Impedance Based Beat Suppression Strategy for PMSM Drives With Small DC-Link Capacitors

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1. Introduction

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Electrolytic capacitor

- Short lifetime
- Affected by ripple current
- Low reliability

Film capacitor

- Long lifetime
- Less affected by ripple current
- High reliability

Replacing electrolytic capacitor with film capacitor can reduce system cost, improve power density and extend system life.

Film capacitors are widely used in various fields.

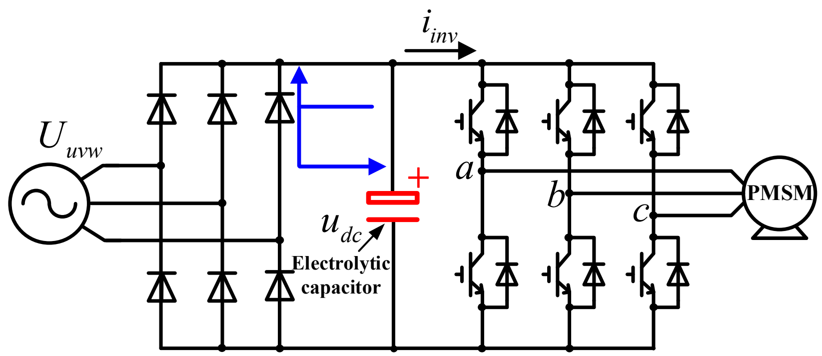
Wind Power Generation

Photovoltaics

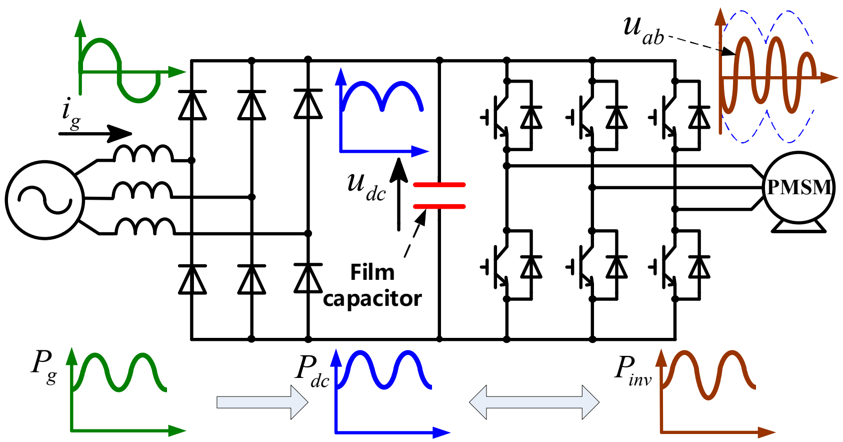
Electric Vehicle

Household appliances

1. Introduction



Conventional motor drives



Electrolytic capacitorless motor drives

➢ **Benefits :**

Capacitance can be reduced to 1/50

Better performance in grid currents

Higher reliability, lower cost and volume

■ **Challenges :**

1. Beat suppression technology
2. Torque harmonic suppression
3. Anti-overvoltage control
4. LC resonance suppression
5. Overmodulation technology
6. Low harmonic flux-weakening method

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2. Beat Phenomenon in Drives With Small Capacitors

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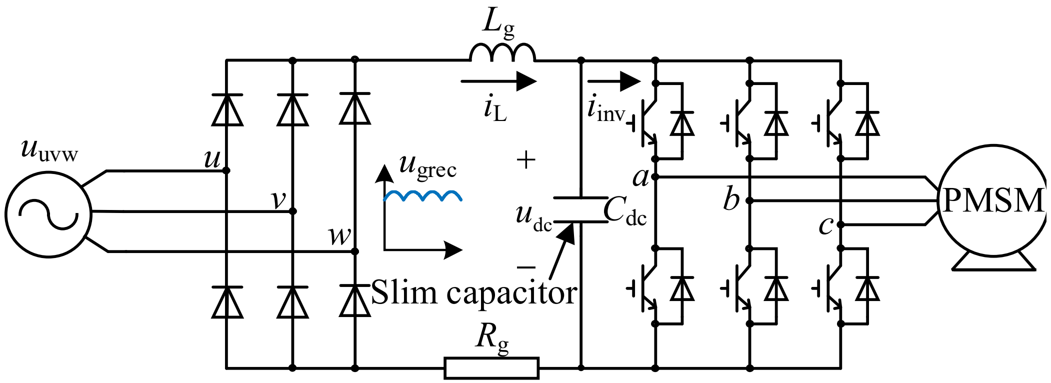

Topology of PMSM drive with small DC-link capacitors

- **Due to the fluctuation of DC-link voltage, there exists beat phenomenon problem in the phase current.**
- **The motor current is introduced additional harmonics at the frequencies of $6\omega_g - \omega_e$ and $6\omega_g + \omega_e$.**

Fluctuated DC-link voltage

$$u_{dc} = U_{dc,0} + \sum_{k=1}^{\infty} U_{dc,k} \sin\left(6k\omega_g t + \varphi_k\right)$$

Motor voltage at *dq*-axes

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \left|\boldsymbol{u}_s^*\right| \left[1 + \frac{4}{35}\sin(\varphi_d)\sin\left(6\omega_g t - \frac{\varphi_d}{2}\right)\right] \sin(\varphi_e) \\ -\left|\boldsymbol{u}_s^*\right| \left[1 + \frac{4}{35}\sin(\varphi_d)\sin\left(6\omega_g t - \frac{\varphi_d}{2}\right)\right] \cos(\varphi_e) \end{bmatrix}$$

Phase current

$$i_a = i_{a0} + \sum_{k=1}^{\infty}\left(i_{ak-} + i_{ak+}\right) = I_{a,0}\sin\left(\omega_e t + \varphi_e\right)$$
$$+ \sum_{k=1}^{\infty}\left\{ I_{k-}\sin\left[\left(6k\omega_g - \omega_e\right)t + \varphi_{k-}\right]\right.$$
$$\left. + I_{k+}\sin\left[\left(6k\omega_g + \omega_e\right)t + \varphi_{k+}\right]\right\}$$

2. Beat Phenomenon in Drives With Small Capacitors

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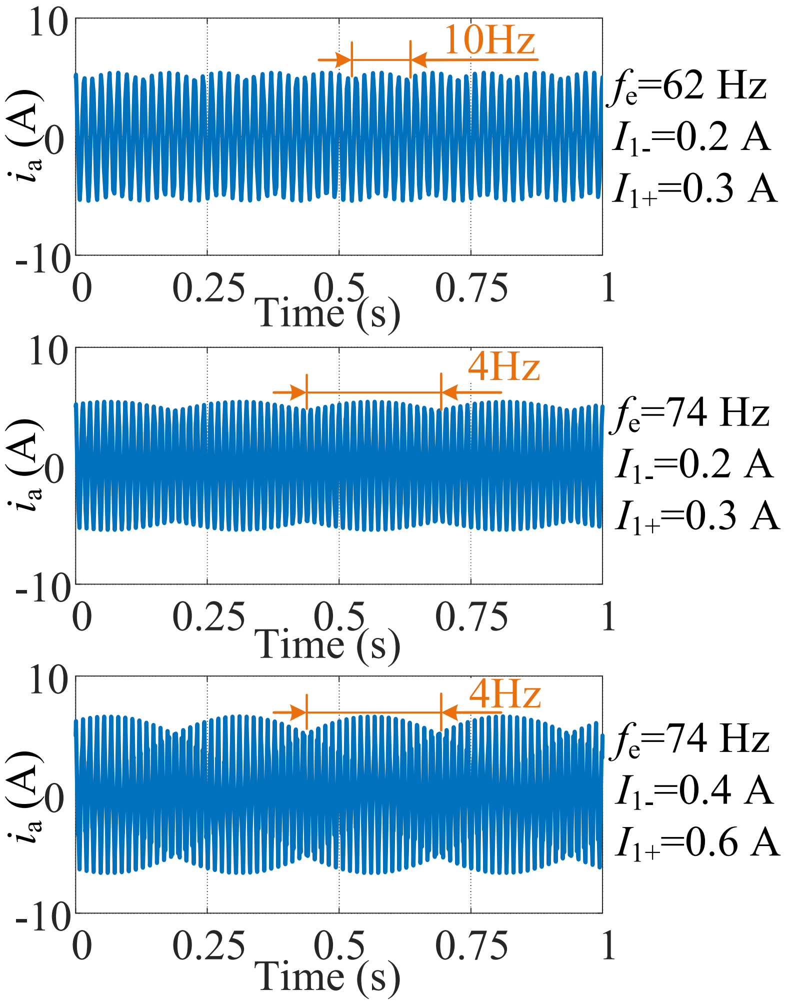

Phase current under different fundamental frequencies and harmonics

Composition points of beat envelop

$$
\begin{aligned}
F(t) &= -I_{k-}\cos\left[6k\omega_g t + \varphi_e + \varphi_{k-}\right] \\
&\quad + I_{k+}\cos\left[6k\omega_g t - \varphi_e + \varphi_{k+}\right]\Big|_{t=(2\pi N+\pi/2-\varphi_e)/\omega_e} \\
&= -I_{k-}\cos\left[12k\pi N\omega_g/\omega_e + \varphi_{bk} + \varphi_e + \varphi_{k-}\right] \\
&\quad + I_{k+}\cos\left[12k\pi N\omega_g/\omega_e + \varphi_{bk} - \varphi_e + \varphi_{k+}\right]\Big|_{N=0,1,2,\cdots}
\end{aligned}
$$

- **The beat envelope is formed by the local maximum value of the beat current;**
- **Beat frequency and amplitude are determined by harmonics and phase difference.**

2. Beat Phenomenon in Drives With Small Capacitors

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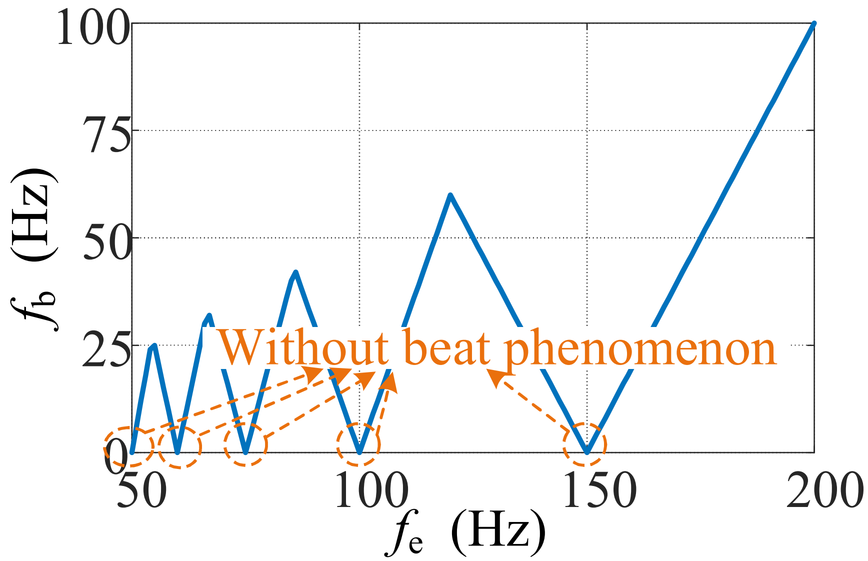
- **Beat frequency**

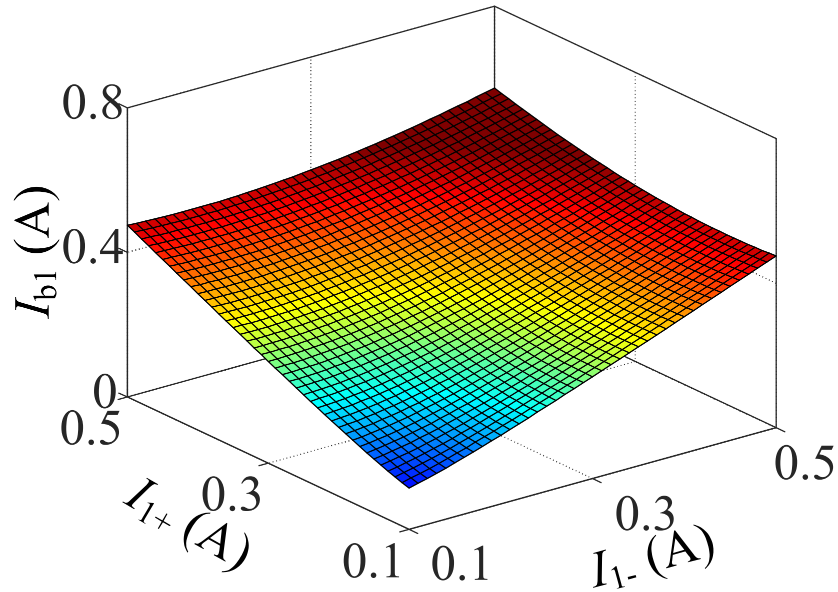
$$\omega_{bk} = 2\pi d_k / (2\pi/\omega_e) = \omega_e \left[R_k - \boldsymbol{R}(R_k) \right]$$

- **Beat amplitude**

$$I_{bk} = \sqrt{I_{k-}^2 + I_{k+}^2 - 2I_{k-}I_{k+}\cos(2\varphi_e + \varphi_{k-} - \varphi_{k+})}$$



Beat frequency under different fundamental frequencies

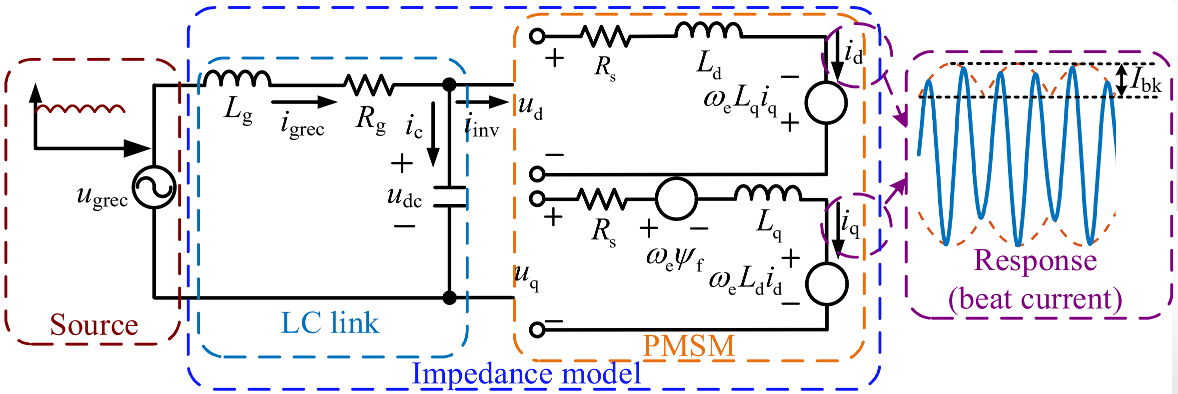


Beat amplitude under different amplitudes of harmonics

① **The motor currents do not show the beat phenomenon when the fundamental frequency is the common factor of $6k\omega_g$;**

② **The beat amplitude is proportional to the amplitudes of harmonics.**

2. Beat Phenomenon in Drives With Small Capacitors



Model of the electrolytic capacitorless drive

dq-axis actual voltage ripple

$$\begin{bmatrix}\Delta u_d\\ \Delta u_q\end{bmatrix}=\begin{bmatrix}R_s+pL_d & -\omega_e L_q\\ \omega_e L_d & R_s+pL_q\end{bmatrix}\begin{bmatrix}\Delta i_d\\ \Delta i_q\end{bmatrix}$$

dq-axis reference voltage ripple

$$\begin{bmatrix}\Delta u_{dref}\\ \Delta u_{qref}\end{bmatrix}=e^{-0.5sT_s}\begin{bmatrix}-\boldsymbol{G}_d & -\omega_e L_q\\ \omega_e L_d & -\boldsymbol{G}_q\end{bmatrix}\begin{bmatrix}\Delta i_d\\ \Delta i_q\end{bmatrix}$$

Relationship between actual and reference voltage ripple

$$\begin{bmatrix}\Delta u_d\\ \Delta u_q\end{bmatrix}=\left\{e^{-sT_s}\begin{bmatrix}\Delta u_{dref}\\ \Delta u_{qref}\end{bmatrix}+\frac{\left(1-e^{-1.5sT_s}\right)\Delta u_{dc}}{U_{dc0}}\begin{bmatrix}U_{dref0}\\ U_{qref0}\end{bmatrix}\right\}\cdot\begin{bmatrix}\cos 1.5\omega_e T_s & \sin 1.5\omega_e T_s\\ -\sin 1.5\omega_e T_s & \cos 1.5\omega_e T_s\end{bmatrix}$$

Ratio between *dq*-axis current and DC-link voltage

$$\left\{\begin{aligned}&\begin{bmatrix}\boldsymbol{W}_d\\ \boldsymbol{W}_q\end{bmatrix}=\frac{\left(1-e^{-1.5sT_s}\right)}{U_{dc0}\left[\boldsymbol{A}_{2q}\boldsymbol{A}_{1d}-\boldsymbol{A}_{2d}\boldsymbol{A}_{1q}\right]}\begin{bmatrix}U_{dref0}\boldsymbol{A}_{2q}-U_{qref0}\boldsymbol{A}_{1q}\\ U_{qref0}\boldsymbol{A}_{1d}-U_{dref0}\boldsymbol{A}_{2d}\end{bmatrix}\\ &\begin{bmatrix}\boldsymbol{A}_{1d} & \boldsymbol{A}_{1q}\\ \boldsymbol{A}_{2d} & \boldsymbol{A}_{2q}\end{bmatrix}=\boldsymbol{C}_0^{-1}\begin{bmatrix}R_s+pL_d & -\omega_e L_q\\ \omega_e L_d & R_s+pL_q\end{bmatrix}\\ &\qquad+e^{-1.5sT_s}\begin{bmatrix}\boldsymbol{G}_d & \omega_e L_q\\ -\omega_e L_d & \boldsymbol{G}_q\end{bmatrix}\end{aligned}\right.$$

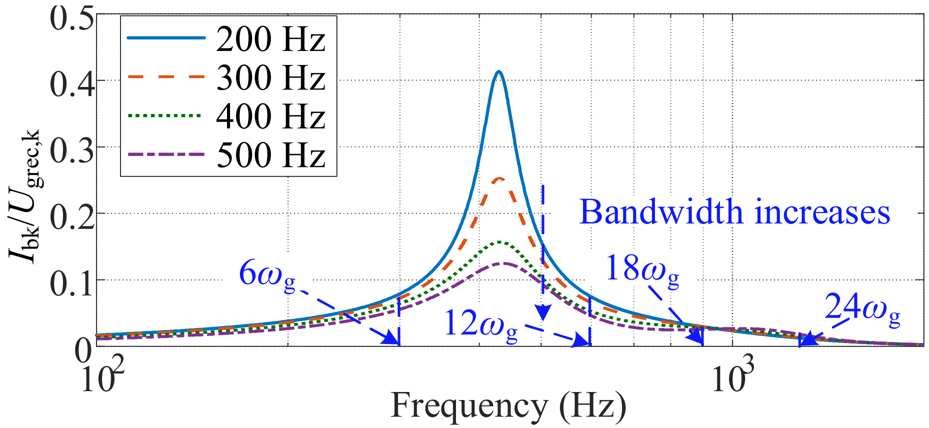
2. Beat Phenomenon in Drives With Small Capacitors

➤ **Influence of the rectified voltage on the stator current**

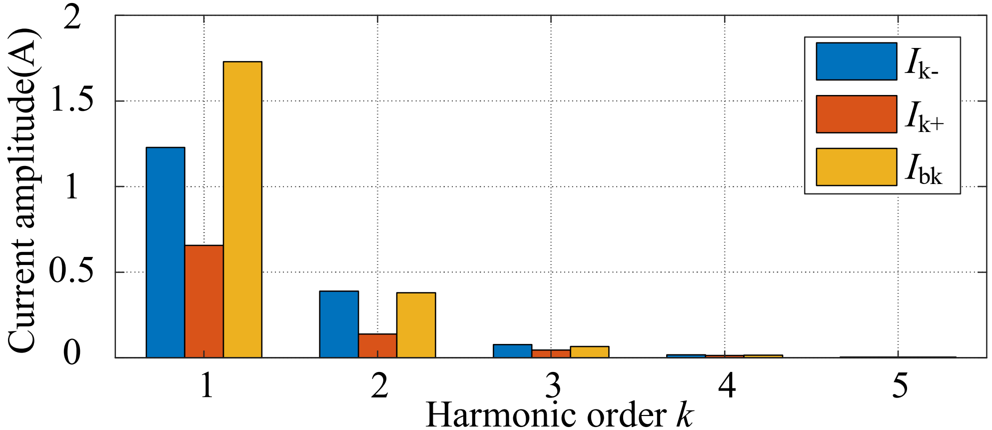
$$\frac{I_{bk}}{U_{grec,k}} = \frac{|\boldsymbol{K}_{mk}|}{\sqrt{2}} \cdot \sqrt{\begin{aligned}&|\boldsymbol{W}_{dk}|^2 + |\boldsymbol{W}_{qk}|^2 - 2\cos(2\varphi_e + \varphi_{k-} - \varphi_{k+})[|\boldsymbol{W}_{dk}|^4 \\ &+ |\boldsymbol{W}_{qk}|^4 + 2|\boldsymbol{W}_{dk}\boldsymbol{W}_{qk}|^2 \cos 2\{\angle \boldsymbol{W}_{dk} - \angle \boldsymbol{W}_{qk}\}]^{0.5}\end{aligned}}$$

➤ **Amplitude of the beat current**

$$I_{bk} = \frac{6U_g|\boldsymbol{K}_{mk}|}{\pi(36k^2-1)} \sqrt{\begin{aligned}&|\boldsymbol{W}_{dk}|^2 + |\boldsymbol{W}_{qk}|^2 - 2\cos(2\varphi_e + \varphi_{k-} - \varphi_{k+})[|\boldsymbol{W}_{dk}|^4 \\ &+ |\boldsymbol{W}_{qk}|^4 + 2|\boldsymbol{W}_{dk}\boldsymbol{W}_{qk}|^2 \cos 2\{\angle \boldsymbol{W}_{dk} - \angle \boldsymbol{W}_{qk}\}]^{0.5}\end{aligned}}$$



Ratios of $I_{bk}/U_{grec,k}$ with different bandwidths of the current controllers



Amplitude of harmonics in the motor current

① **The increase of the bandwidth can reduce the beat current at the frequencies of $6\omega_g$ and $12\omega_g$;**

② **The harmonics related to $6\omega_g$ and $12\omega_g$ are the dominated components.**

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3. Beatless Method Based on Impedance Reshaping

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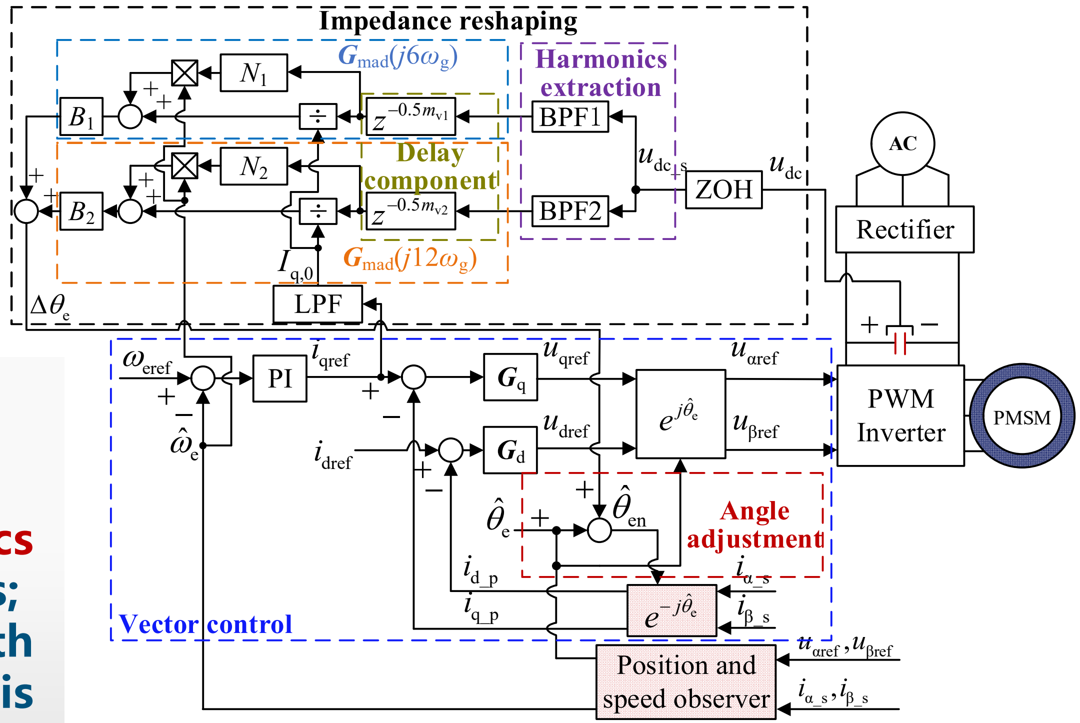
Goal

1. Reshaping the impedance between the *dq*-axis current and the DC-link voltage;
2. Improve the adaptability of the beat suppression method

Control process

1. Obtaining the inherent harmonics of DC-link voltage by bandpass filters;
2. Generating the adjusting angle with the motor speed and the q-axis current;
3. Adding the adjustment angle to the current vector angle.



Beatless Method Based on Impedance Reshaping

3. Beatless Method Based on Impedance Reshaping

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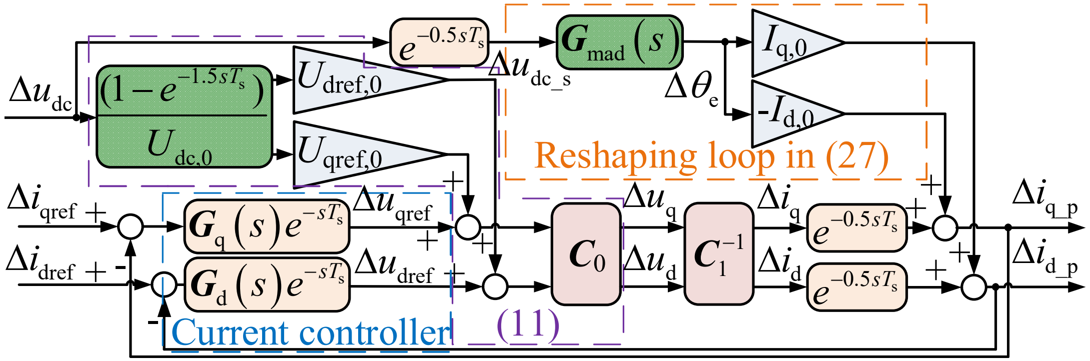

Small-signal model with the impedance reshaping strategy

- Regulation **of current vector angle** is equivalent to introduce additional adjusting currents, whose amplitudes **vary adaptively with the operation condition.**
- **Transfer function G_{mad}** is hard to realize, which needs to be further designed.

Equivalent feedback currents after angle regulation

$$\begin{bmatrix} I_{d\_p,0}+\Delta i_{d\_p} \\ I_{q\_p,0}+\Delta i_{q\_p} \end{bmatrix} = \begin{bmatrix} I_{d,0}+e^{-0.5sT_s}\Delta i_d + I_{q,0}\Delta\theta_e \\ I_{q,0}+e^{-0.5sT_s}\Delta i_q - I_{d,0}\Delta\theta_e \end{bmatrix}$$

Additional adjusting currents

Ratio between dq-axis current and DC-link voltage after control

$$\begin{bmatrix} \boldsymbol{W}_{dmad} \\ \boldsymbol{W}_{qmad} \end{bmatrix} = \begin{bmatrix} \boldsymbol{W}_{d} \\ \boldsymbol{W}_{q} \end{bmatrix} + \frac{e^{-1.5sT_s}\boldsymbol{G}_{mad}}{\boldsymbol{A}_{2q}\boldsymbol{A}_{1d}-\boldsymbol{A}_{2d}\boldsymbol{A}_{1q}} \begin{bmatrix} -I_{q,0}\boldsymbol{G}_d\boldsymbol{A}_{2q}-I_{d,0}\boldsymbol{G}_q\boldsymbol{A}_{1q} \\ I_{d,0}\boldsymbol{G}_q\boldsymbol{A}_{1d}+I_{q,0}\boldsymbol{G}_d\boldsymbol{A}_{2d} \end{bmatrix}$$

Transfer function from adjusting angle to DC-link voltage

$$\boldsymbol{G}_{mad} = \frac{\Delta\theta_e}{\Delta u_{dc}} = \frac{\left(e^{1.5sT_s}-1\right)\left(U_{dref,0}\boldsymbol{A}_{2d}-U_{qref,0}\boldsymbol{A}_{1d}\right)}{U_{dc,0}I_{q,0}\boldsymbol{G}_d\boldsymbol{A}_{2d}}$$

3. Beatless Method Based on Impedance Reshaping

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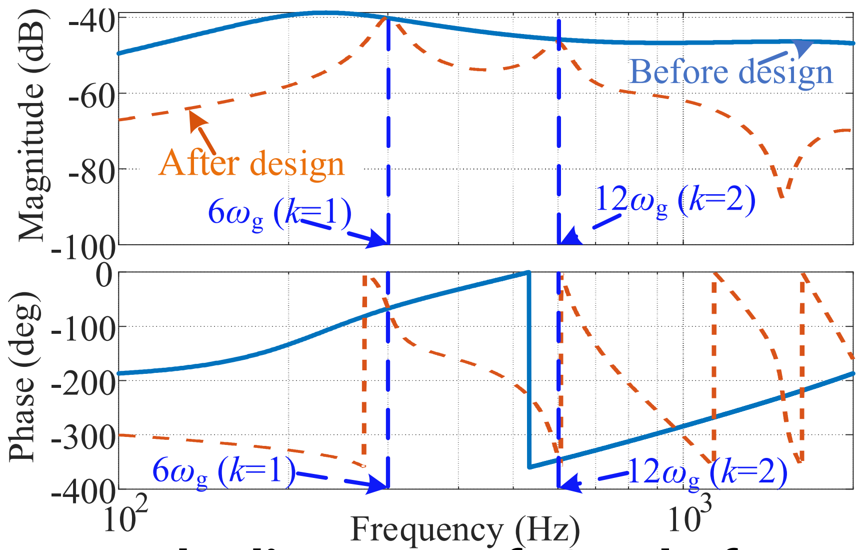

Bode diagrams of G_{mad} before and after the design

G_{mad} ignoring the resistance loss

$$G_{mad} \approx \frac{\left(R_s I_{q,0} + \omega_e \psi_f\right)\left(R_s + L_d s + e^{-1.5sT_s} G_d\right) + \omega_e^2 L_d L_q I_{q,0}}{U_{dc,0} I_{q,0} \omega_e L_d G_d \Big/ \left(1 - e^{1.5sT_s}\right)}$$

G_{mad} after design

$$G_{mad} = B_1\left(1/I_{q,0} + N_1\omega_e\right) G_{BPF1} e^{-0.5 m_{v1} T_s s} + B_2\left(1/I_{q,0} + N_2\omega_e\right) G_{BPF2} e^{-0.5 m_{v2} T_s s}$$

- **Steady state values ω_e and $I_{q,0}$ in G_{mad} can be separated out to improve the adaptability;**
- **The frequency characteristics of G_{mad} before and after design are close at $6\omega_g$ and $12\omega_g$.**

Proportional coefficient:

$$\begin{cases} B_k = \dfrac{\left|1 - e^{j9k\omega_g T_s}\right| \left|e^{-j9k\omega_g T_s}\left(K_{id} + j6kK_{pd}\omega_g\right) - 36L_d k^2 \omega_g^2 + j6kR_s\omega_g\right| \psi_f}{L_d U_{dc,0}\left|K_{id} + j6kK_{pd}\omega_g\right|} \\ N_k = \dfrac{6kL_d L_q \omega_g}{\left|e^{-j9k\omega_g T_s}\left(K_{id} + j6kK_{pd}\omega_g\right) - 36L_d k^2 \omega_g^2 + j6kR_s\omega_g\right| \psi_f} \end{cases}$$

Equivalent delay:

$$m_{v1} = \boldsymbol{R}\left[-\frac{2\angle G_{mad}\left(j6\omega_g\right)}{6\omega_g T_s}\right], m_{v2} = \boldsymbol{R}\left[-\frac{2\angle G_{mad}\left(j12\omega_g\right)}{12\omega_g T_s}\right]$$

3. Beatless Method Based on Impedance Reshaping

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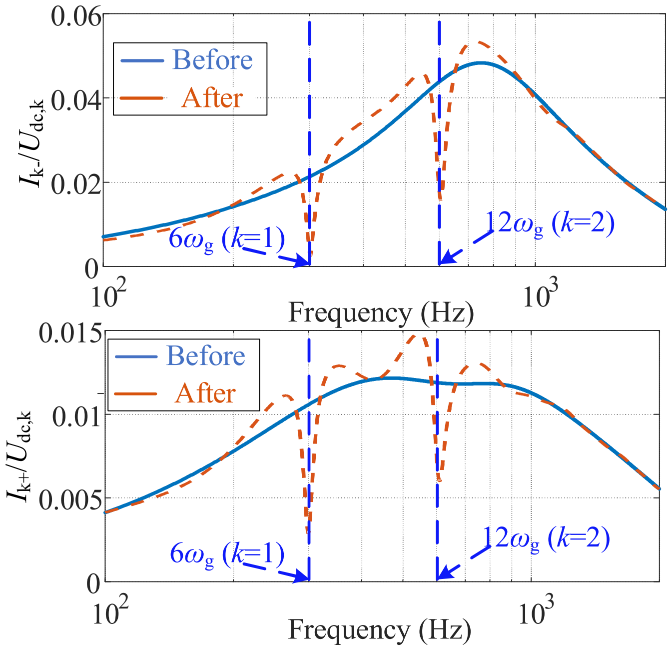
Stator harmonics and DC-link fluctuation

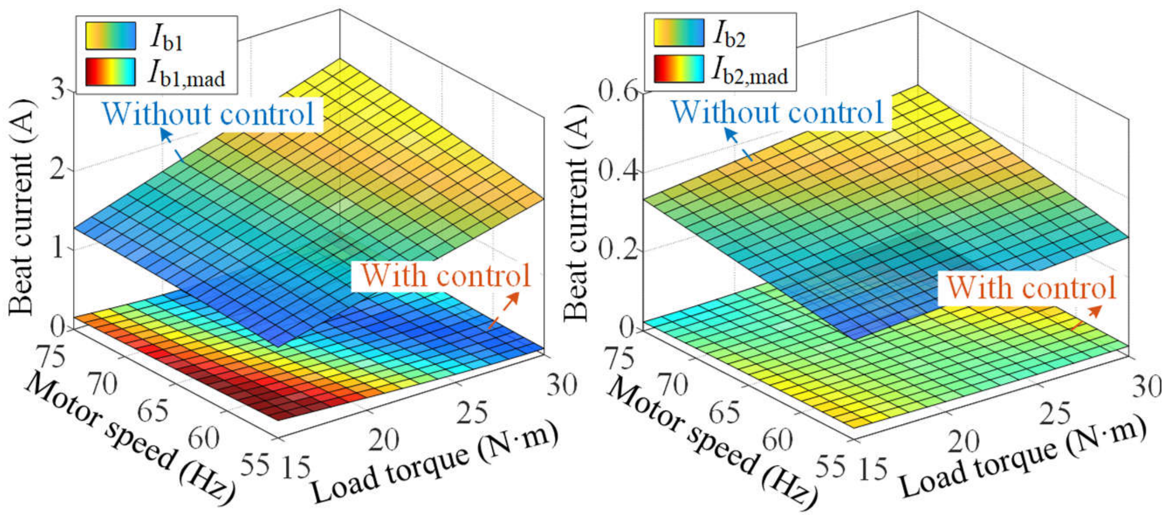
$$\frac{I_{k\mp}}{U_{dc,k}} = \frac{\sqrt{\left|\boldsymbol{W}_{dmadk}\right|^2 + \left|\boldsymbol{W}_{qmadk}\right|^2 \mp 2\left|\boldsymbol{W}_{dmadk}\boldsymbol{W}_{qmadk}\right| \cdot \sin\left\{\angle\boldsymbol{W}_{dmadk} - \angle\boldsymbol{W}_{qmadk}\right\}}}{2}$$

Amplitude of beat current after control

$$I_{bk,mad} = \frac{6U_g\left|\boldsymbol{K}_{mmadk}\right|}{\pi(36k^2-1)}\sqrt{\left|\boldsymbol{W}_{dmadk}\right|^2 + \left|\boldsymbol{W}_{qmadk}\right|^2 - 2\cos\left(2\varphi_e + \varphi_{k-} - \varphi_{k+}\right) \cdot \sqrt{\left|\boldsymbol{W}_{dmadk}\right|^4 + \left|\boldsymbol{W}_{qmadk}\right|^4 + 2\left|\boldsymbol{W}_{dmadk}\boldsymbol{W}_{qmadk}\right|^2 \cdot \cos 2\left\{\angle\boldsymbol{W}_{dmadk} - \angle\boldsymbol{W}_{qkmad}\right\}}}$$



$I_{k\mp}/U_{dc,k}$ before and after control



Beat harmonics under different conditions

> ➢ **The proposed impedance reshaping based beat suppression method with the designed coefficients can work effectively in a wide speed and torque region.**

3. Beatless Method Based on Impedance Reshaping

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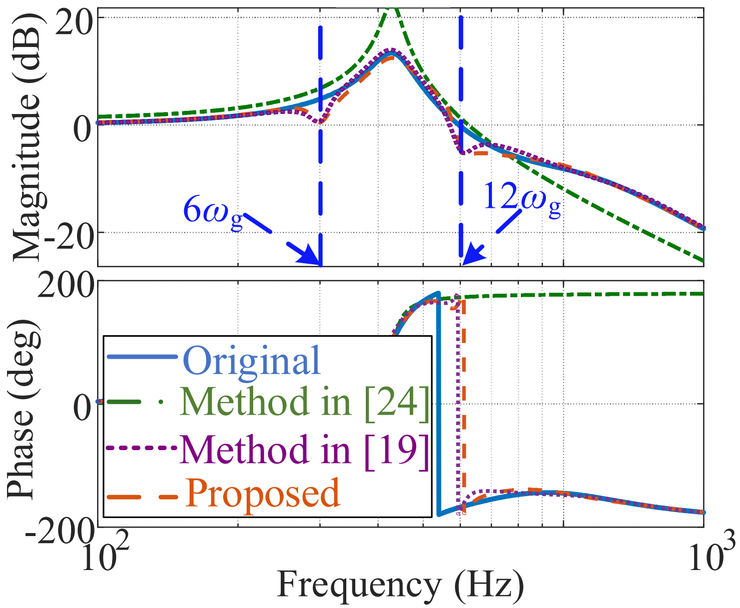
Rectified voltage and DC-link voltage with the method

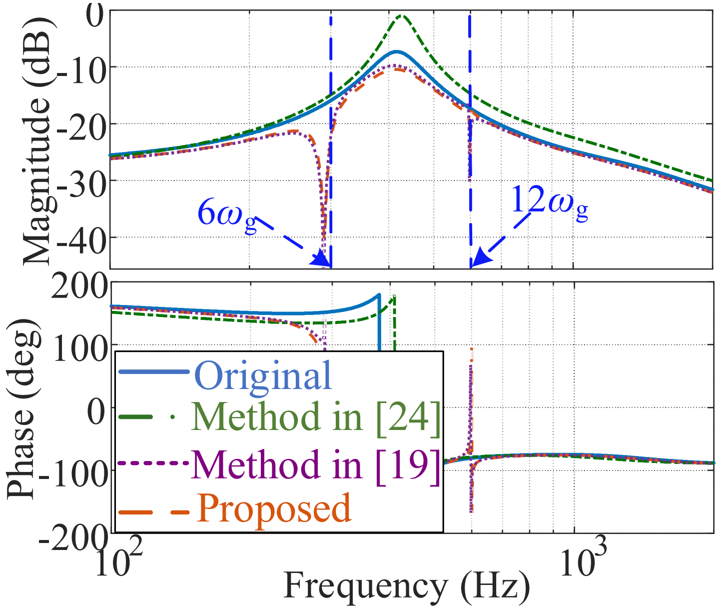
$$K_{\text{mmad}} = \frac{\Delta u_{\text{dc}}}{\Delta u_{\text{grec}}} = \frac{1}{1+\left(L_{\text{g}}s+R_{\text{g}}\right)\left(Y_{\text{mmad}}+C_{\text{dc}}s\right)}$$



Bode diagrams of K_{mmad}

Rectified voltage and inductor current with the method

$$K_{\text{gmad}} = \frac{\Delta i_{\text{L}}}{\Delta u_{\text{grec}}} = \frac{Y_{\text{mmad}}+C_{\text{dc}}s}{1+\left(L_{\text{g}}s+R_{\text{g}}\right)\left(Y_{\text{mmad}}+C_{\text{dc}}s\right)}$$



Bode diagrams of K_{gmad}

- **The harmonics of the DC-link voltage and grid current related to the frequencies of $6\omega_g$ and $12\omega_g$ can also be suppressed;**
- **The damping performance is close to that of conventional damping method.**

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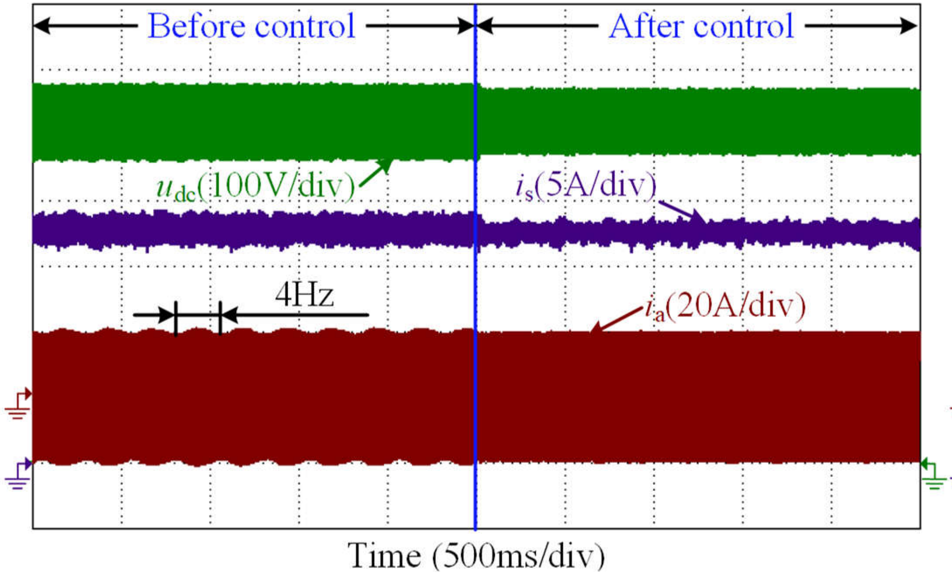
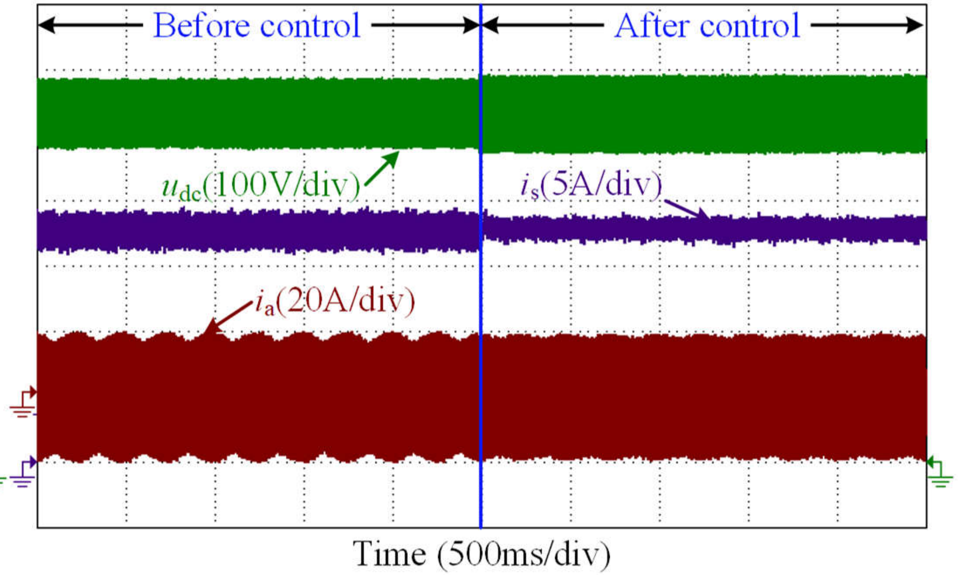
4. Experimental Results



Experimental results with the impedance reshaping at 74Hz



Experimental results with the conventional method at 74Hz

- **The amplitude of the low-frequency envelop with the impedance reshaping can be suppressed from 1.2 A to 0.2 A, and the peak-to-peak value of the DC-link voltage ripple falls from 120 V to 85 V.**
- **The peak-to-peak value of the DC-link voltage ripple increases from 120V to 153 V, which means the LC resonance is aggravated by the conventional method.**

4. Experimental Results

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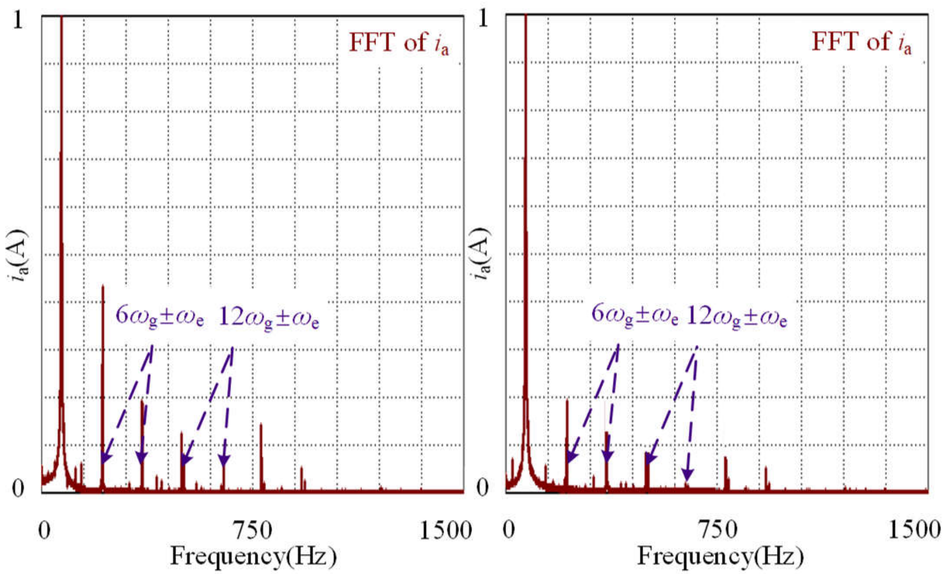
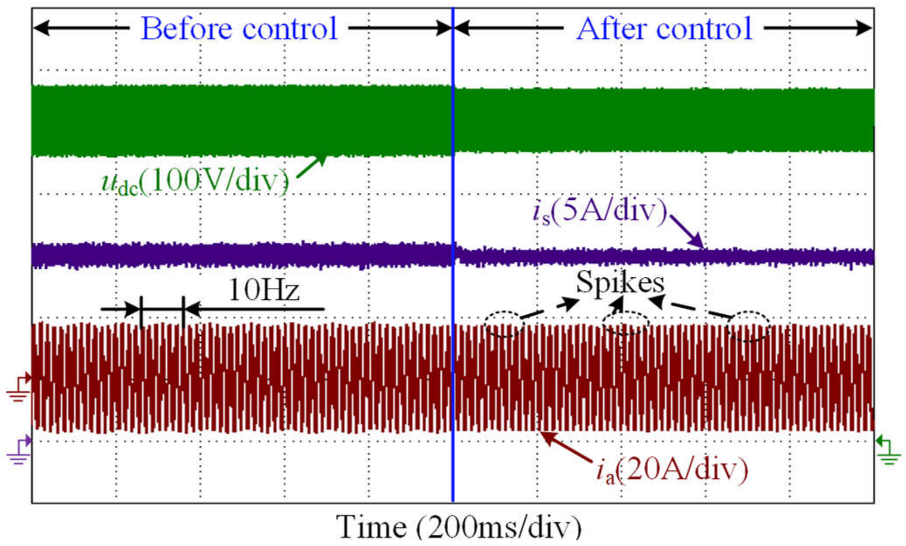


FFT of the phase current before and after impedance reshaping at 74Hz



Experimental results with the impedance reshaping at 62Hz

- The harmonic at the frequency of 226Hz can be reduced **from 0.46A to 0.19A**, and the harmonic at the frequency of 674Hz can be reduced **from 0.08A to 0.01A**.
- The impedance method remains effectively **at the motor frequency of 62 Hz.**

4. Experimental Results

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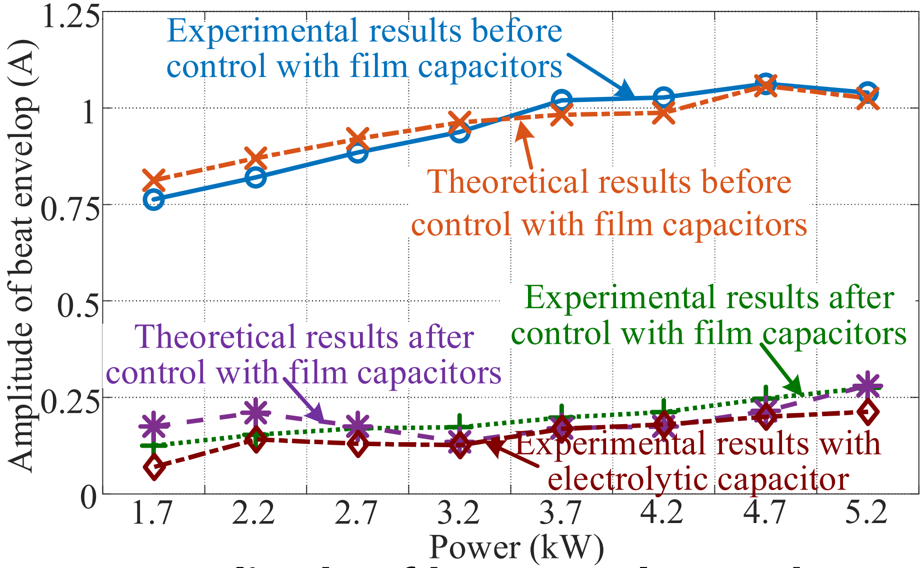
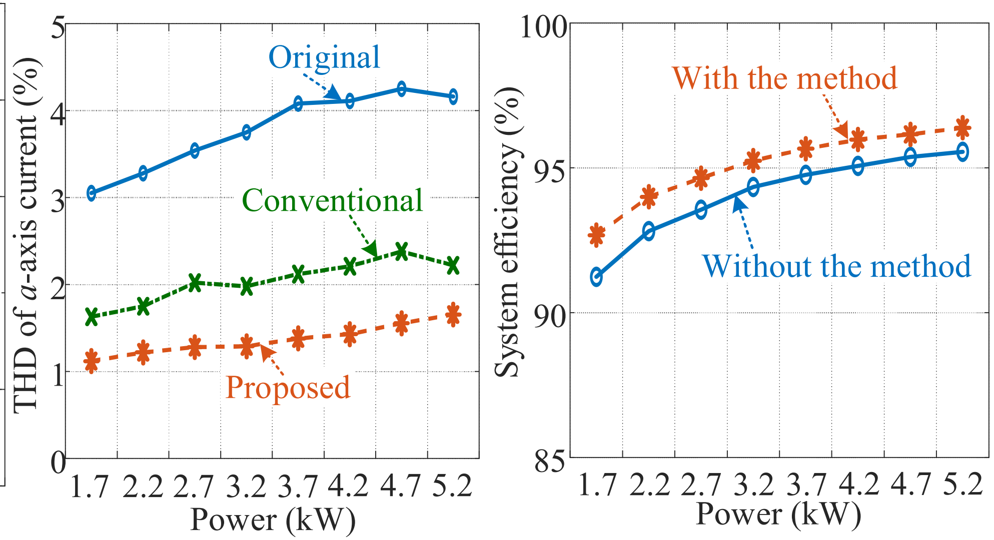


Amplitude of beat envelop under different output power conditions



Motor current THD and system efficiency under different output powers

- The amplitude of the beat envelop can be reduced to 0.25A, and THD of the phase current can be reduced to 1.5% after using the proposed method.
- The system efficiencies can be increased by over 1.5 % with the proposed method in the output power between 1.7 kW and 5.2 kW.

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5. Conclusion

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- The small signal model has been constructed to show the generation of the beat phenomenon **in an impedance perspective**.
- An impedance reshaping method for dominated harmonics, which **is immune to the steady state values of the motor speed and q-axis current**, is proposed by regulating the angle of the motor current vector.
- The proposed beat suppression method will **not aggravate the LC resonance** and increase the harmonics in DC-link voltage.

Thank you for your attention!