A Low Cost Sensorless Drive for Hybrid Stepper Motors Based on Back-EMF Observer and d-Axis Current Injection for Industrial Labelling Machines

Andrea Antonioli, Michele Antonioli
Elta Elettronica SRL, S.Giovanni Lupatoto (VR), Italy

Sandro Calligaro, Roberto Petrella
DIEGM – University of Udine, Udine, Italy

Abstract

- Rare-earth cost makes high-quality PMSMs prohibitive in mid-performance applications
- Hybrid stepper motors have high torque density and much lower cost
- Classical **stepping or microstepping shows low robustness** (vs. load variations, resonance)
- Modelling the **stepper motor** as a **special case** of **PMSM**
  - **Vector control** similar to a common brushless servo motor
- Back-EMF based sensorless control
  - Minimum power **consumption** and **heat** generation
  - High-performance **dynamics**
  - Audible **noise** reduction
- Use of low-cost **three-phase** high-voltage **IGBT module**
- Application to industrial **fast labelling machine**

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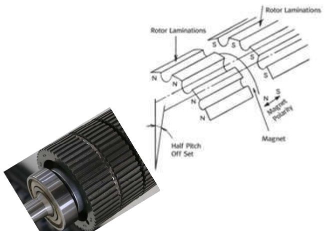
Synchronous Model of Stepper Hybrid Motor

- **From stepper motor model to PMSM equivalent**

$$\tau_{em} = \tau_{PM} = \underbrace{N_r i_f L_{m1}}_{K_\tau}[i_b\cos(N_r\theta) - i_a\sin(N_r\theta)] \triangleq pp(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha)$$

$$= pp\Lambda_{mg}[\cos(\theta_{me})\, i_\beta - \sin(\theta_{me})\, i_\alpha]$$

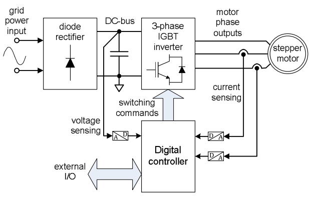
$$\begin{cases} u_\alpha = R_s i_\alpha + L_s\frac{di_\alpha}{dt} - \underbrace{\underbrace{\omega_m N_r}_{\omega_{me}}\underbrace{i_f L_{m1}}_{\Lambda_{mg}}\sin(N_r\theta)}_{\lambda_{mg,\beta}} \\ u_\beta = R_s i_\beta + L_s\frac{di_\beta}{dt} + \underbrace{\omega_m N_r i_f L_{m1}\cos(N_r\theta)}_{\lambda_{mg,\alpha}} \end{cases}$$

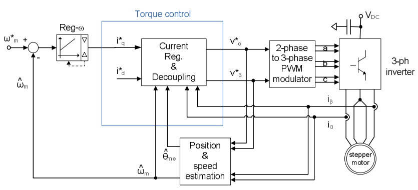


$$\boldsymbol{u_d = Ri_d + L_s\frac{di_d}{dt} - \omega_{me}L_s i_q}$$
$$\boldsymbol{u_q = Ri_q + L_s\frac{di_q}{dt} + \omega_{me}L_s i_d + \omega_{me}\Lambda_{mg}}$$

Sensorless Control Scheme

- **Three-phase inverter operating from rectified 230 Vac grid voltage**
- **Two-phase modulation**
- **Back-EMF observer** in the **stationary** $\alpha\beta$ reference frame
- Constant **non-null $\hat{d}$-axis current** for stabilization





Back-EMF based Estimation

- **Stationary frame back-EMF observer**

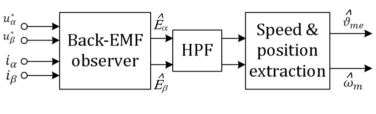
$$s\hat{\boldsymbol{I}}_{\alpha\beta} = \frac{1}{L_s}\left(\boldsymbol{U}^*_{\alpha\beta} - R_s\hat{\boldsymbol{I}}_{\alpha\beta} - \hat{\boldsymbol{E}}_{\alpha\beta}\right) + K_1\left(\boldsymbol{I}_{\alpha\beta} - \hat{\boldsymbol{I}}_{\alpha\beta}\right)$$

$$s\hat{\boldsymbol{E}}_{\alpha\beta} = j\tilde{\omega}_{me}\hat{\boldsymbol{E}}_{\alpha\beta} + K_2\left(\boldsymbol{I}_{\alpha\beta} - \hat{\boldsymbol{I}}_{\alpha\beta}\right)$$

- **Estimation transfer function**

$$\frac{\hat{\theta}_{me}}{\theta_{me}} = \frac{1}{1 - s^2 \frac{L_{SS}}{K_2} - s\left(\frac{R_S}{K_2} + \frac{K_2}{K_1 L_{SS}}\right)}$$

$$\omega_o = \sqrt{-\frac{K_2}{L_{SS}}},\ \xi = \left(\frac{R_S - K_1 L_{SS}}{K_2}\right)\sqrt{-\frac{K_2}{L_{SS}}}$$



Three-Phase IGBT Module for Two-Phase Motors: Modulation Issues

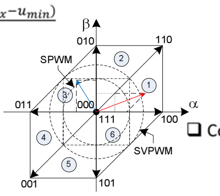
- Modified PWM modulation (common-mode voltage)

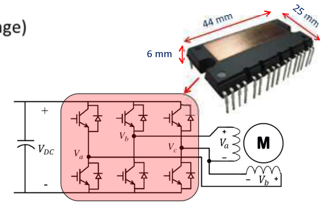
$$\begin{bmatrix}u_a\\u_b\\u_N\end{bmatrix} = \begin{bmatrix}1&0&-1\\0&1&-1\\0&0&1\end{bmatrix}\begin{bmatrix}u_{u0}\\u_{v0}\\u_{w0}\end{bmatrix} \triangleq \boldsymbol{T}\begin{bmatrix}u_{u0}\\u_{v0}\\u_{w0}\end{bmatrix}$$

$$u_N = \frac{U_{dc} - (u_{max} - u_{min})}{2}$$

- Max output

$$V_{phMAX} = \frac{V_{DC}}{\sqrt{2}}$$





- Compact IGBT standard Intelligent Power Module:
  - Compactness & cost advantage
  - High-voltage, reduced parasitics

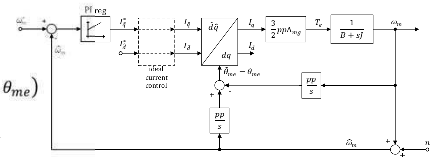
Constant $\hat{d}$-Axis Current Stabilizing Effect

- Estimation errors as additive noise:

$$\widehat{\omega}_m = \omega_m + n$$

- Constant $\hat{d}$-axis current :

$$I_q = I_{\hat{d}}\sin(\hat{\theta}_{me} - \theta_{me}) + I_{\hat{q}}\cos(\hat{\theta}_{me} - \theta_{me})$$

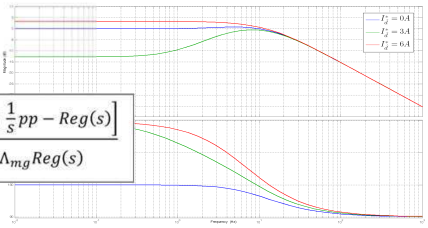


- Linearization (equiv. scheme)

$$\left.\frac{\omega_m(s)}{\omega_m^*(s)}\right|_{n(s)=0} \cdot \omega_m^*(s) + \left.\frac{\omega_m(s)}{n(s)}\right|_{\omega_m^*(s)=0} \cdot n(s)$$

- Effect of noise on speed control

$I_{\hat{d}} = 6A$
$I_{\hat{d}} = 0A$
$I_{\hat{d}} = 3A$



$$\left.\frac{\omega_m(s)}{n(s)}\right|_{\omega_m^*(s)=0} = \frac{\frac{1}{B+sJ}\cdot\frac{3}{2}pp\Lambda_{mg}\cdot\left[I_{\hat{d}}^*\frac{1}{s}pp - Reg(s)\right]}{1 + \frac{1}{B+sJ}\cdot\frac{3}{2}pp\Lambda_{mg}Reg(s)}$$

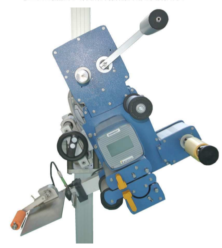
Experimental Setup

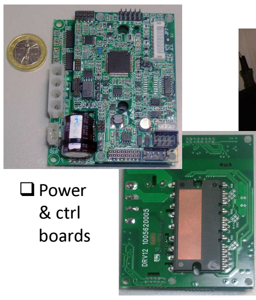
Hybrid stepper motor parameters

Pole pairs, pp	50
Rated frequency, f_n	1000 [Hz]
Stator resistance, R	0.4 [Ω]
Synchronous inductance, L_s	0.005 [H]
PM flux linkage (amplitude), Λ_{mg}	0.013 [Vs]
Rated current, $\lvert i\rvert_{n,rms}$	5.0 [$Arms$]
Rated torque, T_n	4.6 [Nm]

- Compact 1 kW inverter and control board
- 30 A three-phase IGBT module
- 5 A_{RMS} hybrid stepper motor

- Labelling machine

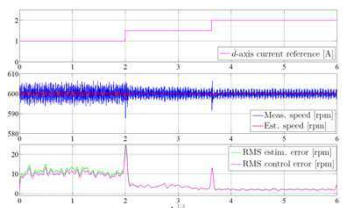




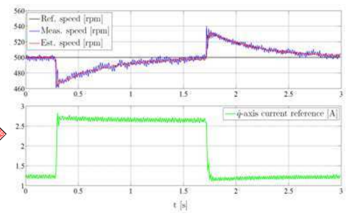
- Power & ctrl boards

- Test bench setup

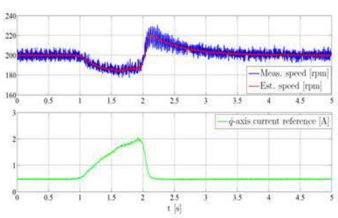
Experimental Results



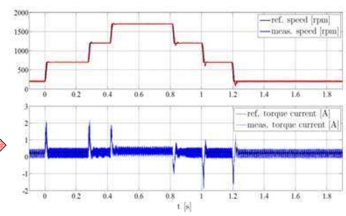
- Effect of $\hat{d}$-axis current on control noise



- Load disturbance at mid-speed (600 rpm)



- Load disturbance at low-speed (200 rpm)



- Speed control operation up to 1700 rpm

Conclusions

- **Sensorless vector control of stepper motors from low-speed → servo-like**
- **Full-torque capability with minimized current consumption**
- **Compact and low-cost three-phase IGBT module for two-phase motor**
- **Successfully applicable to industrial labelling machine**

RESEARCH AND DEVELOPMENT TEAM

PARTNERS

ING. ANDREA ANTONIOLI

MR. MICHELE ANTONIOLI

TASKS:

- design of control and power electronics
- design of power supply and filter
- firmware development
- production and testing

PROF. ROBERTO PETRELLA

PH.D. DR. SANDRO CALLIGARO

TASKS:

- design of control and power electronics
- optimization of converter topology
- study and simulation of control algorithms
- implementation of preliminary control algorithms
- magnetic encoder calibration algorithm