Voltage Modulation Using Virtual Positive Impedance Concept for Active Damping of Small DC-Link Drive System

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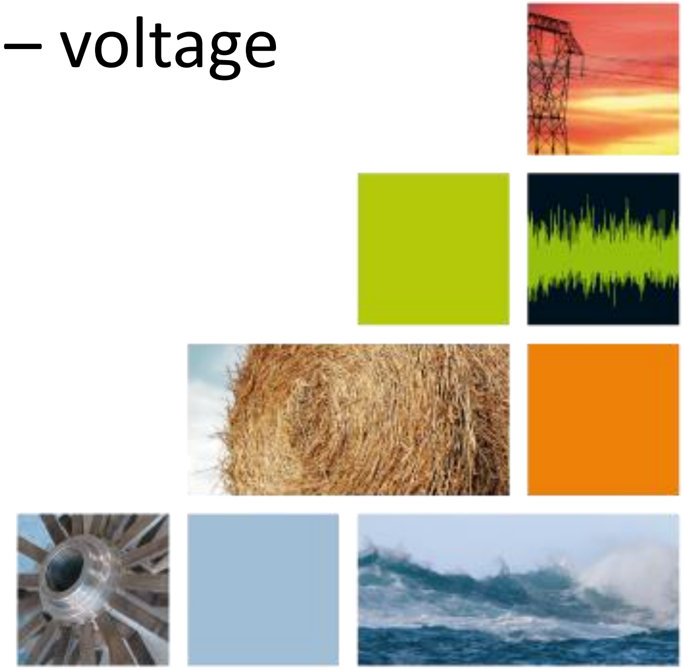
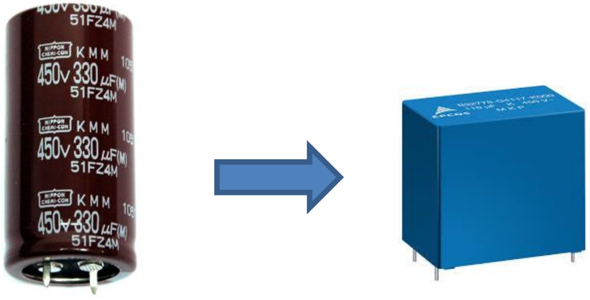


Background – Why small dc-link drive


Electrolytic Capacitor

Film Capacitor

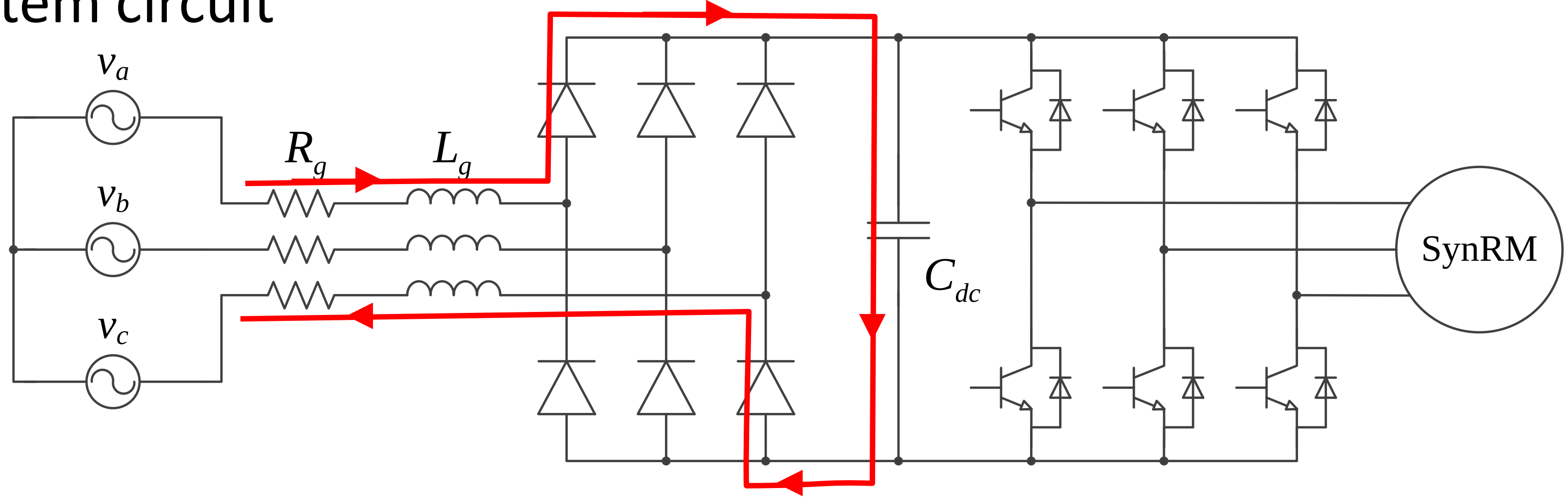
Replacing electrolytic capacitors with film capacitors :

- Improve reliability
  - longer expected service lifetime
    - Be able to withstand for higher ripple currents
- Compact design
  - small total capacitance
    - Higher voltage ratings
    - Be able to withstand for higher ripple currents

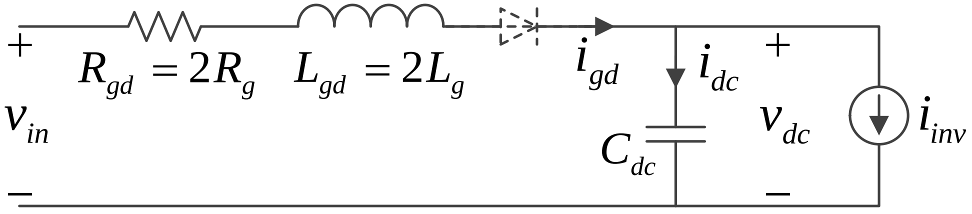
It is known as small dc-link drive or slim dc-link drive.

Background – System analysis

System circuit



Simplified equivalent circuit



$$L_{gd}\frac{di_{gd}}{dt} = v_{in} - R_{gd}i_{gd} - v_{dc}$$

$$C_{dc}\frac{dv_{dc}}{dt} = i_{gd} - i_{inv}$$

Background – System analysis

The PWM inverter with constant power load (CPL) has an negative small signal impedance:

$$i_{inv} = I_{inv} + \tilde{i}_{inv} = \frac{P_L}{v_{dc}} = \frac{P_L}{V_{dc} + \tilde{v}_{dc}} \approx \frac{P_L}{V_{dc}} - \frac{P_L}{V_{dc}^2}\tilde{v}_{dc} \Rightarrow Z_{CPL} = \frac{\tilde{v}_{dc}}{\tilde{i}_{inv}} = -\frac{V_{dc}^2}{P_L}$$

The system can be expressed as:

$$\frac{d^2 v_{dc}}{dt^2} + \left(\frac{R_{gd}}{L_{gd}} - \frac{P_L}{C_{dc}V_{dc}^2}\right)\frac{dv_{dc}}{dt} + \frac{1}{L_{gd}C_{dc}}\left(1 - \frac{R_{gd}P_L}{V_{dc}^2}\right)v_{dc} = \frac{v_{in}}{L_{gd}C_{dc}} - \frac{2R_{gd}P_L}{L_{gd}C_{dc}V_{dc}}$$

The system characteristic equation is:

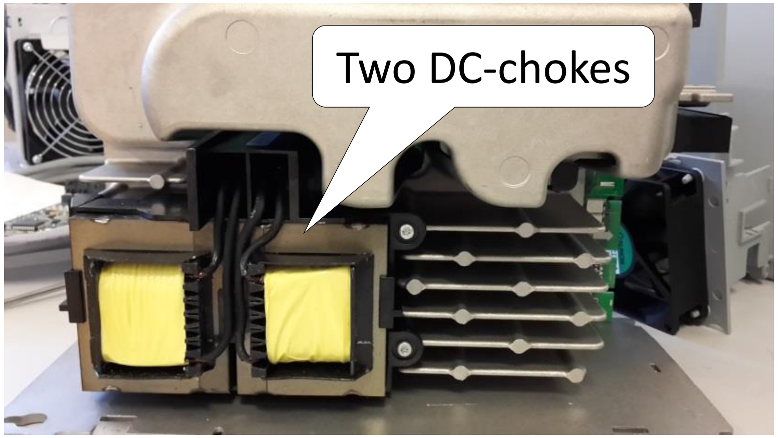
$$s^2 + \underbrace{\left(\frac{R_{gd}}{L_{gd}} - \frac{P_L}{C_{dc}V_{dc}^2}\right)}_{a_{10}} s + \underbrace{\frac{1}{L_{gd}C_{dc}}\left(1 - \frac{R_{gd}P_L}{V_{dc}^2}\right)}_{a_{20}} = 0$$

As P_L increases, a_{10} becomes negative value, system becomes instable.

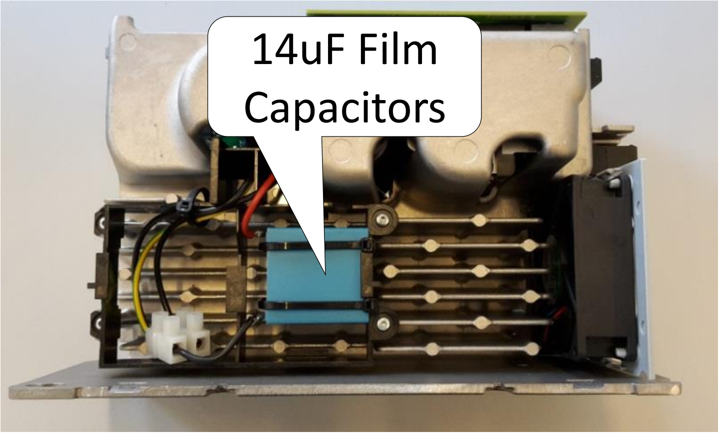
Background – System setup

7.5kW Small DC-link Drive Example

- Original : two 1000μF 450V electrolytic capacitors series connected to achieve 500μF 900V ratings, 2.4mH dc-chokes
- Modified : one 14μF 1300V film capacitor, 1.47mH three-phase line reactor



Original converter



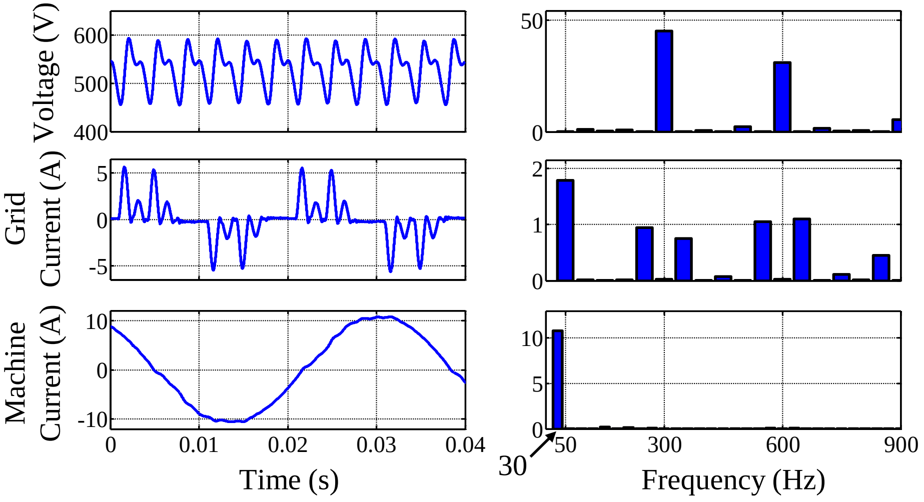
Modified converter

Background – System performance

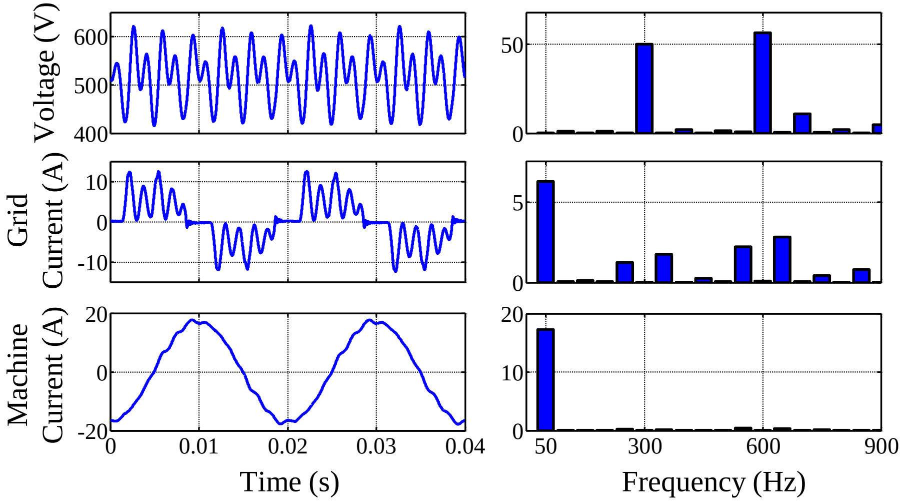
The natural undamped frequency of the system:

$$\omega_0 = \sqrt{a_{20}} \approx \sqrt{\frac{1}{L_{gd} C_{dc}}}$$

- 785Hz with C_{dc} = 14µF and L_{gd} = 2.94mH
- 600Hz component will be amplified.



900rpm (30Hz) 7.5Arms load



1500rpm (50Hz) 12Arms load

Background – Why active damping

Performance need to be improved:

- At rated condition, the grid current with
  - total harmonic distortion (THD) : 66.0%
  - partially weighted harmonic distortion (PWHD) : 74.3%
  - May not satisfy the standard (IEC/EN 61000-3-2)

For most industrial drive applications (pump, compressor, etc.):

- Moderate torque ripple is acceptable
- Low cost solution is preferred
  - Avoid using extra controlled circuit (passive, sub-passive damping)
    - Passive components, e.g. capacitors
    - Controlled switches
  - Using machine windings (active damping method)
    - Current and torque ripples are moderate

Existing active damping methods

Active damping method 1 – Control machine current reference :

Let $i_q^* = I_q^* + \boxed{\tilde{i}_q^*} = I_q^* + \boxed{g_{iq}\tilde{v}_{dc}}$

Then $i_{inv} = \frac{p_L}{v_{dc}} = \frac{3}{2}(v_d i_d + v_q i_q)\frac{1}{v_{dc}} = \frac{3}{2}\left((V_d - \omega_0 L_q \tilde{i}_q)I_d + V_q(I_q + \tilde{i}_q)\right)\frac{1}{V_{dc} + \tilde{v}_{dc}}$

$$\approx \frac{P_L}{V_{dc}} + (\boxed{\frac{3}{2}\frac{(V_q - \omega_0 L_q I_d)g_{iq}}{V_{dc}}} - \frac{P_L}{V_{dc}^2})\tilde{v}_{dc} \triangleq \frac{P_L}{V_{dc}} + (g - \frac{P_L}{V_{dc}^2})\tilde{v}_{dc}$$

The system characteristic equation becomes:

$$s^2 + + \underbrace{\left(\frac{R_{gd}}{L_{gd}} + \frac{1}{C_{dc}}(\boxed{g} - \frac{P_L}{V_{dc}^2})\right)}_{a_{11}} s + \underbrace{\frac{1}{L_{gd}C_{dc}}\left(1 + R_{gd}(\boxed{g} - \frac{P_L}{V_{dc}^2})\right)}_{a_{21}} = 0$$

To achieve a stable system: $g \ge P_L / V_{dc}^2$, i.e. $g_{iq} \ge \frac{2}{3}\frac{P_L}{V_{dc}(V_q - \omega_0 L_q I_d)}$

Existing active damping methods

Active damping method 2 – Control machine voltage reference :

Inject $\tilde{v}_d = g_{vd}\tilde{v}_{dc}$ and $\tilde{v}_q = g_{vq}\tilde{v}_{dc}$

Then

$$i_{inv} = \frac{p_L}{v_{dc}} \approx \frac{P_L}{V_{dc}} + (\boxed{\frac{3}{2}\frac{I_d g_{vd} + I_q g_{vq}}{V_{dc}}} - \frac{P_L}{V_{dc}^2})\tilde{v}_{dc} \triangleq \frac{P_L}{V_{dc}} + (g - \frac{P_L}{V_{dc}^2})\tilde{v}_{dc}$$

The system characteristic equation become:

$$s^2 + + \underbrace{\left(\frac{R_{gd}}{L_{gd}} + \frac{1}{C_{dc}}(\boxed{g} - \frac{P_L}{V_{dc}^2})\right)}_{a_{11}} s + \underbrace{\frac{1}{L_{gd}C_{dc}}\left(1 + R_{gd}(\boxed{g} - \frac{P_L}{V_{dc}^2})\right)}_{a_{21}} = 0$$

To achieve a stable system: $g \geq P_L / V_{dc}^2$, i.e. $(I_d g_{vd} + I_q g_{vq}) \geq \frac{2}{3}\frac{P_L}{V_{dc}}$

The obtainment of g_{iq}, g_{vd}, or g_{vq}, are system parameters dependent.

Proposed active damping method

Recall the system characteristics of small dc-link drive:

$$i_{inv} = I_{inv} + \tilde{i}_{inv} = \frac{P_L}{v_{dc}} = \frac{P_L}{V_{dc} + \tilde{v}_{dc}} \approx \frac{P_L}{V_{dc}} - \frac{P_L}{V_{dc}^2}\tilde{v}_{dc} \quad \Rightarrow \quad Z_{CPL} = \frac{\tilde{v}_{dc}}{\tilde{i}_{inv}} = -\frac{V_{dc}^2}{P_L}$$

$$s^2 + \underbrace{\left(\frac{R_{gd}}{L_{gd}} - \frac{P_L}{C_{dc}V_{dc}^2}\right)}_{a_{10}} s + \underbrace{\frac{1}{L_{gd}C_{dc}}\left(1 - \frac{R_{gd}P_L}{V_{dc}^2}\right)}_{a_{20}} = s^2 + \left(\frac{R_{gd}}{L_{gd}} + \frac{1}{C_{dc}Z_{inv}}\right)s + \frac{1}{L_{gd}C_{dc}}\left(1 + \frac{R_{gd}}{Z_{inv}}\right) = 0$$

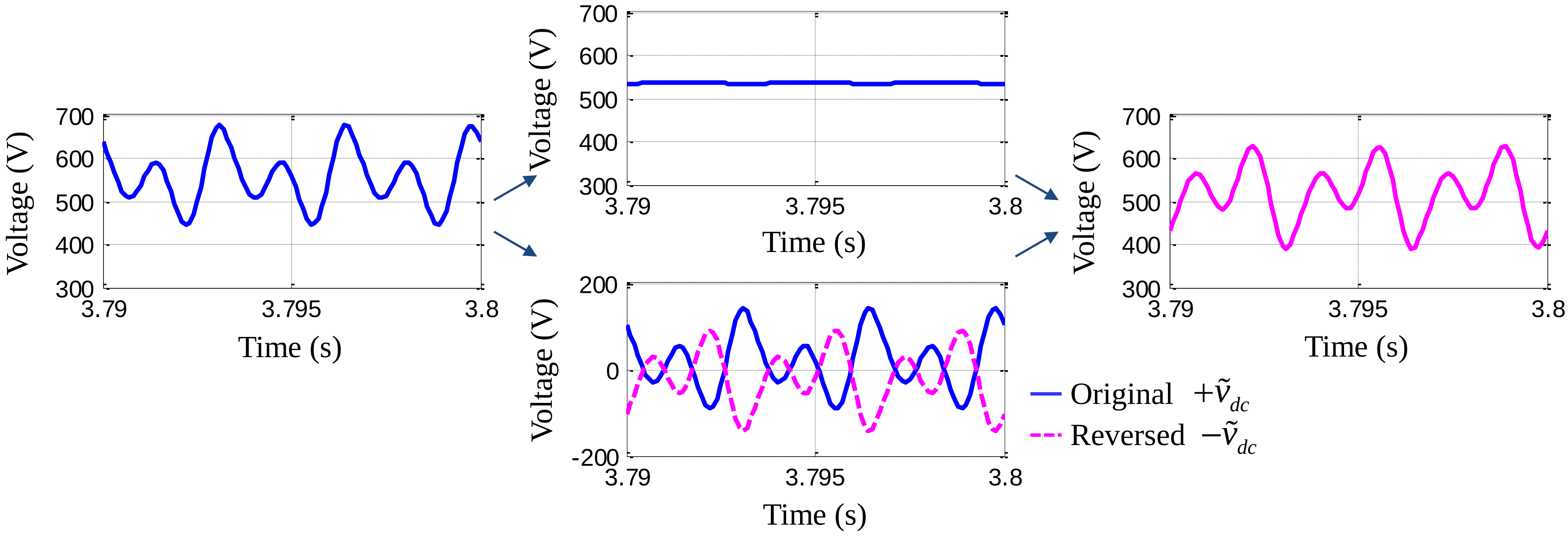
if the sign of the small signal impedance can be reversed by using active damping control:

$$i'_{inv} \approx \frac{P_L}{V_{dc}} + \frac{P_L}{V_{dc}^2}\tilde{v}_{dc} \quad \Rightarrow \quad Z_{ADP} = \frac{\tilde{v}_{dc}}{\tilde{i}_{inv}} = \frac{V_{dc}^2}{P_L}$$

Then, the system can be kept stable.

Proposed active damping method

The reverse operation can be achieved by reconstructing the reference voltage v_{dc}^{*} used in SVM as: $v_{dc}^{*} = V_{dc} - \tilde{v}_{dc}$



P18

Proposed active damping method

With the reconstruction of the reference dc-link voltage:

- Inverter output voltage becomes: $\overline{v}_{abc,rec}=\frac{\overline{v}_{abc}}{v_{dc}^{*}}v_{dc}=\overline{v}_{abc}\frac{V_{dc}+\tilde{v}_{dc}}{V_{dc}-\tilde{v}_{dc}}$
- Output power is: $P_{L,rec}=\overline{v}_{abc,rec}\cdot\overline{i}_{abc}=\frac{V_{dc}+\tilde{v}_{dc}}{V_{dc}-\tilde{v}_{dc}}\overline{v}_{abc}\cdot\overline{i}_{abc}=P_{L}\frac{V_{dc}+\tilde{v}_{dc}}{V_{dc}-\tilde{v}_{dc}}$
- Current drawn from the dc-link:

$$i_{inv}=\frac{P_{L,rec}}{v_{dc}}=P_{L}\frac{V_{dc}+\tilde{v}_{dc}}{V_{dc}-\tilde{v}_{dc}}\frac{1}{v_{dc}}=\frac{P_{L}}{V_{dc}-\tilde{v}_{dc}}\approx\frac{P_{L}}{V_{dc}}+\frac{P_{L}}{V_{dc}^{2}}\tilde{v}_{dc}\quad\Rightarrow\quad Z_{ADP}=\frac{\tilde{v}_{dc}}{\tilde{i}_{inv}}=\frac{V_{dc}^{2}}{P_{L}}$$

- System is stabilized: $s^{2}+\underbrace{\left(\frac{R_{gd}}{L_{gd}}+\frac{P_{L}}{C_{dc}V_{dc}^{2}}\right)}_{a_{12}}s+\underbrace{\frac{1}{L_{gd}C_{dc}}\left(1+\frac{R_{gd}P_{L}}{V_{dc}^{2}}\right)}_{a_{22}}=0$

Proposed active damping method

The proposed method can be further extended/generalized as:

- Reconstructed the reference voltage: $v_{dc}^{*} = k_{v0}V_{dc} - k_{v}\tilde{v}_{dc}$
- Current drawn from the dc-link : $i_{inv} \approx \frac{P_L}{k_{v0}V_{dc}} + \frac{k_v P_L}{k_{v0}^2 V_{dc}^2}\tilde{v}_{dc}$
- System characteristic equation:

$$s^2 + \underbrace{\left(\frac{R_{gd}}{L_{gd}} + \frac{k_v P_L}{C_{dc}k_{v0}^2 V_{dc}^2}\right)}_{a_{13}} s + \underbrace{\frac{1}{L_{gd}C_{dc}}\left(1 + \frac{k_v R_{gd} P_L}{k_{v0}^2 V_{dc}^2}\right)}_{a_{23}} = 0$$

The proposed method is named as Virtual Positive Impedance (VPI) method.

Dc-link voltage variation component

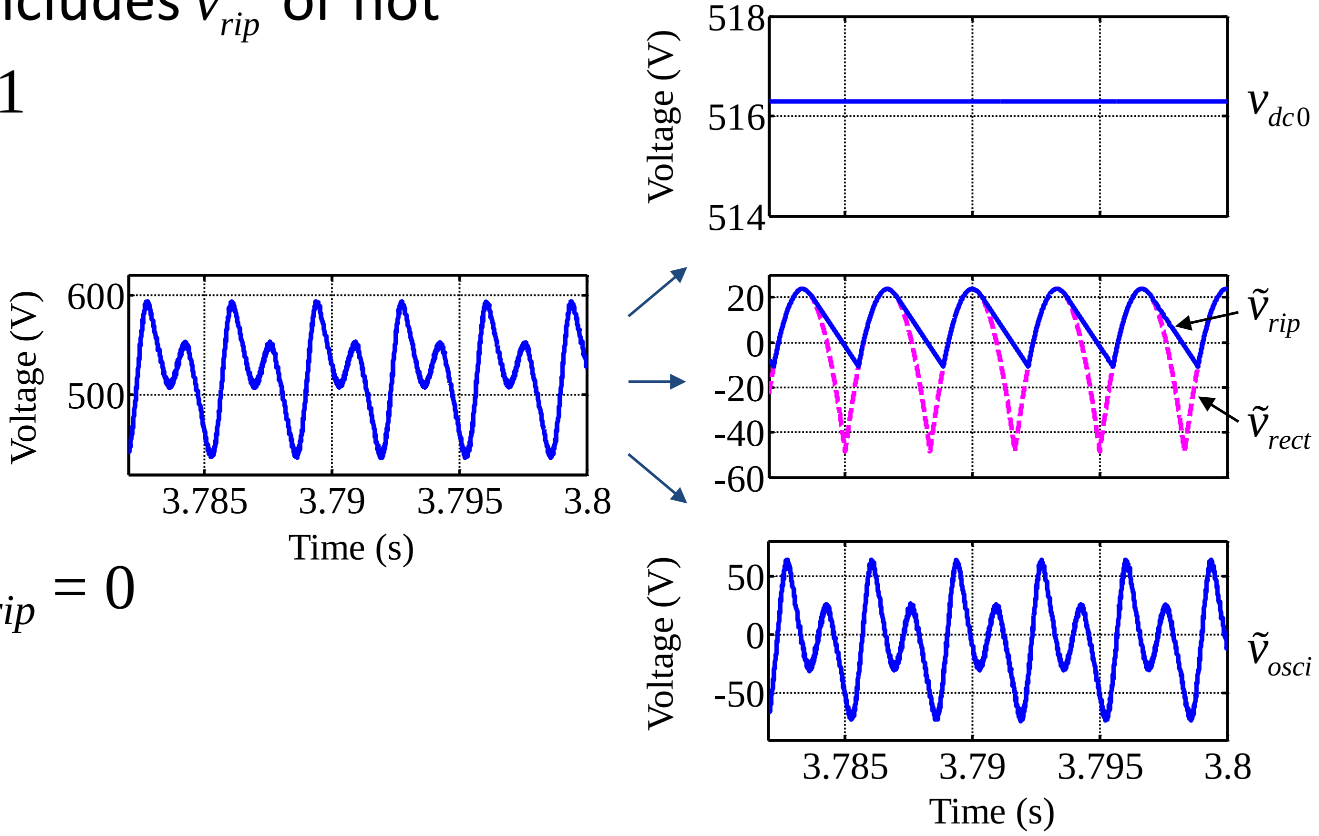
The obtainment of dc-link voltage variation component $\tilde{v}_{dc}$

Large signal V_{dc} includes $\tilde{v}_{rip}$ or not

- Include, $k_{rip} = 1$

$$V_{dc} = v_{dc0} + \tilde{v}_{rip}$$

$$\tilde{v}_{dc} = \tilde{v}_{osci}$$



- Not include, $k_{rip} = 0$

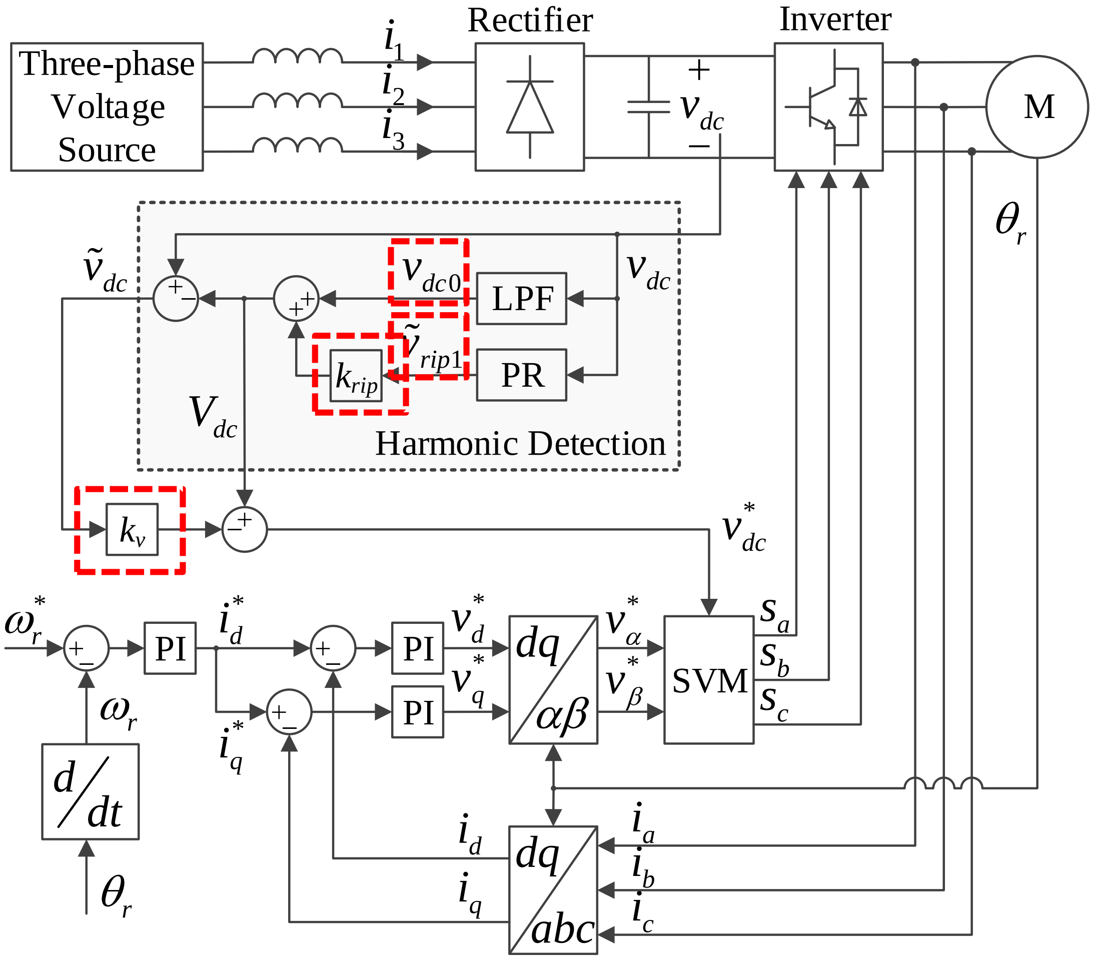
$$V_{dc} = v_{dc0}$$

$$\tilde{v}_{dc} = \tilde{v}_{osci} + \tilde{v}_{rip}$$

Experimental Verification

System block diagram:

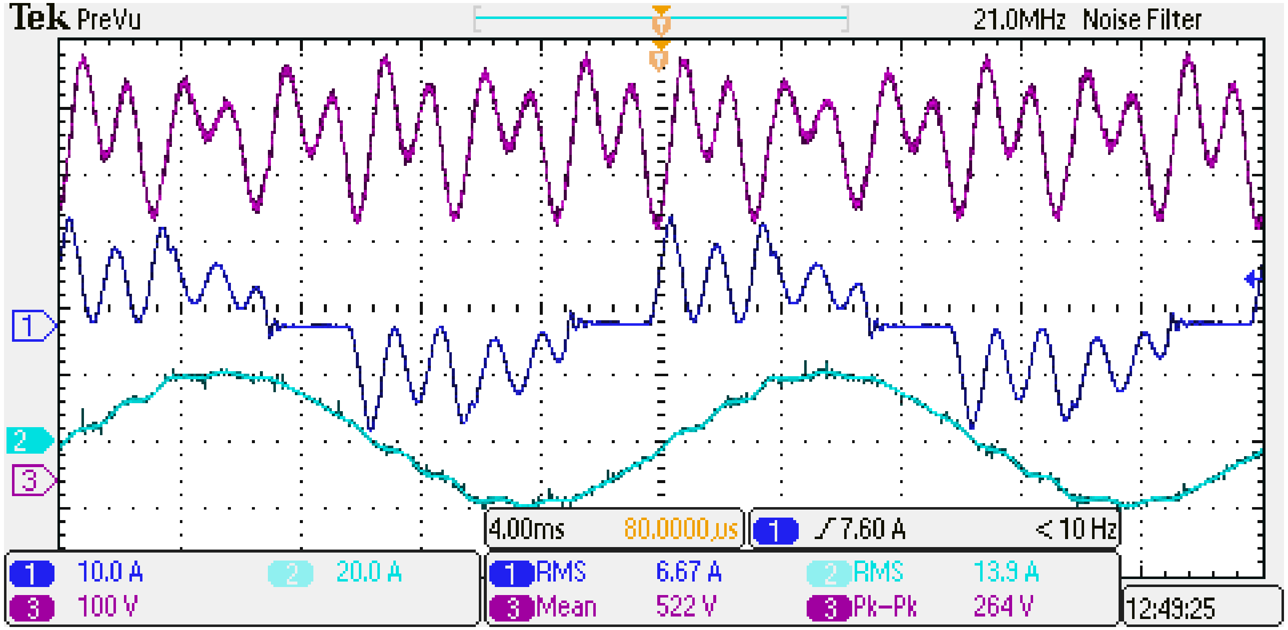
- v_{dc0} is obtained by LPF
- $\tilde{v}_{rip1}$ is used to represent $\tilde{v}_{rip}$ and is obtained by a non-ideal proportional resonant (PR) controller
- V_{dc} is controlled by k_{rip}
- The damping effect is controlled by k_v



Experimental Verification

Small dc-link drive without active damping control:

- Rated condition: rated speed (1500 rpm 50 Hz)
  rated torque (13.9 A load)



Tek PreVu 21.0MHz Noise Filter

4.00ms 80.0000µs 1 ∕ 7.60 A < 10 Hz

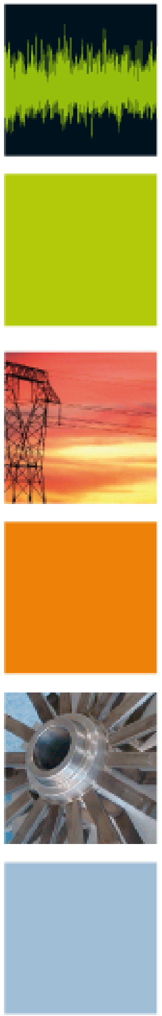
1 10.0 A 2 20.0 A

3 100 V

1 RMS 6.67 A 2 RMS 13.9 A

3 Mean 522 V 3 Pk–Pk 264 V

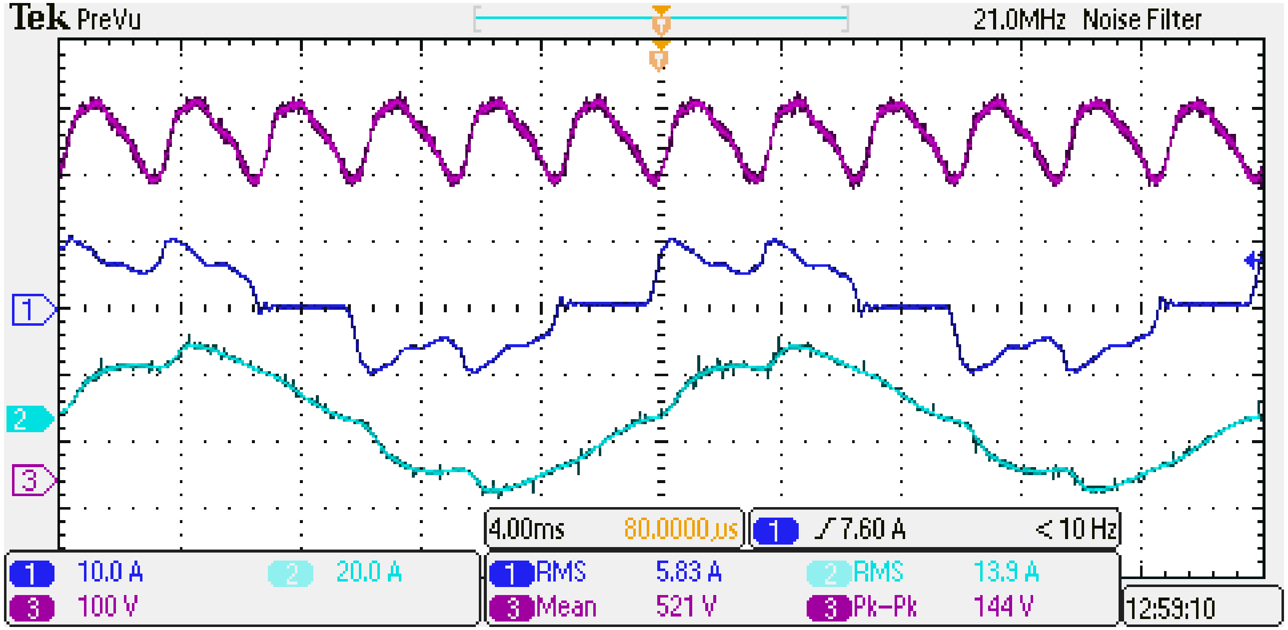
12:49:25



Experimental Verification

Small dc-link drive with VPI active damping control:

- Rated condition
- $k_{rip} = 0$, $k_v = 1$ (with reversed $\tilde{v}_{dc}$ as shown in P12)

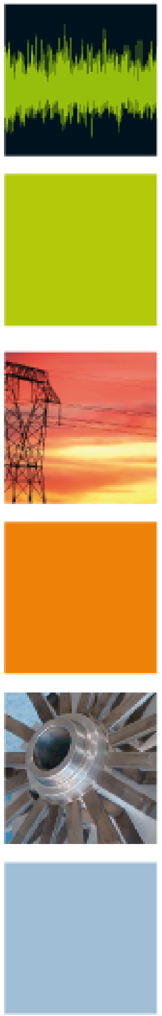


4.00ms 80.0000µs 1 ∕ 7.60 A < 10 Hz

1 10.0 A 2 20.0 A
3 100 V

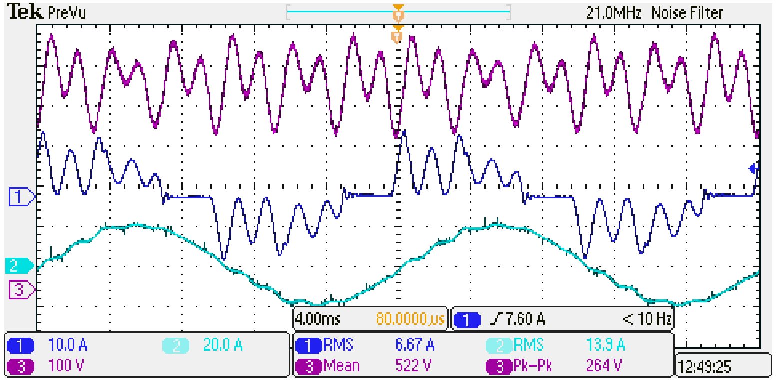
1 RMS 5.83 A 2 RMS 13.9 A
3 Mean 521 V 3 Pk−Pk 144 V

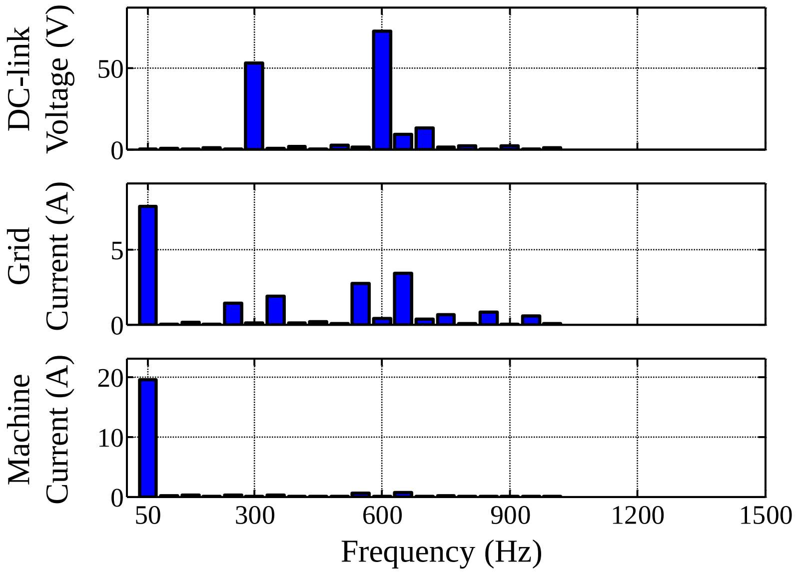
12:59:10



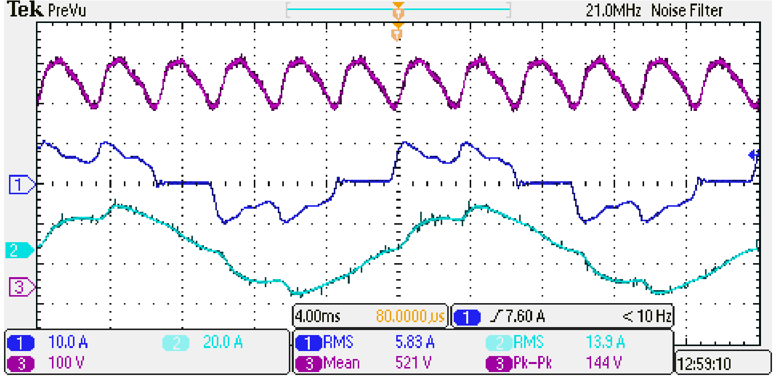
Experimental Verification

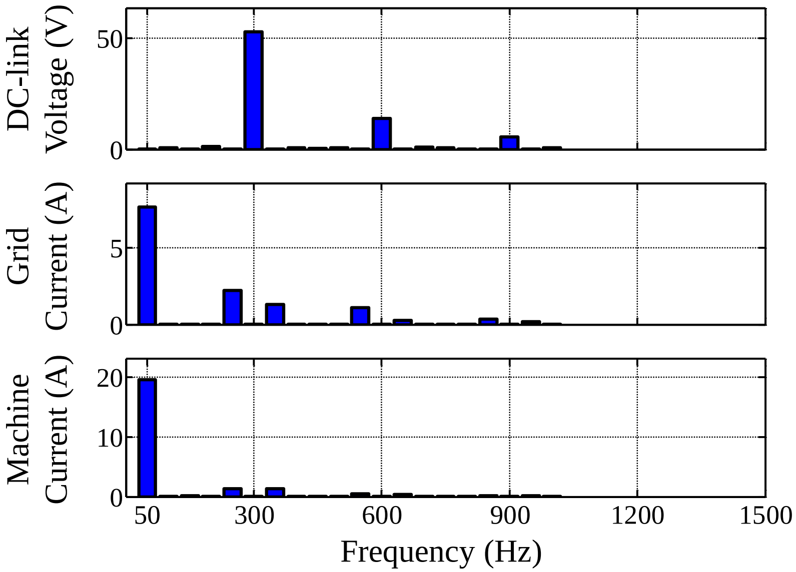
Without active damping





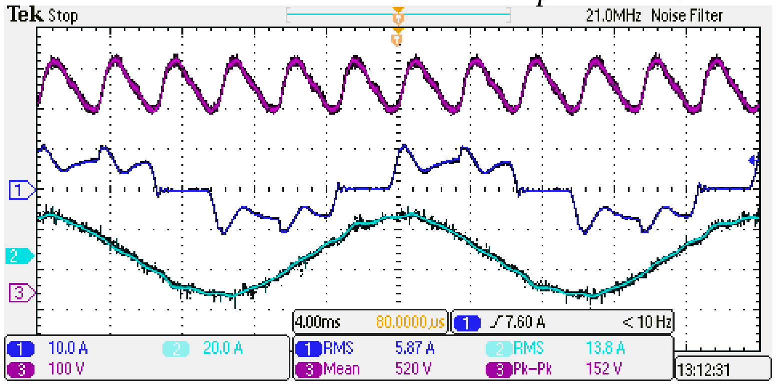
With VPI active damping $k_{rip} = 0$, $k_v = 1$

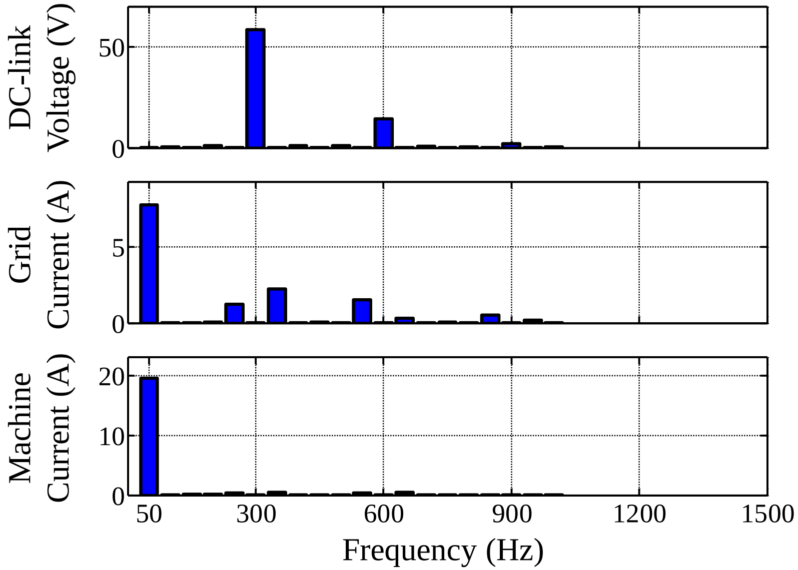




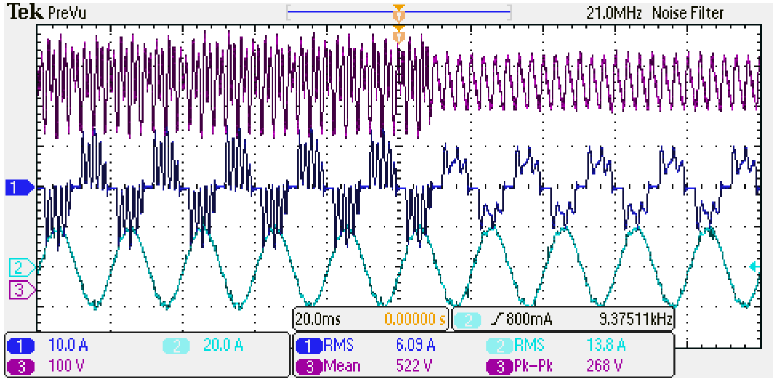
Experimental Verification

With VPI active damping $k_{rip} = 1$, $k_v = 2$

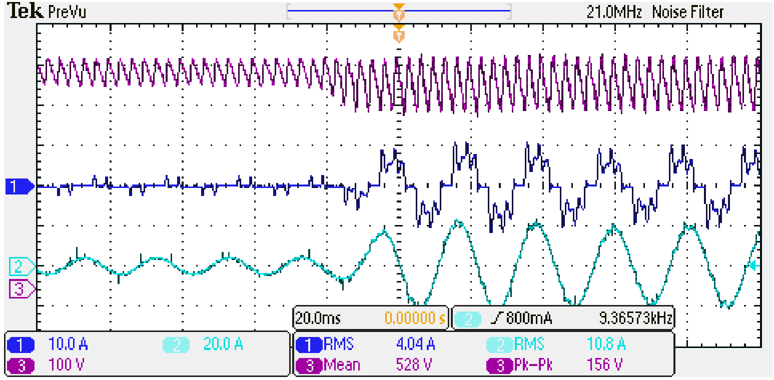




On-line enabling of VPI active damping $k_{rip} = 1$, $k_v = 2$



Step load change VPI active damping $k_{rip} = 1$, $k_v = 2$



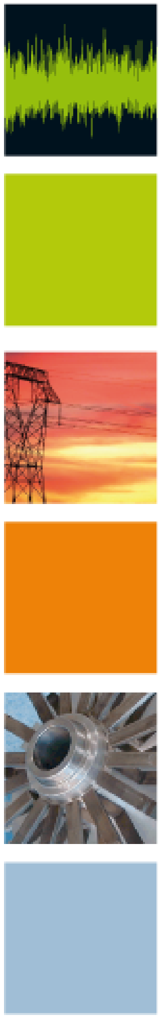
Experimental Verification

VPI active damping performance at rated conditions

Control configurations	v_{dc} variation (V)	V_{dc300} (V)	V_{dc600} (V)	Grid current THD	Grid current PWHD	Machine current THD
No damping	252	53.3	72.6	66.0%	74.3%	5.3%
$k_{rip} = 0, k_v = 0$ [1]	147	53.1	29.0	40.4%	39.3%	6.4%
$k_{rip} = 0, k_v = 1$ [2]	118	53.1	14.0	37.3%	34.0%	10.5%
$k_{rip} = 1, k_v = 0$ [3]	160	56.8	33.4	44.2%	46.5%	3.9%
$k_{rip} = 1, k_v = 1$	135	57.8	19.9	40.6%	43.4%	4.2%
$k_{rip} = 1, k_v = 2$	126	58.4	14.5	39.5%	41.4%	4.8%

1. Set $v_{dc}^{*} = v_{dc0}$ can already help to damp the system
2. Damp of $\tilde{v}_{rip1}$ will cause large machine current ripples
3. Active damp without $\tilde{v}_{rip1}$ may improve the machine current THD

Discussions – Other benefits



Over-modulation control:

- Due to variation of dc-link voltage, the total duty cycle D varies for same voltage output.
- When without active damping, considering the worst case

$$D_0^2 = \left(\frac{\left|\bar{v}_{dq}\right|}{v_{dc}/\sqrt{3}}\right)^2 \approx \boxed{3(v_d^2+v_q^2)\bigg(\frac{1}{V_{dc}^2}} - \frac{2}{V_{dc}^3}\tilde{v}_{dc}\bigg) \triangleq A - \frac{2A}{V_{dc}}\tilde{v}_{dc}$$

- When with VPI control with $k_{v0} = 1$, it can be found that

$$D_1^2 = \left(\frac{\left|\bar{v}_{dq1}\right|}{v_{dc}/\sqrt{3}}\right)^2 = D_0^2\left(1+\frac{1+k_v}{V_{dc}}\tilde{v}_{dc}\right)^2 \approx A + \frac{2A}{V_{dc}}k_v\tilde{v}_{dc}$$

where $\bar{v}_{dq1} = \mathbf{P}\cdot\bar{v}_{abc,rec} \approx \dfrac{\bar{v}_{dq}}{k_{v0}}\left(1+\dfrac{k_{v0}+k_v}{k_{v0}V_{dc}}\tilde{v}_{dc}\right)$, P is dq transformation.

- $k_v = 0$ to minimize the duty cycle variation for the worst case.

Summary

- Characteristics of small dc-link drive is analyzed
- Summary of existing active damping methods
  - System parameters and operation condition dependent
  - Control parameters should be tuned carefully to stabilize the system
- VPI active damping method is proposed
  - System parameters and operation condition independent
  - System can always be stabilized
  - Control parameters are used to control the performance
- Extra control targets can be achieved by VPI method
  - Over-modulation control
  - Etc.

- Any comment?

Thank you!