters and Characteristics**

**Maximum Slew Frequency:** the maximum rate at which the step motor will run and remain in synchronism.

**Maximum Starting Frequency:** the maximum pulse rate (frequency) at which an unloaded step motor can start and run without missing steps or stop without missing steps.

**Pull-out Torque:** the maximum torque that can be applied to the shaft of a step motor (running at constant speed) and not cause it to lose step.
**Hybrid Stepper Motor:**

**Main Parameters and Characteristics**

**Pull-in Torque:** the maximum torque at which a step motor can start, stop and reverse the direction of rotation without losing step. The maximum torque at which an energized step motor will start and run in synchronism, without losing steps, at constant speed.

**Slewing Range:** this is the area between the pull-in and pull-out torque curves where a step motor can run without losing step, when the speed is increased or decreased gradually. Motor must be brought up to the slew range with acceleration and deceleration technique known as ramping.
**HYBRID STEPPER MOTOR:**
**MAIN PARAMETERS AND CHARACTERISTICS**

**START-STOP RANGE:** this is the range where a stepping motor can start, stop and reverse the direction of rotation without losing step.

**ACCURACY:** This is defined as the difference between the theoretical and actual rotor position expressed as a percentage of the step angle. Standard is ±5%. An accuracy of ±3% is available on special request. This positioning error is noncumulative.
**HYSTERESIS ERROR:** this is the maximum accumulated error from theoretical position for both forward and backward direction of rotation.

**RESONANCE:** a step motor operates on a series of input pulses, each pulse causing the rotor to advance one step. In this time the motor’s rotor must accelerate and then decelerate to a stop. This causes oscillation, overshoot and vibration. There are some speeds at which the motor will not run. This is called its resonant frequency. The objective is to design the system so that no resonant frequencies appear in the operating speed range. This problem can be eliminated by means of using mechanical dampers, external electronics, drive methods and step angle changes.
**FULL STEP OPERATION OF HYBRID STEPPER MOTORS**

The 2-Phase Full Step system energizes both Phase A and Phase B and switches between positive and negative to create rotation.

Obtainable resolution is 1.8°/step with a standard 50 teeth rotor.

**ADVANTAGES:**
- simple driving circuit

**DISADVANTAGES:**
- standard resolution
- high vibration and noise (presence of resonance conditions)
Microstep drivers divide the basic step angle of the motor by decreasing the current to one phase while increasing the current to the next phase in increments. This results in the motor taking smaller steps.

With a microstep driver the motor’s basic step can be divided into smaller steps ranging from 1/1 to 1/250. Mechanical issues limit the maximum accuracy (e.g. to about 0.05°).

**Advantages:**
- higher resolution
- smoother operation (lower vibration and noise)

**Requirements/disadvantages:**
- continuous current control on each phase (sin/cos);
- high speed limitations.
**Microstepping Operation of Hybrid Stepper Motors**

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- $I_A 100\% I_B 0\%$
- $I_A 75\% I_B 25\%$
- $I_A 50\% I_B 50\%$
- $I_A 25\% I_B 75\%$
- $I_A 0\% I_B 75\%$
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<table>
<thead>
<tr>
<th>Current Distribution</th>
<th>I_A 100%</th>
<th>I_B 0%</th>
<th>I_A 75%</th>
<th>I_B 25%</th>
<th>I_A 50%</th>
<th>I_B 50%</th>
<th>I_A 25%</th>
<th>I_B 75%</th>
<th>I_A 0%</th>
<th>I_B 75%</th>
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<tbody>
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<td>Step 1</td>
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<td>Step 3</td>
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<td>Step 4</td>
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<td>Step 5</td>
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**Requirements:**
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TORQUE PRODUCTION MECHANISMS
TWO FUNDAMENTAL PRINCIPLES

- Two magnetic fields attract / repel one another
  - Biot-et-Savart law:
    - $\vec{F} = I \times \vec{B} \cdot L$ ($L$ length of wire)
  - Two magnetic fields are needed

- Magnetic field attracts ferromagnetic material
  - Minimum reluctance law
  - Hopkinson’s law: $NI = \mathcal{R}\Phi$
  - $\Phi = B \cdot S$

TWO BASIC PHENOMENA RESPONSIBLE FOR THIS ELECTROMECHANICAL ENERGY CONVERSION OCCUR SIMULTANEOUSLY IN ELECTRICAL MACHINES:

- when a conductor moves in an uniform magnetic field, there will be an induced voltage (motional voltage)
  \[ \bar{e} = (\bar{v} \times \bar{B}) \cdot \bar{l} \]

- alternatively, this is known as Faraday’s law of electromagnetic induction:
  \[ e = -\frac{d\lambda}{dt} = -N \frac{d\phi}{dt} \]

- For the conductor of length \( l \) moving with a uniform velocity in a magnetic field that is perpendicularly directed, the induced voltage is:
  \[ e = Blv \]
**TWO BASIC PHENOMENA RESPONSIBLE FOR THIS ELECTROMECHANICAL ENERGY CONVERSION OCCUR SIMULTANEOUSLY IN ELECTRICAL MACHINES:**

- When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force (Lorentz force):
  \[ \vec{f} = i \vec{l} \times \vec{B} \]

- The force in a magnetic field established by a pair of magnets as shown and a conductor of length \( l \) carrying current \( i \) is \( f = Bil \)
TORQUE PRODUCTION BASICS

CONTINUES ... (DISPENSE)
HYBRID STEPPER MOTOR DYNAMIC MODEL
ENERGETIC APPROACH FOR DYNAMIC MODEL CALCULATION

- Linear magnetic circuit is considered as a simplifying hypothesis: magnetic energy and co-energy are equal:

\[ W_c = W_e = \frac{1}{2} i^T L i \]
\[ i = [i_\alpha, i_\beta, i_f]^T \]

- \( i_\alpha \) and \( i_\beta \) are the winding currents in the two phases
- \( i_f \) is a constant fictitious current taking into account the flux produced by the permanent magnet in the rotor.

- Inductance matrix:

\[ L = \begin{bmatrix}
L_{aa} & L_{ab} & L_{af} \\
L_{ba} & L_{bb} & L_{bf} \\
L_{fa} & L_{fb} & L_{ff}
\end{bmatrix} \]

- \( L_{aa} \) and \( L_{bb} \) are the self-inductance of phases \( a \) and \( b \) respectively;
- \( L_{ab} = L_{ba} \) are the mutual inductances between the two windings;
- \( L_{af} \) and \( L_{bf} \) are the mutual inductances between the two windings and the fictitious rotor winding;
- \( L_{ff} \) is the self-inductance of this last winding.
ENERGETIC APPROACH FOR DYNAMIC MODEL CALCULATION

- All the terms of the inductance matrix are periodic functions of the rotor position $\theta$ and their frequencies can be deducted by the symmetries of the motor.

\[
L_{aa}(\theta) = L_0 + L_1 \cos(2N_r \theta)
\]
\[
L_{bb}(\theta) = L_0 - L_1 \cos(2N_r \theta)
\]
\[
L_{ab}(\theta) = L_1 \sin(2N_r \theta)
\]
\[
L_{af}(\theta) = L_{m0} + \sum_{j=1}^{n} L_{mj} \cos(jN_r \theta)
\]
\[
L_{bf}(\theta) = L_{m0} + \sum_{j=1}^{n} L_{mj} \sin(jN_r \theta)
\]
\[
L_{ff}(\theta) = L_{f0} + \sum_{j=4}^{n} L_{fj} \cos(jN_r \theta)
\]

- Inductance matrix:

\[
L = \begin{bmatrix}
L_{aa} & L_{ab} & L_{af} \\
L_{ba} & L_{bb} & L_{bf} \\
L_{fa} & L_{fb} & L_{ff}
\end{bmatrix}
\]

- $N_r$ is the number of rotor teeth and $n$ is the number of the harmonics considered in the model of the motor torque.

- Higher order harmonics ($n \geq 2$) in the mutual inductance terms $L_{af}$ and $L_{bf}$ model the non-sinusoidal flux distribution in the airgap (with respect to rotor angle).

- $L_{aa}$ and $L_{bb}$ are the self-inductance of phases $a$ and $b$ respectively;
- $L_{ab} = L_{ba}$ are the mutual inductances between the two windings;
- $L_{af}$ and $L_{bf}$ are the mutual inductances between the two windings and the fictitious rotor winding;
- $L_{ff}$ is the self-inductance of this last winding.
**HSM Dynamic Model**

**Electromagnetic Torque:**
- derivative of the magnetic co-energy (or energy in this case) with respect to the rotor position $\theta$:

$$
\tau_{em} = \frac{\partial W_c}{\partial \theta} \bigg|_{i=\text{const}} = \frac{1}{2} i^T \frac{\partial L}{\partial \theta} i
$$

$$
= \frac{\partial L_{af}}{\partial \theta} i_a i_f + \frac{\partial L_{bf}}{\partial \theta} i_b i_f + \frac{1}{2} \frac{\partial L_{aa}}{\partial \theta} i_a^2 + \frac{1}{2} \frac{\partial L_{bb}}{\partial \theta} i_b^2 + \frac{\partial L_{ab}}{\partial \theta} i_a i_b + \frac{1}{2} \frac{\partial L_{ff}}{\partial \theta} i_f^2
$$

- $\tau_{PM}$ is the torque component generated by the interaction between the magnetic fields produced by the stator windings and the permanent magnet;
- $\tau_{VR}$ is the reluctance torque and depends on the variations in the self and mutual inductances of the windings mainly due to saliency effects and geometric imperfections;
- $\tau_{CG}$ is the cogging (or detent) torque, and it is mainly due to variations in the self-inductance of the fictitious rotor winding caused by the presence of stator slots; cogging torque is present even in absence of windings currents and its periodicity is directly related to that of stator slots. Thus it is a function of the rotor position due to the variable reluctance paths of the permanent magnet flux.
HSM Dynamic Model

Ideal HSM Model: Simplifying Hypothesis

\[ L_{aa} = L_{bb} = L_0, \quad L_{ab} = L_{ba} = 0, \quad L_{mj} = 0 \quad j \geq 2 \]

- Phase inductance is constant (i.e. \( L_1 = 0 \), rotor saliency can be neglected);
- The two phases are magnetically decoupled;
- The surface of stator and rotor teeth are shaped so that the magnetic flux in the air gap is almost sinusoidal.

- Corresponding torque components become:
  \[
  \tau_{PM} = -i_a i_f L_{m1} N_r \sin(N_r \theta) + i_b i_f L_{m1} N_r \cos(N_r \theta) \\
  \tau_{VR} = 0 \\
  \tau_{CG} = -\frac{1}{2} \sum_{j=4}^{n} L_{fj} j N_r \sin(N_r \theta) i_f^2
  \]

- A second approximation can be introduced, i.e. cogging torque can be neglected (\( L_{fj} = 0 \quad j \geq 4 \)), with the aim of obtaining a model that can be simply compared to the two-phase stationary reference frame \( \alpha \beta \) model of non-salient two-phase PMSMs, leading to:
**HSM Dynamic Model**

**Ideal HSM Model: Simplifying Hypothesis**

\[ \tau_{em} = \tau_{PM} = \frac{N_r i_f L_{m1}}{K_t} \left[ i_b \cos(N_r \theta) - i_a \sin(N_r \theta) \right] \triangleq pp \left( \lambda_\alpha i_\beta - \lambda_\beta i_\alpha \right) \]

\[ = pp \Lambda_{mg} \left[ \cos(\theta_m) i_\beta - \sin(\theta_m) i_\alpha \right] \]

- where \( K_t \) is the torque (or voltage) constant, \( pp \) and \( \Lambda_{mg} \) are respectively the number of pole pairs and permanent magnet flux linkage amplitude of the equivalent PMSM.

\[ N_r = pp \quad i_f L_{m1} = \Lambda_{mg} \]

- i.e. the simplified model of HSM is equivalent to the one of PMSM having \( N_r \) pole pairs and \( i_f L_{m1} \) permanent magnet flux linkage amplitude

- where \( R_s \) and \( L_s \) are phase resistance and inductance respectively, \( \omega_m \) it the mechanical rotor speed.

- where \( U_{\alpha\beta}, I_{\alpha\beta}, E_{\alpha\beta} \) are the space vectors of the stator voltage, stator current and back-EMF respectively.
FIELD ORIENTED CONTROL OF HYBRID STEPPER MOTORS
FIELD ORIENTED CONTROL OF HYBRID STEPPER MOTORS

**Motivation:**
maximize the torque-to-current ratio by a proper control of the motor.

**Advantages:**
- instantaneous control of electromagnetic torque is possible \( \rightarrow \) **noise reduction**;
- max torque-to-current ratio \( \rightarrow \) excellent **dynamical performance** and **higher efficiency**;
- smooth (sinusoidal) current shape \( \rightarrow \) **noise reduction** and **less EMI issues**.

**Requirements:**
- measurement of rotor position and phase currents;
- complex control algorithms \( \rightarrow \) **high performance processing** is needed.
FIELD ORIENTED CONTROL OF HYBRID STEPPER MOTORS:
STATIONARY REFERENCE FRAME MODEL

FOC BASICS:
- motor model equations are taken into account (voltage and electromagnetic torque) in the stationary reference frame (motor phase reference frame);

VOLTAGE EQUATIONS:

\[
\frac{di_\alpha}{dt} = \frac{1}{L} [u_\alpha - Ri_\alpha + K_m \omega_m \sin(N_r \theta_m)]
\]

\[
\frac{di_\beta}{dt} = \frac{1}{L} [u_\beta - Ri_\beta + K_m \omega_m \cos(N_r \theta_m)]
\]

ELECTROMAGNETIC TORQUE EQUATION:

\[
\tau_{em} = K_m \omega_m \cos(N_r \theta_m) i_\beta - K_m \omega_m \sin(N_r \theta_m) i_\alpha
\]

MECHANICAL MODEL:

\[
J \frac{d\omega_m}{dt} = \tau_{em} - \tau_l - B \omega_m
\]

Measurement of phase currents is needed
FIELD ORIENTED CONTROL OF HYBRID STEPPER MOTORS: SYNCHRONOUS REFERENCE FRAME MODEL

FOC BASICS:
- a proper rotating reference frame is considered to simplify torque equation (aligned with rotor permanent magnet flux direction, synchronous reference frame);

VOLTAGE EQUATIONS:
\[ \frac{d i_d}{dt} = \frac{1}{L} [u_d - R_i + N_r L \omega_m i_q] \]
\[ \frac{d i_q}{dt} = \frac{1}{L} [u_q - R_i - N_r L \omega_m i_d - K_m \omega_m] \]

ELECTROMAGNETIC TORQUE EQUATION:
\[ \tau_{em} = K_m i_q \]

MECHANICAL MODEL:
\[ J \frac{d \omega_m}{dt} = \tau_{em} - \tau_l - B \omega_m \]

Torque equation is simple!
Measurement of rotor position is needed
**FIELD ORIENTED CONTROL OF HYBRID STEPPER MOTORS:**

**CONTROL SCHEME**

**FOC BASICS:**
- cascaded current/speed (/position) control is considered.
Digital controller
DC-bus
switching commands
position transducer
grid power input
diode rectifier
DC-bus
3-phase IGBT inverter
motor phase outputs
stepper motor
current sensing
voltage sensing
switching commands
external I/O
Digital controller
A/D
D/A
D/A
I/F
PWM STRATEGIES
PWM STRATEGIES

**Motivation:**
reduction of power electronics requirements and costs with respect to classical H-bridge

**Possible Solution:**
adoption of standard three-phase inverter

**Advantages:**
fewer switches (and drive circuits) are needed

the same drive hardware can be adopted for two- and three-phase machines, leading to a more flexible motor drive
PWM STRATEGIES

**Calculations:**

- The conduction state of each power switch is associated to the (six) binary variables $s_{uh}, s_{ul}, s_{vh}, s_{vl}, s_{wh}, s_{wl}$, assuming values in the set $[0; 1]$, with 0 meaning that the corresponding switch is open;
- The two switching state pairs of the same leg (e.g. $s_{uh}$ and $s_{ul}$) are complementary, i.e. $s_{uh} = 1 - s_{ul}$, etc.;
- The motor windings voltage can be expressed as a function of the state of each leg and dc bus voltage $U_{dc}$, i.e.:

$$
\begin{align*}
    u_a &\triangleq u_{AN} = u_A - u_N = u_{AO} - u_{NO} = u_{uO} - u_{wO} \\
    &\quad = (s_{uh} - s_{wh})U_{dc} \\
    u_b &\triangleq u_{BN} = u_B - u_N = (s_{vh} - s_{wh})U_{dc} \\
    u_N &\triangleq u_{NO}
\end{align*}
$$

- In matrix form:

$$
\begin{bmatrix} u_a \\ u_b \\ u_N \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{uO} \\ u_{vO} \\ u_{w0} \end{bmatrix} \triangleq T \begin{bmatrix} u_{uO} \\ u_{vO} \\ u_{w0} \end{bmatrix}
$$

Hybrid Stepper Motor

3-phase IGBT inverter
**PWM STRATEGIES**

**REMARKS:**

- in this case the inverter sees a non-balanced load, differently from a standard three-phase load;

- the instantaneous (and average) voltage of the common motor terminal $N$ can be directly selected by modulating the third inverter leg voltage $u_{wo}$ and represents a degree of freedom for a convenient PWM modulation strategy, as it will be discussed hereafter;

- the obtainable phase voltages for all the 8 possible states of the three-phase inverter legs can be obtained very easily:

<table>
<thead>
<tr>
<th>$s_{uh}$</th>
<th>$s_{vh}$</th>
<th>$s_{wh}$</th>
<th>$u_a$</th>
<th>$u_b$</th>
</tr>
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<tbody>
<tr>
<td>0</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>$U_{dc}$</td>
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<td>$U_{dc}$</td>
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<td>$-U_{dc}$</td>
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<td>$-U_{dc}$</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$-U_{dc}$</td>
</tr>
</tbody>
</table>
**PWM STRATEGIES**

**REMARKS:**

- Winding voltages can be represented in the complex αβ plane (as shown in right figure), and adjacent vectors space vector PWM can be derived as for three-phase motors, on the basis of the average voltage during one modulation period;

- Inversion of (.) allows to calculate the inverter output voltages $u_{ao}, u_{vo}$ and $u_{wo}$ as a function of the required windings phase voltage $u_a$ and $u_b$, and of the additional voltage $u_N$, as follows:

\[
\begin{bmatrix}
  u_a \\
  u_b \\
  u_N
\end{bmatrix} =
\begin{bmatrix}
  1 & 0 & -1 \\
  0 & 1 & -1 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  u_{uo} \\
  u_{vo} \\
  u_{wo}
\end{bmatrix} \triangleq T
\begin{bmatrix}
  u_{uo} \\
  u_{vo} \\
  u_{wo}
\end{bmatrix} \Rightarrow
\begin{bmatrix}
  u_{uo} \\
  u_{vo} \\
  u_{wo}
\end{bmatrix} = U_{dc}
\begin{bmatrix}
  \delta_u \\
  \delta_v \\
  \delta_w
\end{bmatrix} = T^{-1}
\begin{bmatrix}
  u_a \\
  u_b \\
  u_N
\end{bmatrix} =
\begin{bmatrix}
  1 & 0 & 1 \\
  0 & 1 & 1 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  u_a \\
  u_b \\
  u_N
\end{bmatrix}
\]

- Where $\delta_u$, $\delta_v$ and $\delta_w$ are the duty cycles of each leg.

<table>
<thead>
<tr>
<th>$s_{uh}$</th>
<th>$s_{vh}$</th>
<th>$s_{wh}$</th>
<th>$u_a$</th>
<th>$u_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$U_{dc}$</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$U_{dc}$</td>
<td>$U_{dc}$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$U_{dc}$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$-U_{dc}$</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$-U_{dc}$</td>
<td>$-U_{dc}$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$-U_{dc}$</td>
</tr>
</tbody>
</table>
PWM STRATEGIES

**CHOICE OF COMMON MODE VOLTAGE:**

- Voltage $u_N$ can be arbitrarily chosen in order to maximize the inverter dc bus utilization:
  - If constant $\delta_w = 0.5$ is chosen, i.e. average $u_N = \frac{U_{dc}}{2}$, a standard sinusoidal PWM is obtained and the operating region in the complex voltage plane is the smaller one in figure, having a radius of 50% of the dc bus voltage;
  - If $\delta_w$ is properly chosen and dynamically changed as a function of the required voltage space vector, SVPWM is obtained and the wider area in figure can be exploited in linear conditions, having a radius of about 70% of the available dc bus voltage, i.e. about 20% increase with respect to SPWM;
  - Over-modulation allows to extend the output voltage by the introduction of low-frequency unwanted harmonics.

- Selection of common mode voltage $u_N$ is done in a similar way as in conventional three-phase inverter/load:

  $$ u_N = 0.5 \cdot [U_{dc} - (u_{max} - u_{min})] $$

  $$ u_{max} = \max\{u_a, u_b, 0\}, \; u_{min} = \min\{u_a, u_b, 0\} $$
TECHNOLOGY DESCRIPTION
**DIGITAL CONTROL IMPLEMENTATION:**
**DIGITAL SIGNAL CONTROLLER**

**FEATURES:**
- high performance 32bit fixed-point Digital Signal Processor 60MHz;
- specific peripherals for electric drives and power electronics control (e.g. high-speed multi-channel ADC, PWM generation, CAN communication, etc.)

**ADVANTAGES:**
- high-performance FOC control implementation (low sampling period, i.e. 50 μs)
- high-reliability, efficiency and low cost;
- small package (10 x 10mm) and low weight;
- embedding of some PLC functions of the machine.
**POWER CONVERSION:**

**INTELLIGENT POWER MODULE**

**FEATURES:**

adoption of standard 3-phase high-voltage IGBT Intelligent Power Module

**ADVANTAGES:**

- less power switches are needed;
- high efficiency due to reduced parasitics;
- high integration \(\rightarrow\) integrated gate drivers and protections;
- high voltage \(\rightarrow\) reduction of power supply cost and requirements;
- high reliability \(\rightarrow\) ruggedness and integrated protections;
- very low cost due to integration;
- integration \(\rightarrow\) less parasitics \(\rightarrow\) lower EMI issues
- small package and low weight.

**REQUIREMENTS:**

- proper modulation algorithm is required;
- optimization allows output voltage maximization.
**POSITION FEEDBACK: MAGNETIC ENCODER**

**STRUCTURE:**
- A small magnet (6mm diameter) is embedded into the rear shaft of the motor;
- A “sensing” and “processing” chip (5.3 x 6.2mm) is positioned on the magnet axis.
MAGNETIC ENCODER
**Magnetic Encoder**

**Advantages:**
- High resolution (i.e. 4096 imp/rev)
- Small size and weight;
- Low cost;
- Proprietary product;
- Possibility for integrated drive.

**Disadvantages:**
- Mechanical assembly must guarantee accurate air gap and alignment with respect to the magnet;
- Accuracy is limited (i.e. ±0.9 mechanical degrees)

For a 50 pole pairs this leads to ±45 electrical degrees error range

FOC is not possible !?
EXPERIMENTAL RESULTS AND COMPARISON WITH CONVENTIONAL SYSTEMS
EXPERIMENTAL COMPARISON:
MICROSTEPPEING AND FIELD ORIENTED CONTROL

VIDEOS:
- Experimental setup
- Microstepping control @500 rpm
  - performance;
  - power consumption.
- FOC control @500 rpm
  - performance;
  - power consumption.
- FOC control @1000 rpm
EXPERIMENTAL RESULTS ON THE LABELLING MACHINE

TRANSIENT 0-890-0 rpm (15ms RAMP)

Motor Speed

890 rpm

Phase Current

~ 7.5 A

distribuz.etichetta 250mm RPM_890 Vac_230 RMPACC_15ms
EXPERIMENTAL RESULTS ON THE LABELLING MACHINE

TRANSIENT 0-890 RPM (15MS RAMP) ZOOM

Motor speed

890 rpm

15 ms

Phase current

~ 7.5 A

distribuz. etichetta 250mm RPM_890 Vac_264 RMPACC_15ms
EXPERIMENTAL RESULTS ON THE LABELLING MACHINE

FAST LABELLING 0-890-0 RPM (10MS ACCELERATION, 15MS DECELERATION)
RESULTS:
STEPPER COST AND SERVO PERFORMANCE!
FUTURE DEVELOPMENTS
**FUTURE DEVELOPMENTS: SENSOR-LESS CONTROL**

Removal of position/speed sensor and **real-time estimation** through the microcontroller

- **lower cost and increased reliability**

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**Diagram Description**

- **Diode rectifier**
  - Grid power input
  - DC-bus

- **3-phase IGBT inverter**
  - Motor phase outputs
  - Current sensing

- **Digital controller**
  - External I/O
  - Voltage sensing

- **Stepper motor**
  - Position transducer

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**Key Components**

- **D/A (Digital to Analog)**
- **A/D (Analog to Digital)**
- **I/F (Input/Output)**
FUTURE DEVELOPMENTS: SENSOR-LESS CONTROL

SENSOR-LESS CONTROL
removal of position/speed sensor and real-time estimation through the digital control system → lower cost and increased reliability
Types of Stepper Motors
Motor lead configurations

4-lead

5-lead

6-lead

8-lead