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

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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
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.

\[ |d_1 + \Delta d_1| + |d_2 - \Delta d_2| \leq 1, \quad |d_1 - \Delta d_1| + |d_2 + \Delta d_2| \leq 1 \]
Proposed HFSI method

The injected voltage vector:

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

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

- The injected voltage vector (carrier signal)

$$\Delta \bar{V}_{c,pu} = \bar{V}_{1,pu} - \bar{V}_{2,pu} = \left((d_1 + \Delta d_1)\bar{U}_{4,pu} + (d_2 - \Delta d_2)\bar{U}_{6,pu}\right) - \left((d_1 - \Delta d_1)\bar{U}_{4,pu} + (d_2 + \Delta d_2)\bar{U}_{6,pu}\right)$$

$$= \frac{4}{\sqrt{3}} \Delta d_1 \cdot e^{j0} - \frac{4}{\sqrt{3}} \Delta d_2 \cdot e^{j\frac{\pi}{3}}$$
Duty cycle shifting – Type 1

Duty cycle shifting with fixed $\Delta d_1$ and $\Delta d_2 = 0$:

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

Can be used for existing position estimation algorithm [1]

Duty cycle shifting – Type 1

Maximum $\Delta d_1 = 1 - d_1$, i.e. $\bar{U}_4$ occupies a full period $s_1$ 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 $\Delta d_1$ always available $\Delta d_1 = 1 - \sqrt{3}/2 = 0.134$
- For $U_{dc} = 575V$ and $\Delta d_2 = 0$:
  \[
  \Delta \bar{V}_c = \frac{U_{dc}}{\sqrt{3}} \Delta \bar{V}_{c,pu} = \frac{U_{dc}}{\sqrt{3}} \frac{4}{\sqrt{3}} \Delta d_1 \cdot e^{j0} = 102.73e^{j0}
  \]

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:

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

Can be used for existing position estimation algorithm [1]

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 \( \Delta \bar{V}_{c,pu} = -j2\Delta d \cdot e^{j\delta} \) which is perpendicular to \( \bar{V}_0 = V_0e^{j\delta} \)
- \( f_s = 9\text{kHz} \)

Can be used for existing position estimation algorithm \([2]\)

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 algorithm:

- Based on the changing of flux-linkage and current during two neighboring switching periods
- SynRM flux-linkage in the stator frame: \( \bar{\lambda}_{\alpha\beta} = L_1 \bar{i}_{\alpha\beta} + L_2 \bar{i}_{\alpha\beta}^* e^{i2\theta_r} \)
  where \( L_1 = (L_d + L_q)/2 \) and \( L_2 = (L_d - L_q)/2 \)
- Define \( \bar{A} = \bar{\lambda}_{\alpha\beta_2} \bar{i}_{\alpha\beta_1} - \bar{\lambda}_{\alpha\beta_1} \bar{i}_{\alpha\beta_2} \)
- Then \( \bar{A} = L_2 \text{Im}(\bar{i}_{\alpha\beta_2}^* \bar{i}_{\alpha\beta_1}) \cdot 2je^{i2\theta_r} \Rightarrow 2\hat{\theta}_r = \angle \bar{A} + \pi/2 \)
- 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:

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

- Then

$$ \vec{A} = (L_2 + l_{dq}) \text{Im}(i_{\alpha\beta_2}^* i_{\alpha\beta_1}) \cdot 2 j e^{j2\hat{\theta}_r} = L'_2 \text{Im}(i_{\alpha\beta_2}^* i_{\alpha\beta_1}) \cdot 2 j e^{j(2\hat{\theta}_r + \varepsilon)} $$

$$ \text{where } \varepsilon = \arctan \frac{2l_{dq}}{L_d - L_q} $$

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

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

- Instead of the rotor mechanical saliency ($\hat{\theta}_r$), the distorted magnetic saliency ($\theta_{\text{est}}$) is obtained.
Sensorless FOC with high torque per ampere operation:

- Torque: \( T = \frac{3}{2} p(i_q \lambda_d - i_d \lambda_q) = \frac{3}{2} \frac{pL_2 I_m^2}{L} \sin(2\theta_r^r - \varepsilon) \)
  and maximum torque is obtained when \( 2\theta_r^r - \varepsilon = \pi/2 \)

- Current vector location in the stationary frame:
  \[ \theta_i^s = \pi/4 + \varepsilon/2 + \hat{\theta}_r = \pi/4 + \theta_{est} \]

- The current vector should locate at 45° with respect to \( \theta_{est} \)
  i.e. 45° in the estimated rotor frame (magnetic saliency)

- There is no need to compensate the error (\( \varepsilon \)) 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 $\Delta d_1 = 0.065$

100 V 50 Hz output

220 V 50 Hz output
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 $\Delta d = 0.05$
Proposed HFSI based position estimation method:

- With position encoder
- 300rpm, no load
- Duty cycle shifting with $\Delta d_1 = 0.065$
- 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

- Maximum voltage output achieved ($v_\beta$ 320Vpk at 0.02s)
- 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 $\Delta d_1$ and $\Delta d_2$
  - 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?