*Proceedings of International Conference on Technology and Social Science 2020*

*(ICTSS 2020)* Dec. 3, 2020

# Phase Margin Test for Power-Stage of DC-DC Buck Converter

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# Outline

## 1. Research Background

- Motivation, objectives and achievements
- Characteristics of an adaptive feedback network

## 2. Analysis of Power-Stage of DC-DC Converter

- Operating regions of $2^{nd}$-order systems
- Phase margin of power-stage of DC-DC converter

## 3. Ripple Reduction for DC-DC Converters

- LC Harmonic Notch filter
- Nichols chart of power stage of buck converter

## 4. Conclusions

# 1. Research Background

## Noise in Electronic Systems

### Performance of a system

Signal to Noise Ratio: $\text{SNR} = \dfrac{\text{Signal power}}{\text{Noise power}}$

### Performance of a device

Figure of Merit: $F = \dfrac{\text{Output SNR}}{\text{Input SNR}}$

### Common types of noise:

- Electronic noise
- Thermal noise,
- Intermodulation noise,
- Cross-talk,
- Impulse noise,
- Shot noise, and
- Transit-time noise.

### Device noise:

- Flicker noise,
- Thermal noise,
- White noise.

**DC-DC converters**

- Overshoot,
- Ringing
- Ripple

# 1. Research Background

## Effects of Ripple and Ringing on Electronic Systems

- Ringing is overshoot/undershoot voltage or current when it's seen on time domain.
- Ripple is wasted power, and has many undesirable effects on analog circuits.

Ringing does the following things:

- Causes EMI noise,
- Heats components,
- Consumes the power,
- Decreases the performance,
- Damages the devices.

Ripple does the following things:

- Increases current flow,
- Increases noise,
- Creates the distortion,
- Causes digital circuits to operate improperly.

# 1. Research Background

## Objectives of Study

- Investigation of behaviors of power-stage of DC-DC converters
- Ripple reduction for DC-DC buck converter using LC Harmonic Notch filter
- Measurement of self-loop function in power-stage of DC-DC buck converter
- Observation of phase margin at unity gain on the Nichols chart

# 1. Research Background

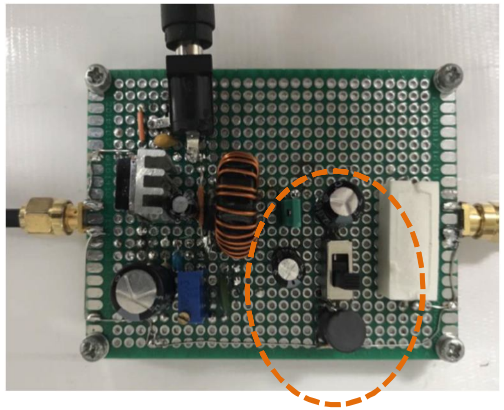
## Achievements of Study

### Alternating current conservation for deriving self-loop function

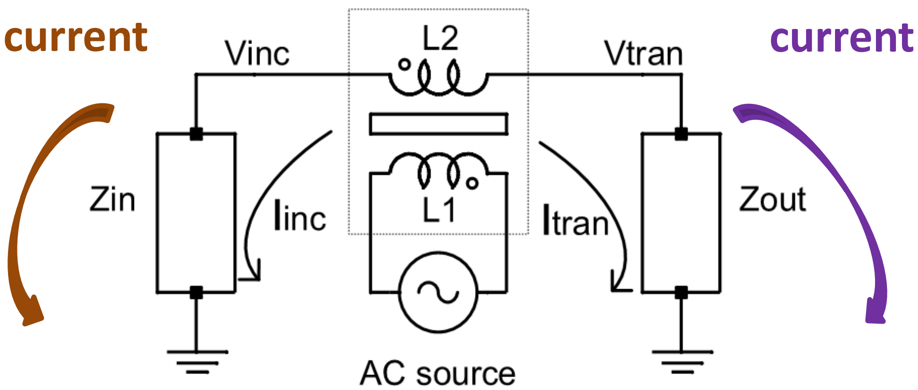
$$L(\omega) = -\frac{V_{inc}}{V_{trans}}$$

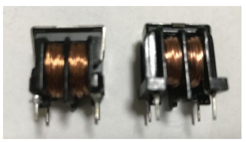
➡ **Stability test for power-stage**

### Implemented circuit

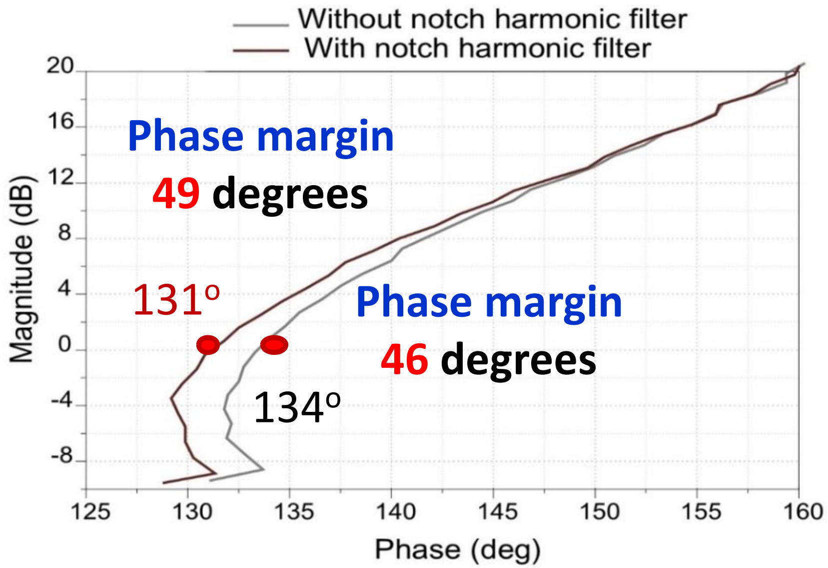



### Derivation of self-loop function



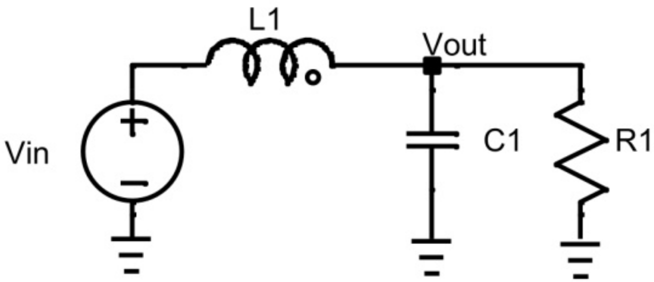
### Phase margin of power stage



# 1. Research Background

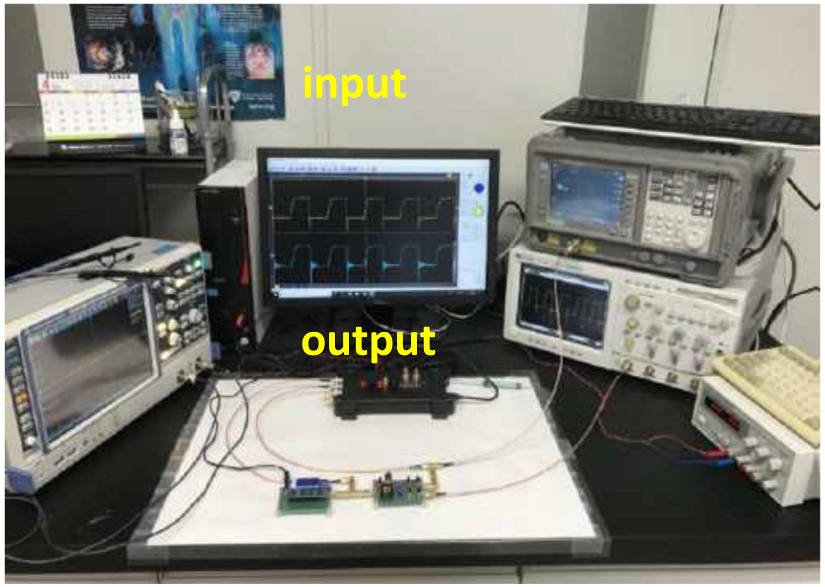
## Approaching Methods

### Simplified power-stage

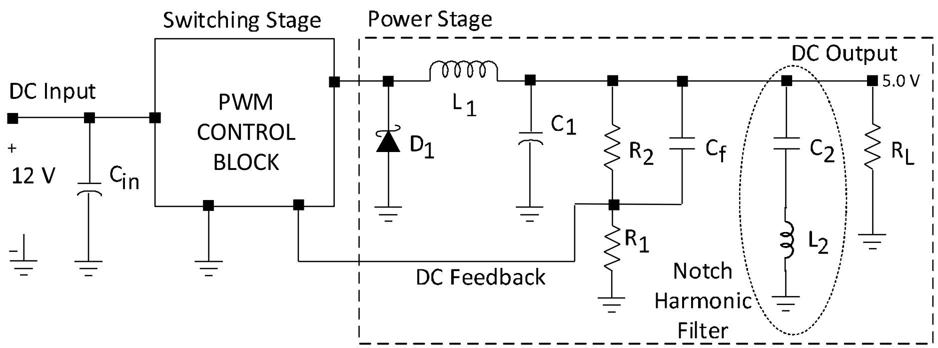



### Balun transformer

### Measurement set up



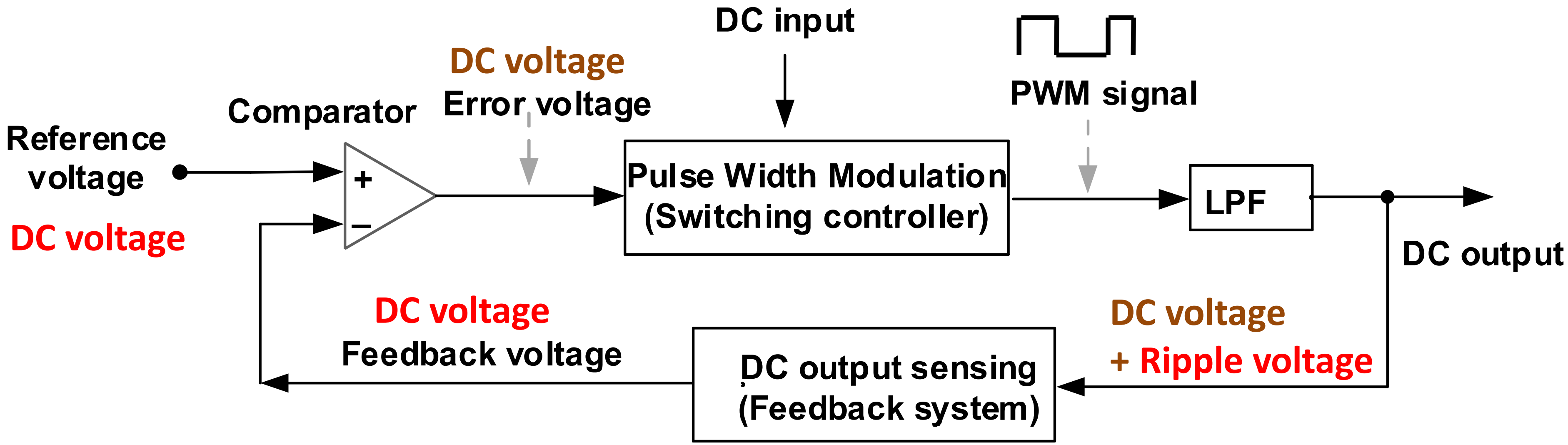

### Design of DC-DC buck converter



# 1. Research Background

## Characteristics of Adaptive Feedback Network

**Block diagram of a typical adaptive feedback system**




**Adaptive feedback is used to control the output source along with the decision source (DC-DC Buck converter).**

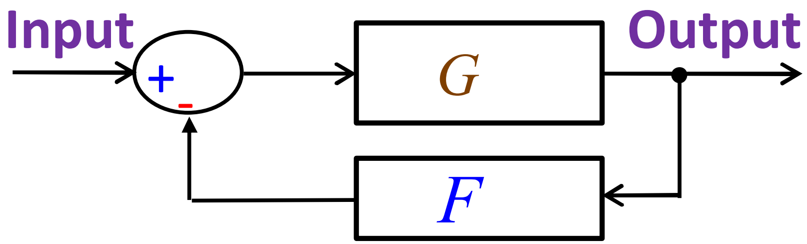
**Transfer function of an adaptive feedback network is significantly different from transfer function of a linear negative feedback network.**

**→ Loop gain is independent of frequency variable (referent voltage, feedback voltage, and error voltage are DC voltages).**

# 1. Research Background

## Loop Gain in Feedback Control Systems

### Adaptive feedback systems

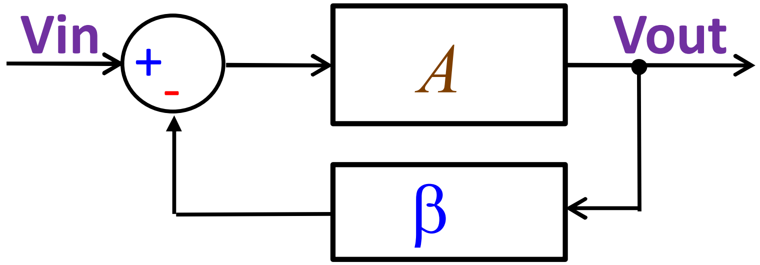



**Transfer function**

**GF : loop gain**

$$H = \frac{G}{1+GF} \approx 1$$

### Inverting amplifier

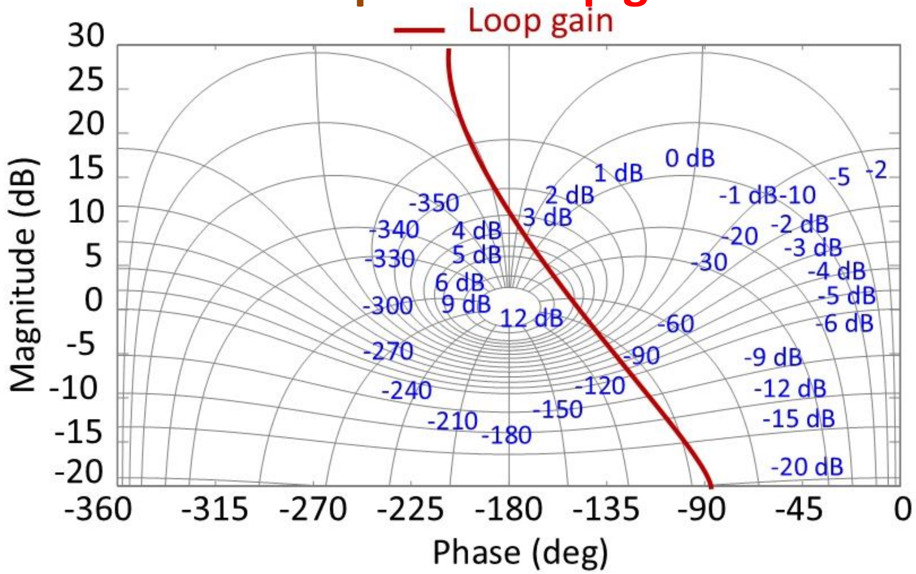



**Transfer function**

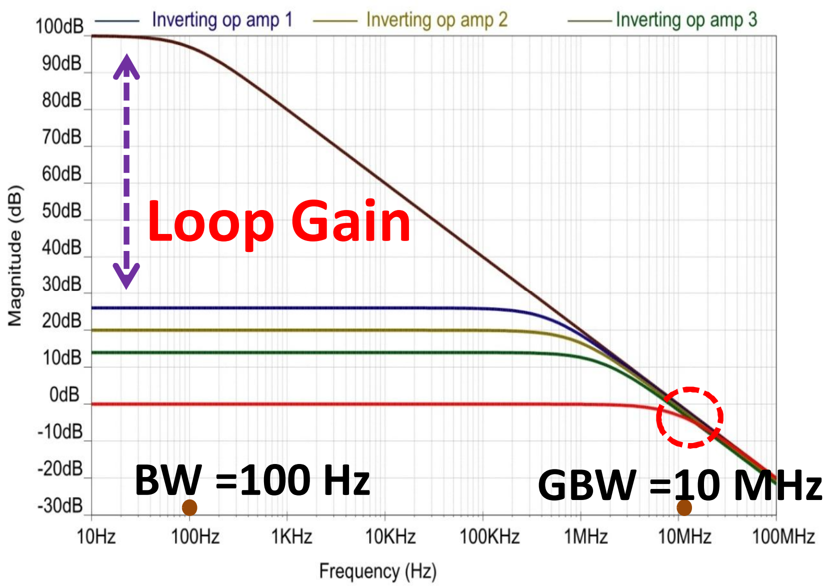
**Aβ : loop gain**

$$H = \frac{A}{1+A\beta} \approx \frac{1}{\beta}$$

### Nichols plot of loop gain



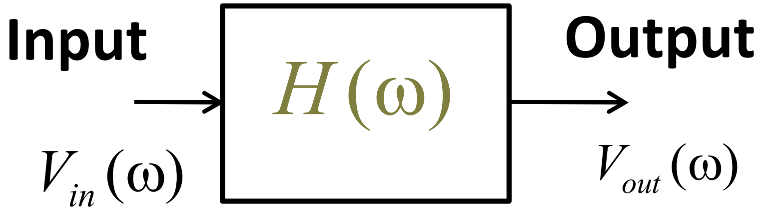

### Gain reduction



# 1. Research Background

## Self-loop Function in A Transfer Function

### Linear system




### Model of a linear system

$$H(\omega) = \frac{b_0(j\omega)^n + \ldots + b_{n-1}(j\omega) + b_n}{a_0(j\omega)^n + \ldots + a_{n-1}(j\omega) + a_n}$$

### Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{A(\omega)}{1 + L(\omega)}$$

$A(\omega)$ **: Numerator function**

$H(\omega)$ **: Transfer function**

$L(\omega)$ **: Self-loop function**

**Variable: angular frequency (ω)**

- **Polar chart → Nyquist chart**
- **Magnitude-frequency plot**
- **Angular-frequency plot**

  (Magnitude-frequency plot and Angular-frequency plot) → **Bode plots**
- **Magnitude-angular diagram → Nichols diagram**

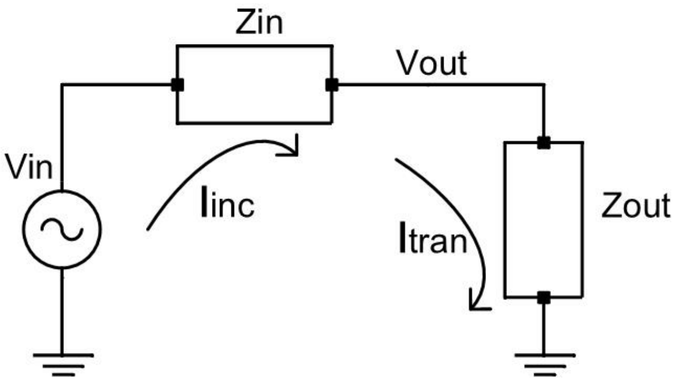
# 1. Research Background

## Alternating Current Conservation

### Transfer function

$$H(\omega)=\frac{V_{out}(\omega)}{V_{in}(\omega)}=\frac{1}{1+\dfrac{Z_{in}}{Z_{out}}}$$

$$\Rightarrow L(\omega)=\frac{Z_{in}}{Z_{out}};$$




**Simplified linear system**

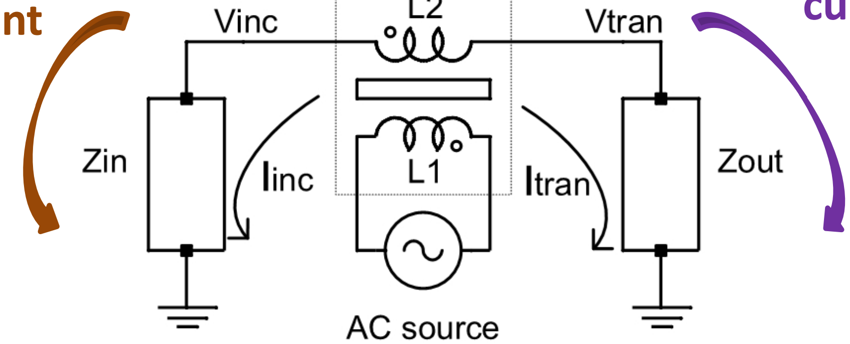
### Self-loop function

$$\frac{V_{inc}}{Z_{in}}=-\frac{V_{trans}}{Z_{out}}\Rightarrow L(\omega)=-\frac{V_{inc}}{V_{trans}}=\frac{Z_{in}}{Z_{out}}$$

**10 mH inductance**

Incident current

Transmitted current




**Derivation of self-loop function**

# 1. Research Background

## Limitations of Conventional Methods

- **Middlebrook's measurement of loop gain**

→ **Applying only in feedback systems (DC-DC converters).**

- **Replica measurement of loop gain**

→ **Using two identical networks (not real measurement).**

- **Nyquist's stability condition**

→ **Theoretical analysis for feedback systems (Lab tool).**

- **Nichols chart of loop gain**

→ **Only used in feedback control theory (Lab tool).**

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- **Operating regions of 2$^{nd}$-order systems**
- **Phase margin of power-stage of DC-DC converter**

3. Ripple Reduction for DC-DC Converters
- LC Harmonic Notch filter
- Nichols chart of power stage of buck converter

4. Conclusions

# 2. Analysis of Power-Stage of DC-DC Converter

## Behaviors of Second-order Transfer Function

**Second-order transfer function:** $$H(\omega)=\frac{1}{1+a_0(j\omega)^2+a_1 j\omega}$$

| Case | Over-damping | Critically damping | Under-damping |
|---|---|---|---|
| **Delta** ($\Delta$) | $\frac{1}{a_0}<\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0>0$ | $\frac{1}{a_0}=\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0=0$ | $\frac{1}{a_0}>\left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta=a_1^2-4a_0<0$ |
| **Module** $\lvert H(\omega)\rvert$ | $\frac{\frac{1}{a_0}}{\sqrt{\omega^2+\left(\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}\sqrt{\omega^2+\left(\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}\right)^2}}$ | $\frac{\frac{1}{a_0}}{\left[\omega^2+\left(\frac{a_1}{2a_0}\right)^2\right]}=\frac{1}{2}=-6dB$ | $\frac{\frac{1}{a_0}}{\sqrt{\left(\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}\right)^2+\left(\frac{a_1}{2a_0}\right)^2}}$ |
| **Angular** $\theta(\omega)$ | $-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}-\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)-\arctan\left(\frac{\omega}{\frac{a_1}{2a_0}+\sqrt{\left(\frac{a_1}{2a_0}\right)^2-\frac{1}{a_0}}}\right)$ | $-2\arctan\left(\frac{2a_0\omega}{a_1}\right)$ | $-\arctan\left(\frac{\omega-\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)-\arctan\left(\frac{\omega+\sqrt{\frac{1}{a_0}-\left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$ |
| $\omega_{cut}=\frac{a_1}{2a_0}$ | $\lvert H(\omega_{cut})\rvert<\frac{2a_0}{a_1}$; $\theta(\omega_{cut})>-\frac{\pi}{2}$ | $\lvert H(\omega_{cut})\rvert=\frac{2a_0}{a_1}$; $\theta(\omega_{cut})=-\frac{\pi}{2}$ | $\lvert H(\omega_{cut})\rvert>\frac{2a_0}{a_1}$; $\theta(\omega_{cut})<-\frac{\pi}{2}$ |

# 2. Analysis of Power-Stage of DC-DC Converter

## Behaviors of Second-order Self-loop Function

**Second-order self-loop function:** $L(\omega) = j\omega\left[a_0 j\omega + a_1\right]$

| Case | Over-damping | | Critical damping | | Under-damping | |
|---|---|---|---|---|---|---|
| **Delta** $(\Delta)$ | $\Delta = a_1^2 - 4a_0 > 0$ | | $\Delta = a_1^2 - 4a_0 = 0$ | | $\Delta = a_1^2 - 4a_0 < 0$ | |
| $\lvert L(\omega)\rvert$ | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | |
| $\theta(\omega)$ | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | |
| $\omega_1 = \frac{a_1}{2a_0}\sqrt{\sqrt{5}-2}$ | $\lvert L(\omega_1)\rvert > 1$ | $\pi - \theta(\omega_1) > 76.3^o$ | $\lvert L(\omega_1)\rvert = 1$ | $\pi - \theta(\omega_1) = 76.3^o$ | $\lvert L(\omega_1)\rvert < 1$ | $\pi - \theta(\omega_1) < 76.3^o$ |
| $\omega_2 = \frac{a_1}{2a_0}$ | $\lvert L(\omega_2)\rvert > \sqrt{5}$ | $\pi - \theta(\omega_2) > 63.4^o$ | $\lvert L(\omega_2)\rvert = \sqrt{5}$ | $\pi - \theta(\omega_2) = 63.4^o$ | $\lvert L(\omega_2)\rvert < \sqrt{5}$ | $\pi - \theta(\omega_2) < 63.4^o$ |
| $\omega_3 = \frac{a_1}{a_0}$ | $\lvert L(\omega_3)\rvert > 4\sqrt{2}$ | $\pi - \theta(\omega_3) > 45^o$ | $\lvert L(\omega_3)\rvert = 4\sqrt{2}$ | $\pi - \theta(\omega_3) = 45^o$ | $\lvert L(\omega_3)\rvert < 4\sqrt{2}$ | $\pi - \theta(\omega_3) < 45^o$ |

# 2. Analysis of Power-Stage of DC-DC Converter

## Operating Regions of 2nd-Order System

- **Under-damping:**

  $L_1(\omega) = (j\omega)^2 + j\omega;$

- **Critical damping:**

  $L_2(\omega) = (j\omega)^2 + 2j\omega;$

- **Over-damping:**

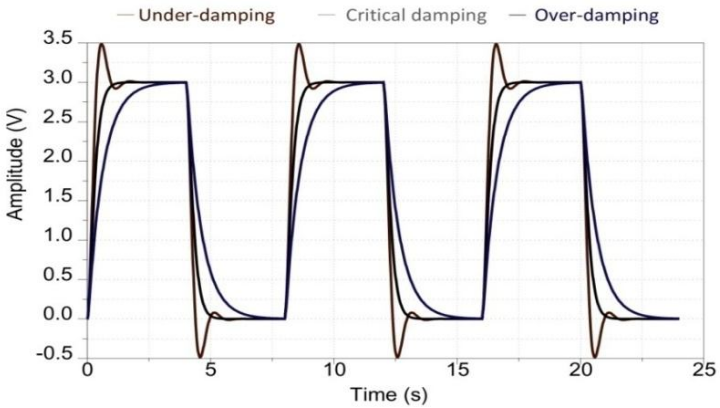
  $L_3(\omega) = (j\omega)^2 + 3j\omega;$

$$H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1};$$

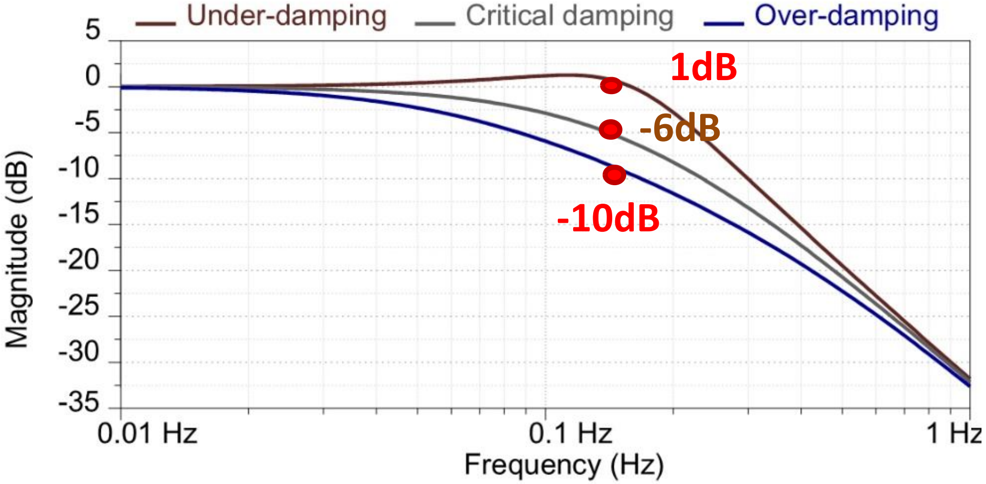
$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};$$

$$H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1};$$

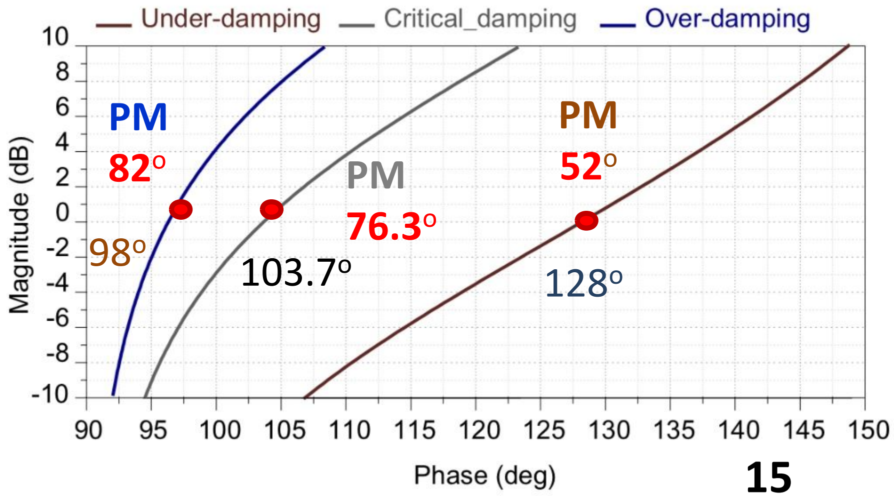
### Transient response




### Bode plot of transfer function



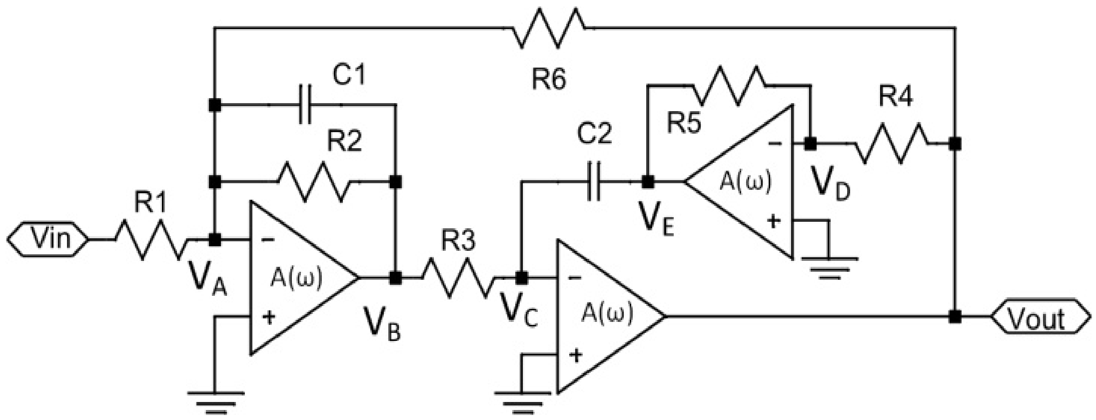

### Nichols plot of self-loop function



# 2. Analysis of Power-Stage of DC-DC Converter

## Implemented Circuit of Åkerberg-Mossberg LPF

### Schematic of Åkerberg-Mossberg LPF




### Transfer function & self-loop function

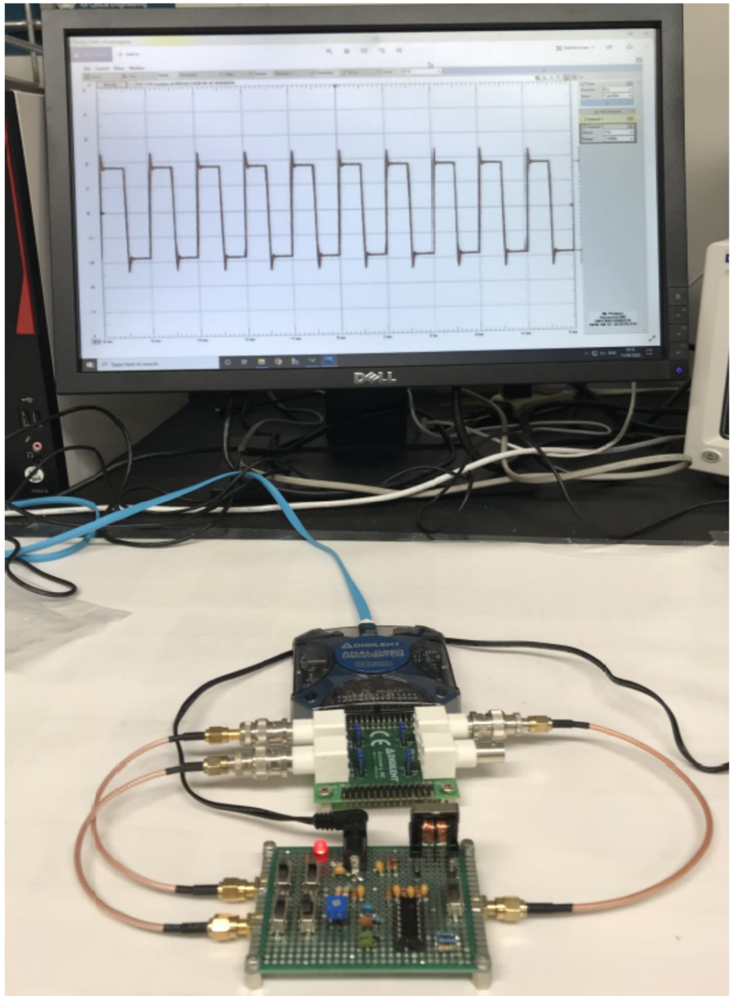
$$H(\omega) = -\frac{b_0}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$

**where,** $b_0 = \frac{R_6}{R_1};$

$$a_0 = \frac{R_3}{R_4} R_5 R_6 C_1 C_2; a_1 = \frac{R_3 R_5 R_6}{R_4 R_2} C_2;$$

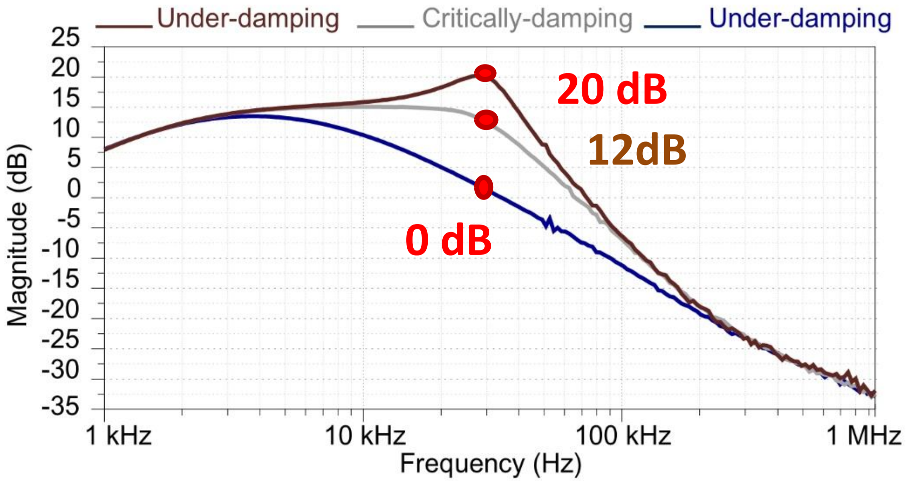
### Measurement set up



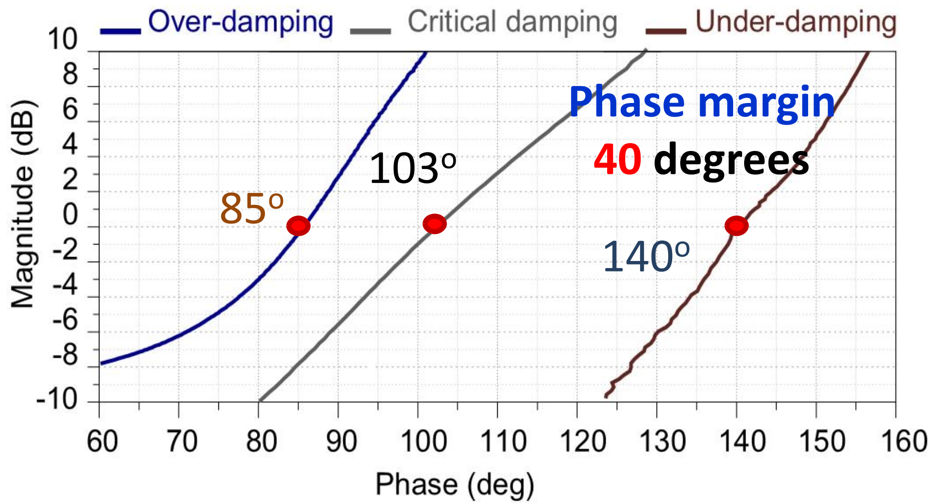
# 2. Analysis of Power-Stage of DC-DC Converter

# Measurement Results of Åkerberg-Mossberg LPF

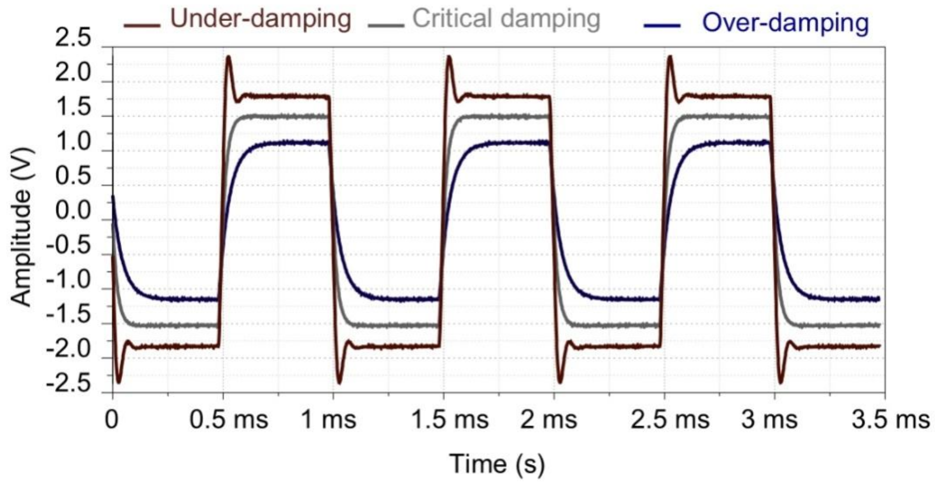
## Bode plot of transfer function




## Nichols plot of self-loop function




## Transient response




**Over-damping:**

**→Phase margin is 95 degrees.**

**Critical damping:**

**→Phase margin is 77 degrees.**

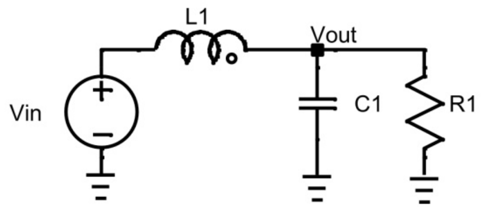
**Under-damping:**

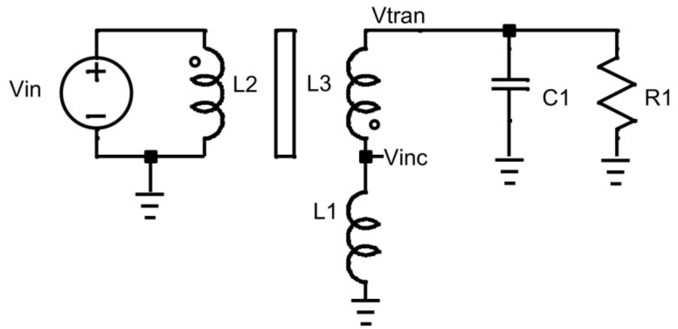
**→Phase margin is 40 degrees.**

# 2. Analysis of Power-Stage of DC-DC Converter

## Behaviors of power-stage of DC-DC Converter

**Parallel RLC low-pass filter**




**Transfer function & self-loop function:**

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{1 + a_0 \left( j\omega \right)^2 + a_1 j\omega};$$

$$L(\omega) = a_0 \left( j\omega \right)^2 + a_1 j\omega;$$

**Where:** $a_0 = LC; \quad a_1 = \dfrac{L}{R};$

$$\omega_0 = 1/\sqrt{LC};$$

$$\left| Z_L \right| = \omega_0 L; \quad \left| Z_C \right| = 1/\omega_0 C;$$

**Operating regions**

- **Over-damping:** $\dfrac{1}{LC} < \left( \dfrac{R}{2L} \right)^2 \Leftrightarrow \left| Z_L \right| = \left| Z_C \right| < R/2$
- Critical damping: $\dfrac{1}{LC} = \left( \dfrac{R}{2L} \right)^2 \Leftrightarrow \left| Z_L \right| = \left| Z_C \right| = R/2$
- **Under-damping:** $\dfrac{1}{LC} > \left( \dfrac{R}{2L} \right)^2 \Leftrightarrow \left| Z_L \right| = \left| Z_C \right| > R/2$

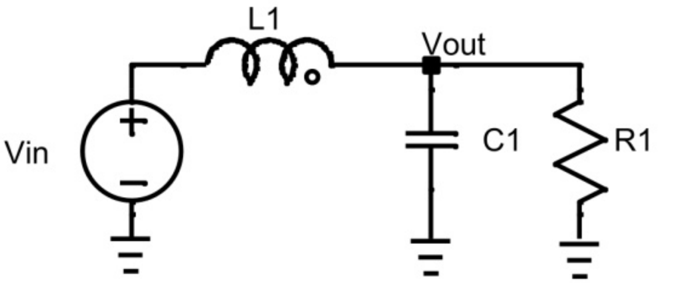
$$\left| Z_L \right| = \left| Z_C \right| = 2R$$

**Balanced charging-discharging time condition**

# 2. Analysis of Power-Stage of DC-DC Converter

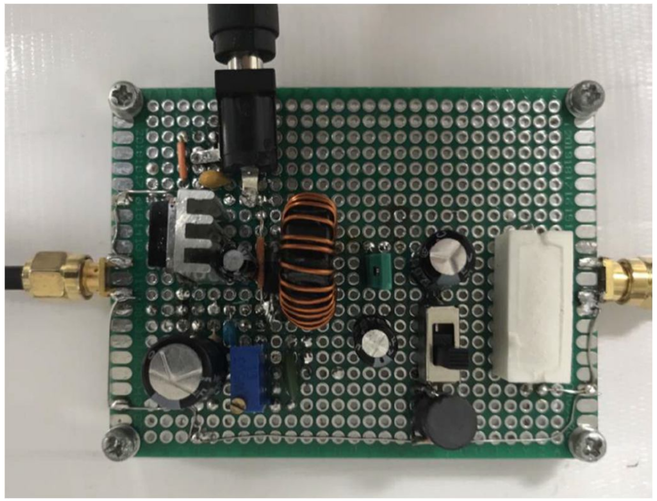
## Phase Margin of Power-Stage of DC-DC Converter

### Simplified power-stage



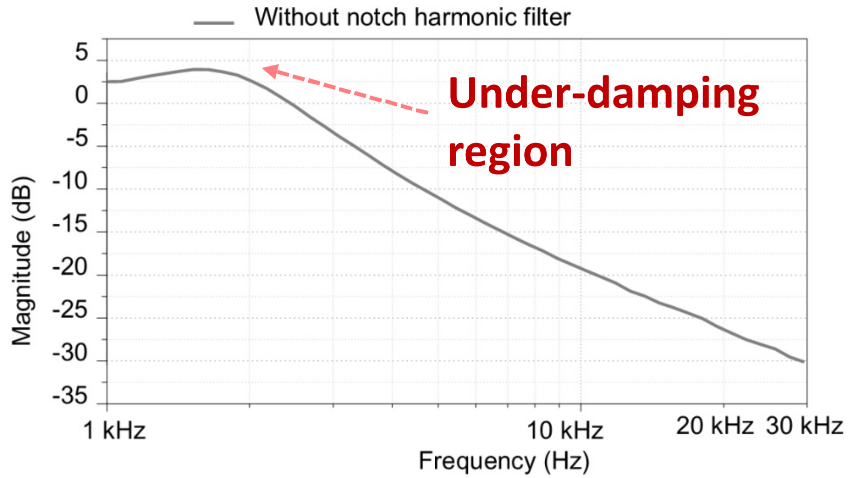

$L_1$ = 220 uH, $C_1$ = 100 uF, $R_1$ = 5 Ω,

### Implemented circuit

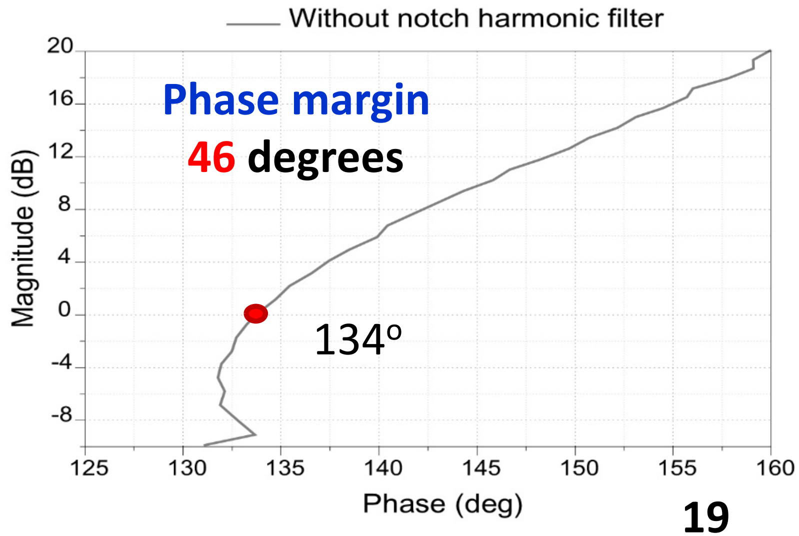


### Measured results

**Bode plot of transfer function**




**Nichols plot of self-loop function**



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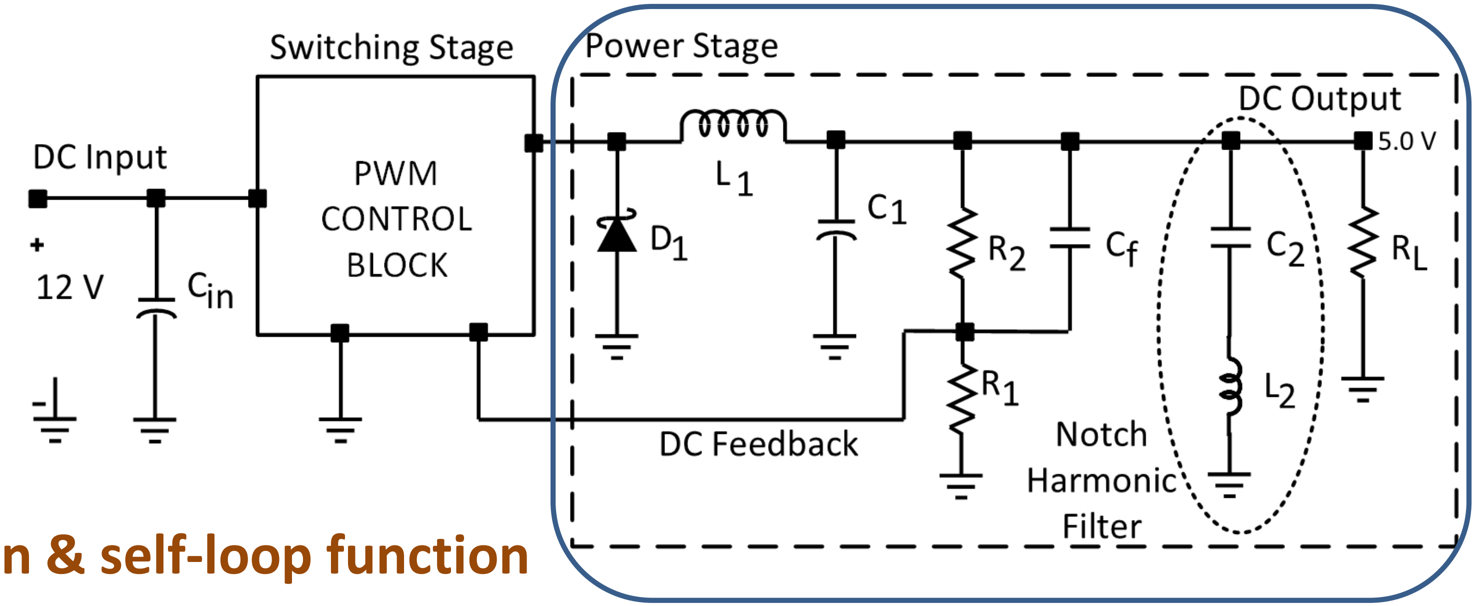
   - Operating regions of $2^{nd}$-order systems
   - Phase margin of power-stage of DC-DC converter
3. Ripple Reduction for DC-DC Converters
   - LC Harmonic Notch filter
   - Nichols chart of power stage of buck converter
4. Conclusions

# 3. Ripple Reduction for DC-DC Converters

## Ripple Reduction using LC Harmonic Notch Filter

**Schematic diagram of DC-DC buck converter**




**Transfer function & self-loop function**

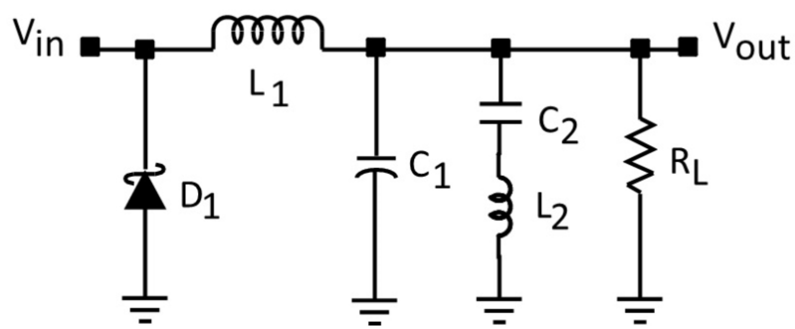
$$H(\omega) = \frac{b0(j\omega)^2 + 1}{a_0(j\omega)^4 + a_1(j\omega)^3 + a_2(j\omega)^2 + a_3 j\omega + 1}$$

$$L(\omega) = a_0(j\omega)^4 + a_1(j\omega)^3 + a_2(j\omega)^2 + a_3 j\omega$$

**Where,** $b_0 = L_2C_2; a_0 = L_1C_1L_2C_2;$

$$a_1 = \frac{L_1L_2C_2}{R_L}; a_2 = L_1C_1 + L_2C_2 + L_1C_2; a_3 = \frac{L_1}{R_L};$$

**Simplified model of power-stage**



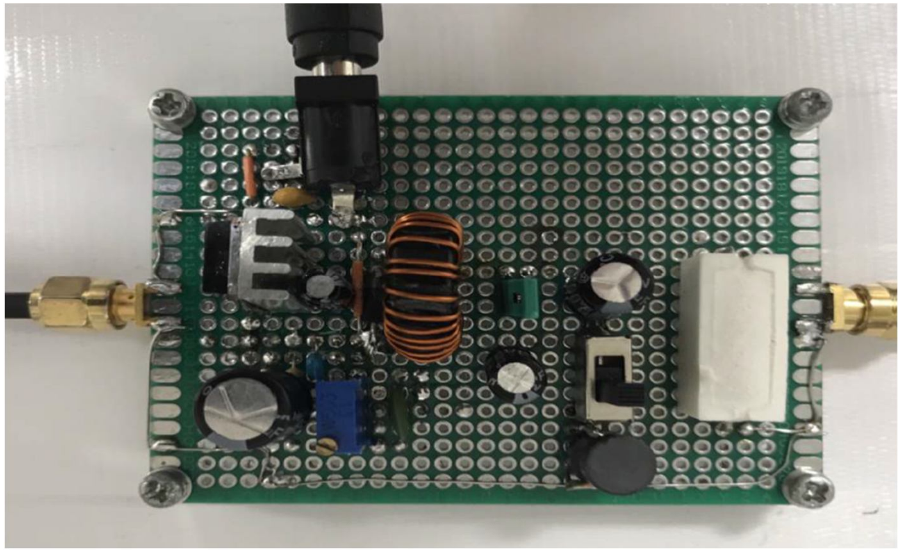
# 3. Ripple Reduction for DC-DC Converters

## Implemented Circuit for DC-DC Converter

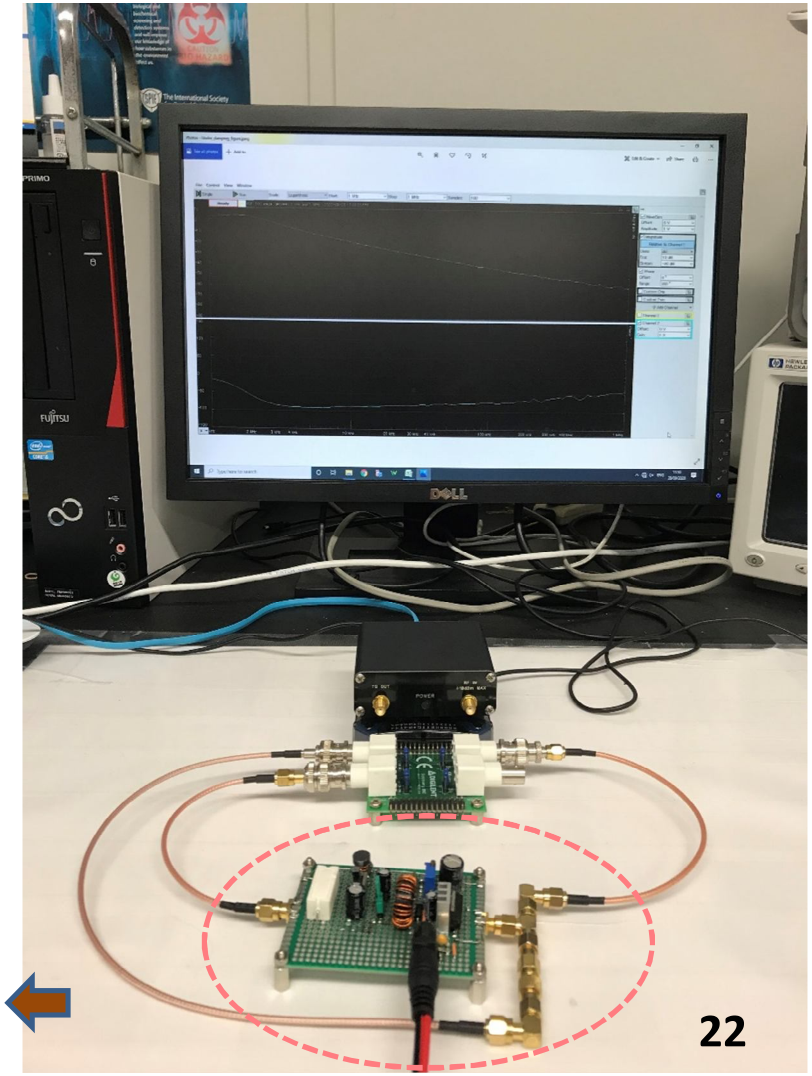
**Design parameters**

| | |
|---|---|
| Input voltage (Vin) | 12 V |
| Output voltage (Vo) | 5.0 V |
| Output current (Io) | 1 A |
| Clock frequency (Fck) | 180 kHz |
| Output ripple | < 10 mVpp |

**Implemented circuit**



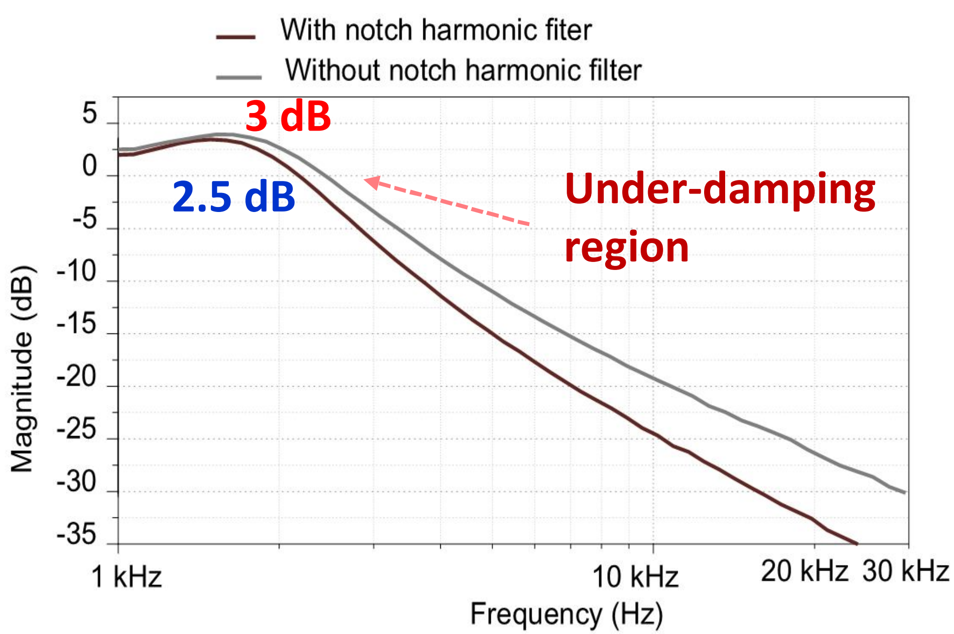
**Measurement set up**



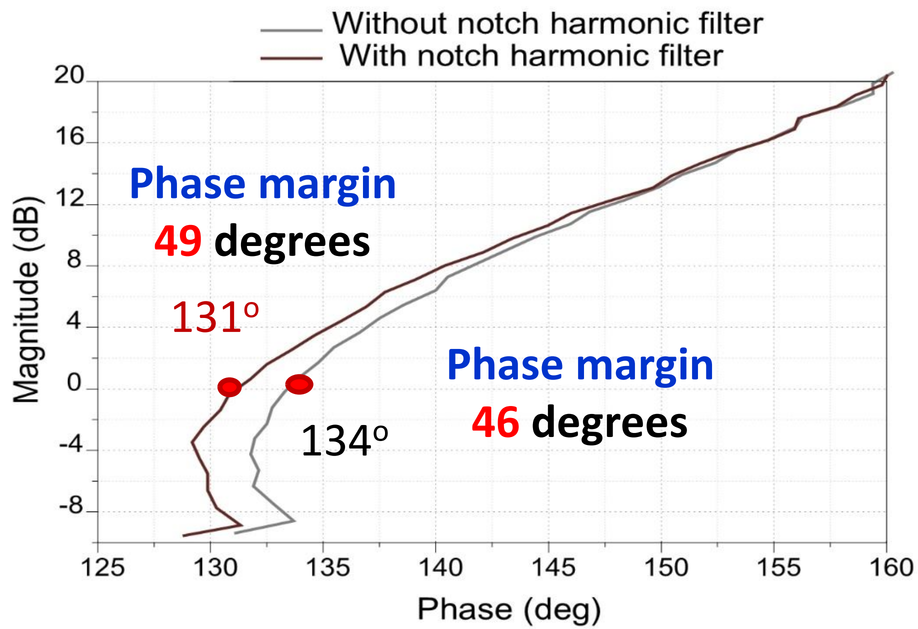
# 3. Ripple Reduction for DC-DC Converters

## Measurement Results of Proposed Design Circuit

**Bode plot of transfer function**




**Nichols plot of self-loop function**




- **Reduce the cut-off frequency of the power-stage**

  → **Reduce the ripple caused by high-order harmonic signals**

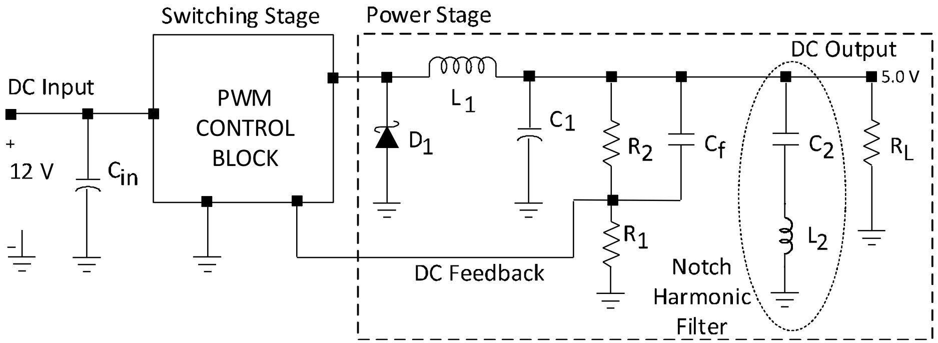
- **Improvement of phase margin of the power-stage**

  → **Reduce the overshoot caused by the passive components**

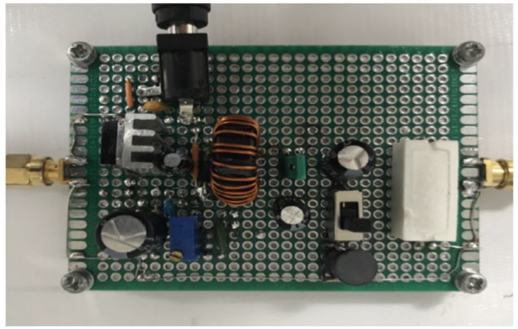
# 3. Ripple Reduction for DC-DC Converters

## Ripple Reduction using Harmonic Notch Filter

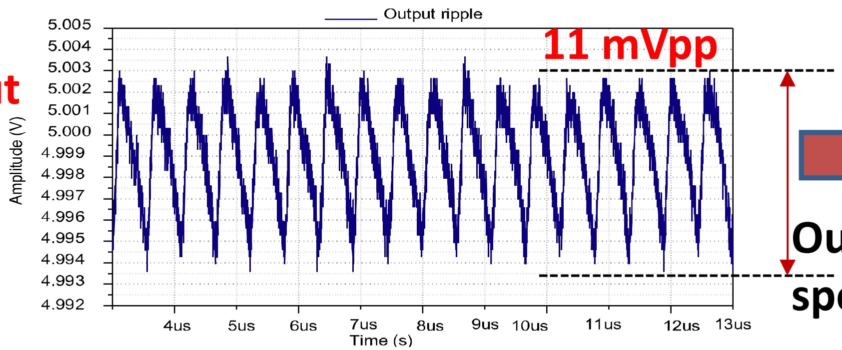
### Schematic diagram of DC-DC Buck converter



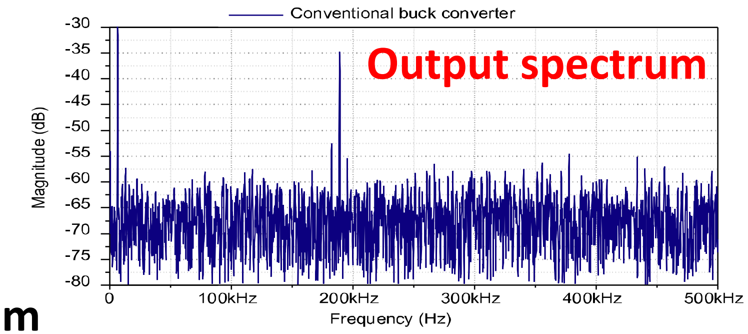

### Implemented circuit



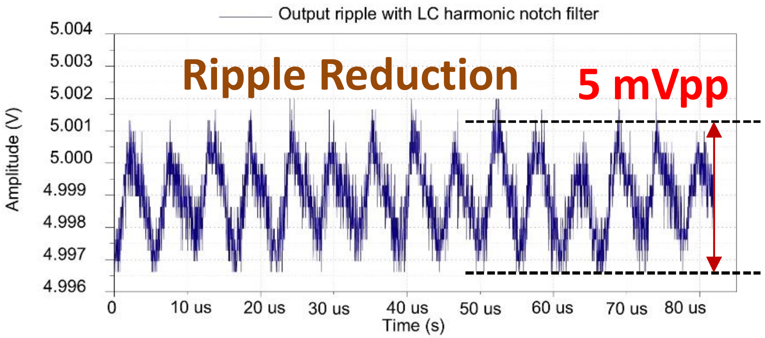
**Without notch filter**



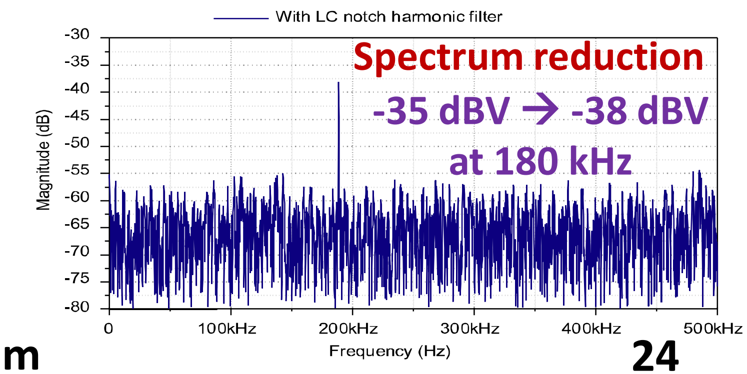

**Output spectrum**




**With notch filter**




**Output spectrum**



# Outline

1. Research Background
    - Motivation, objectives and achievements
    - Characteristics of an adaptive feedback network
2. Analysis of Power-Stage of DC-DC Converter
    - Operating regions of power-stage of DC-DC converter
    - Passive parallel RLC network
3. Ripple Reduction for DC-DC Converters
    - LC Harmonic Notch filter
    - Nichols chart of power stage of buck converter
4. **Conclusions**

# 4. Discussion and Comparison

## Merits of Self-loop Function Derivation Techniques

| Features | Comparison measurement | Alternating current conservation | Replica measurement | Middlebrook's method |
|---|---|---|---|---|
| Main objective | Self-loop function | Self-loop function | Loop gain | Loop gain |
| Transfer function accuracy | Yes | Yes | No | No |
| Breaking feedback loop | No | Yes | Yes | Yes |
| Operating region accuracy | Yes | Yes | No | No |
| Phase margin accuracy | Yes | Yes | No | No |
| Passive networks | Yes | Yes | No | No |

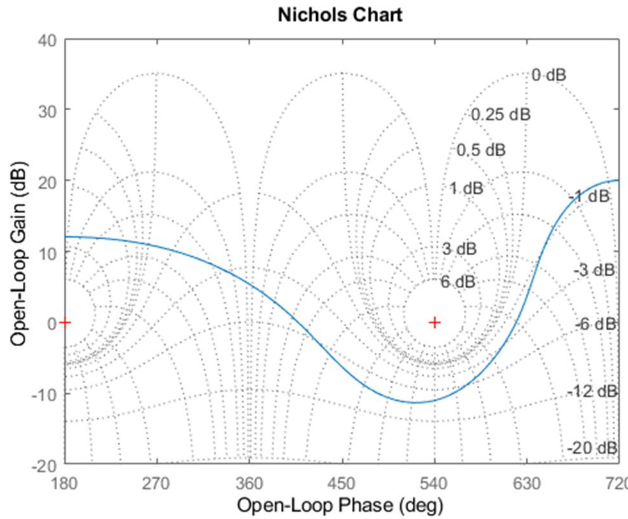
# 4. Discussion and Comparison

## Limitations of Loop Gain on Nichols Charts

- Loop gain is independent of frequency variable.

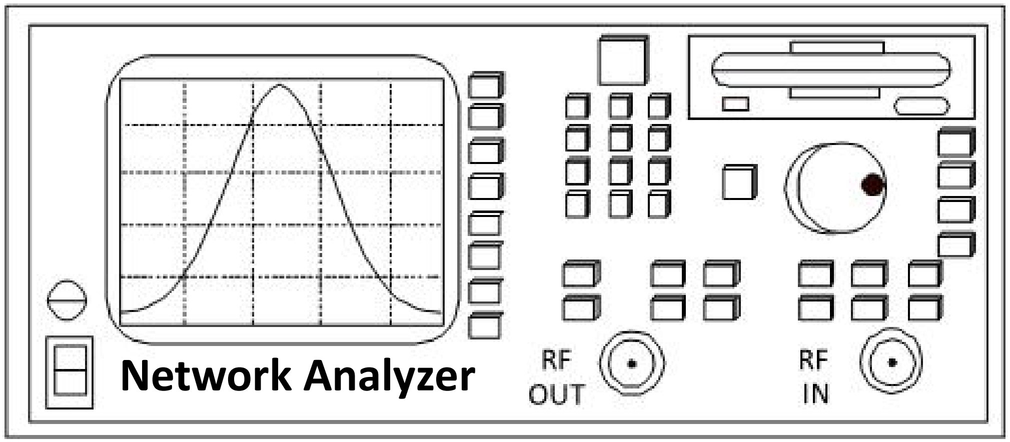
→Loop gain in adaptive feedback network is significantly different from self-loop function in linear negative feedback network.

Nichols chart is only used in MATLAB simulation.




https://www.mathworks.com/help/control/ref/nichols.html

Nichols chart isn't used widely in practical measurements (only used in control theory).




(Technology limitations)

# 4. Conclusions

## This work:

- Investigation of behaviors of power-stage in DC-DC converters based on alternating current conservation
- Proposed design of passive LC harmonic notch filters for ripple reduction

  → Phase margin improvement from 46 degrees into 49 degrees

  → Ripple reduction from 11 mVpp into 5 mVpp

## Future work:

- Stability test for dynamic loads, and parasitic components in printed circuit boards

# References


[1] P. Wang, S. Feng, P. Liu, N. Jiang, X. Zhang, "*Nyquist stability analysis and capacitance selection method of DC current flow controllers for meshed multi-terminal HVDC grids*", J. Power and Energy Systems, pp. 1-13, 2020.

[2] M. Liu, I. Dassios, G. Tzounas, F. Milano, "*Stability Analysis of Power Systems with Inclusion of Realistic-Modeling of WAMS Delays*", IEEE Trans. Power Systems, Vol. 34(1), pp. 627-636, 2019.

[3] N. Kumar, V. Mummadi, "*Stability Region Based Robust Controller Design for High-gain Boost DC-DC Converter*", IEEE Trans. Industrial Electronics, Feb. 2020.

[4] A. Nakhmani, M. Lichtsinder, E. Zeheb, "*Generalized Bode envelopes and generalized Nyquist theorem for analysis of uncertain systems*", Int. J. Robust and Nonlinear Control, Vol. 21(7), pp. 752-767, 2010.

[5] A. Riccobono, M. Cupelli, A. Monti, E. Santi, T. Roinila, "*Stability of shipboard dc power distribution: Online impedance-based systems methods*", IEEE Electrification Magazine, vol.v5 no. 3, pp. 55-67, Sept. 2017.

[6] X. Zhang, X. Jiang, Q. Han, "*An improved stability criterion of networked control systems*", Proc. 2010 American Control Conference, Baltimore, USA, July 2010.

[7] M. Sanz, "*The Nyquist stability criterion in the Nichols chart*", Int. J. Robust and Nonlinear Control, Vol. 26(12), pp. 2643-2651, 2015.

[8] J. Slater, "*Application of the Nyquist Stability Criterion on the Nichols Chart*", J. Guidance, Control, and Dynamics, Vol. 22 (2), pp. 360-362, 1999.

[9] X. Jiang, Q. Han, S. Liu, A. Xue, "*A new H stabilization criterion for networked control systems*", IEEE Trans. Autom. Control, Vol. 53(4), pp. 1025–1032, 2008.

[10] M. Tran, Y. Sun, N. Oiwa, Y. Kobori, A. Kuwana, H. Kobayashi, "*Mathematical Analysis and Design of Parallel RLC Network in Step-down Switching Power Conversion System*", Proc. Int. Conf. Technology and Social Science, Kiryu, Japan, May 2019.

[11] J. Anagnost, C. A. Desoer, R. Minnichelli, "*Generalized Nyquist Tests for Robust Stability: Frequency Domain Generalizations of Kharitonov's Theorem*", J. Robustness in Identification and Control, pp. 79-96, NY, 1989.

[12] Y. He, G. Liu, D. Rees, M. Wu, "*Improved stabilization method for networked control systems*", IET Control Theory Applications, Vol. 1(6), pp.1580–1585, 2007.

# References


[13] N. Cohen, Y. Chait, O. Yaniv, C. Borghesa, "*Stability Analysis Using Nichols Charts*", Proc. the 31st IEEE Conf. Decision and Control, Tucson, USA, Dec. 1992.

[14] A. Riccobono, E. Santi, "*Comprehensive review of stability criteria for dc power distribution systems*", IEEE Trans. Industry Applications, Vol. 50(5), pp. 3525-3535, Sept. 2014.

[15] C. Peng, M. Fei, "*A refined delay-partitioning approach to the stability of linear systems with interval time-varying delays*", Proc. Int. Symp. Industrial Electronics, Taipei, Taiwan, July 2013.

[16] K. Liu, E. Fridman, "*Networked-based stabilization via discontinuous Lyapunov functionals*", Int. J. Robust Nonlinear Control, Vol. 22(4), pp. 420–436, 2012.

[17] R. Middlebrook, "*Measurement of Loop Gain in Feedback Systems*", Int. J. Electronics, vol. 38(4), pp.485-512, 1975.

[18] M. Tran, A. Kuwana, H. Kobayashi, "*Design of Active Inductor and Stability Test for Ladder RLC Low Pass Filter Based on Widened Superposition and Voltage Injection*", The 8th IIAE Int. Conf. Industrial Application Engineering, Shimane, Japan, March 2020.

[19] H. Shao, "*Further improvement on delay-dependent stability results for linear systems with time-varying delays*", Proc. 30th Chinese Control Conference, Yantai, China, July 2011.

[20] X. Zhu, G. Yang, "*New results on stability analysis of networked control systems*", Proc. 2008 American Control Conference, pp.3792–3797, 2008.

[21] L. Fan, Z. Miao, "*Admittance-Based Stability Analysis: Bode Plots, Nyquist Diagrams or Eigenvalue Analysis*", IEEE Trans. Power Systems, Vol. 35(4), July 2020.

[22] M. Tran, A. Kuwana, H. Kobayashi, "*Design of Active Inductor and Stability Test for Passive RLC Low Pass Filter*", 10th Int. Conf. Signal and Image Processing, London, UK, July 2020.

[23] H. Shao, X. Shi, H. Wang, "*Improvements on delay-dependent stability criteria for linear delayed systems*", Proc. 7th Word Conf. Intelligent Control and Automation, Chongqing, China, 2008.

[24] N. Cohen, Y. Chait, O. Yaniv, C. Borghesani, "*Stability analysis using Nichols charts*" J. Robust and Nonlinear Control, Vol. 39, 1994.

[25] G. Walsh, H. Ye, L. Bushnell, "*Stability analysis of networked control systems*", IEEE Trans. Control Systems Technology, Vol. 10(3), pp. 438-446, 2002.

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# Thank you very much!

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