Speed Sensorless Control of a Long-Stator Linear Synchronous-Motor arranged by Multiple Sections

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Organization

- Introduction
- Motor Model
- Speed and position observer
- Experimental results
- Conclusions

Introduction

Linear Motion ⇨

- Usually: Rotative motors + rotative-to-linear transmission
  - belts and pulleys
  - racks and pinions
  - screw systems

- Alternative: Linear Motors
  - higher dynamic response
  - no backslash
  - higher efficiency
  - still more expensive (motor + control)

Introduction

Linear Motor ⇨

- Permanent Magnet (PM) synchronous motors.
  - high efficiency
  - high power density
  - allows a higher air gap

- Long stator (carriageway) - Short mover (vehicle)
  - passive mover: no brushes or cables connected
  - longer travel distance

- Stator arranged by several electrically independent sections
  - reduced reactive power and loses
  - several vehicles in the same carriageway
  - two inverters + power switching among sections
  - one inverter for each section

Introduction

Control ⇨

- Field Orientation -> Mover position required to be known.

- Position sensors
  - expensive
  - reduce the reliability of the whole system
  - sensors are dispersed along the carriageway
  - very difficult to implement in curves

Avoiding position sensors in linear motors is even more important than in rotative motors

- Sensorless methods
  - Position is derived from measured stator voltage and current.
  - Different constrains depending on the method used.

Introduction

Sensorless methods ⇨

• EMF based

- loose performance as speed decreases
- does not work at standstill
- simple to implement.
- non-periodic EMF
- transition between sections

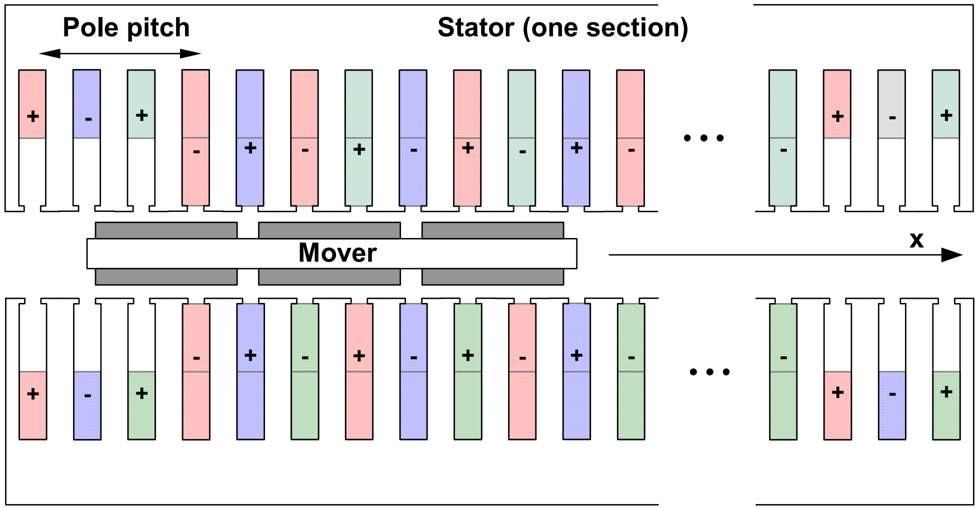
• Based on Magnetic Anisotropies.

- Require detectable position dependent inductances.
- More complex.
- Difficult at high speed.
- non-periodic anisotropies
- transition between sections
- higher leakage inductance (position independent)

→ Motor scheme

Motor Model

Scheme of one section of the linear synchronous motor



- Pole pitch = 30 mm
- Stator: 13 poles arranged in 39 slots
- Mover: 3 poles
- Consecutive sections connected with a 180° phase shift.

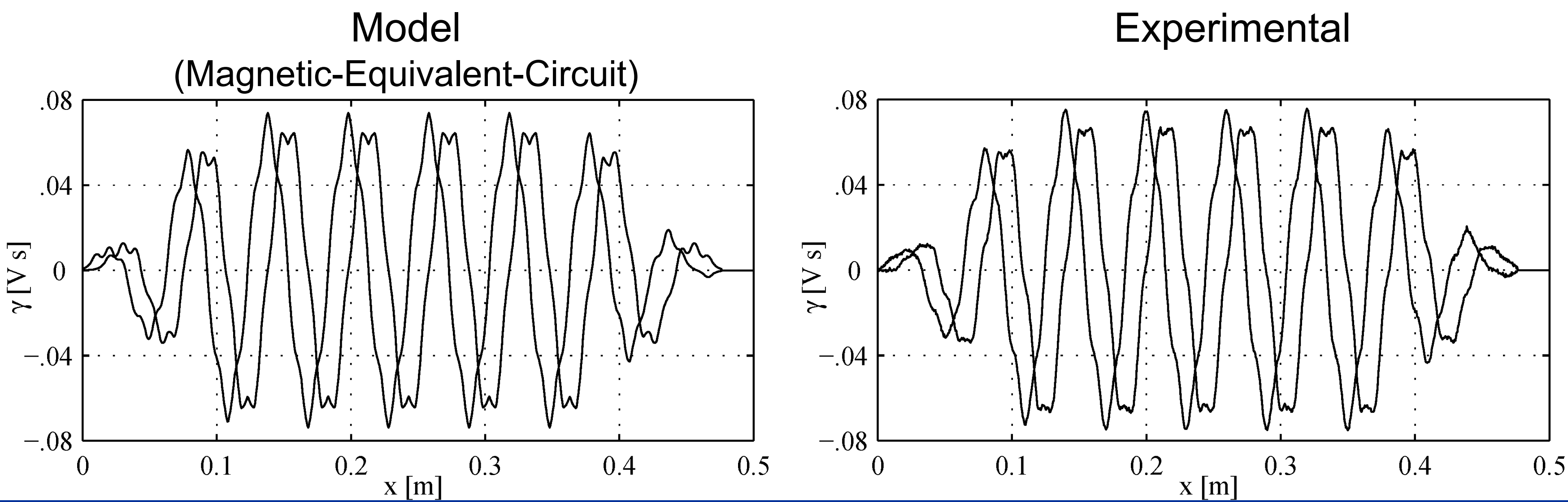
Motor Model

$$\mathbf{u} = \mathbf{i}\,R + \frac{d\,\boldsymbol{\lambda}}{d\,t} \qquad \frac{d\,\boldsymbol{\lambda}_{\mathbf{L}}}{d\,t} = \mathbf{u} - \mathbf{i}\,R - \mathbf{e}$$

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_{\mathbf{L}} + \boldsymbol{\lambda}_{\mathbf{PM}}(x) \qquad \mathbf{e} = \frac{d\,\boldsymbol{\lambda}_{\mathbf{PM}}}{dt} = \boldsymbol{\gamma}(\theta)\,\omega$$

$$\boldsymbol{\lambda}_{\mathbf{L}} = \mathbf{L}\,\mathbf{i} \qquad \theta = x\,\pi / \tau_p$$

Normalized EMF space-vector $\boldsymbol{\gamma}(\theta)$



Motor Model

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$$\mathbf{e} = \frac{d\,\boldsymbol{\lambda}_{\mathbf{PM}}}{dt} = \boldsymbol{\gamma}(\theta)\,\omega$$

$$\theta = x\,\pi / \tau_p$$

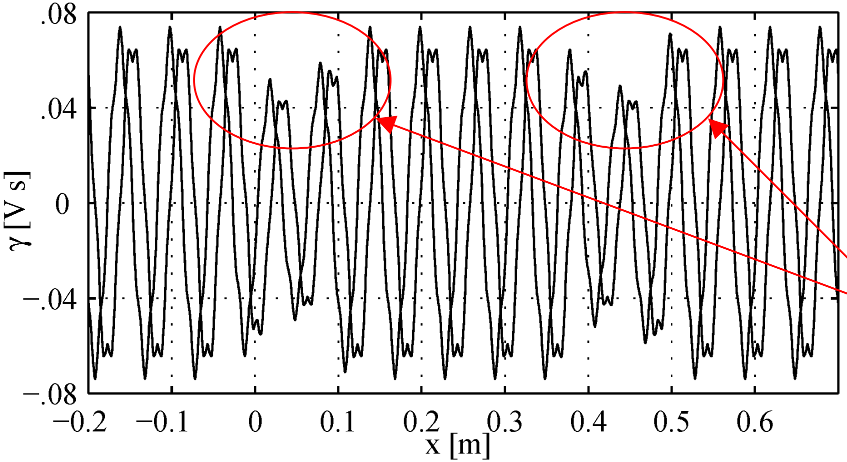
$$\frac{d\,x}{d\,t} = v$$

$$\frac{d\,v}{d\,t} = \frac{1}{M} F - \frac{B}{M} v - F_L$$

$$F = \frac{3}{2}\frac{\pi}{\tau_p}\boldsymbol{\gamma}(\theta)^T\,\mathbf{i}$$

Normalized EMF space-vector $\boldsymbol{\gamma}(\theta)$

Waveform resulting from adding the EMF of three sections



Magnitude reduction due to section transition

Speed and position observer

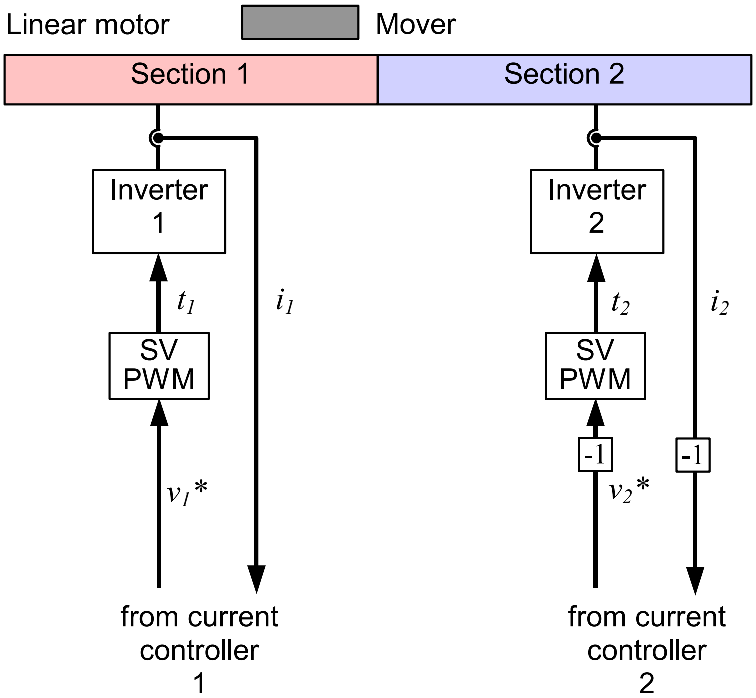
EMF observer

- Speed is assumed constant
- PM flux linkage sinusoidal

$$\mathbf{e} = \omega\, f_m \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

$$\frac{d\,\mathbf{e}}{d\,t} = \omega^2 f_m \begin{bmatrix} -\cos\theta \\ -\sin\theta \end{bmatrix} = -\mathbf{J}\,\omega\,\mathbf{e} \qquad \mathbf{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

$$\begin{cases} \dfrac{d\,\hat{\boldsymbol{\lambda}}_\mathbf{L}}{d\,t} = \mathbf{u} - \mathbf{i}\,R - \hat{\mathbf{e}} + \mathbf{G}_1\left(\mathbf{i} - \mathbf{L}^{-1}\hat{\boldsymbol{\lambda}}_\mathbf{L}\right) \\ \dfrac{d\,\hat{\mathbf{e}}}{d\,t} = -\mathbf{J}\,\omega\,\hat{\mathbf{e}} + \mathbf{G}_2\left(\mathbf{i} - \mathbf{L}^{-1}\hat{\boldsymbol{\lambda}}_\mathbf{L}\right) \end{cases}$$



Speed and position observer

- Two EMF observers (active sections i.e. where the mover is and the following)

EMF observer

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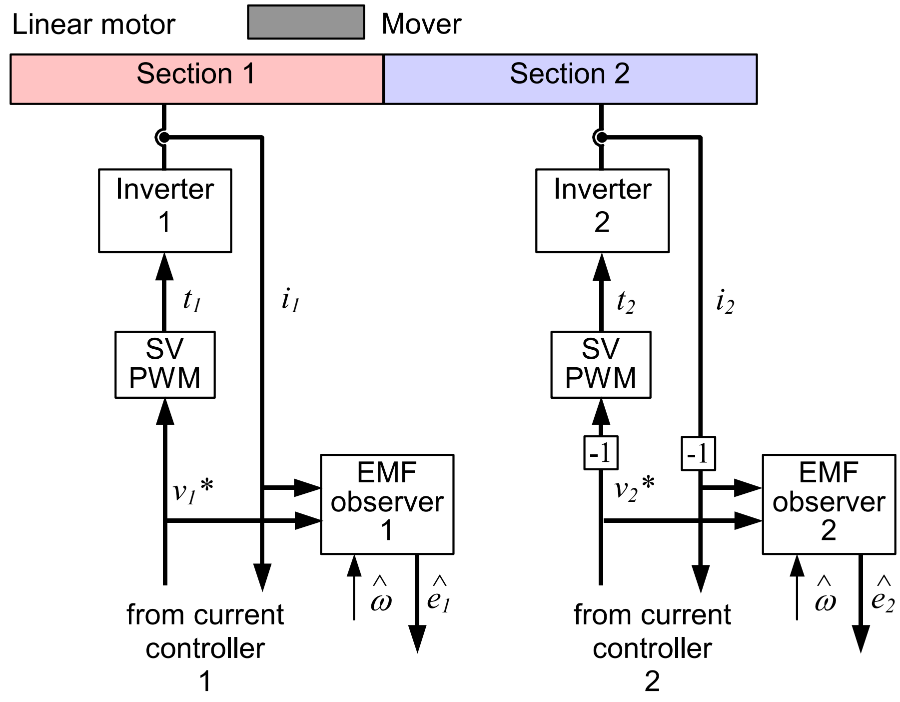
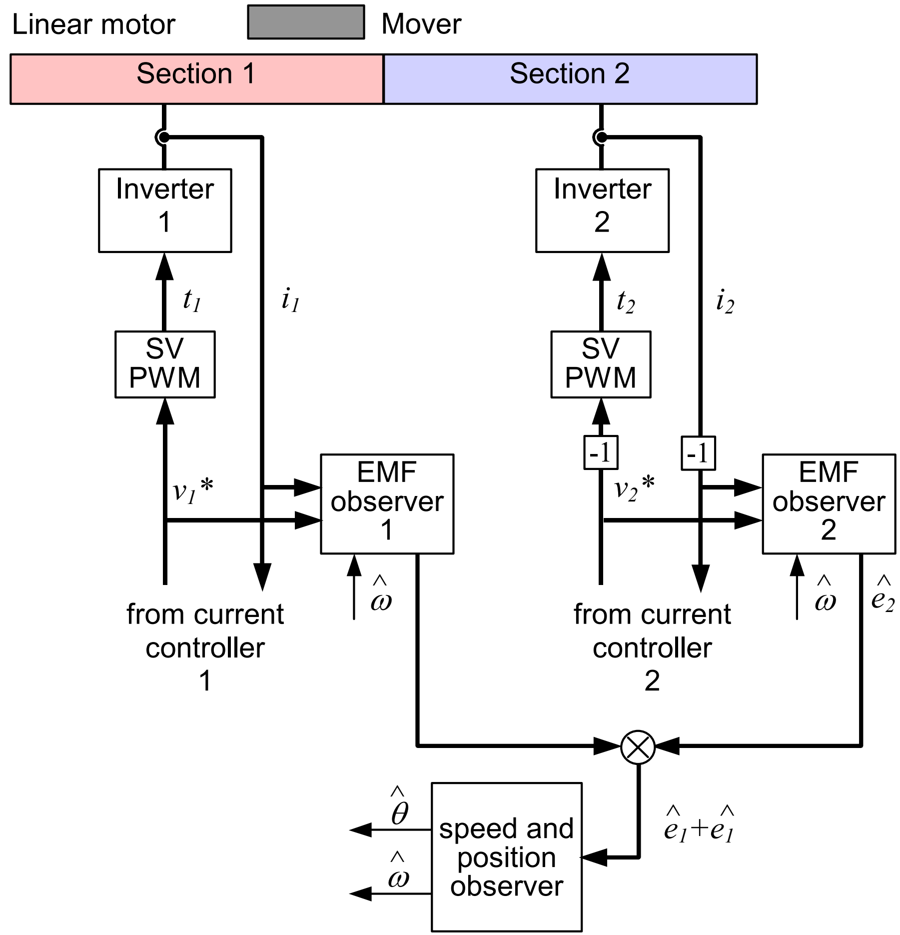


Speed and position observer

- Two EMF observers (active sections i.e. where the mover is and the following)
- Addition of both EMF space vectors
- One speed and position observer



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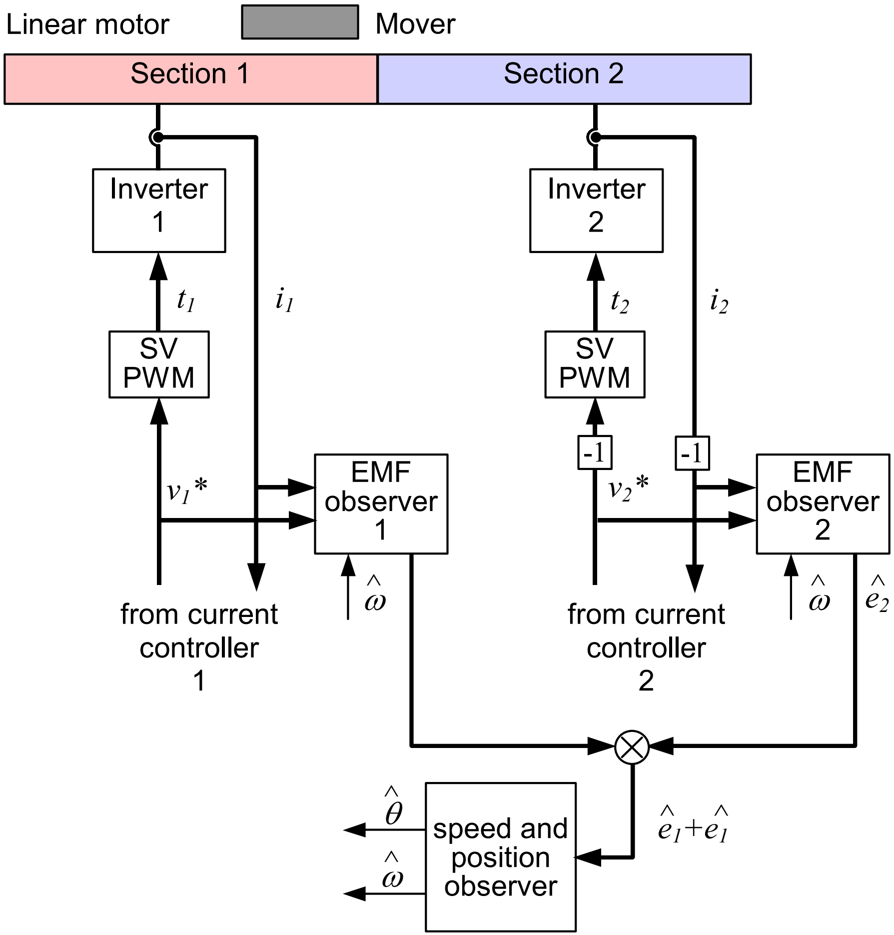
Speed and position observer

$$c = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \end{bmatrix} \hat{\mathbf{e}}$$

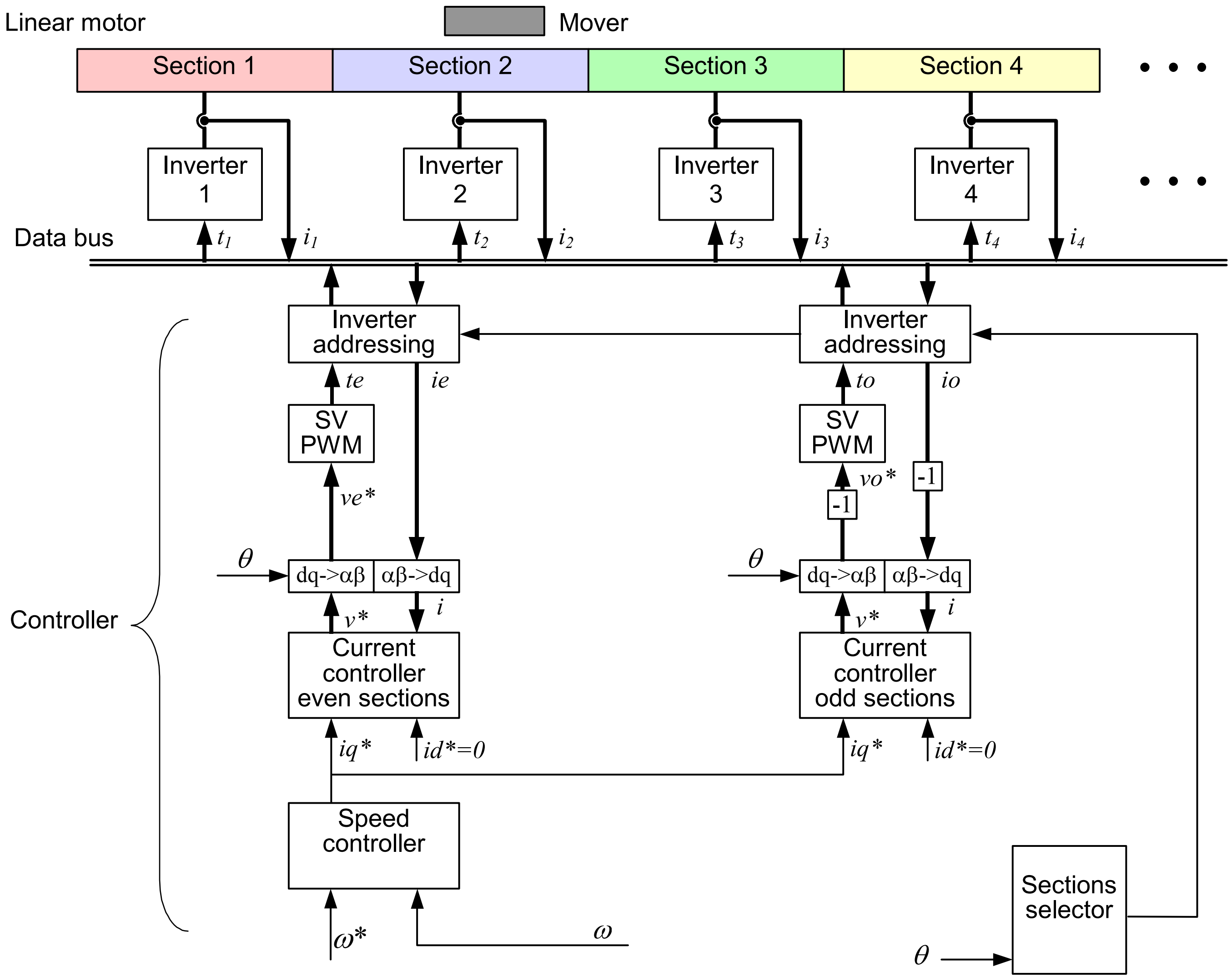
$$c = \hat{\omega}\, f_m \sin(\hat{\theta} - \theta) \cong \hat{\omega}\, f_m\, (\hat{\theta} - \theta)$$

$$\begin{cases} \dfrac{d\hat{\omega}}{dt} = -K_I\, c \\ \dfrac{d\hat{\theta}}{dt} = \hat{\omega} - K_P\, c \end{cases}$$



Speed and position observer

Integration into the control loop



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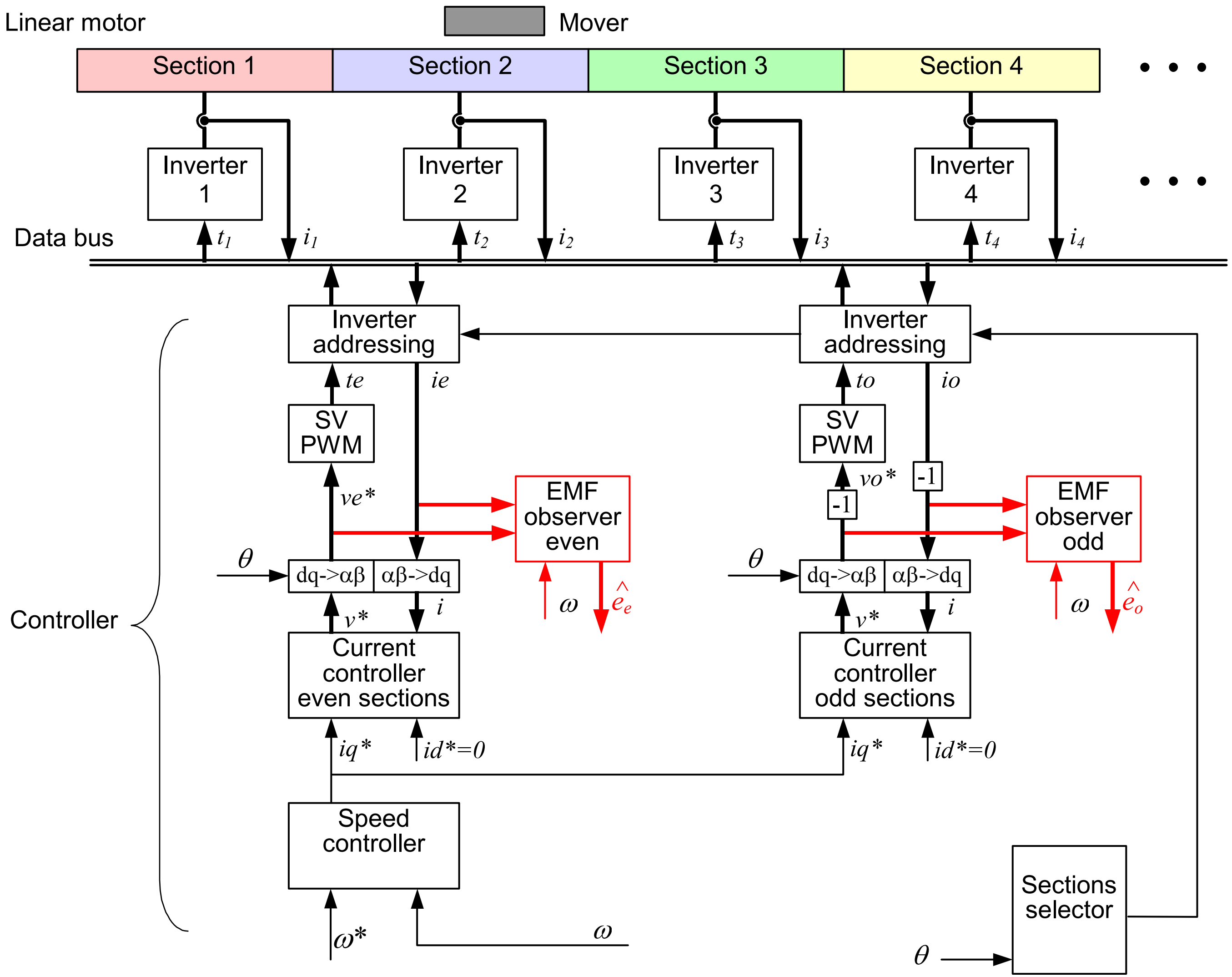

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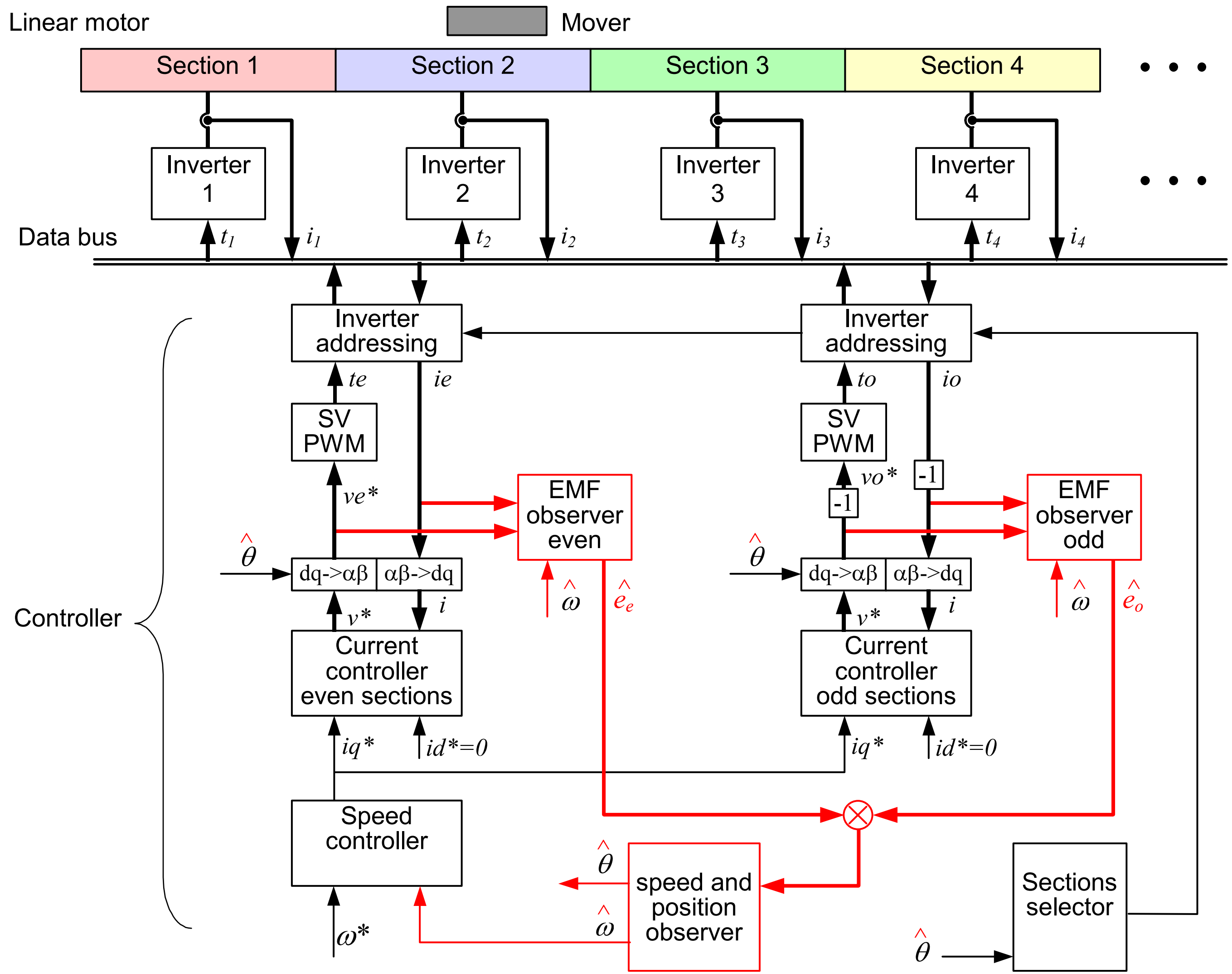

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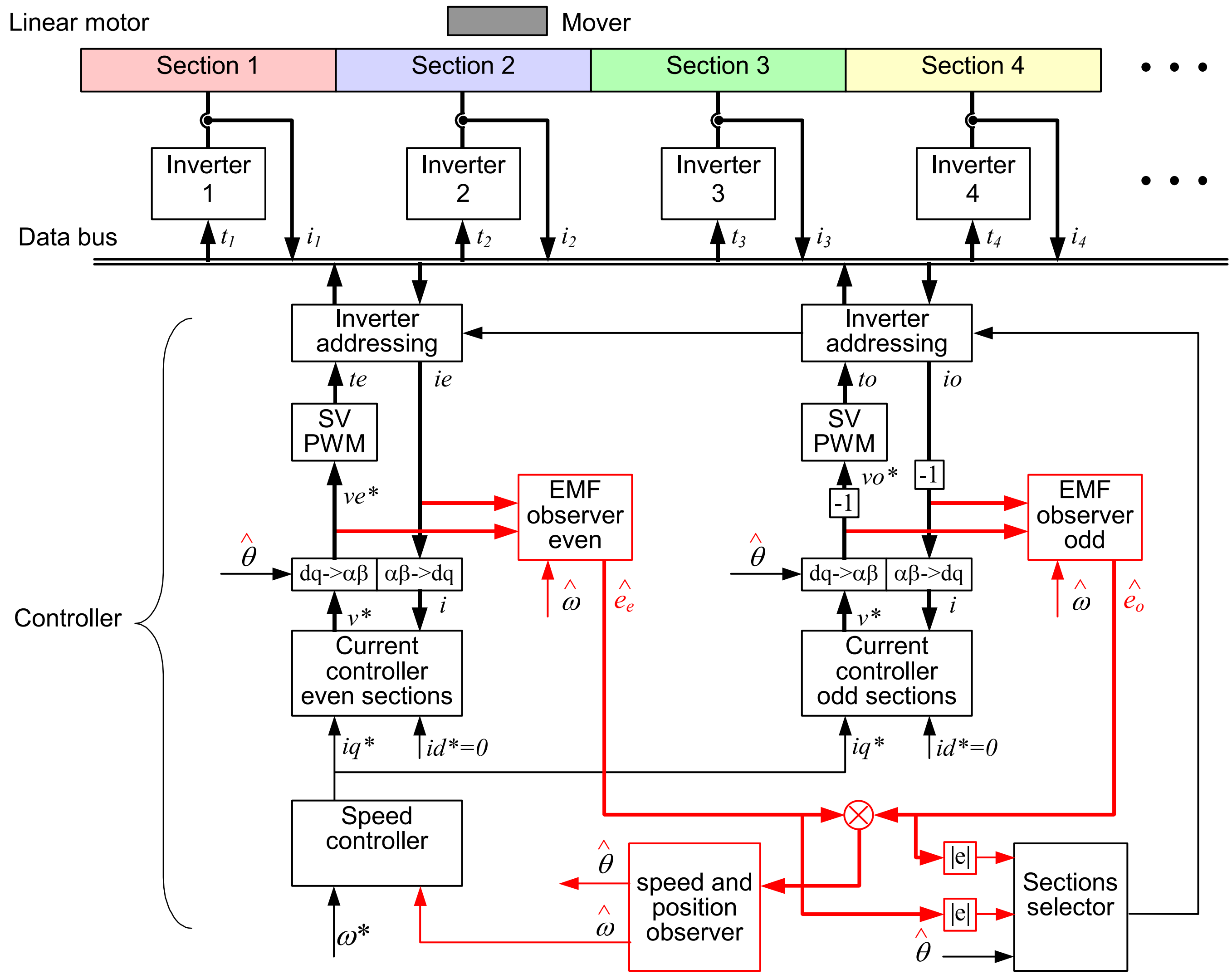
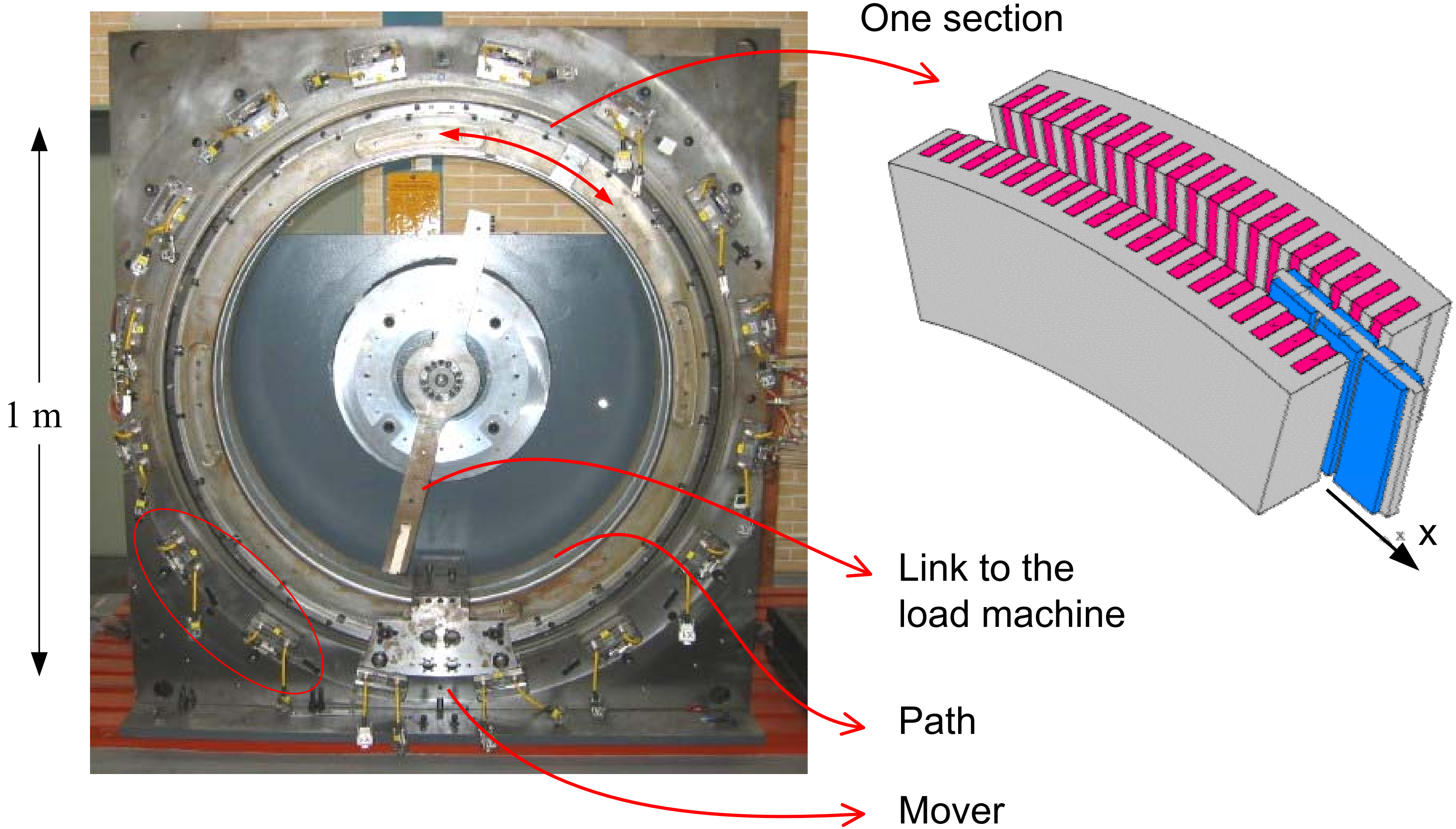
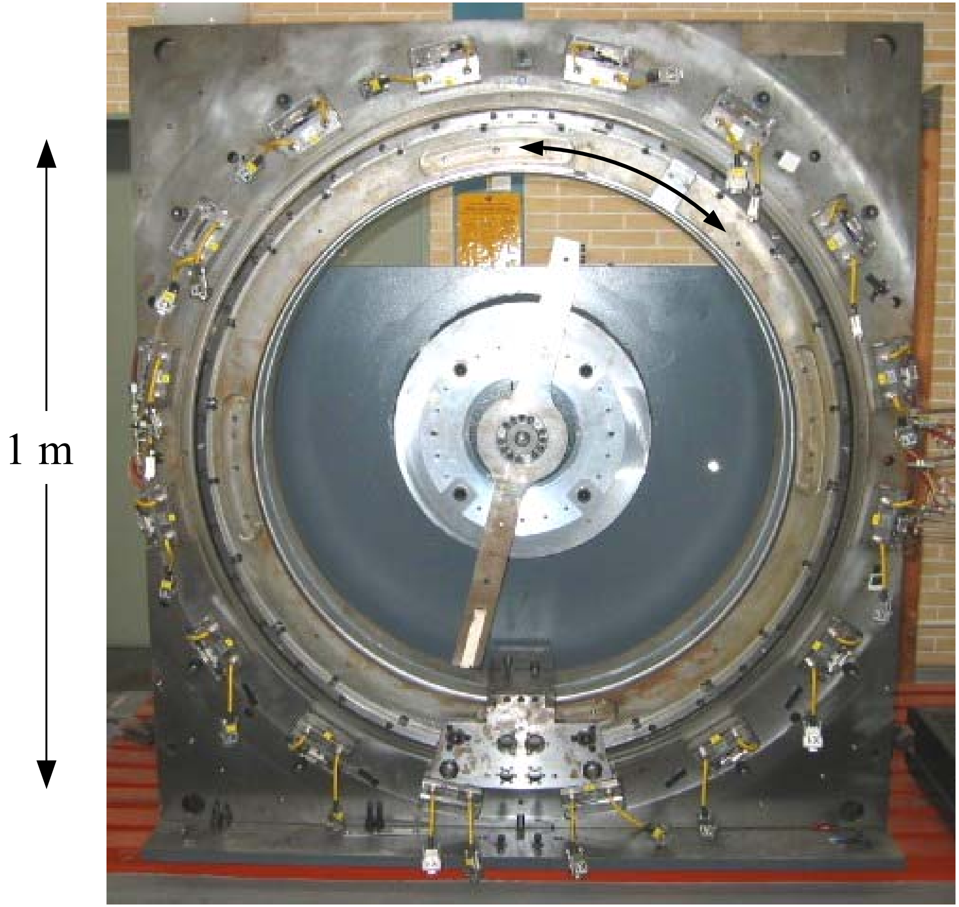


Experimental results



Experimental results

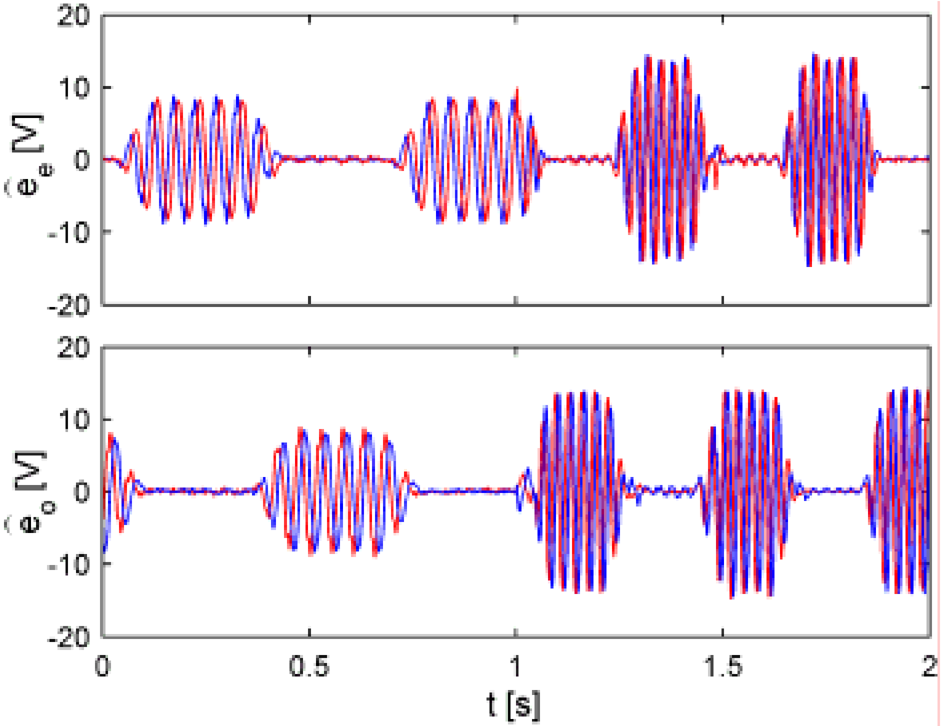


Nominal current	52 Arms
Peak current	104 Arms
Nominal force	900 N
Stator resist.	1.1 Ω
Stator induct.	6.4 mH
Mover Mass	12.5 Kg
Flux	0.068 Vs
Load	122 sin(θ/52) N

Experimental results

Speed 1.17 m/s
Step to 1.95 m/s
at t = 1 s

EMF in αβ



Experimental results

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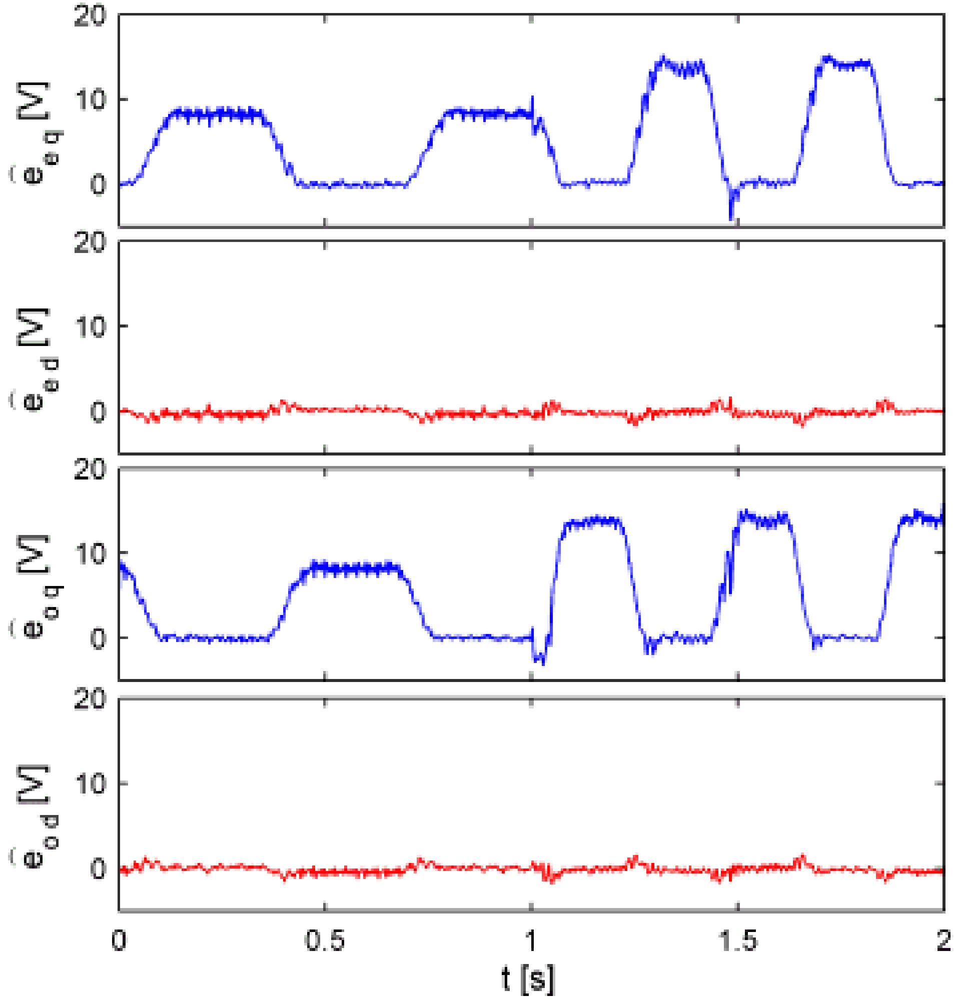
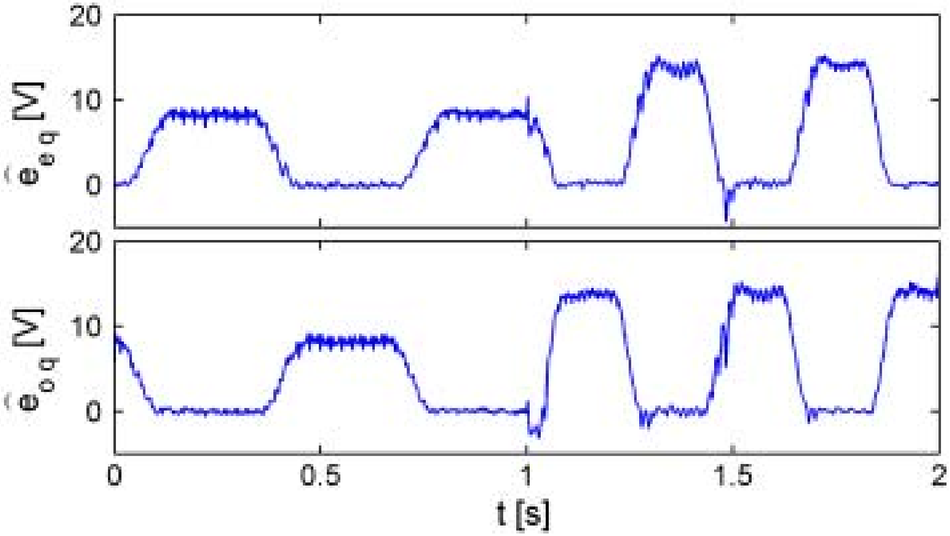
EMF in *dq*



Experimental results

Speed 1.17 m/s
Step to 1.95 m/s
at t = 1 s

EMF in *dq*

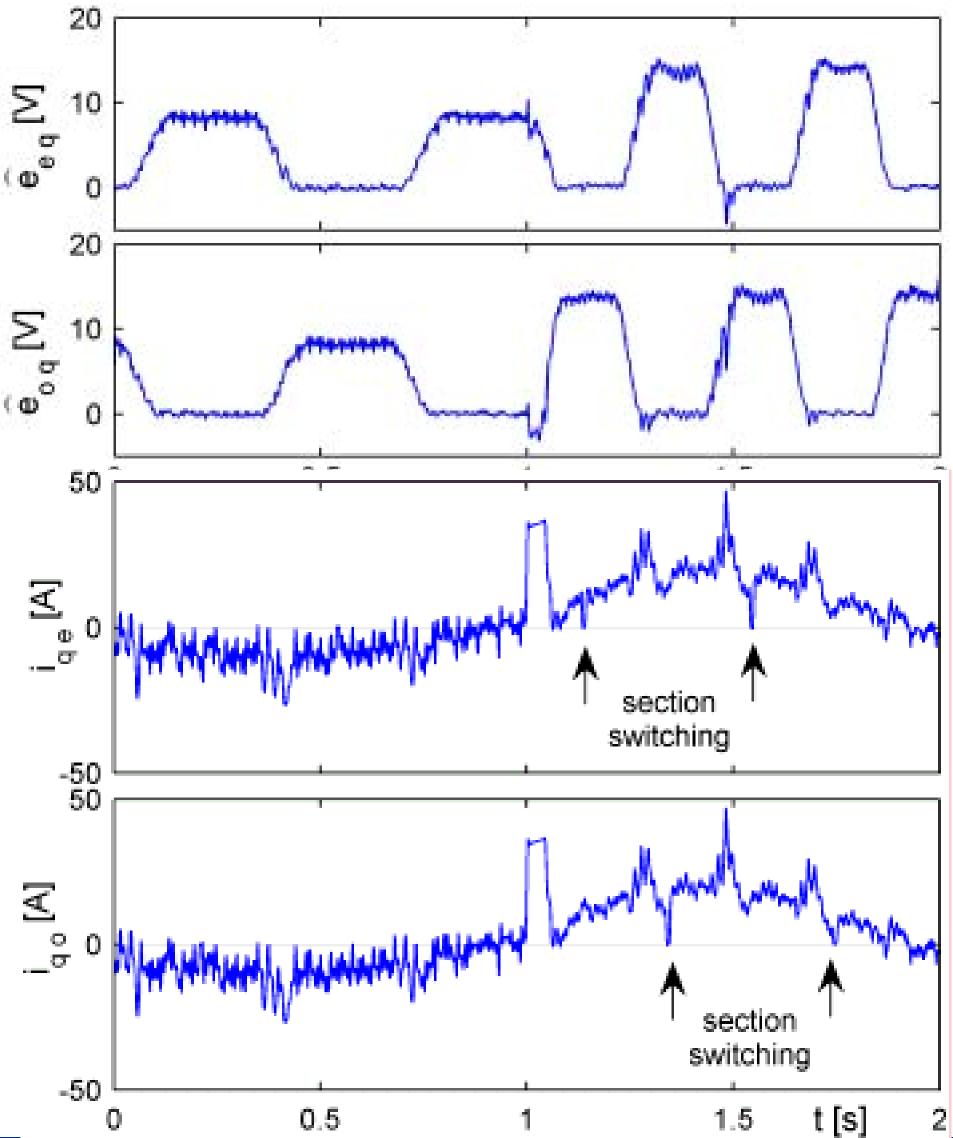


Experimental results

Speed 1.17 m/s
Step to 1.95 m/s
at t = 1 s

EMF in *dq*

***q* axis current**



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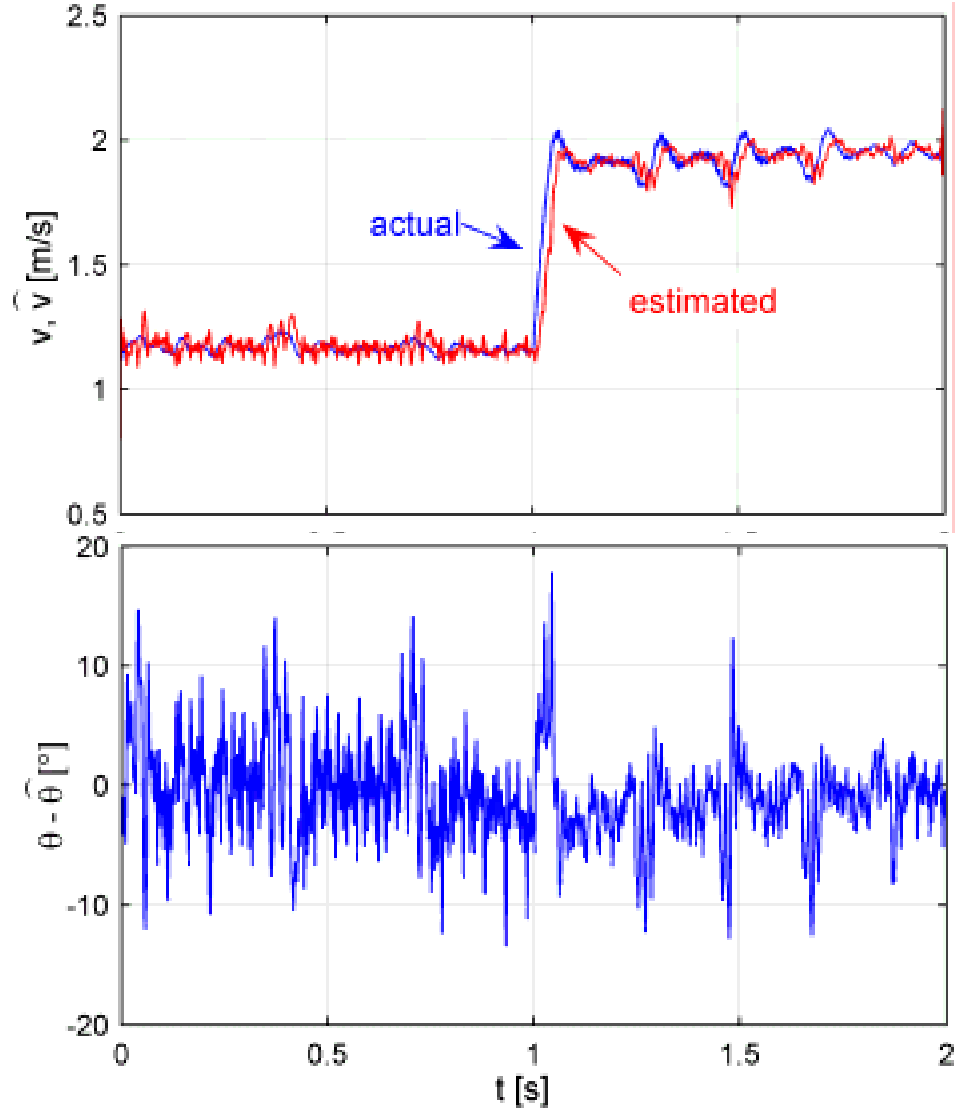
Linear Speed

Position Error (electrical angle)



Conclusions

- Control of Linear Synchronous-Motors without speed or position sensors.
- Speed control of the mover in a multi-section carriageway.
- Also provides the means to select the sections to be driven.
- Experimental tests in closed loop.
- High agreement between observed and actual values of speed and position, even when the mover is loaded.
- Validate the model simplifications introduced for the EMF observer as well as the overall proposal.

Alexander von Humboldt
Stiftung / Foundation

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http://www.humboldt-foundation.de