Cascaded DC-DC Converter Systems: Stability Criteria and Solutions

Presented by

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Outlines

- Backgrounds
- General Impedance-Based Stability for Cascaded System
- Input Impedance Regulation for Load Converter
- Adaptive Impedance Adaptor
- Conclusions

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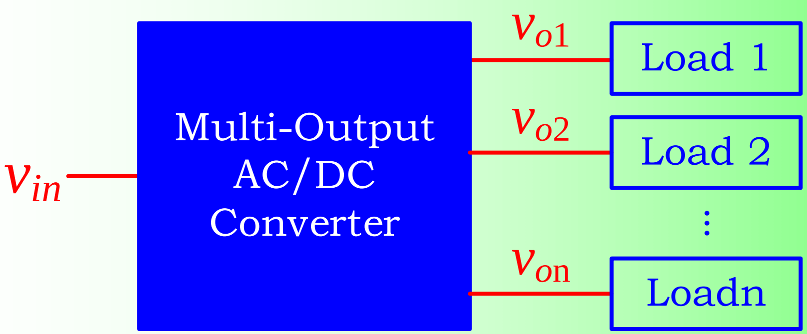
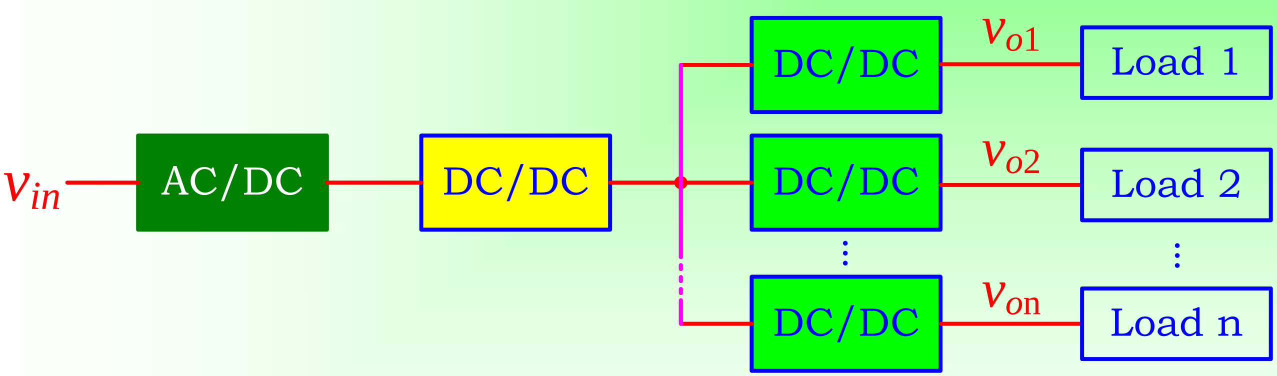
- **Backgrounds**
- **General Impedance-Based Stability for Cascaded System**
- **Input Impedance Regulation for Load Converter**
- **Adaptive Impedance Adaptor**
- **Conclusions**

Centralized Power System vs DPS



Centralized Power System

- ☹ Poor cross-regulation;
- ☹ Poor dynamic response;
- ☹ Large loss due to long distance between the power supply and load.



Distributed Power System

- ☺ Modular design;
- ☺ Tight regulation of each output.
- ☺ Lower loss in the transmission line.

Applications of Distributed Power System

More-Electric- and All-Electric Aircrafts

Aerospace Stations

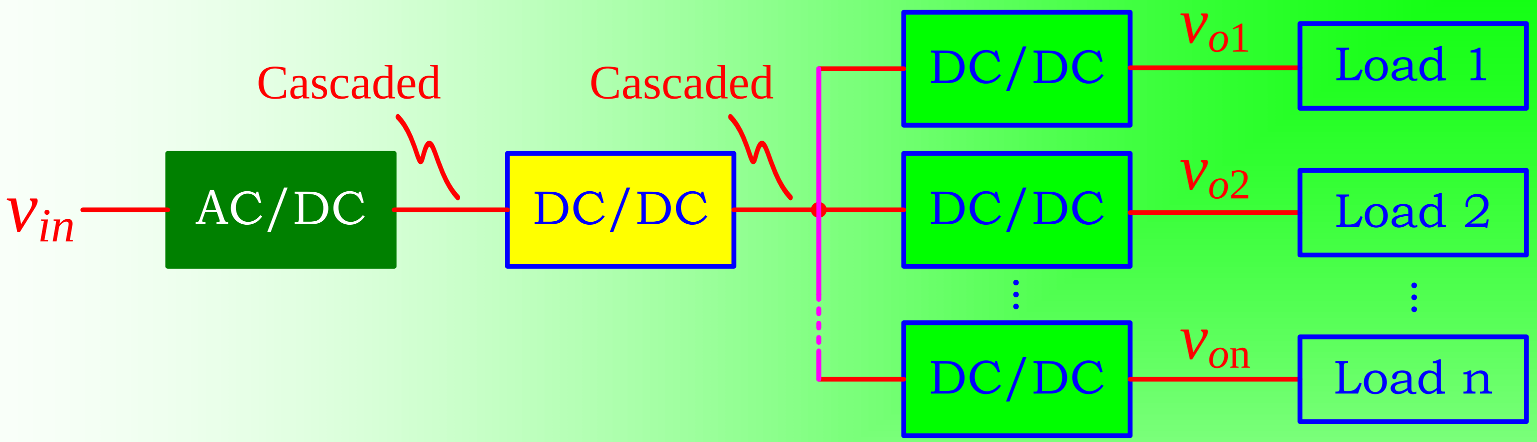
Warships

Personal Computer

Electric Vehicle

Server

Issues of Cascaded DC-DC Converter System



A Typical Distributed Power System

System stability criterion?

Solutions to improve system stability?

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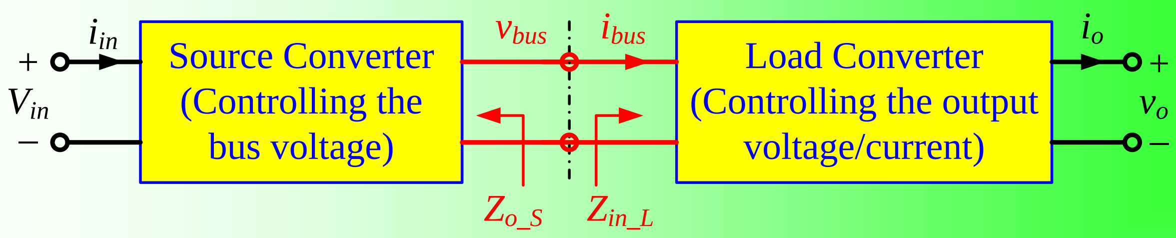
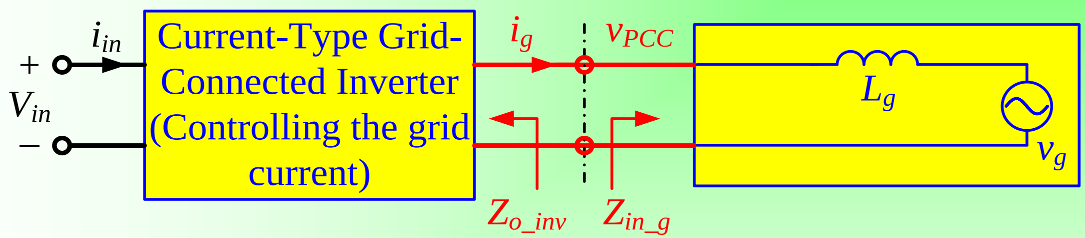
Existing Impedance-Based Stability Criterion



Equivalent loop gain:

$$T_m = \frac{Z_{o\_S}(s)}{Z_{in\_L}(s)}$$

R. D. Middlebrook, "Input filter considerations in design and application of switching regulators," in Proc. IEEE IAS, 1979.



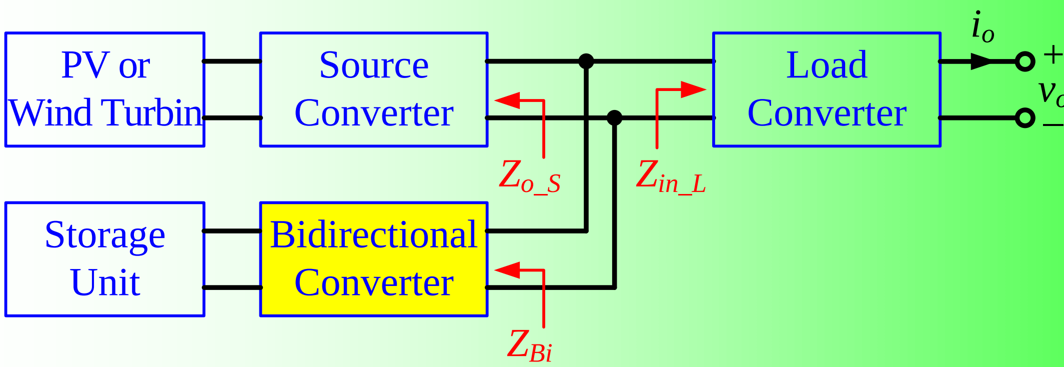
Equivalent loop gain:

$$T_m = \frac{Z_{in\_g}(s)}{Z_{o\_inv}(s)}$$

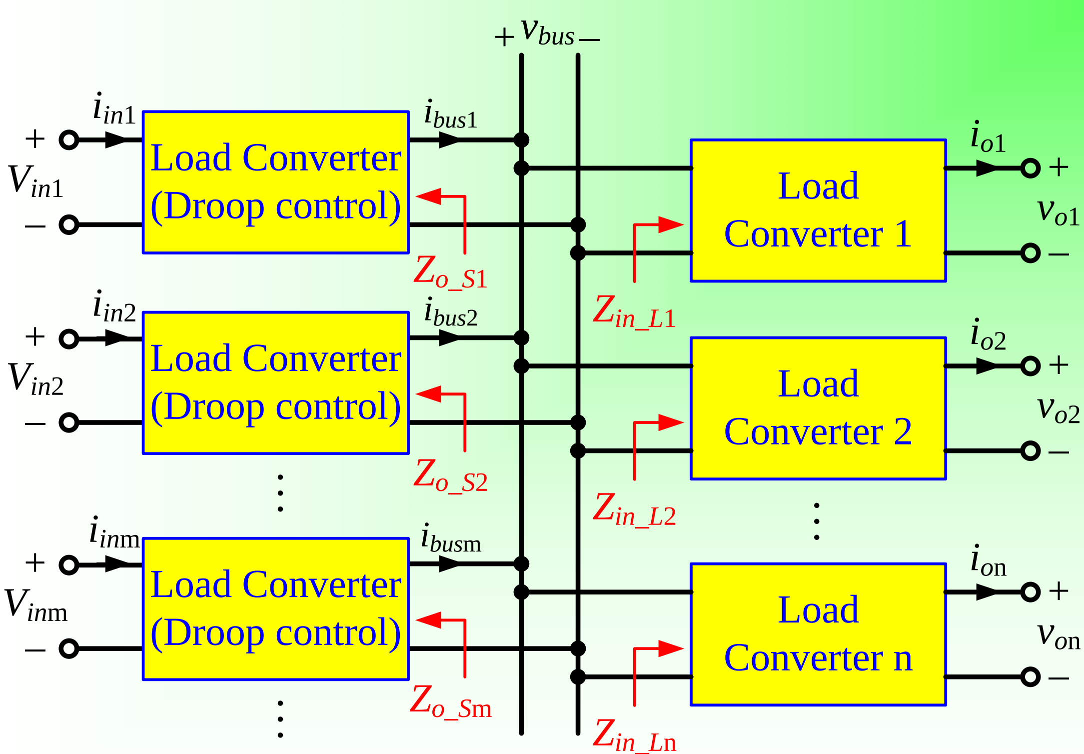
J. Sun, "Impedance-based stability criterion for grid-connected inverters," IEEE Trans on. Power Electronics, vol. 26, no. 11, 2011.

The above two stability criteria is **contradictory**.

Limitations of the Existing Stability Criteria

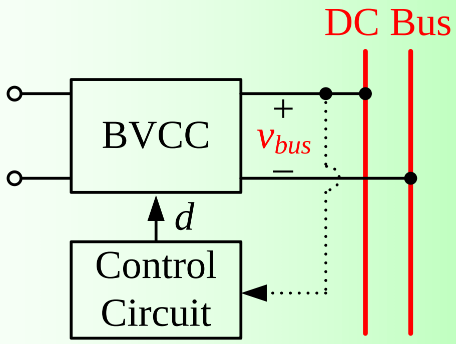


The bidirectional converter is **a source converter or a load converter**?

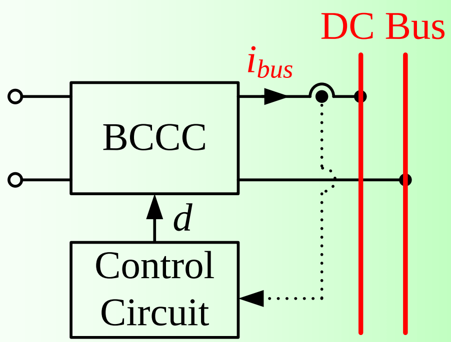


All the source converters control the intermediate bus voltage. How to obtain the **output impedance**?

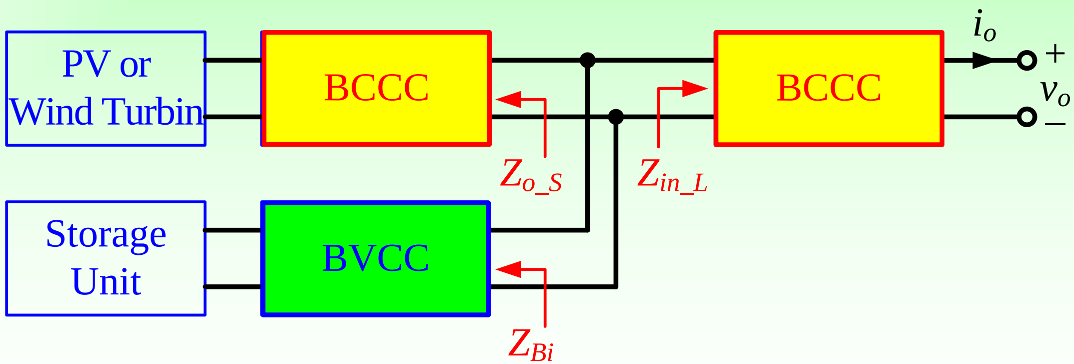
Classifications of Converters: BVCC and BCCC



- **Bus Voltage Controlled Converter (BVCC)**
  - Directly control v_{bus}, or
  - Indirectly control v_{bus} by regulating the power.

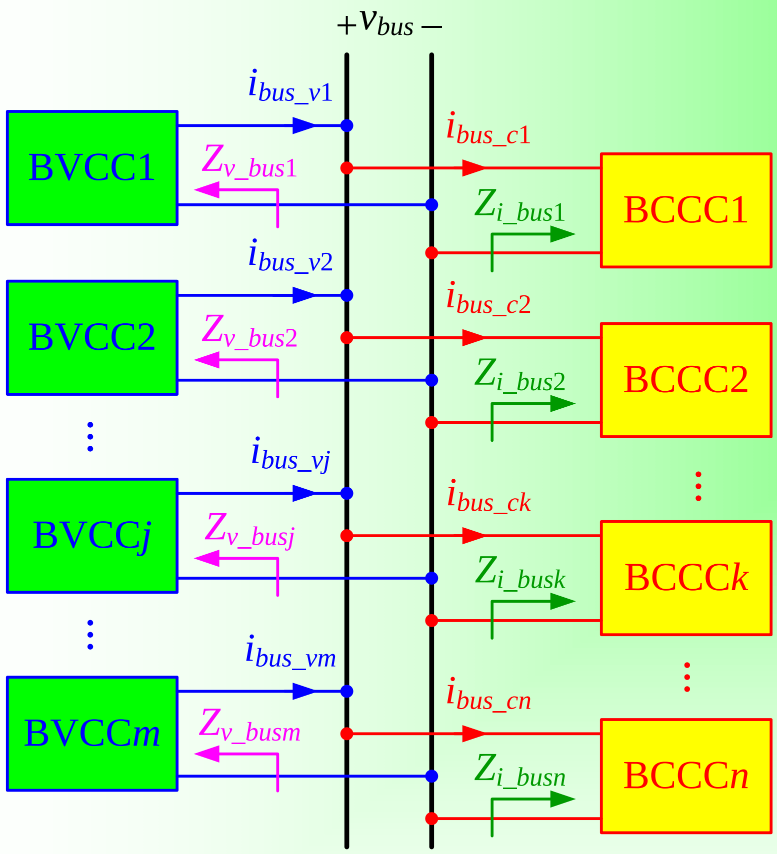


- **Bus Current Controlled Converter (BCCC)**
  - Directly control i_{bus}, or
  - Indirectly control i_{bus} by regulating the power.

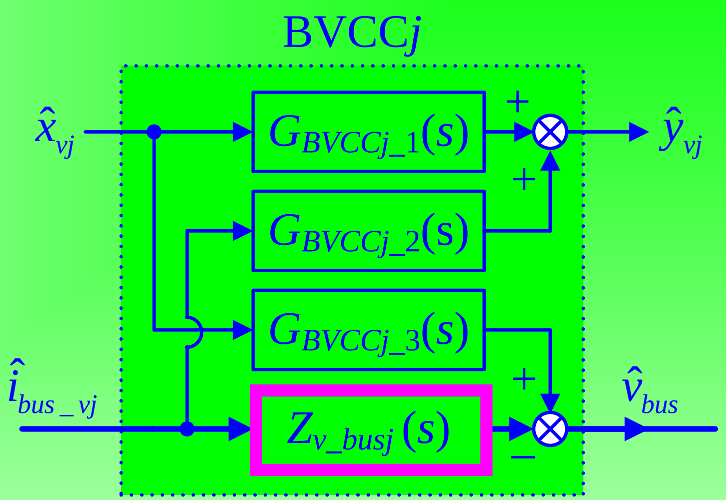


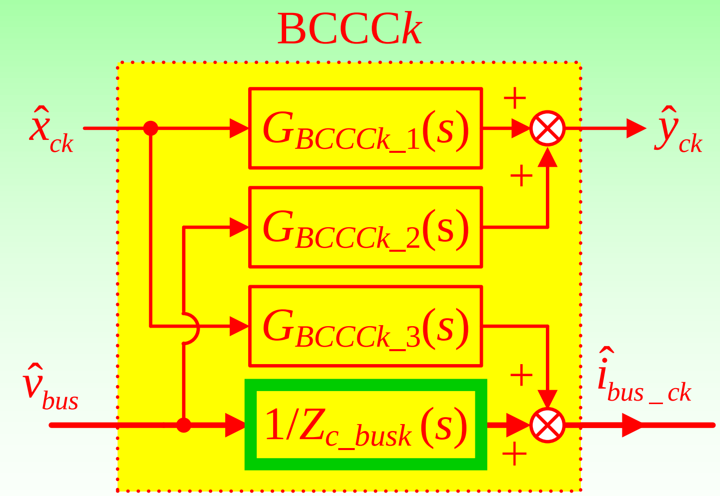
Standard Form of Cascaded System

Standard Form of Cascaded System

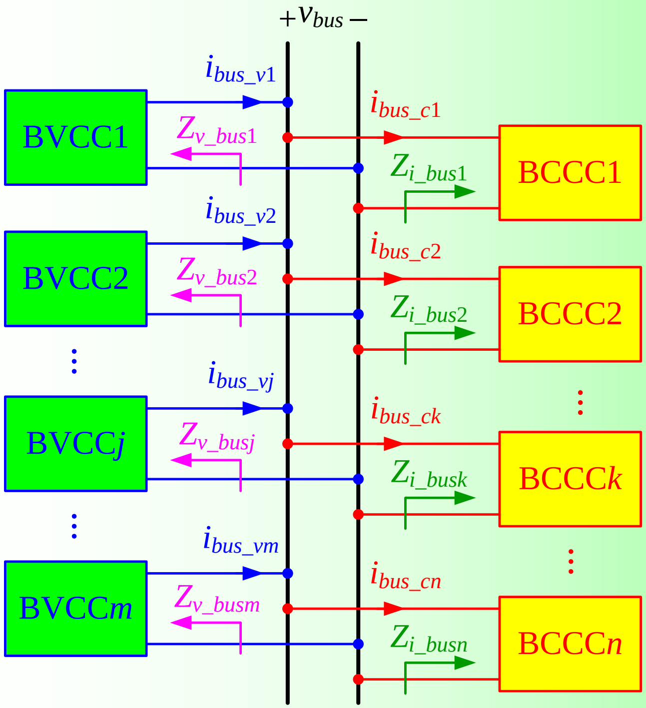


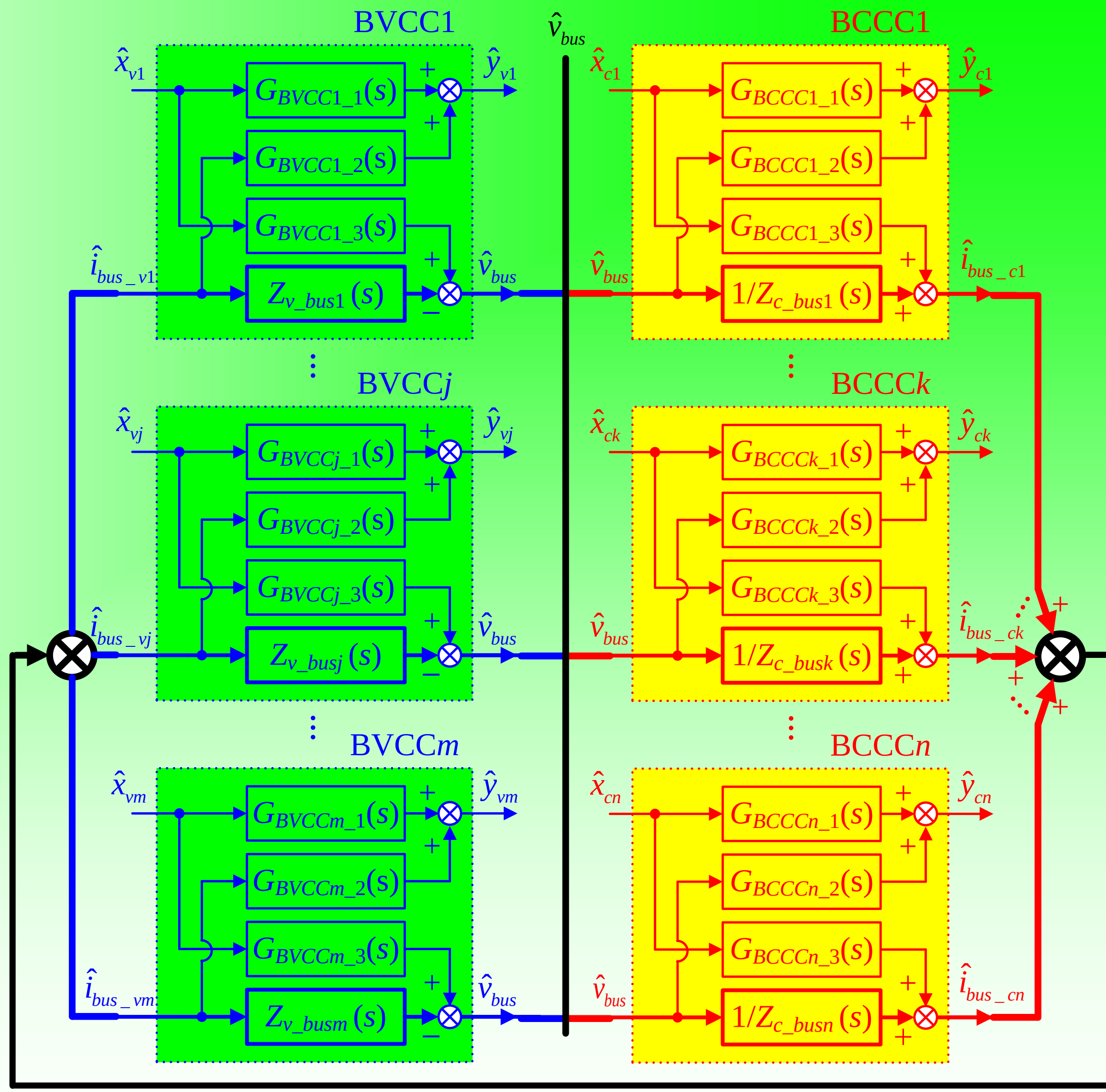
Small-Signal Two-Port Model





Small-Signal Model of Cascaded System

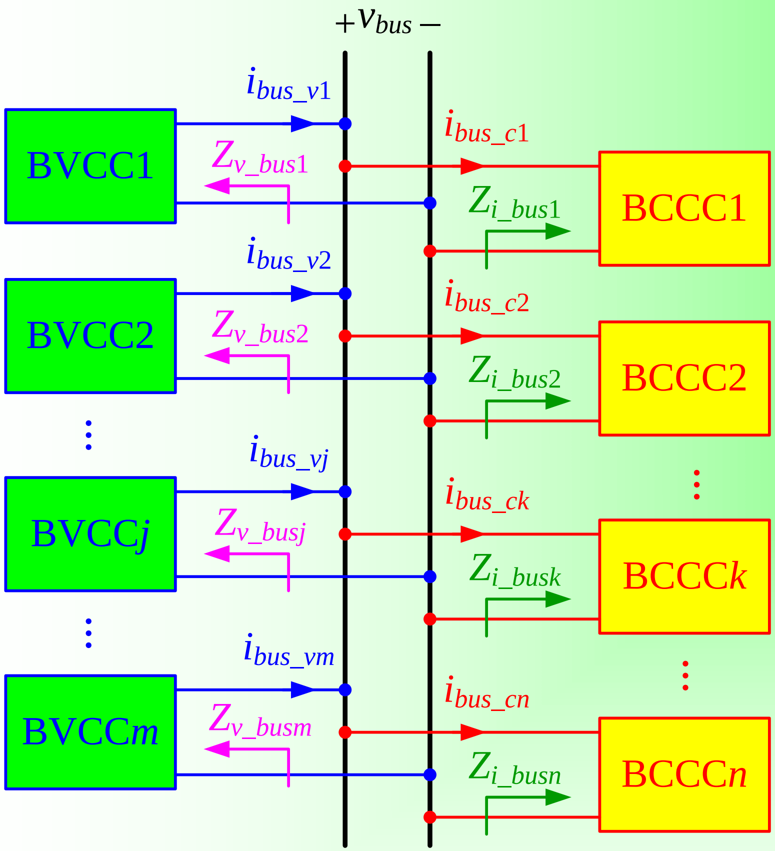




Equivalent Loop Gain of Cascaded System

$$T_m = \frac{\left(\sum_{j=1}^{m} \frac{1}{Z_{v\_busj}}\right)^{-1}}{\left(\sum_{k=1}^{n} \frac{1}{Z_{i\_busk}}\right)^{-1}}$$

General Impedance-Based Stability Criterion of Cascaded System



Equivalent Loop Gain of Cascaded System

$$T_m = \frac{\left(\sum_{j=1}^{m} \frac{1}{Z_{v\_busj}}\right)^{-1}}{\left(\sum_{k=1}^{n} \frac{1}{Z_{i\_busk}}\right)^{-1}} = \frac{Z_{v\_bus}}{Z_{i\_bus}}$$

Z_{v_bus}: Shunt impedance of the **bus-side-port-impedances** of all the BVCCs.

Z_{i_bus}: Shunt impedance of the **bus-side-port-impedances** of all the BCCCs.

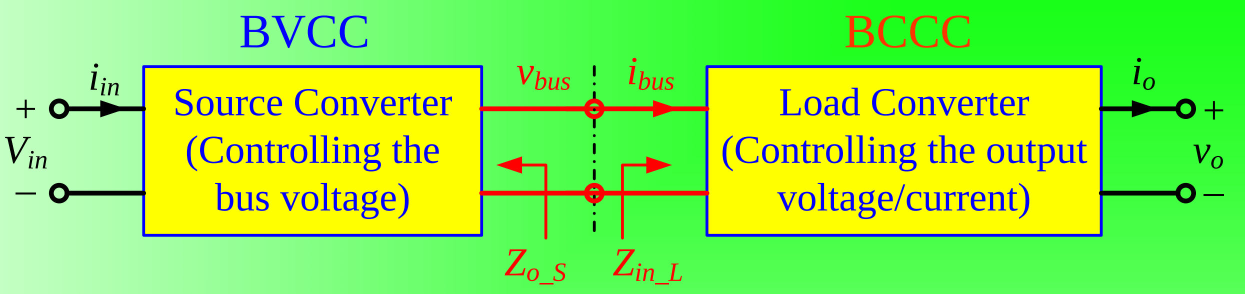
General Impedance-Based Stability Criterion of Cascaded System

- Each converter is stable when working alone;
- T_m satisfies the Nyquist criterion.

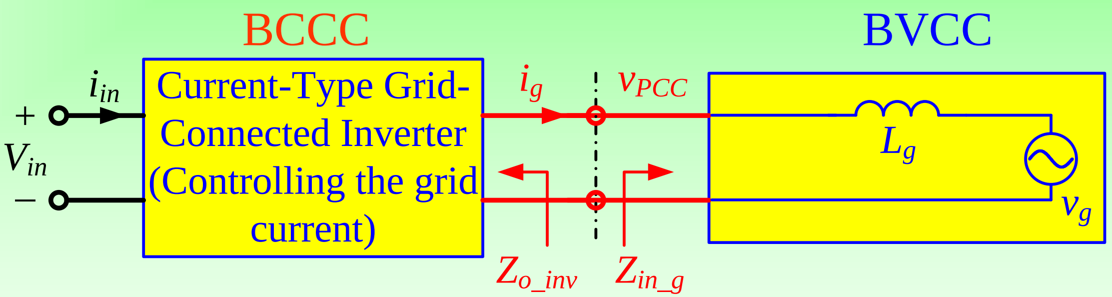
Application of General Impedance-Based Stability Criterion

Equivalent Loop Gain

$$T_m = \frac{\left(\sum_{j=1}^{m} \frac{1}{Z_{v\_busj}}\right)^{-1}}{\left(\sum_{k=1}^{n} \frac{1}{Z_{i\_busk}}\right)^{-1}}$$



Equivalent loop gain: $T_m = \frac{Z_{o\_s}(s)}{Z_{in\_L}(s)}$



Equivalent loop gain: $T_m = \frac{Z_{in\_g}(s)}{Z_{o\_inv}(s)}$

Application of General Impedance-Based Stability Criterion

Equivalent Loop Gain

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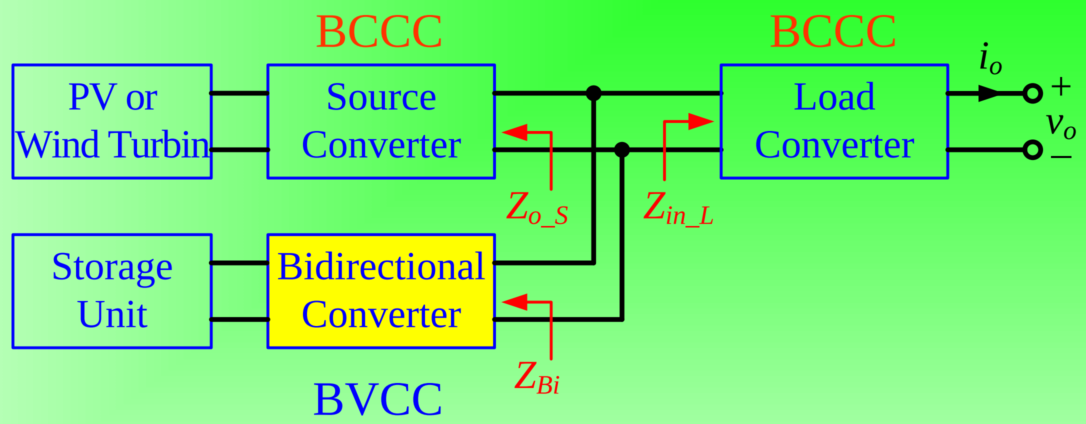
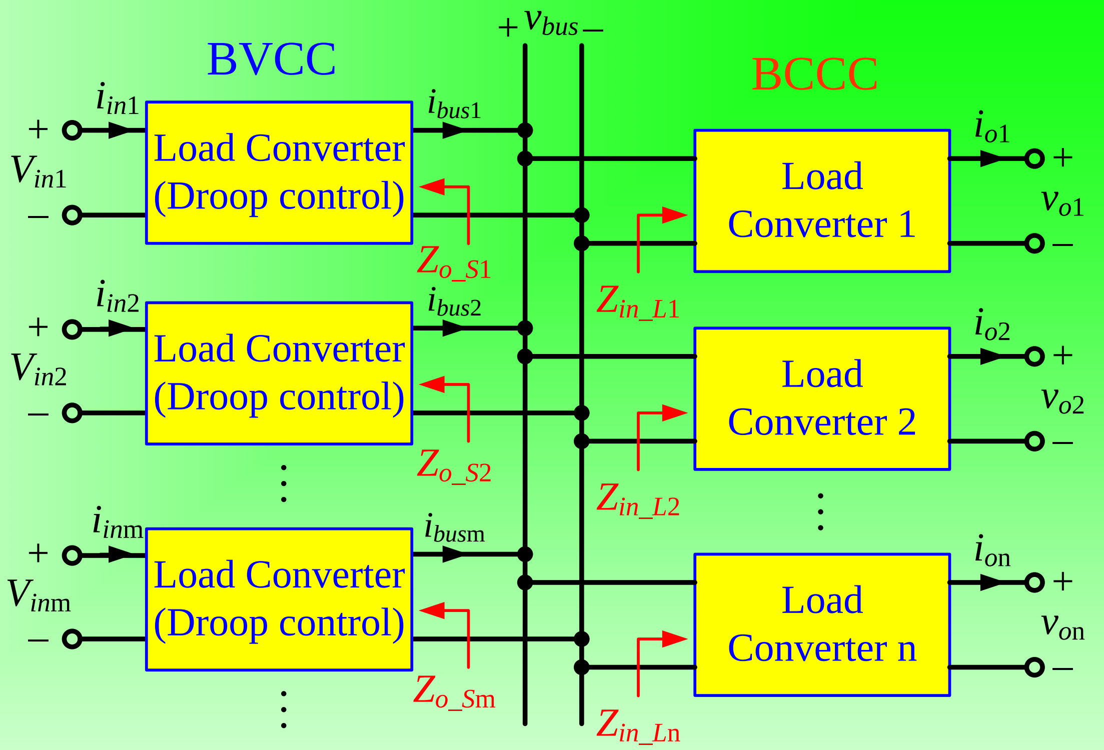


Equivalent loop gain: $T_m = \frac{Z_{Bi}(s)}{Z_{o\_s} // Z_{in\_L}(s)}$

Application of General Impedance-Based Stability Criterion

Equivalent Loop Gain

$$T_m = \frac{\left(\sum_{j=1}^{m} \frac{1}{Z_{v\_busj}}\right)^{-1}}{\left(\sum_{k=1}^{n} \frac{1}{Z_{i\_busk}}\right)^{-1}}$$



Equivalent loop gain: $$T_m = \frac{\left(\sum_{j=1}^{m} \frac{1}{Z_{o\_Sj}}\right)^{-1}}{\left(\sum_{k=1}^{n} \frac{1}{Z_{in\_Lk}}\right)^{-1}}$$

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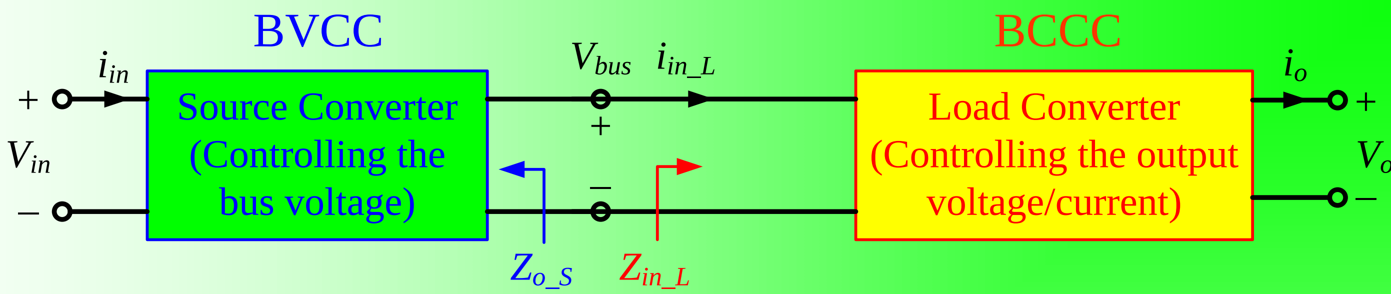
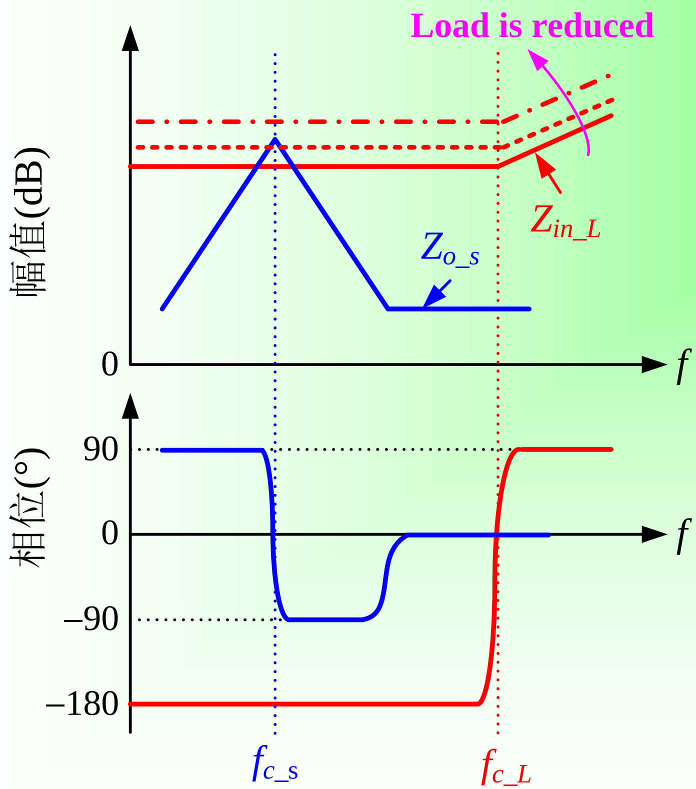
- ☐ General Impedance-Based Stability for Cascaded System
- ☐ **Input Impedance Regulation for Load Converter**
- ☐ Adaptive Impedance Adaptor
- ☐ Conclusions

Input and Output Impedances of Power Converter





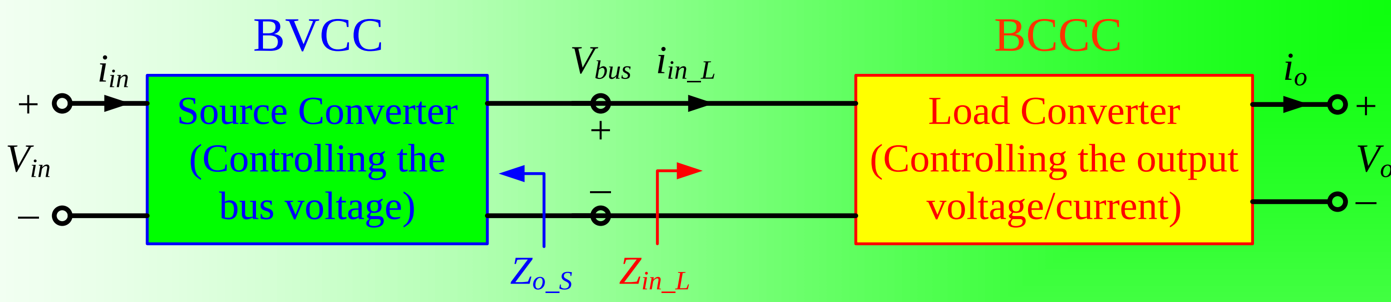
Load Converter

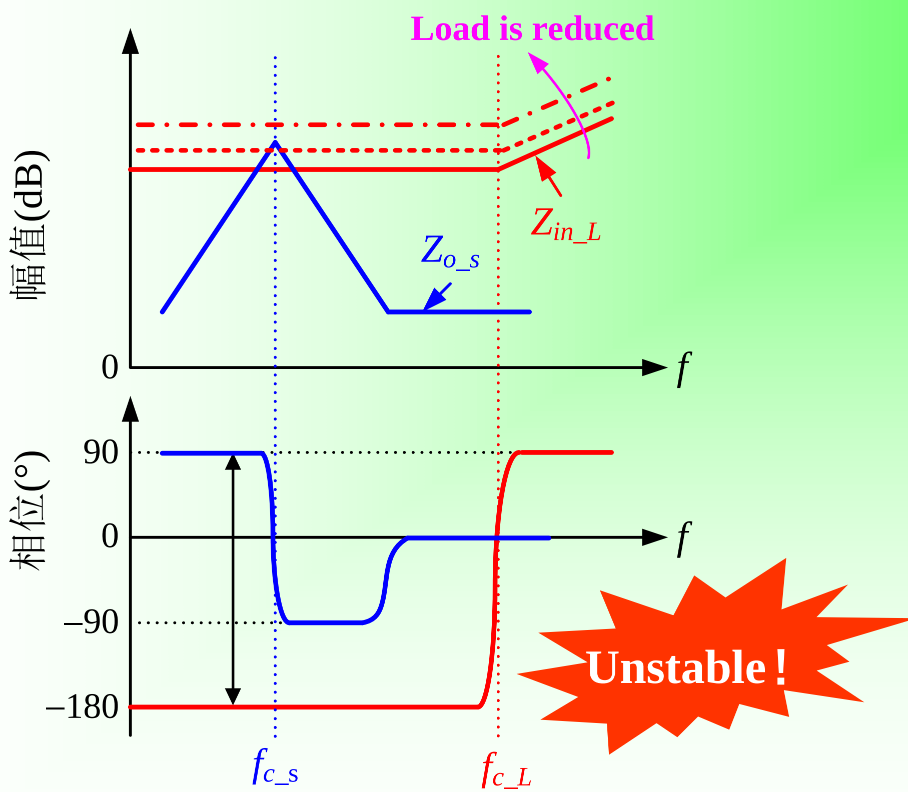
- $f < f_{c\_L}$, $Z_{in\_L} = -V_{bus}^2 / P_o$ Negative resistor
- $f > f_{c\_L}$, Z_{in_L} behaves as an inductor.

Source Converter

- At the cut-off frequency f_{c_S}, Z_{o_s} has a resonant peak.
- The magnitude of the resonant peak is **inversely proportional to** the output filter capacitor.

Analysis of Stability of Cascaded System



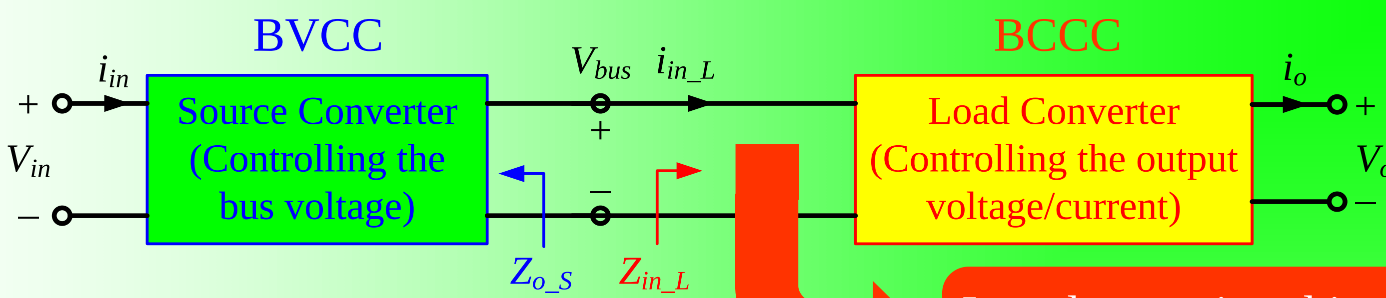


Equivalent loop gain: $T_m = \dfrac{Z_{o\_S}(s)}{Z_{in\_L}(s)}$

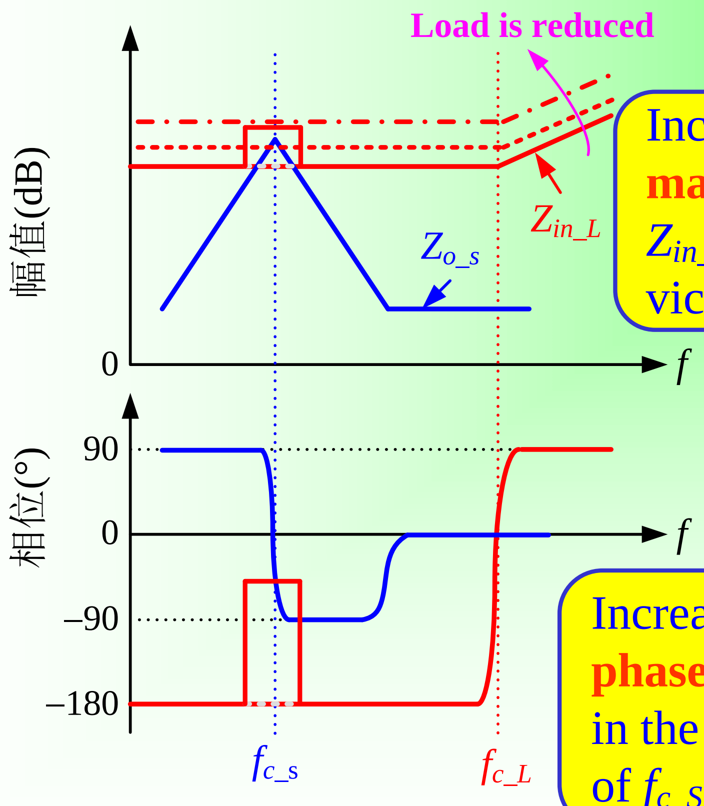
T_m satisfied Nyquist criterion

- In the entire frequency range, Z_{o_S} never intersects with Z_{in_L}, i.e.,$|Z_{o\_S}|<|Z_{in\_L}|$; or
- At the frequency of intersection, $\angle Z_{o\_S} - \angle Z_{in\_L} < 180°$.

Improving the Stability of Cascaded System



Introduce a virtual impedance Z_{vir} at the bus-side of load converter



Increase the **magnitude** of Z_{in_L} in the vicinity of f_{c_S}

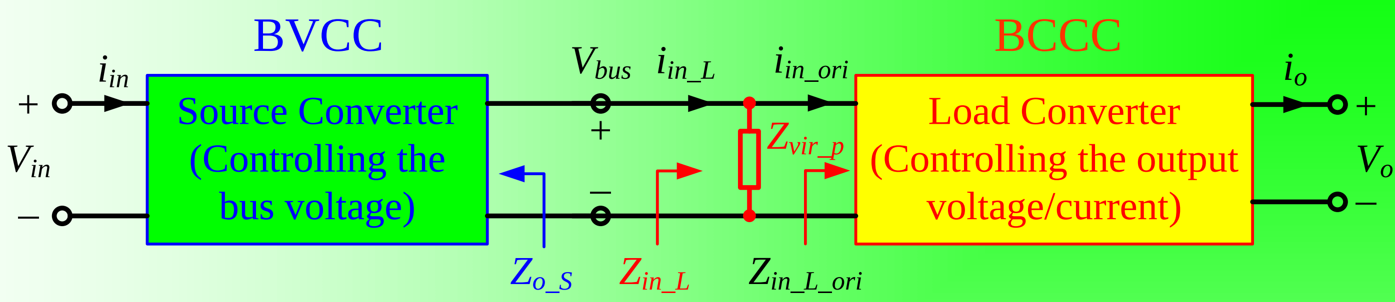
Increase the **phase** of Z_{in_L} in the vicinity of f_{c_S}

Equivalent loop gain: $T_m = \dfrac{Z_{o\_S}(s)}{Z_{in\_L}(s)}$

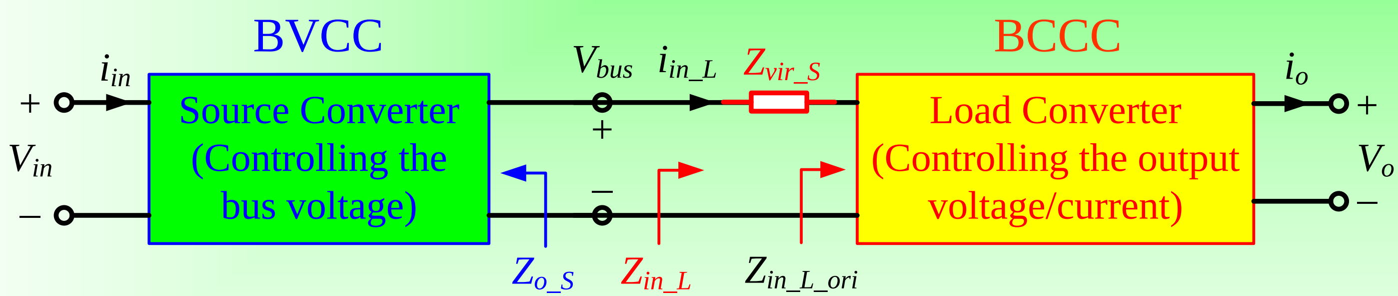
T_m satisfied Nyquist criterion

- In the entire frequency range, Z_{o_S} never intersects with Z_{in_L}, i.e., $|Z_{o\_S}| < |Z_{in\_L}|$; or
- At the frequency of intersection, $\angle Z_{o\_S} - \angle Z_{in\_L} < 180°$.

Introduce Virtual Impedance for Regulating Z_{in_L}

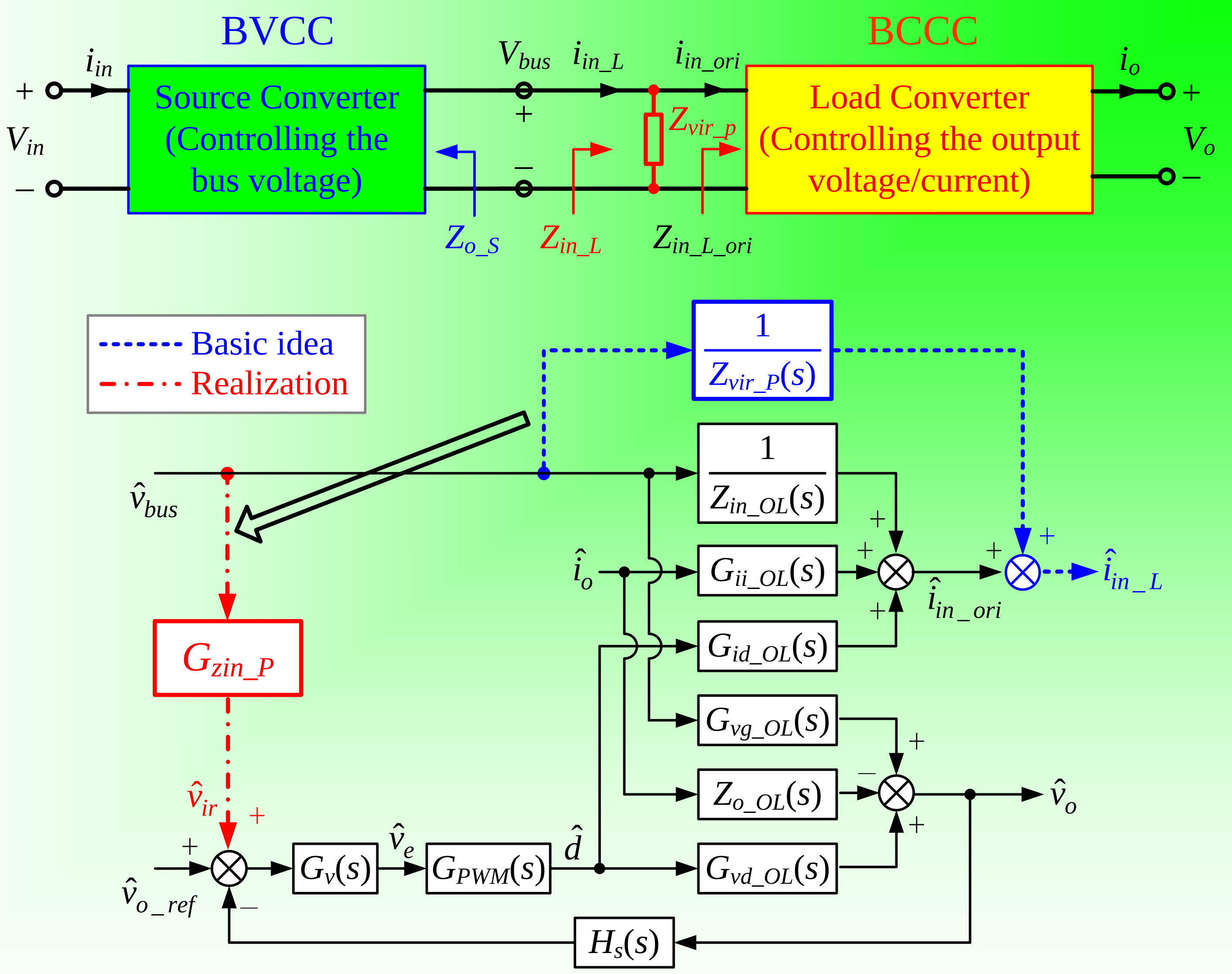


Parallel Virtual Impedance (PVI)

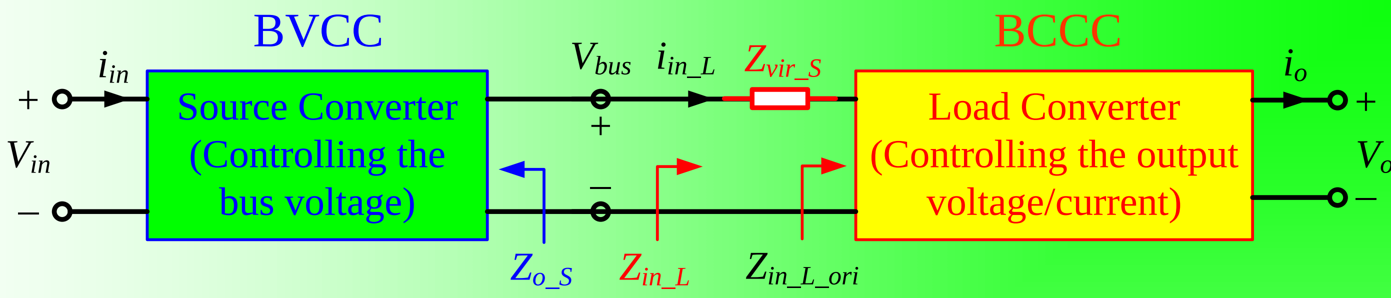


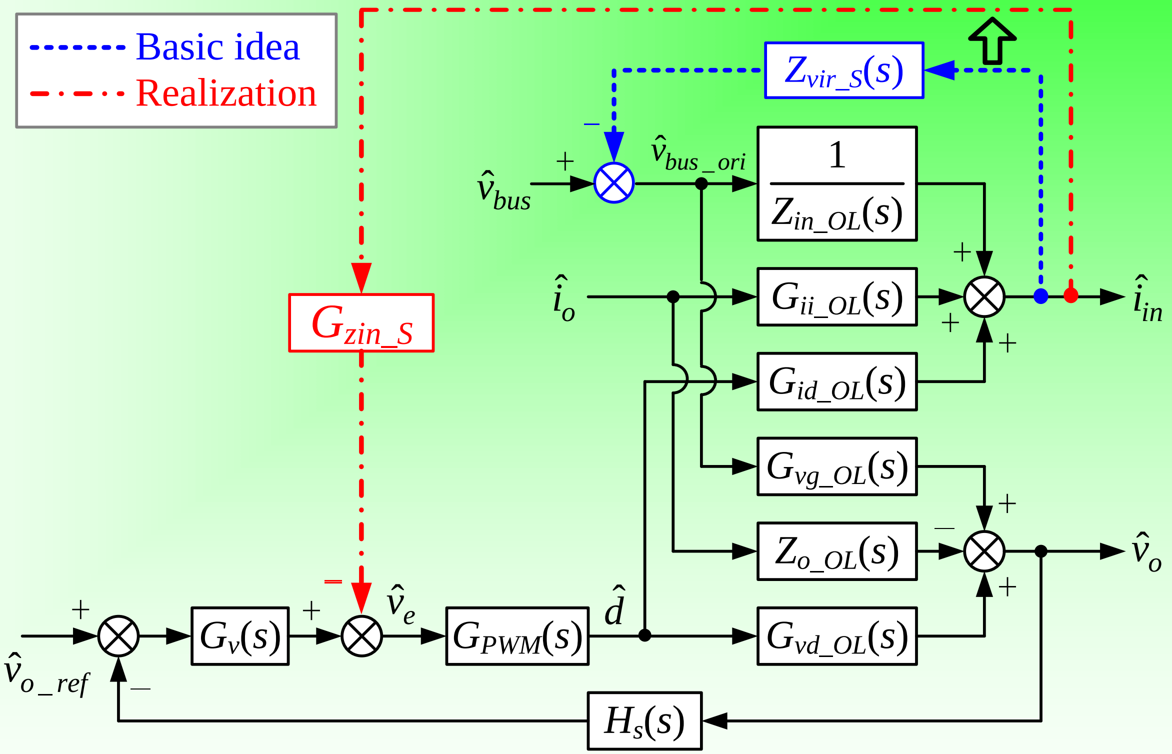
Series Virtual Impedance (SVI)

Realization of Parallel Virtual Impedance

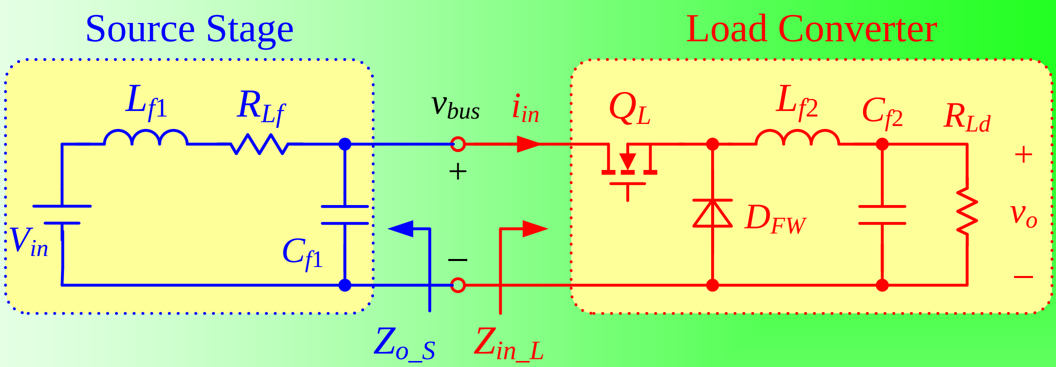


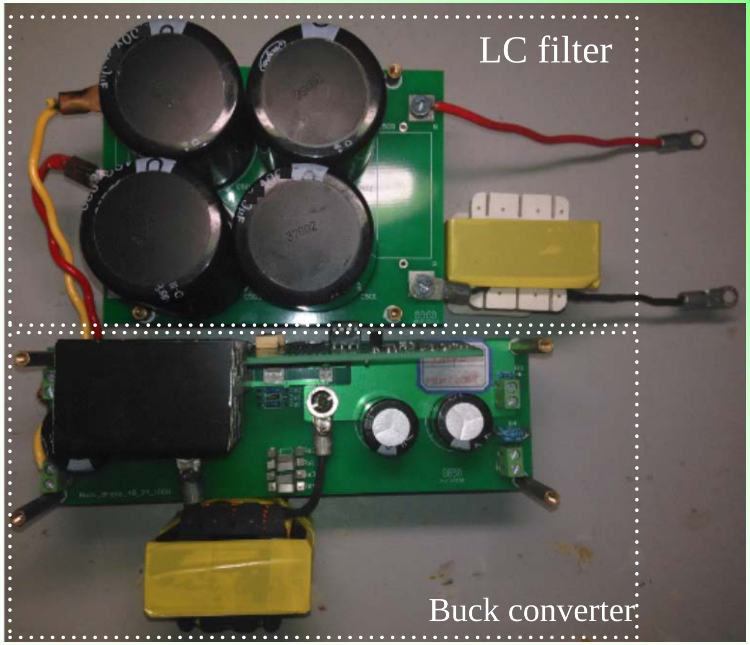
Realization of Series Virtual Impedance





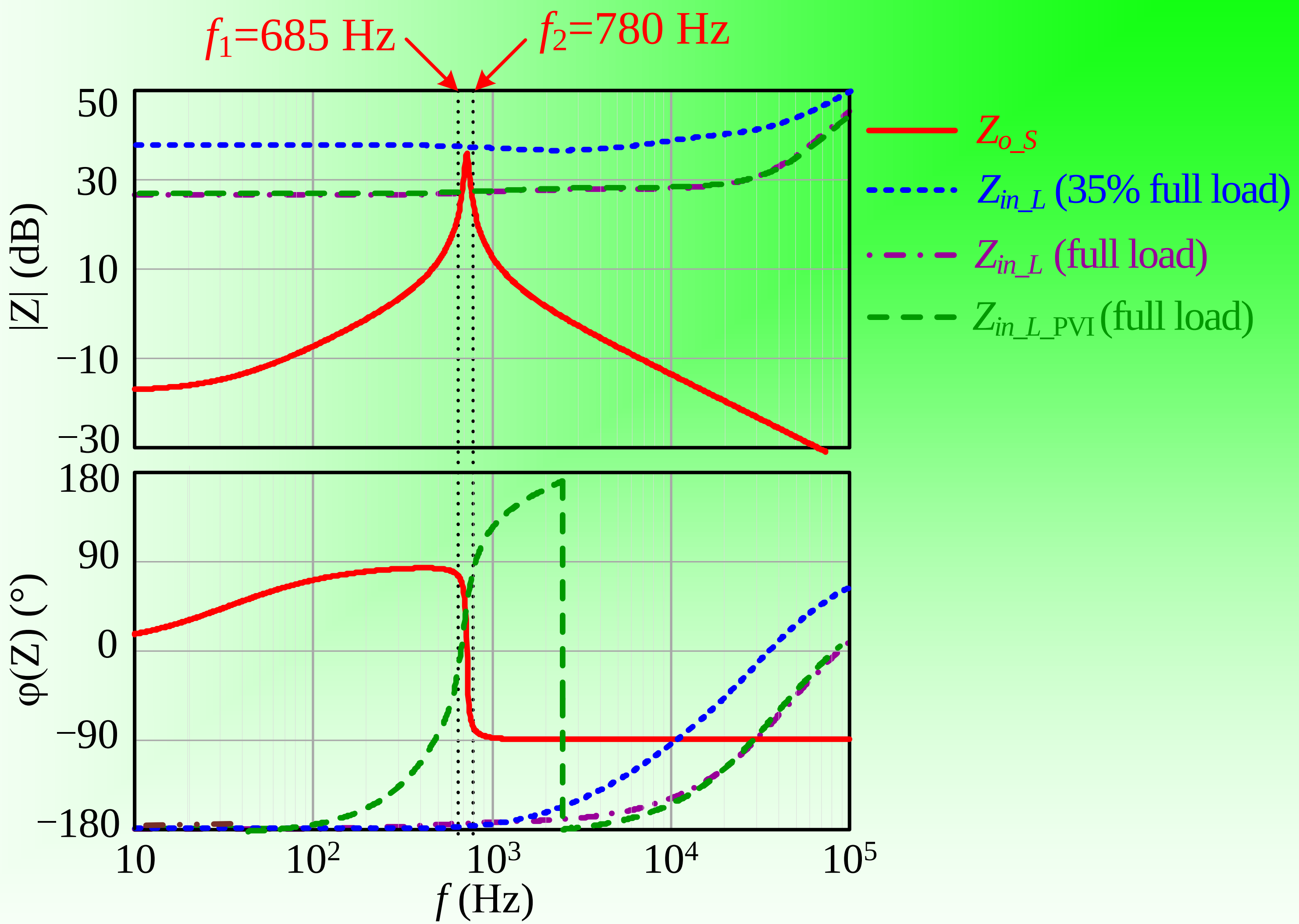
Prototype



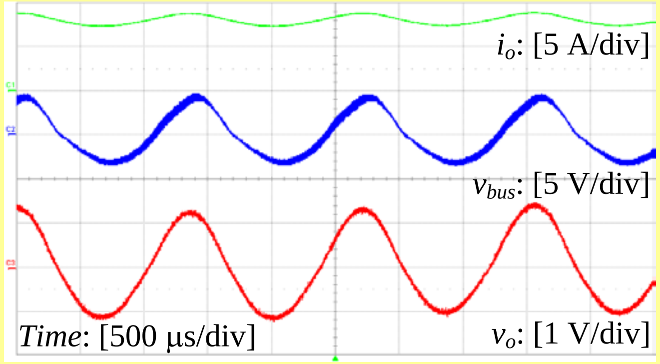
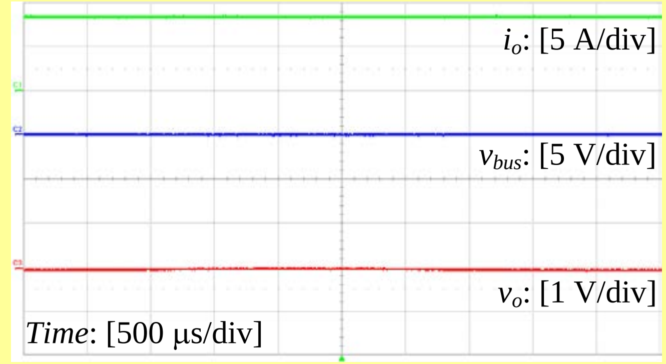


- Input voltage V_{in}: 48 VDC
- Output voltage V_o: 12 VDC
- Rated output power P_o: 100 W
- Input filter inductor L_{f1}: 700 μH
- Input filter capacitor C_{f1}: 68 μF
- Output filter inductor L_{f2}: 33 μH
- Output filter capacitor C_{f2}: 2400 μF
- Switching frequency f_s: 100 kHz

Input and Output Impedances with PVI



Experimental Waveforms

<table>
<tr><th></th><th>W/O parallel virtual impedance</th><th>With parallel virtual impedance</th></tr>
<tr><td>Full Load</td><td>
</td><td>
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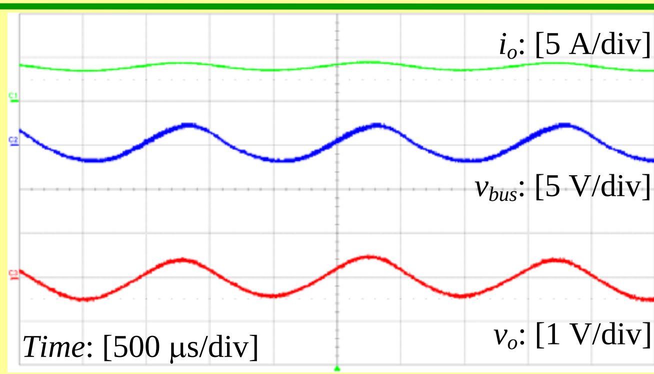
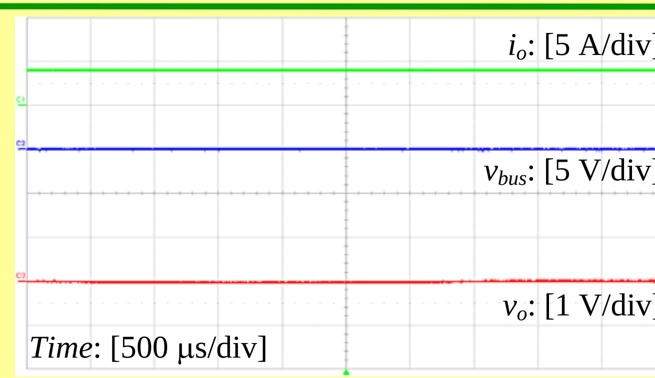
<tr><td>Half Load</td><td>
</td><td>
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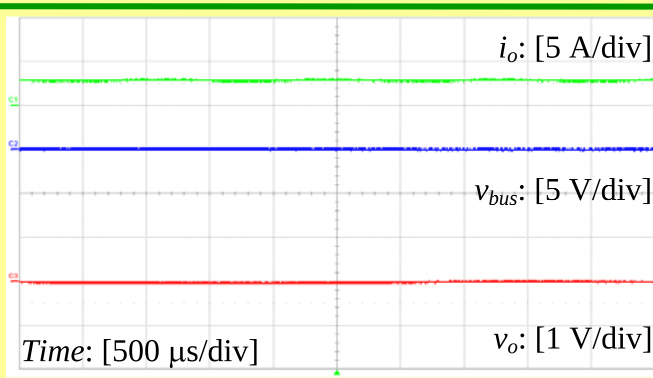
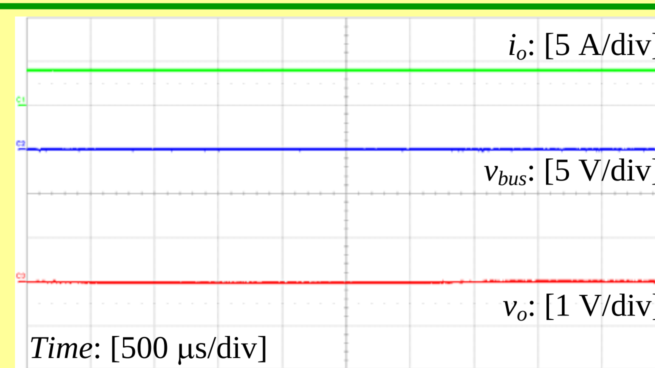
<tr><td>35% Full Load</td><td>
</td><td>
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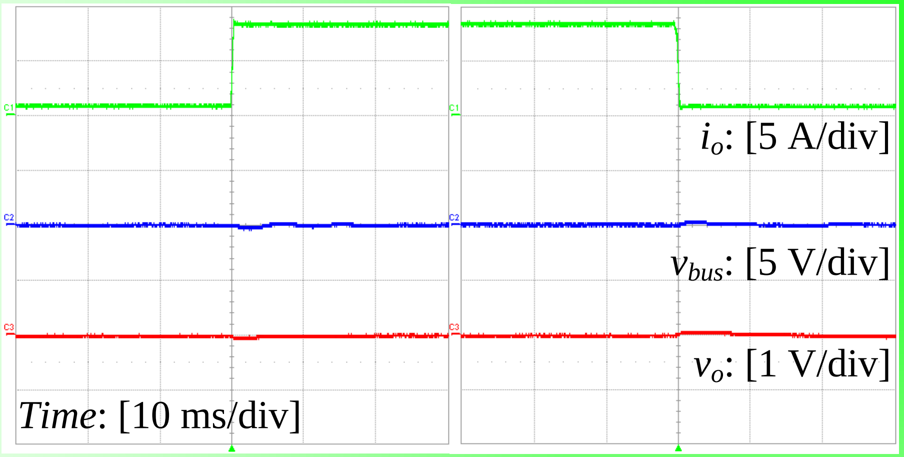
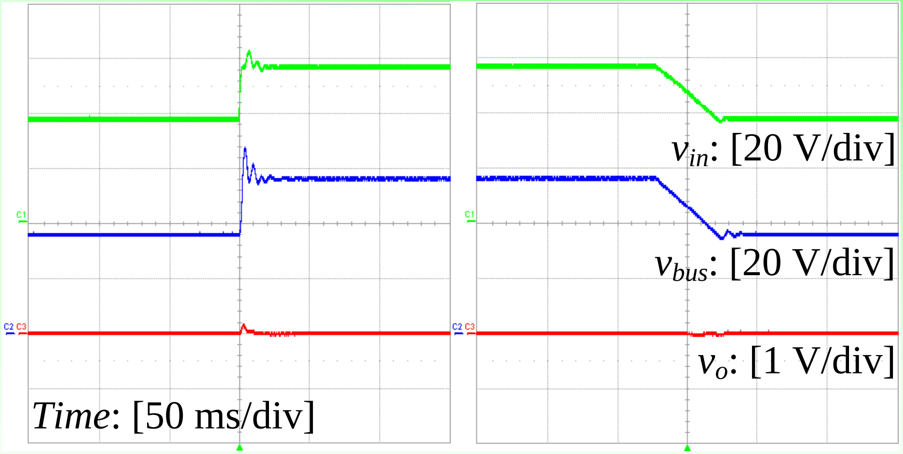
Dynamic Response with PVI



The load is stepped change



The input voltage is stepped changed

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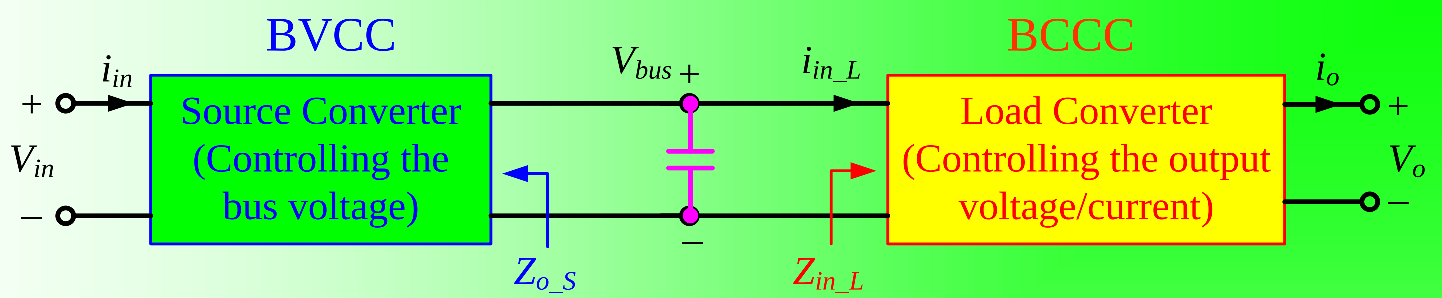
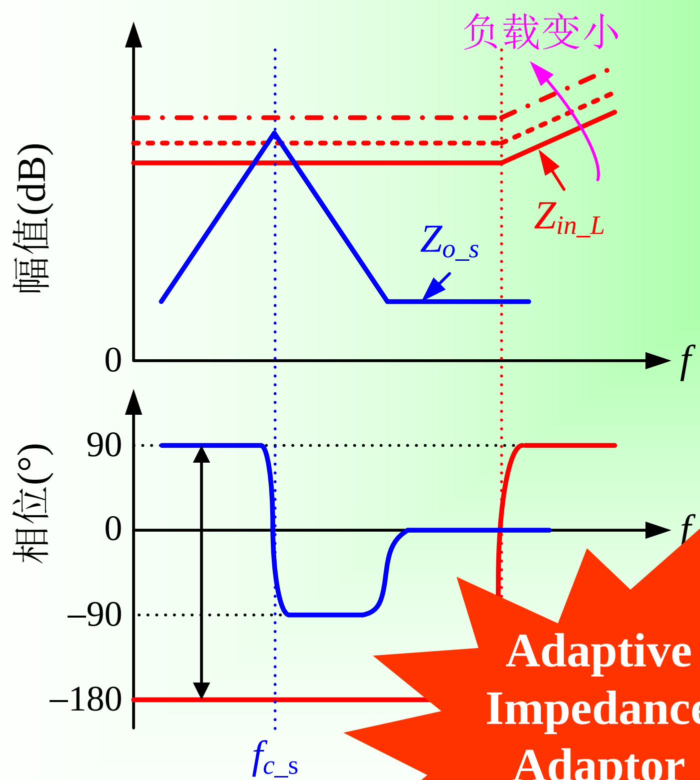
Adaptive Impedance Adaptor: Basic Concept





Adaptive Impedance Adaptor

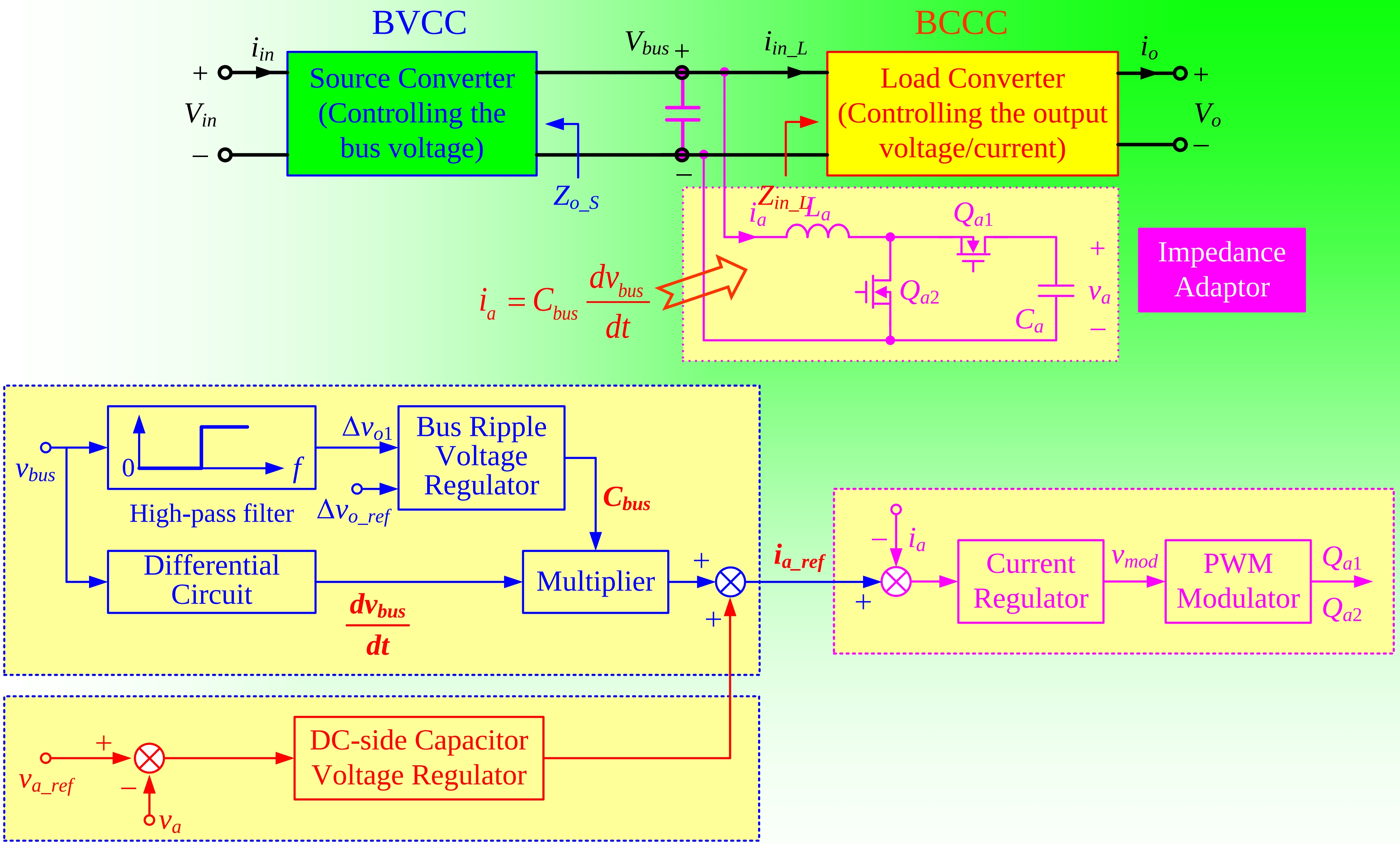
Reduce **the magnitude** of the BVCC's bus-side port impedance, and it is **adaptively vary with the load**, ensuring the cascaded system stable **critically**.

Add a capacitor in parallel with the dc bus

The capacitance adaptively vary with the load.

Propose an **active capacitor converter**, and **the emulated capacitor is required to vary with the load**.

Adaptive Impedance Adaptor: Circuits Implementation and Control Method



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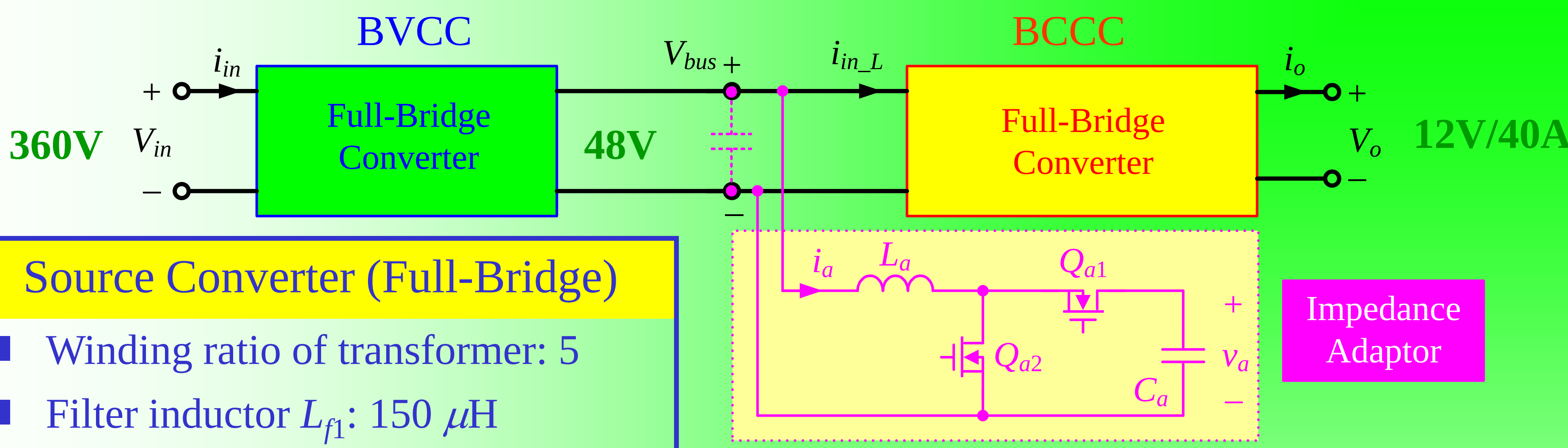
Adaptive Impedance Adaptor: Prototype



Source Converter (Full-Bridge)

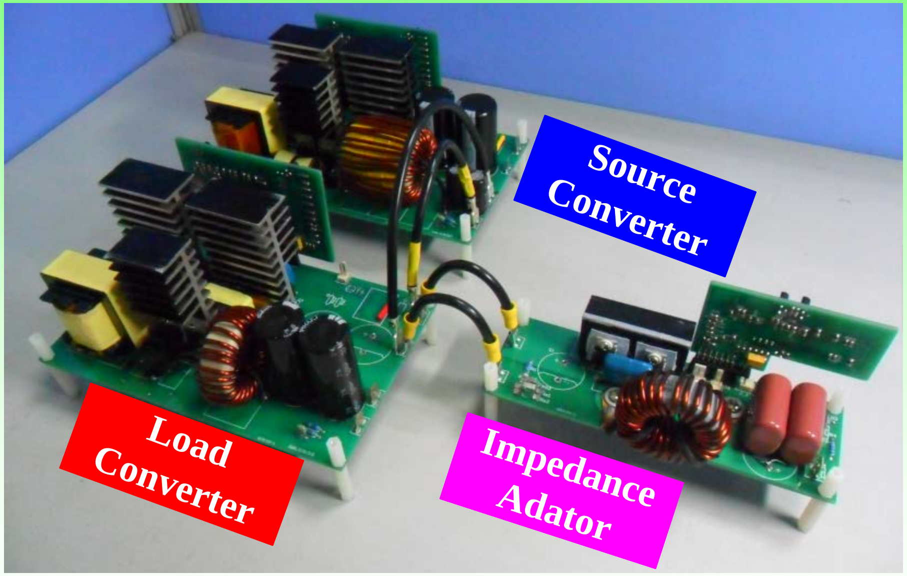
- Winding ratio of transformer: 5
- Filter inductor L_{f1}: 150 μH
- Filter capacitor C_{f1} : 680 μF

Load Converter (Full-Bridge)

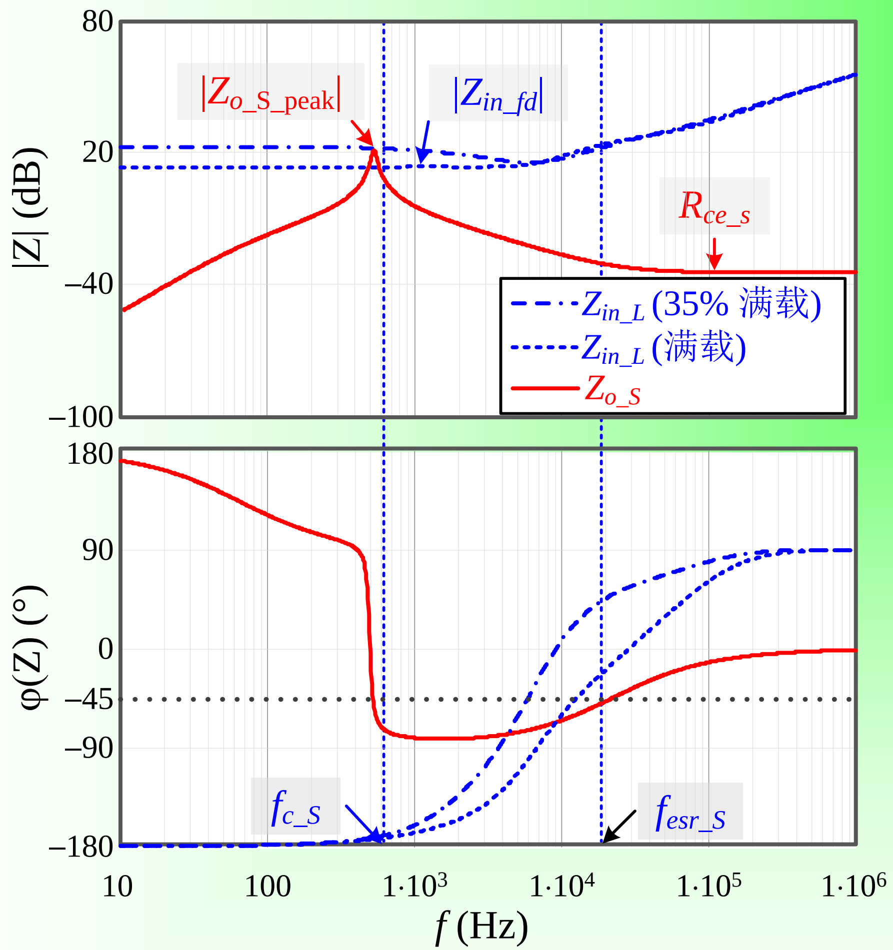
- Winding ratio of transformer: 3
- Filter inductor L_{f2}: 2.2 μH
- Filter capacitor C_{f2} : 4700 μF

Impedance Adaptor (Buck/Boost)

- Inductor L_a: 395 μH
- DC-side capacitor C_a: 20 μF



Output Impedance of Source Converter and Input Impedance of Load Converter



- At higher than 35% full-load, Z_{o_s} intersects with Z_{in_L}. This means that the cascaded system is **unstable**.
- At lower than 35% full-load, Z_{o_s} does not intersect with Z_{in_L}. This means that the cascaded system is **stable**.

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Adaptive Impedance Adaptor: Experimental Verificatio

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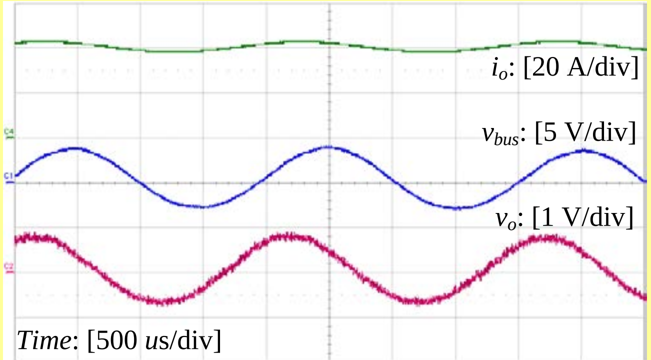
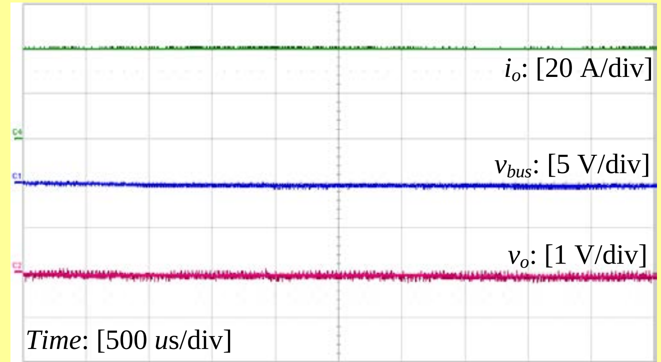
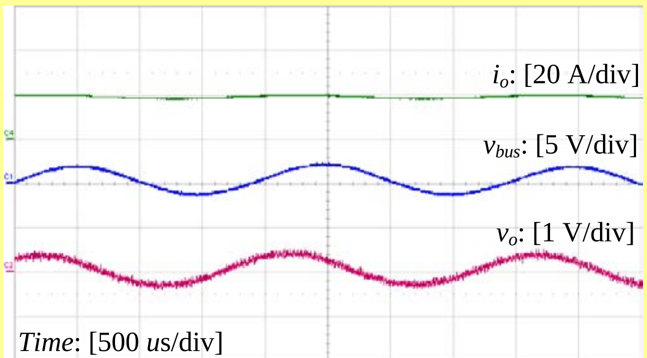
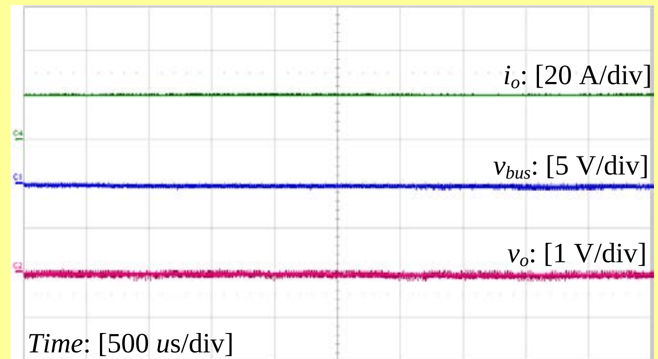
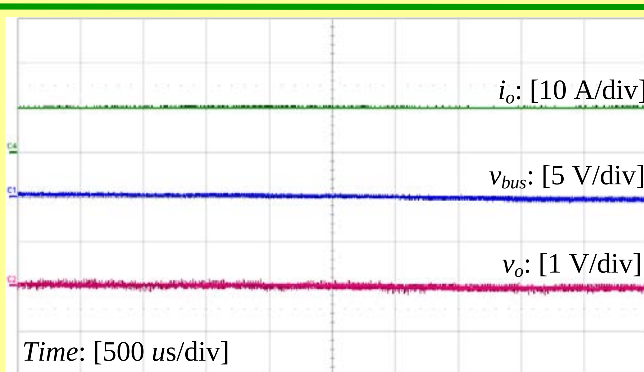
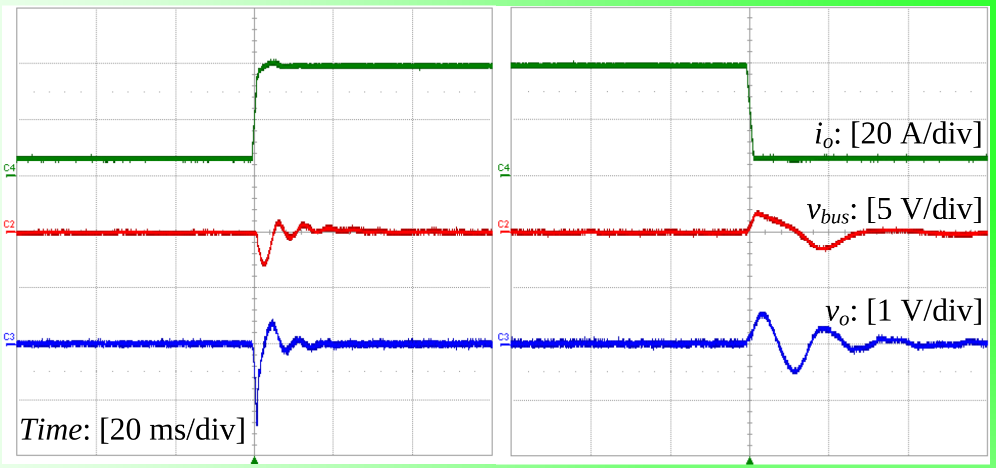
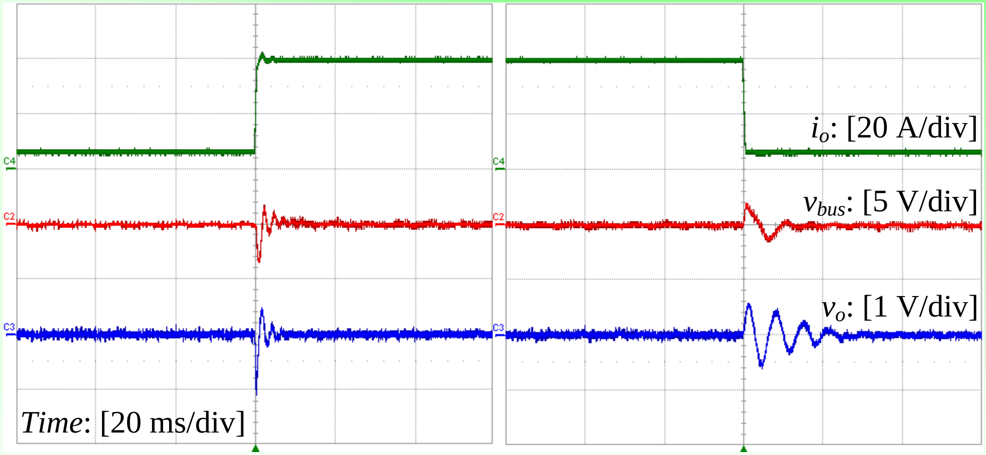
<tr><th></th><th>W/O Impedance Adaptor</th><th>With Impedance Adaptor</th></tr>
<tr><td>Full Load</td><td>
</td><td>
</td></tr>
<tr><td>Half Load</td><td>
</td><td>
</td></tr>
<tr><td>35% Full Load</td><td>
</td><td>The impedance adaptor is not required to operate, and it is shut down.</td></tr>
</table>

Adaptive Impedance Adaptor: Experimental Verification



With 1950μF Electrolytic capacitor



With the impedance adaptor

Fast dynamic response!

- Backgrounds
- General Impedance-Based Stability for Cascaded System
- Input Impedance Regulation for Load Converter
- Adaptive Impedance Adaptor
- **Conclusions**

Conclusions

- The concept of **bus voltage controlled converter (BVCC)** and **bus current controlled converter (BCCC)** is proposed, and any converter in the cascaded system can be classified as either a BVCC or a BCCC, thus a cascaded system can be represented in a general form regardless of its structure and operating mode.
- The **general impedance-based stability criterion** for cascaded system is proposed, and the equivalent loop gain is equal to the ratio of the shunt impedance of the **bus-side-port-impedances** of all the BVCCs and the **bus-side-port-impedances** of all the BCCCs.
- Regarding the load converter, which is a BCCC, **a method of regulating the input impedance based on virtual impedance** is proposed, which increases the **magnitude** or **phase** of the input impedance in the vicinity of the intersection frequency, thus ensuring the cascaded system stable.
- The **adaptive impedance adaptor** is proposed, which emulates a capacitor connected in parallel with the dc bus. This emulated capacitor **varies adaptively with the load**, and avoiding the impedance intersection over the full frequency range, ensuring the cascaded system stable. The adaptive impedance adaptor has the advantages of **fast dynamic response** compared with the passive capacitor and **modular design** without any information of the converters in the system.

Acknowledgement

This work is supported by the ***National Nature Science Foundation of China*** under Award 51277097.

Thank you very much for Your attention!