A New High Frequency Signal Injection Method Without Maximum Fundamental Voltage Magnitude Loss and its Application

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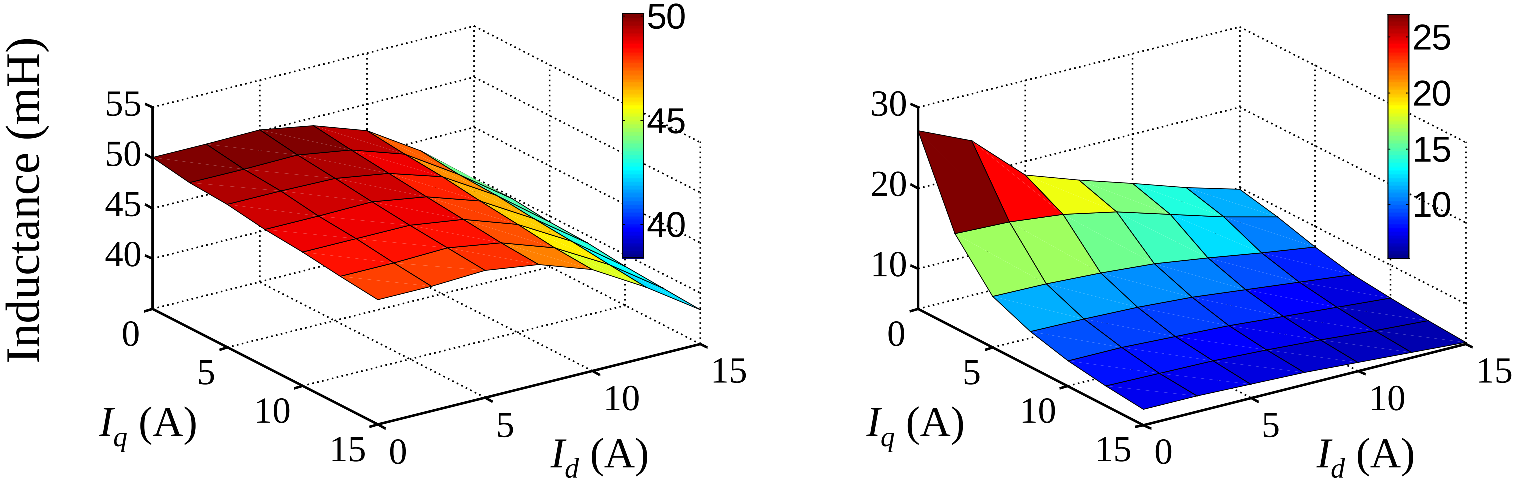
- Proposed HFSI method – duty cycle shifting
- Application example – sensorless FOC
- Summary

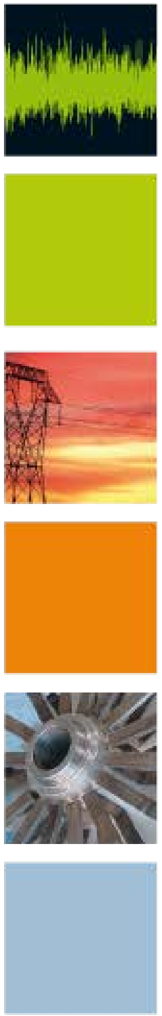
Background

Why new HFSI method?

- Most HFSI based position estimation algorithms are machine parameter independent
  - Do not require machine inductance profile

Machine inductance variation caused by self- and cross-saturation

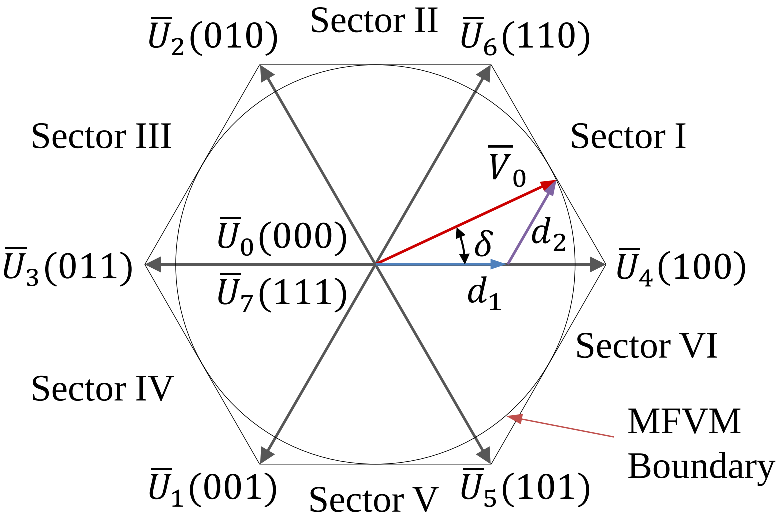


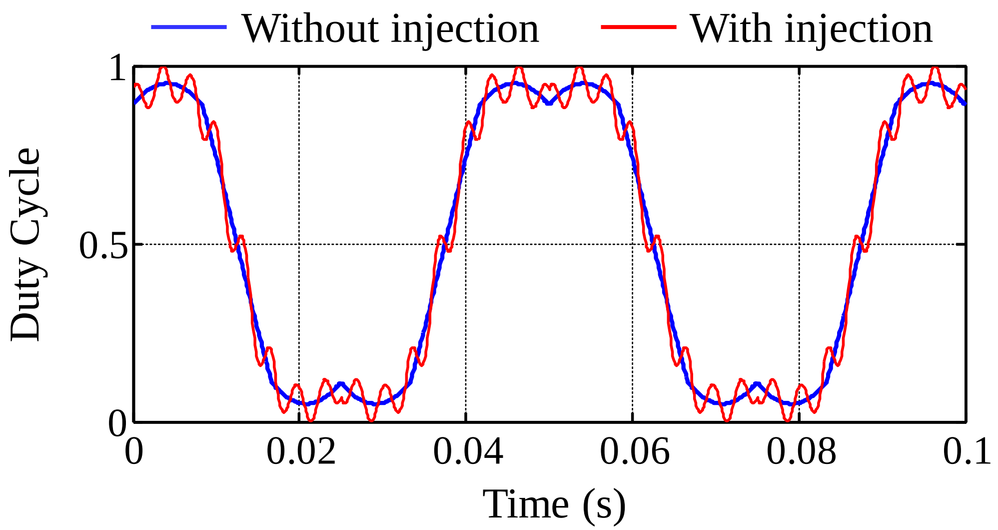


Background

Why new HFSI method?

- Existing HFSI methods have the drawback of
  - Maximum fundamental voltage magnitude (MFVM) loss
  - Limited the machine speed and load operation range

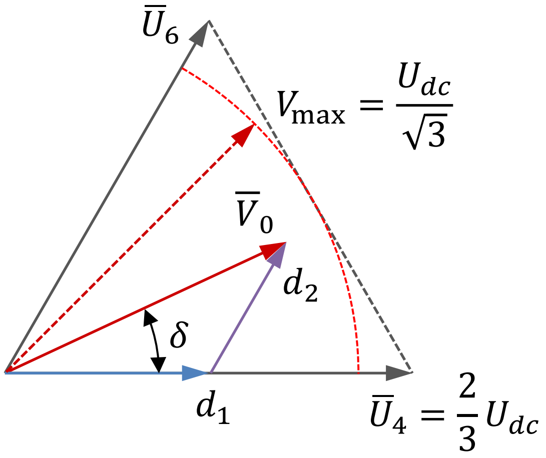


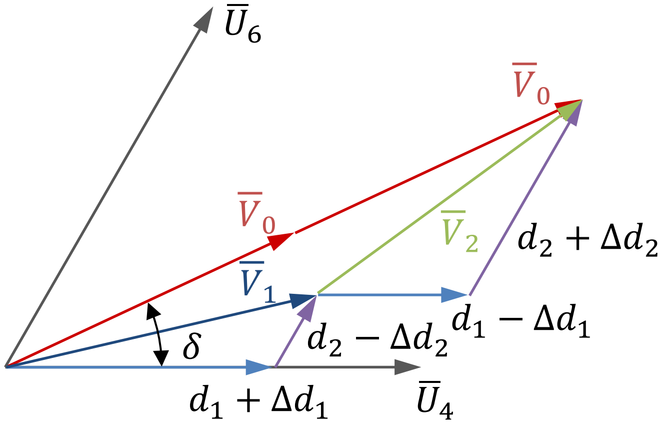


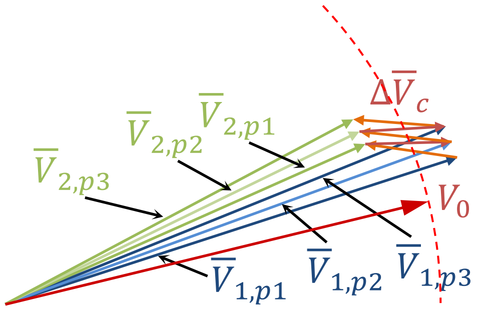
Proposed HFSI method

General idea of proposed method – duty cycle shifting:

- Shifting between two neighboring switching periods
- The average voltage vector is kept to the commanded vector
- The total duty cycle within each switching period should be limited to one, i.e $|d_1+\Delta d_1|+|d_2-\Delta d_2|\le 1,\ |d_1-\Delta d_1|+|d_2+\Delta d_2|\le 1$







Proposed HFSI method

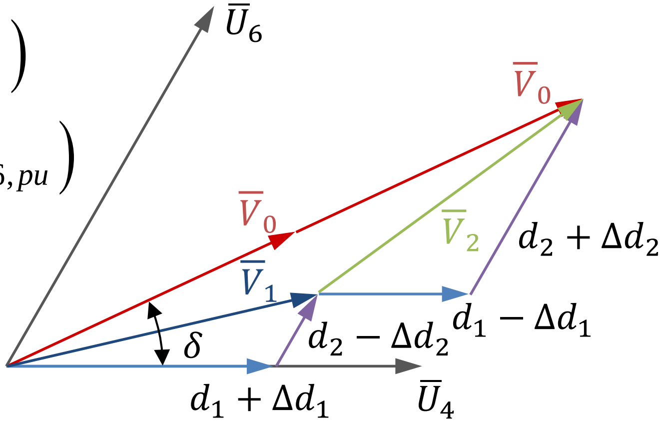
The injected voltage vector:

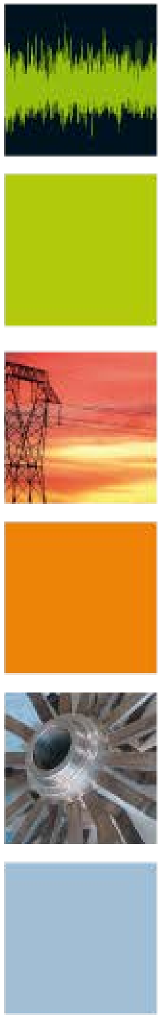
- Per-unit value of $\bar{U}_4$ and $\bar{U}_6$

$$\bar{U}_{4,pu} = \frac{\bar{U}_4}{V_{\max}} = \frac{(2/3)U_{dc}e^{j0}}{U_{dc}/\sqrt{3}} = \frac{2}{\sqrt{3}}e^{j0},\ \bar{U}_{6,pu} = \frac{\bar{U}_6}{V_{\max}} = \frac{2}{\sqrt{3}}e^{j\frac{\pi}{3}}$$

- The injected voltage vector (carrier signal)

$$\begin{aligned}\Delta\bar{V}_{c,pu} &= \bar{V}_{1,pu} - \bar{V}_{2,pu} \\ &= \left((d_1+\Delta d_1)\bar{U}_{4,pu} + (d_2-\Delta d_2)\bar{U}_{6,pu}\right) \\ &\quad -\left((d_1-\Delta d_1)\bar{U}_{4,pu} + (d_2+\Delta d_2)\bar{U}_{6,pu}\right) \\ &= \frac{4}{\sqrt{3}}\Delta d_1 \cdot e^{j0} - \frac{4}{\sqrt{3}}\Delta d_2 \cdot e^{j\frac{\pi}{3}}\end{aligned}$$

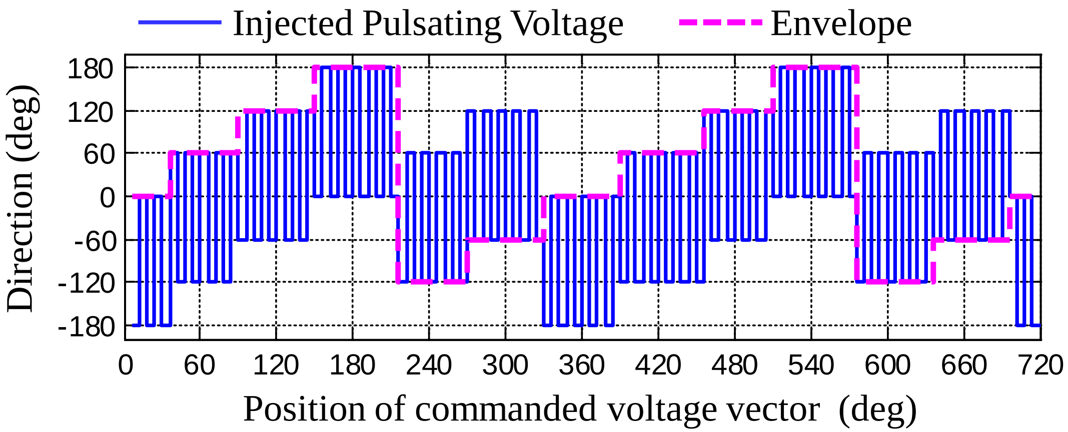


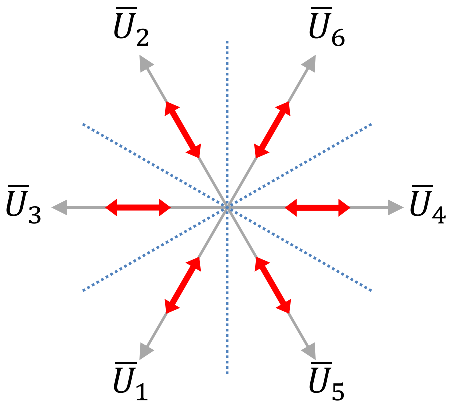


Duty cycle shifting – Type 1

Duty cycle shifting with fixed Δd_1 and $\Delta d_2 = 0$:

- Injected voltage vector: $\Delta \bar{V}_{c,pu} = \frac{4}{\sqrt{3}} \Delta d_1 \cdot e^{j0}$
- Fixed injection in each switching vector range, (f_s=3kHz)



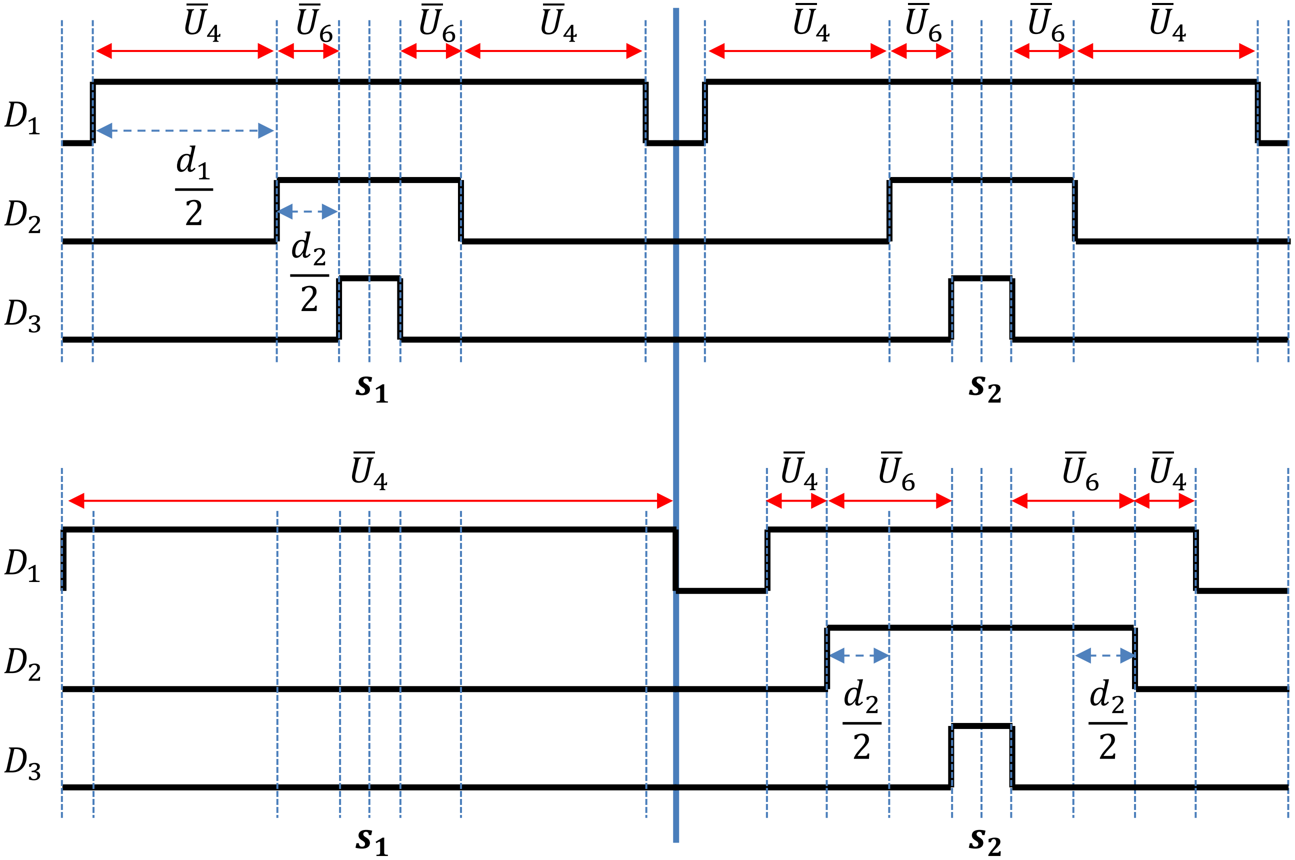


Can be used for existing position estimation algorithm [1]

[1] D. Paulus, P. Landsmann, and R. Kennel, "Sensorless field- oriented control for permanent magnet synchronous machines with an arbitrary injection scheme and direct angle calculation," in *Proc. SLED*, pp. 41–46, Sep. 2011

Duty cycle shifting – Type 1

Maximum $\Delta d_1 = 1 - d_1$, i.e. $\overline{U}_4$ occupies a full period $\mathbf{s}_1$ for $0 \leq \delta < 30^\circ$



- Before shifting
- After shifting

Duty cycle shifting – Type 1

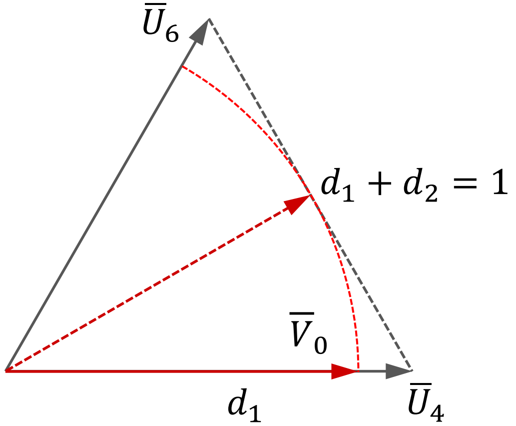
Maximum $\Delta d_1 = 1 - d_1$:

- Maximum d_1 of traditional SVM is $d_1 = \sqrt{3}/2$
- Maximum Δd_1 always available $\Delta d_1 = 1 - \sqrt{3}/2 = 0.134$
- For $U_{dc} = 575\text{V}$ and $\Delta d_2 = 0$:

$$\Delta \overline{V}_c = \frac{U_{dc}}{\sqrt{3}} \Delta \overline{V}_{c,pu} = \frac{U_{dc}}{\sqrt{3}} \frac{4}{\sqrt{3}} \Delta d_1 \cdot e^{j0} = 102.73 e^{j0}$$

When $d_1 + d_2 + \Delta d_1 > 1$,

- $\Delta d_2 \neq 0$,
- e.g. $\Delta d_2 = d_1 + d_2 + \Delta d_1 - 1$

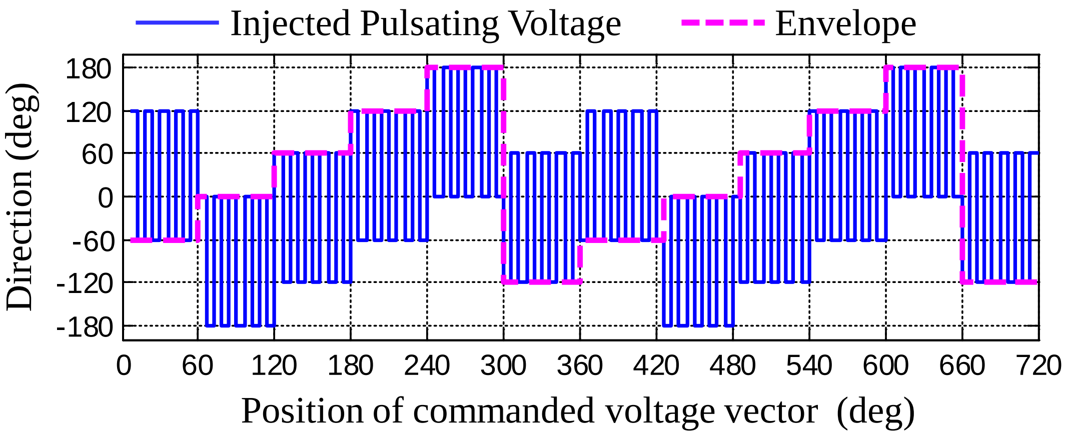


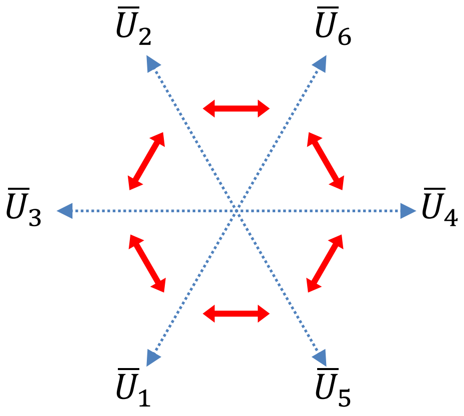
Duty cycle shifting – Type 2

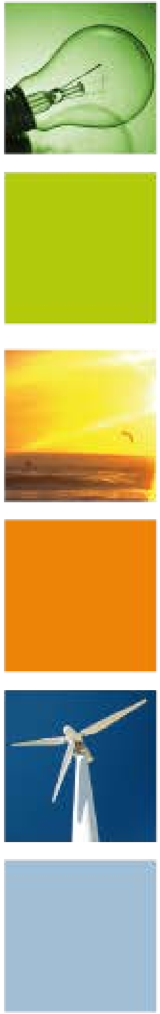
Duty cycle shifting with $\Delta d_1 = \Delta d_2$:

- Injected voltage vector:

$$\Delta\overline{V}_{c,pu} = \frac{4}{\sqrt{3}}\Delta d_1 \cdot e^{j0} - \frac{4}{\sqrt{3}}\Delta d_2 \cdot e^{j\frac{\pi}{3}} = \frac{4}{\sqrt{3}}\Delta d_1 \cdot e^{-j\frac{\pi}{3}}$$







Can be used for existing position estimation algorithm [1]

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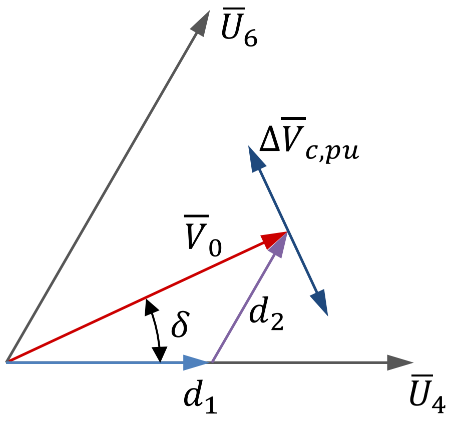
Duty cycle shifting – Type 3



Rotary Pulsating Carrier Signal:

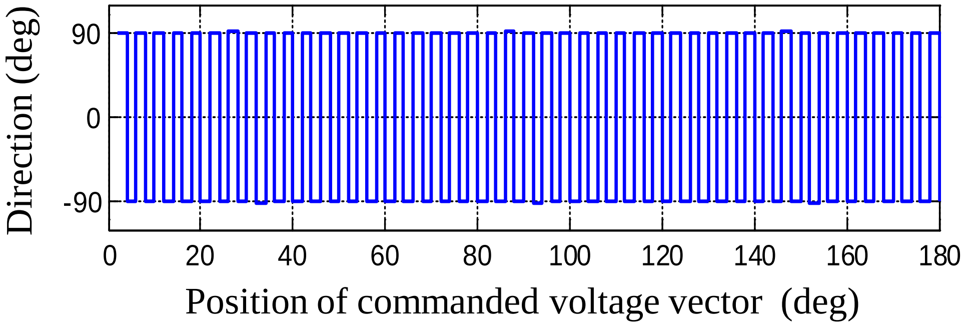
- With $\Delta d_1 = \Delta d \cdot \cos(\pi/3 - \delta)$

  $\Delta d_2 = \Delta d \cdot \cos\delta$

- The injected voltage is $\Delta\overline{V}_{c,pu} = -j2\Delta d \cdot e^{j\delta}$

  which is perpendicular to $\overline{V}_0 = V_0 e^{j\delta}$

- $f_s = 9\text{kHz}$



Can be used for existing position estimation algorithm [2]

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[2] Y. D. Yoon, S. K. Sul, S. Morimoto, and K. Ide, “High-bandwidth sensorless algorithm for AC machines based on square-wave-type voltage injection,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1361–1370, May/Jun. 2011

Proposed position estimation method

Existing HFSI based position estimation methods:

- Requires BPF and/or LPF for:
  - carrier response demodulation
  - machine saliency information extraction
- with the cost of:
  - error caused by phase shift of filters
  - degraded dynamic performance

Proposed position estimation method

Proposed algorithm:

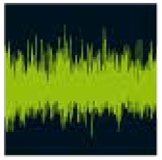
- Based on the changing of flux-linkage and current during two neighboring switching periods
- SynRM flux-linkage in the stator frame: $\overline{\lambda}_{\alpha\beta} = L_1 \overline{i}_{\alpha\beta} + L_2 \overline{i}_{\alpha\beta}^{*} e^{j2\theta_r}$

  where $L_1 = (L_d + L_q)/2$ and $L_2 = (L_d - L_q)/2$
- Define $\overline{A} = \overline{\lambda}_{\alpha\beta 2} \overline{i}_{\alpha\beta 1} - \overline{\lambda}_{\alpha\beta 1} \overline{i}_{\alpha\beta 2}$
- Then $\overline{A} = L_2 \operatorname{Im}(\overline{i}_{\alpha\beta 2}^{*} \overline{i}_{\alpha\beta 1}) \cdot 2 j e^{j2\hat{\theta}_r} \Rightarrow \boxed{2\hat{\theta}_r = \angle \overline{A} + \pi/2}$
- The inductance L_2 will only influence the magnitude of $\bar{A}$, not the argument (angle). The proposed algorithm is machine inductance independent.

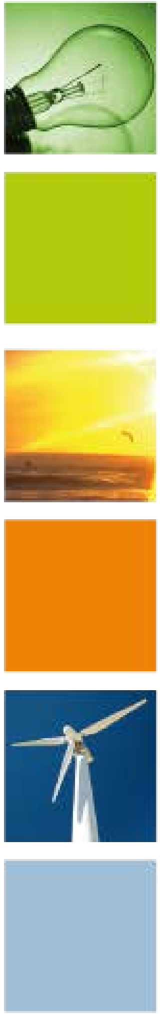
Proposed position estimation method

Proposed algorithm:

- Pros
  - No special requirement to current sampling
  - No BPF and/or LPF needed
  - Suitable for proposed HFSI method, till rated speed
- Cons
  - Flux-linkage needed, not suitable for very low speed to standstill



Proposed position estimation method



Cross-saturation effect:

- l_{dq} term is introduced and distort the magnetic saliency axes
- SynRM flux-linkage in the rotor frame:

$$\bar{\lambda}_{dq} = L_d i_d + l_{dq} i_q + j(L_q i_q + l_{dq} i_d) = L_1 \bar{i}_{dq} + (L_2 + l_{dq}) \bar{i}_{dq}^{*}$$

- Then $\bar{A} = (L_2 + l_{dq}) \operatorname{Im}(\bar{i}_{\alpha\beta 2}^{*} \bar{i}_{\alpha\beta 1}) \cdot 2 j e^{j 2\hat{\theta}_r}$

$$= L_2' \operatorname{Im}(\bar{i}_{\alpha\beta 2}^{*} \bar{i}_{\alpha\beta 1}) \cdot 2 j e^{\boxed{j(2\hat{\theta}_r + \varepsilon)}} \qquad \text{where } \varepsilon = \arctan \frac{2 l_{dq}}{L_d - L_q}$$

- The estimated position by using the indication vector $\bar{A}$

$$\boxed{\theta_{est} = \angle \bar{A}/2 + \pi/4 = \hat{\theta}_r + \varepsilon/2}$$

- Instead of the rotor mechanical saliency ($\hat{\theta}_r$), the distorted magnetic saliency (θ_{est}) is obtained.

Application example – sensorless FOC

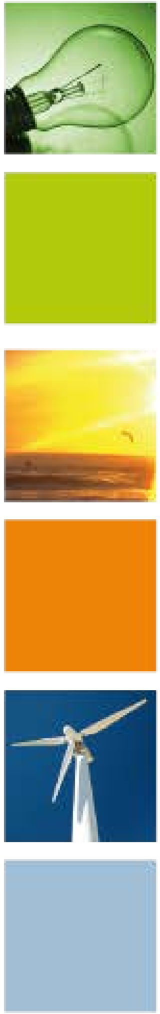
Sensorless FOC with high torque per ampere operation:

- Torque $T = \frac{3}{2} p(i_q \lambda_d - i_d \lambda_q) = \frac{3}{2} \frac{p L_2 I_m^2}{\cos\varepsilon} \sin(2\theta_i^r - \varepsilon)$

  and maximum torque is obtained when $2\theta_i^r - \varepsilon = \pi/2$
- Current vector location in the stationary frame

  $$\boxed{\theta_i^s = \pi/4 + \varepsilon/2 + \hat{\theta}_r = \pi/4 + \theta_{est}}$$
- The current vector should locate at 45° with respect to θ_{est}

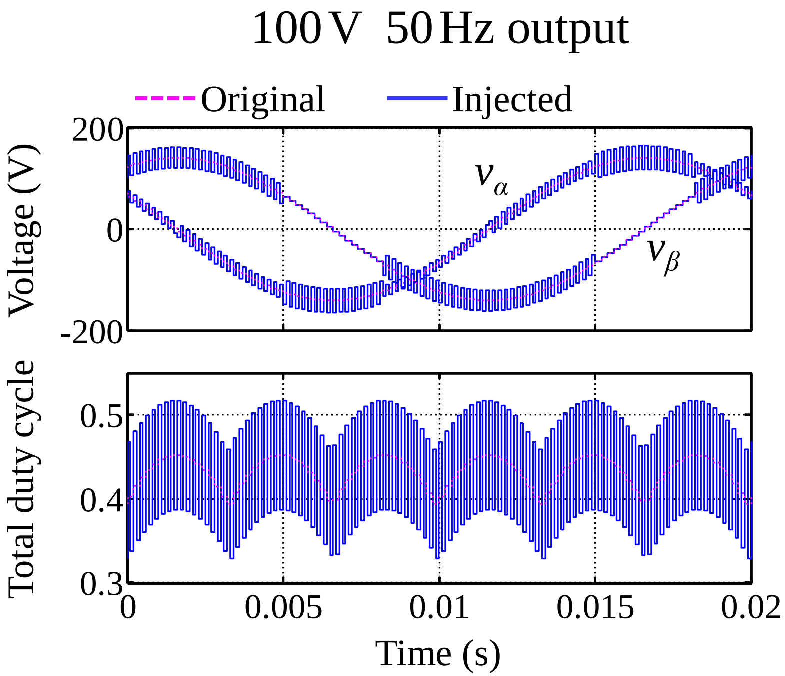
  i.e. 45° in the estimated rotor frame (magnetic saliency)
- There is no need to compensate the error (ε) caused by cross-saturation effect
- Sensorless FOC do not require any inductance information

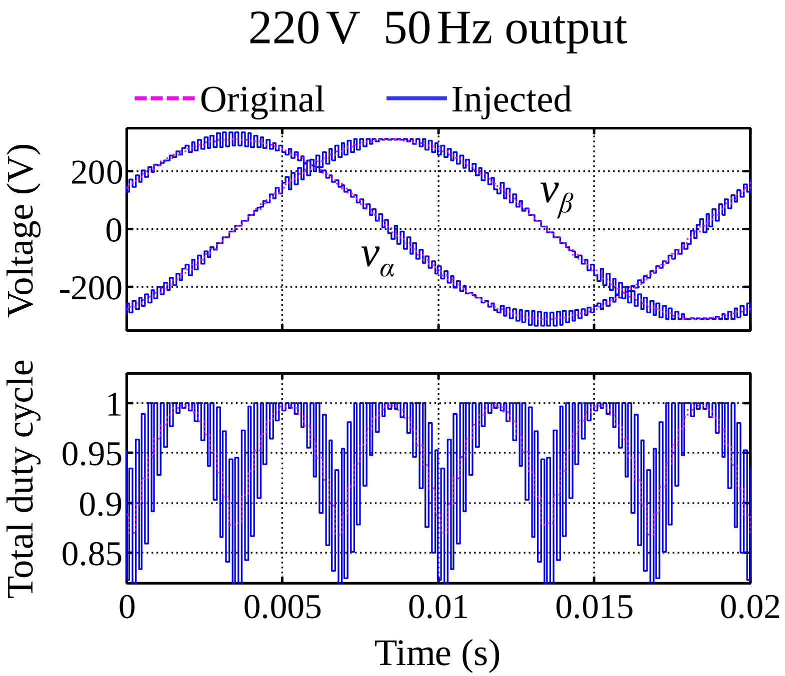


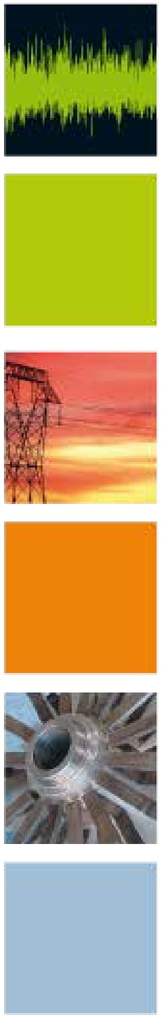
Experiment results

Verification of proposed HFSI method:

- Open-circuit no-load tests
- Type 1 with 220V grid input and Δd_1 = 0.065



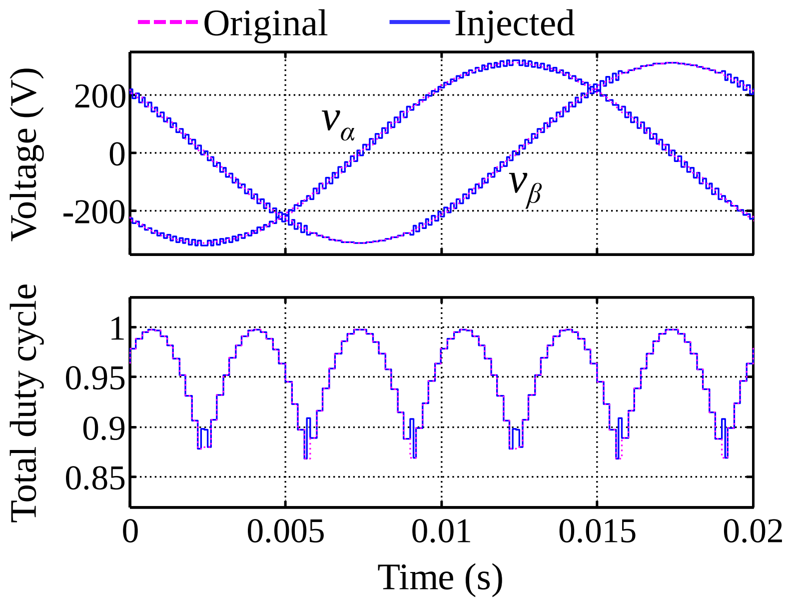




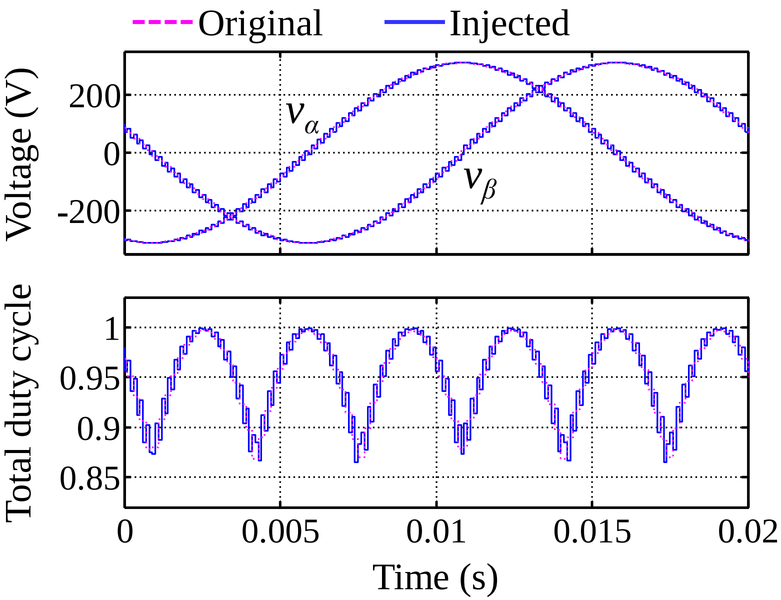
Experiment results

Verification of proposed HFSI method:

- Type 2 with full voltage output and $\Delta d_1 = \Delta d_2 = 0.05$
- Type 3 with full voltage output and $\Delta d = 0.05$

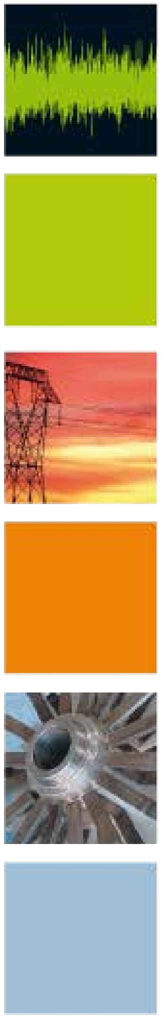


Duty cycle shifting – Type 2



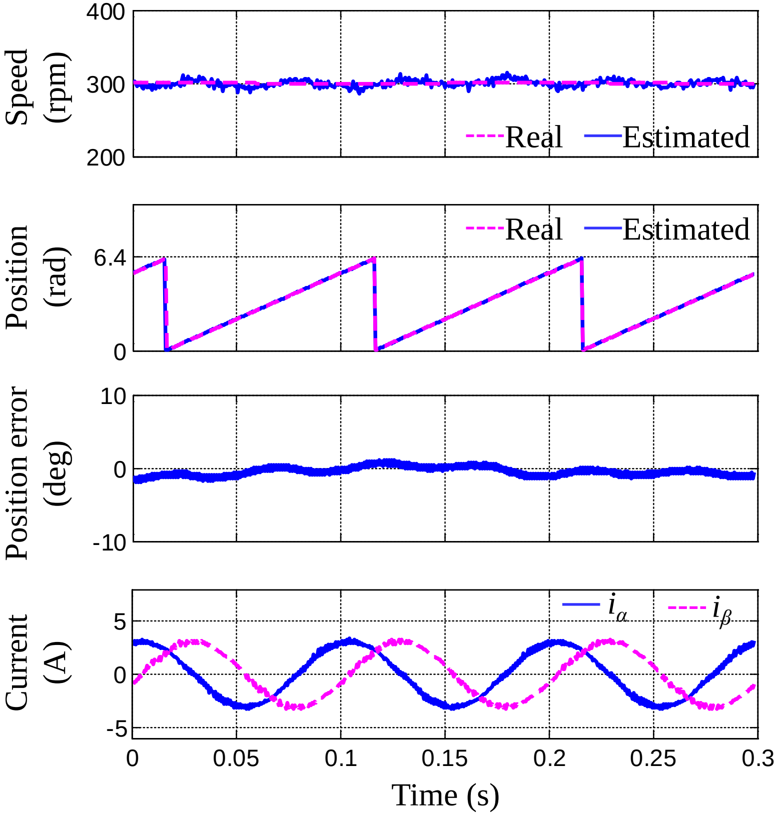
Duty cycle shifting – Type 3

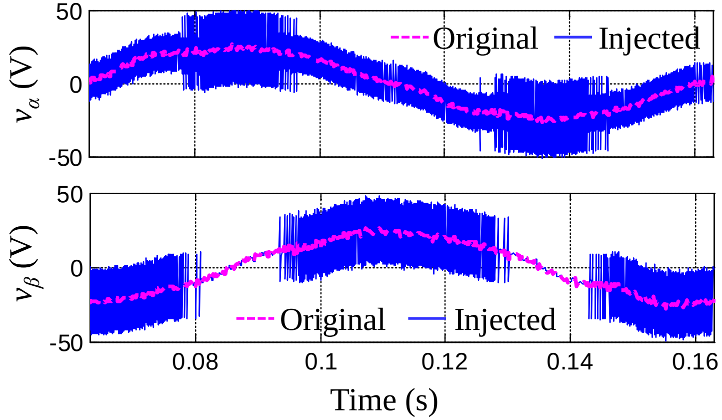
Experiment results



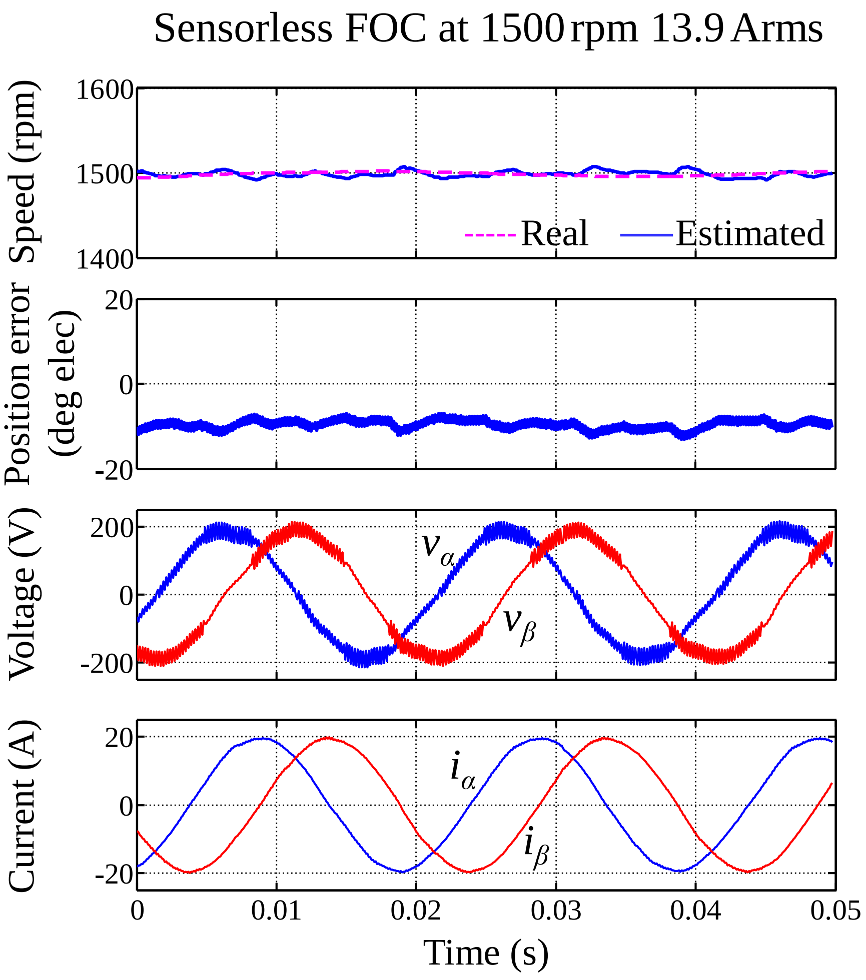
Proposed HFSI based position estimation method:

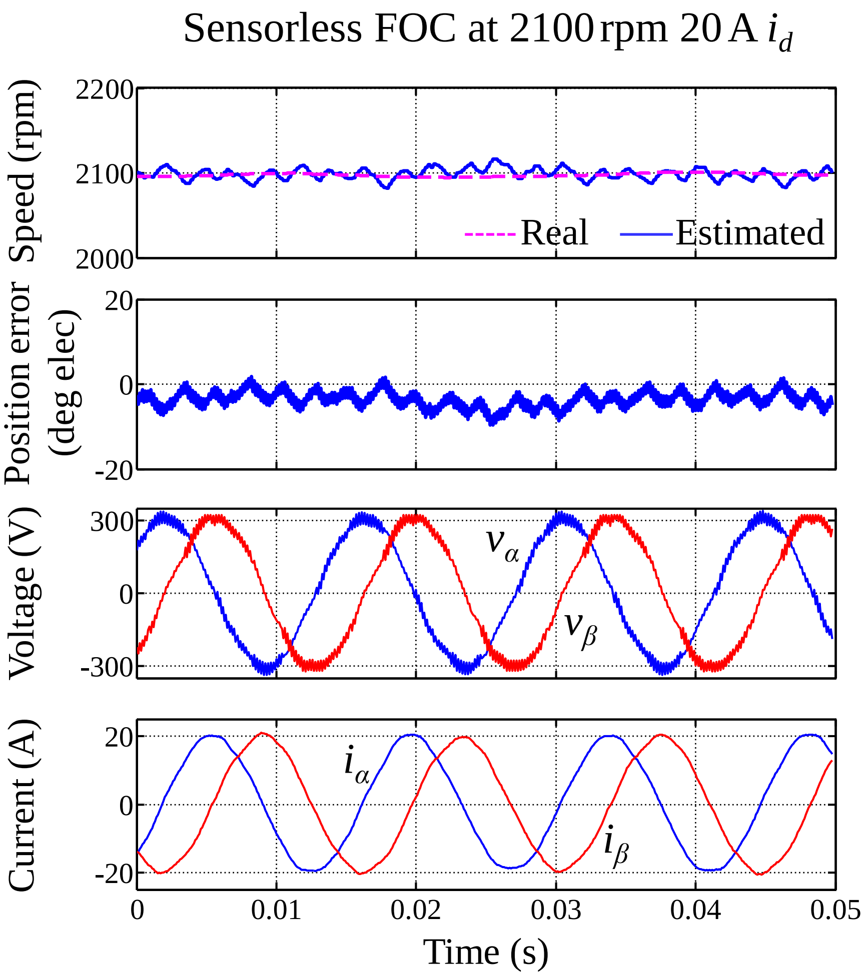
- With position encoder
- 300rpm, no load
- Duty cycle shifting with Δd_1 = 0.065
- Injected current is 0.6A



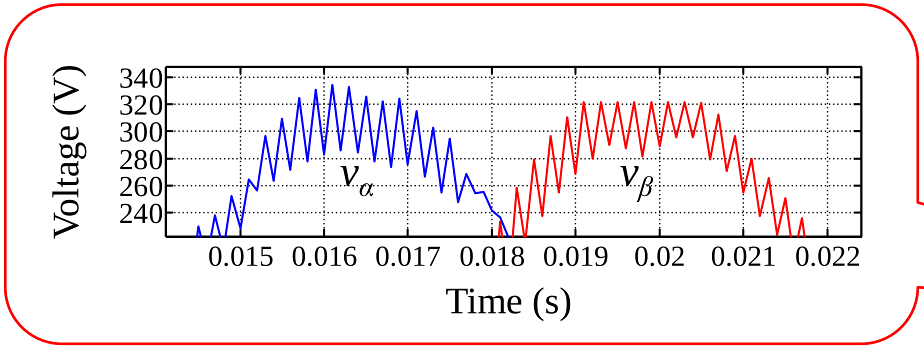


Experiment results

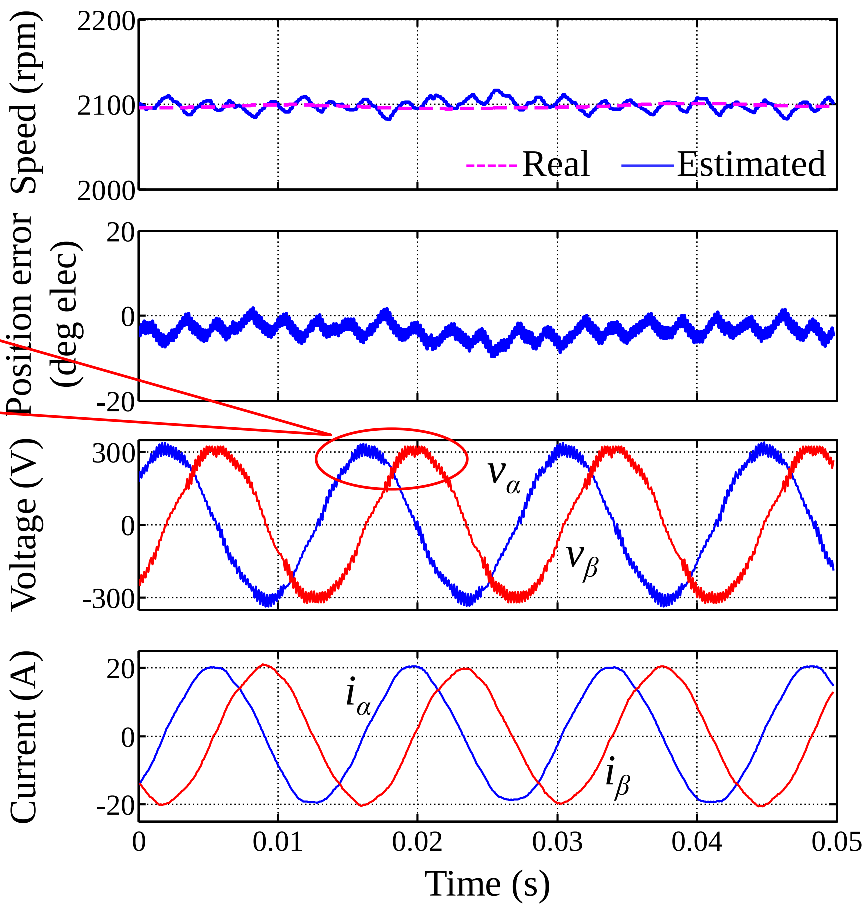

Sensorless FOC at 1500 rpm 13.9 Arms


Sensorless FOC at 2100 rpm 20 A i_d

Experiment results



Sensorless FOC at 2100 rpm 20 A i_d



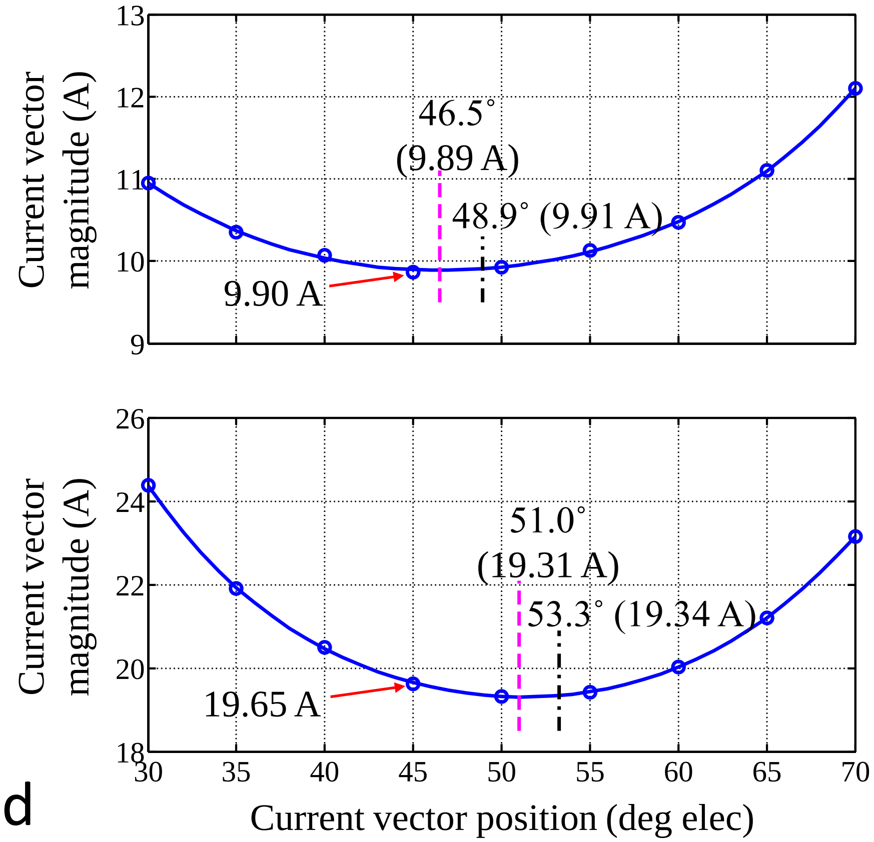
- Maximum voltage output achieved (v_β 320 Vpk at 0.02 s)
- Signal injection without influence the fundamental output

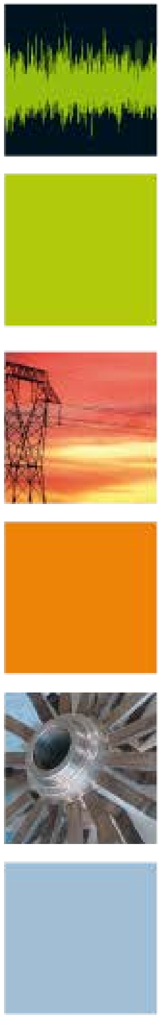
Experiment results

High torque per ampere operation:

Current vector position 45°

- Top: constant load of 7 Arms motor current (amplitude 9.90 A) 48.9° – 46.5° = 2.4°
- bottom: constant load of 13.9 Arms motor current (amplitude 19.65 A) 53.3° – 51.0° = 2.3°
- The position error is consistent at different load





Summary

- A new HFSI method is proposed and verified
  - with the advantage of no output voltage amplitude sacrifice
  - different types of injection can be achieved by controlling the values of Δd_1 and Δd_2
  - open the possibilities to apply HFSI based inductance independent position estimation method at full speed and load
- New position estimation algorithm is proposed and verified
  - machine inductance independent
  - with arbitrary voltage injection, including the proposed HFSI
  - no BPF and/or LPF needed for position information extraction
  - for middle to high-speed operation range of SynRM drive

- Any comment?

Thank you!