# DC Output Power

# Introduction

- IPT systems rely on ac coupling to transfer power
- Most practical applications require DC voltage and currents

- This section focuses on methods of converting the coupled ac power into practical dc power
- Many topologies to achieve this
  - **Full bridge rectifiers**
  - Half bridge rectifiers
  - Active rectifiers
  - Current doublers
  - Voltage doublers

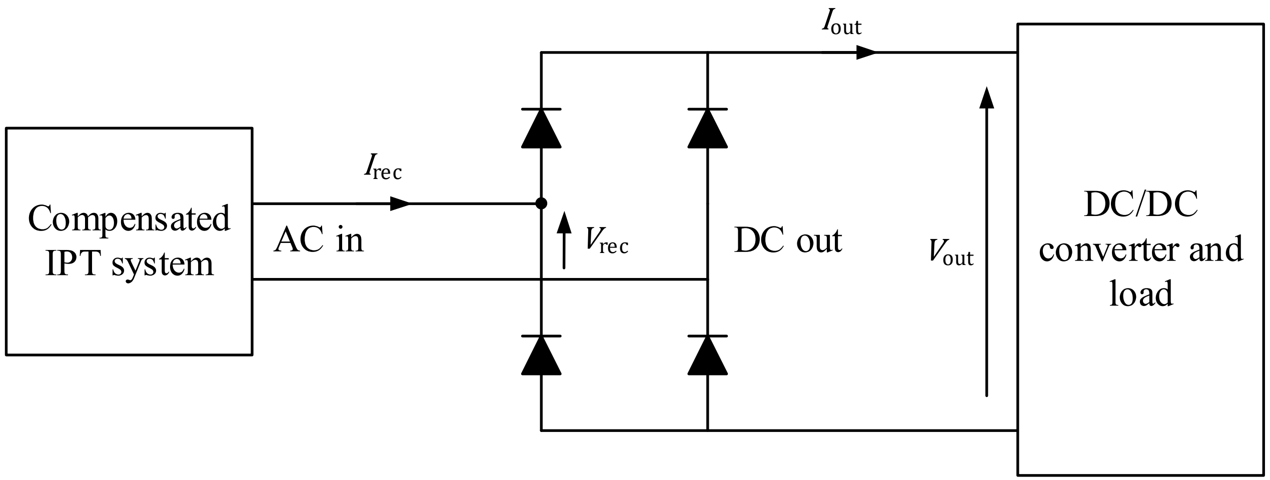
# Learning Objectives

- By the end of this section, students will:
  - Learn about passive rectifiers and practical constraints
  - Be able to calculate output power for various tuning topologies
  - Be introduced to active rectifiers

- How you will be assessed:
  - Assignment 1
  - Test
  - Practical build

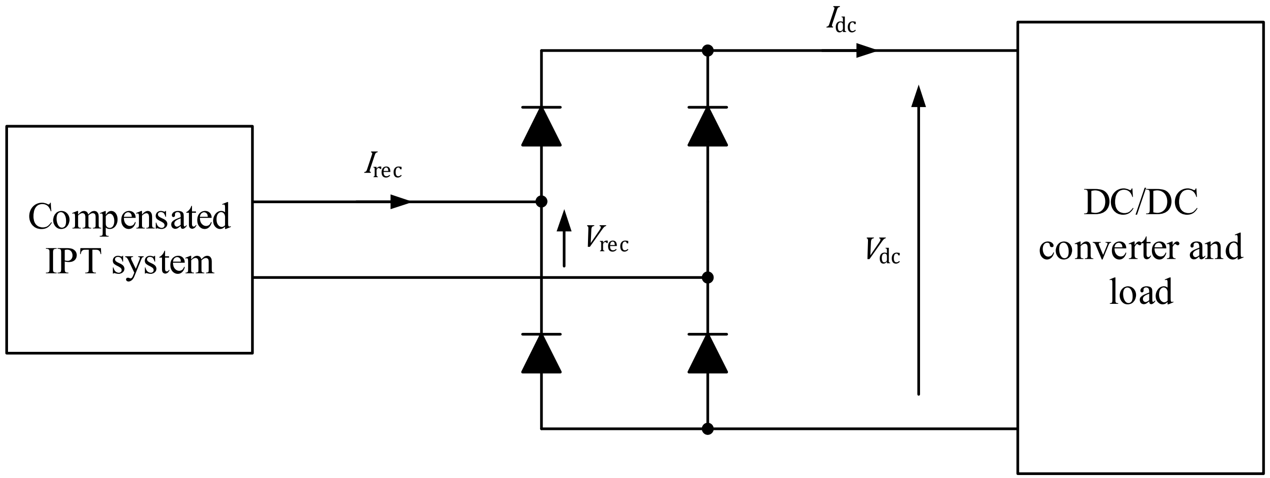
# The passive full bridge rectifier

- A passive full bridge rectifier consists of four diodes
- On the left hand side, there is the IPT system with an ac input
  - Could be voltage or current sourced depending on compensation topology
- On the right hand side, there is the DC/DC converter
  - Needs to be the correct topology depending on the AC input
  - How do we know which one to use?



# Voltages and currents through reactive components

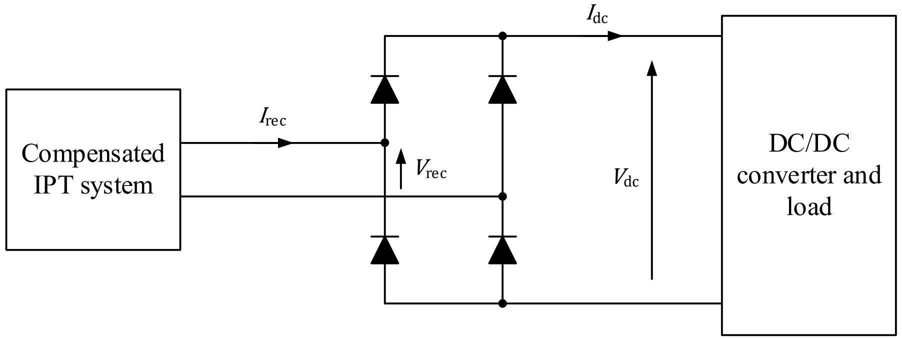
- Critical equations
  - Voltage across an inductor: $v_L = L\frac{di_L}{dt}$
    - Current cannot change instantaneously across and inductor, otherwise $v_L \to \infty$
  - Current through a capacitor: $i_C = C\frac{dv_C}{dt}$
    - Voltage cannot change instantaneously through a capacitor, otherwise $i_c \to \infty$
- In the past, you will have used full bridge rectifiers where the source ($V_{rec}$) is connected directly to the input
  - In IPT systems, $V_{oc}$ is tuned to an operating point through at least an inductor and a capacitor

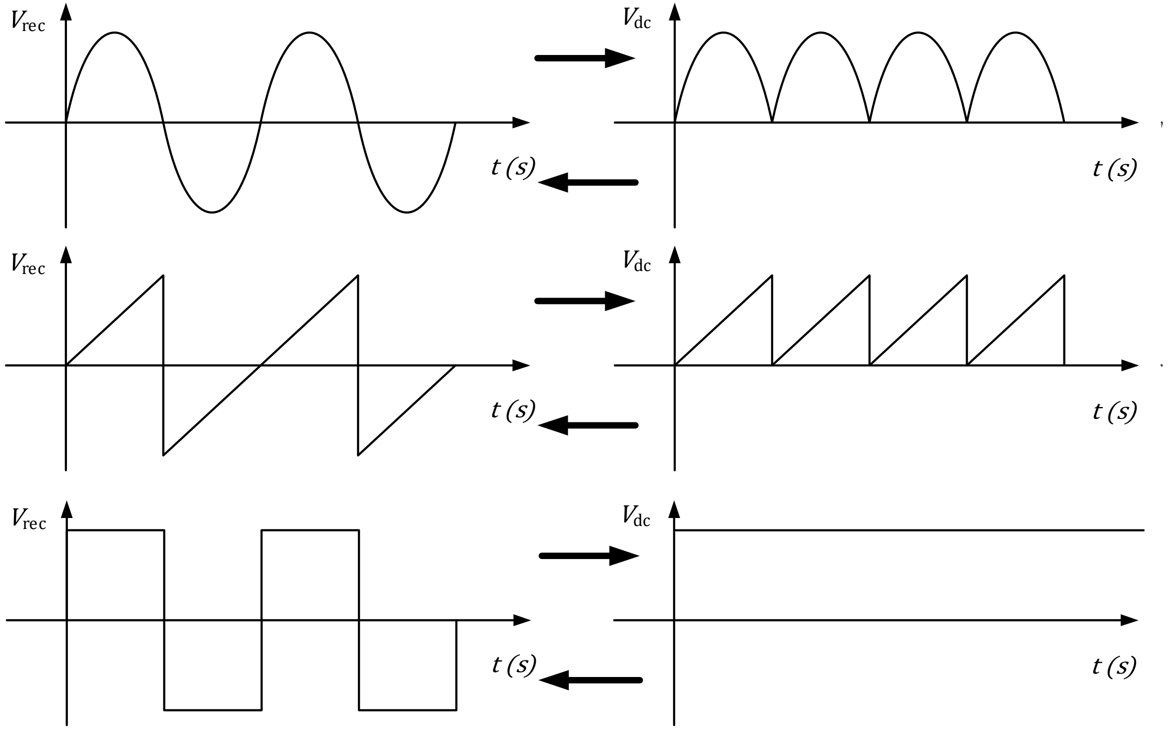


# The passive full bridge rectifier

- How does a rectifier work?
- Input and output waveforms are linked
    - If the input is sinusoidal, the output is a half-rectified wave
        - If the output is a half-rectified wave, **the input must be sinusoidal**
    - **If the output is dc, the input waveform must be a square wave**

- In an IPT system, the type of DC/DC converter sets the waveform at the input of the rectifier



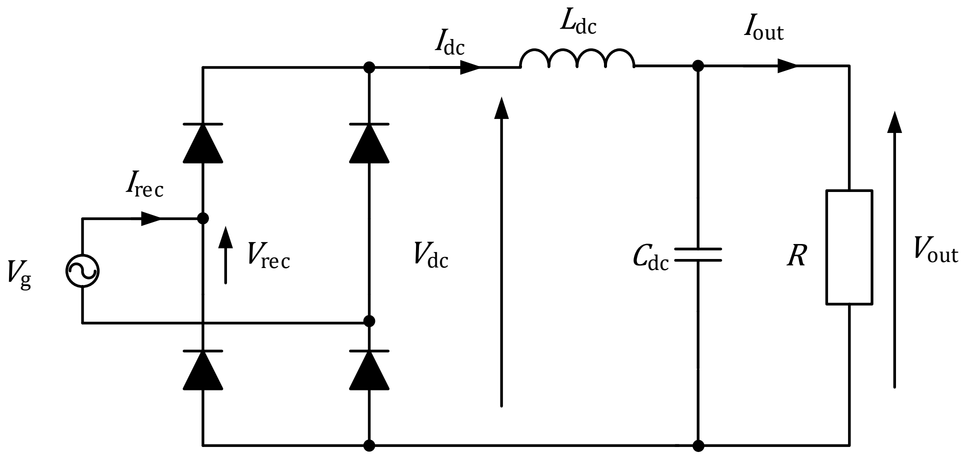
# The passive full bridge rectifier – Continuous conduction

- Rectifiers operate in one of two conditions, continuous conduction and discontinuous conduction.
  - Depends on the design of the input and the output stage

- Take this standard grid tied rectifier with an LC filter on the output

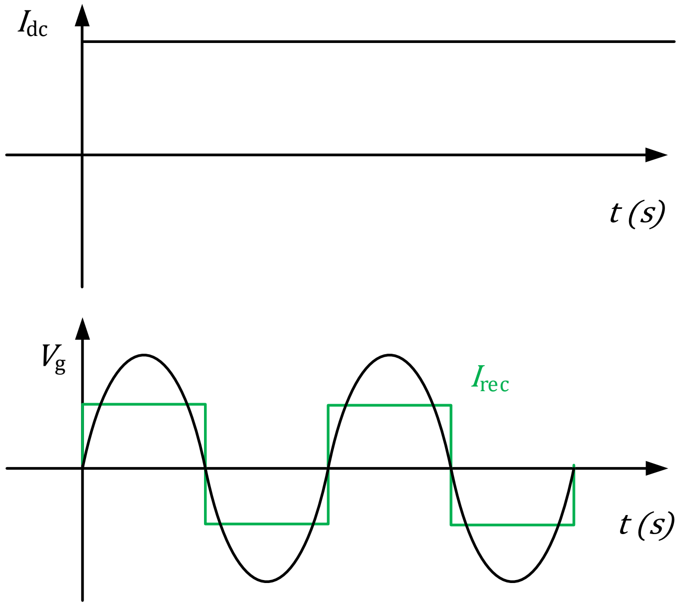
- If L is very large, then $I_{dc}$ must be a constant dc amplitude
  - Using KCL, two of the diodes must always be conducting at any given time

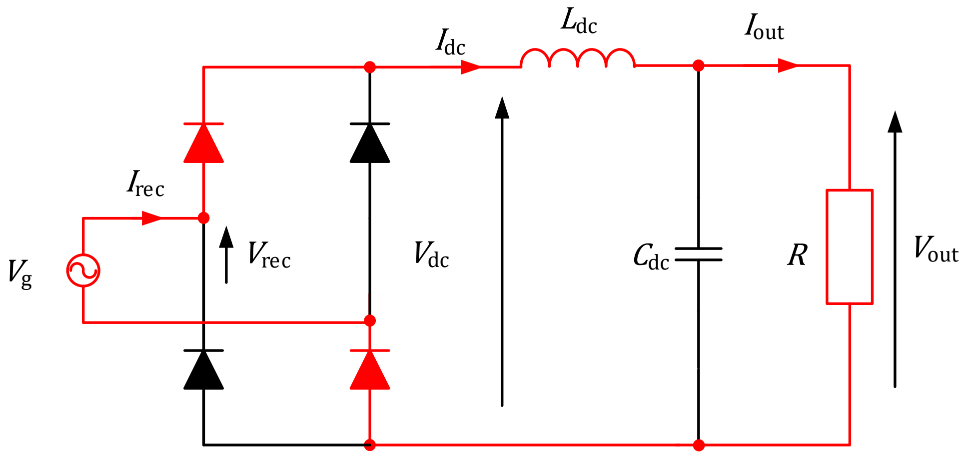
- Relationship between input and output power is linear

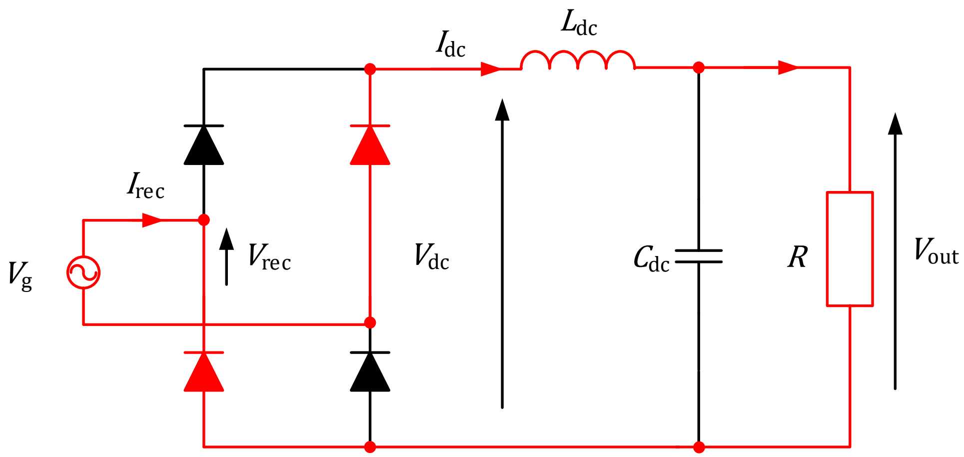


# The passive full bridge rectifier – Continuous conduction

- Under continuous conduction mode:
  - Input current ($I_{rec}$) is a square wave
  - $I_{rec}$ is in phase with the rectifier voltage ($V_{rec}$)



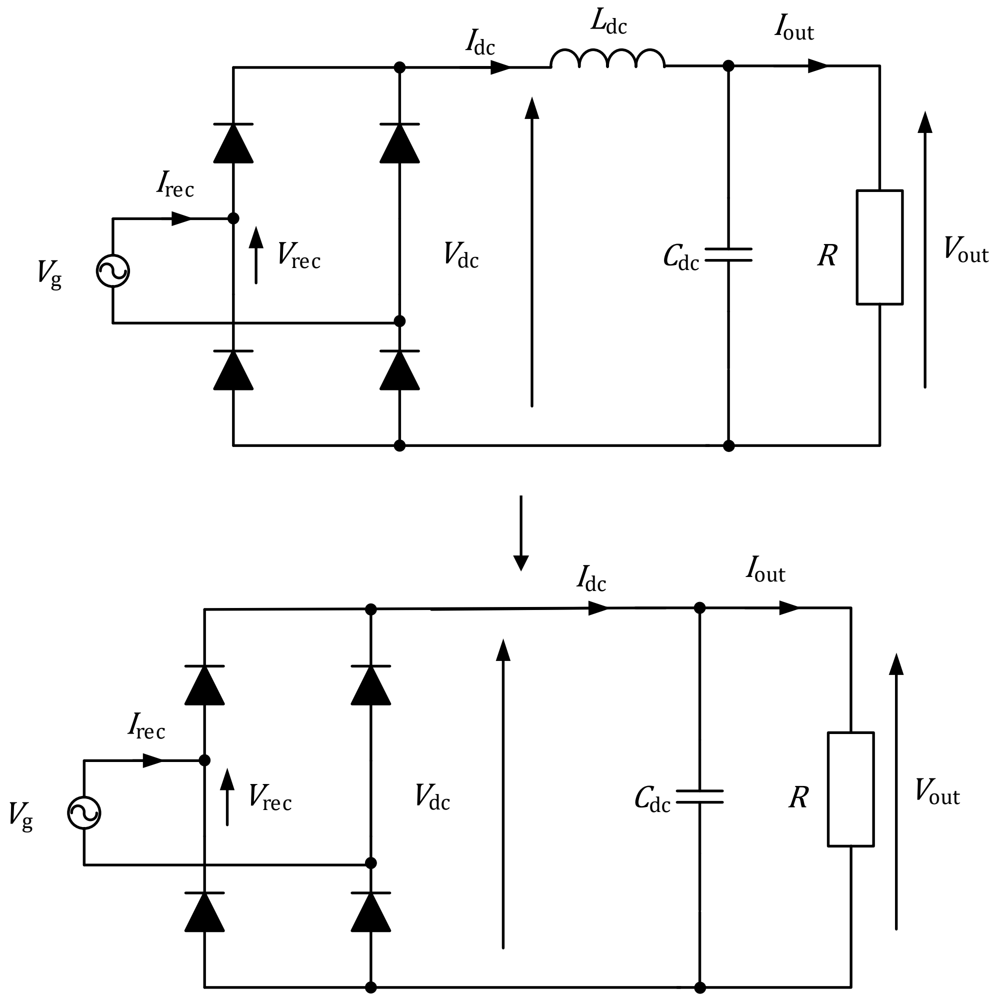



# The passive full bridge rectifier – Discontinuous conduction

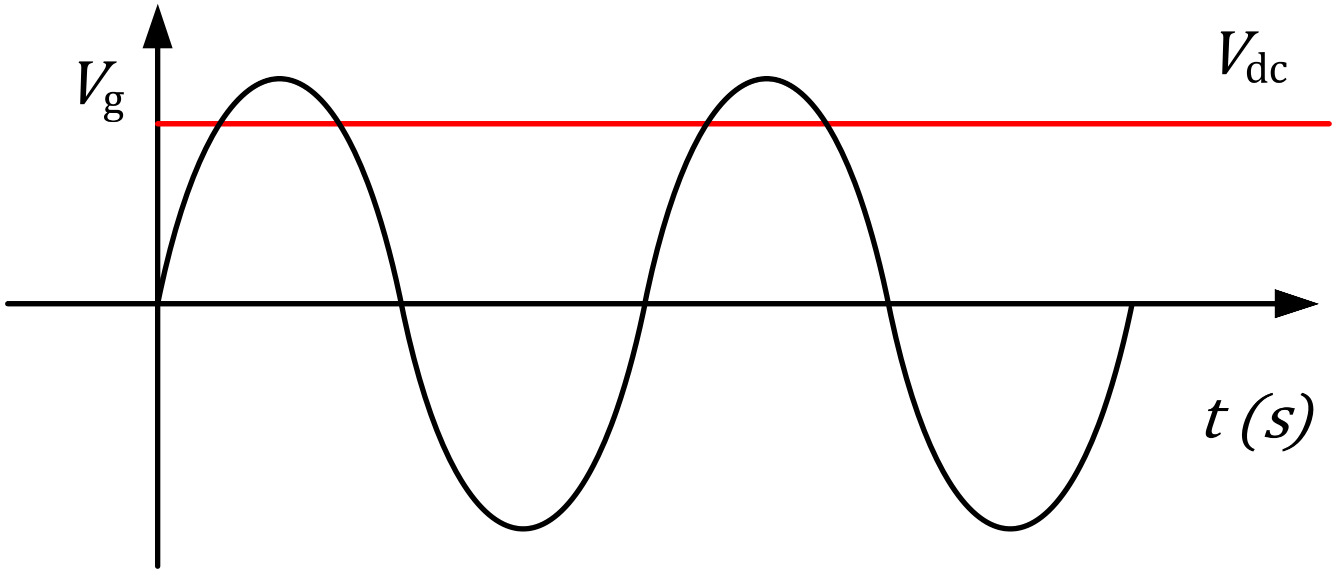
- As $L_{dc}$ decreases in size, it will slowly become a short circuit
  - The current $I_{dc}$ will not be a constant dc value
  - The effect of the output capacitor $C_{dc}$ begins to dominate
    - The voltage $V_{dc}$ becomes a constant dc value

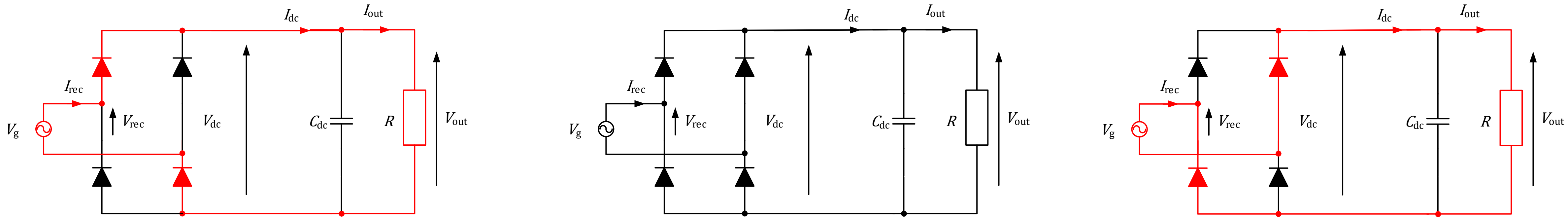
- Due to properties of a diode, rectifier cannot conduct until the forward voltage threshold is met.

- Relationship between ac input and dc output is no longer linear
  - Not always a bad thing, but hard to analyse



# The passive full bridge rectifier – Discontinuous conduction



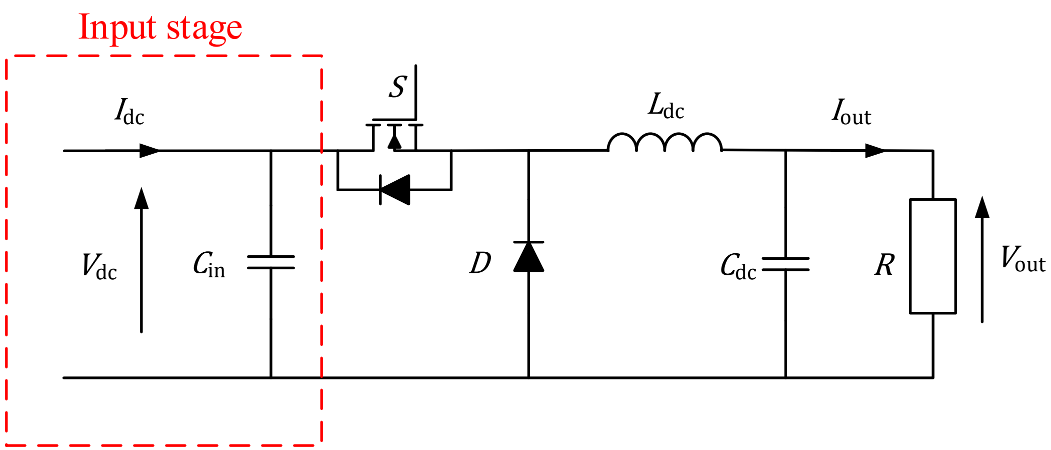
# The passive full bridge rectifier – summary

- Full bridge rectifiers are commonly used to convert ac to dc
- Two modes of operation
  - Continuous conduction
  - Discontinuous conduction
- Examples given with a fixed voltage source input

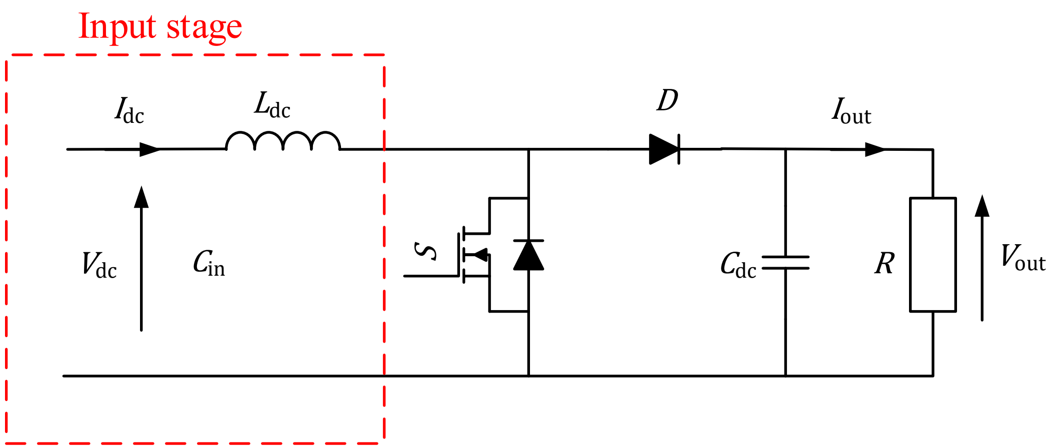
- IPT systems have some slight differences
  - Input is no longer a fixed voltage source
  - $V_{oc}$ is ‘buffered’ through a resonant network
- Impact on the dc side is more important to consider

# DC/DC converters – brief introduction

- Two types of DC/DC converters taught in this course
  - Buck Converter
  - Boost Converter
- In this section, the focus will be on the input stage of the buck or the boost



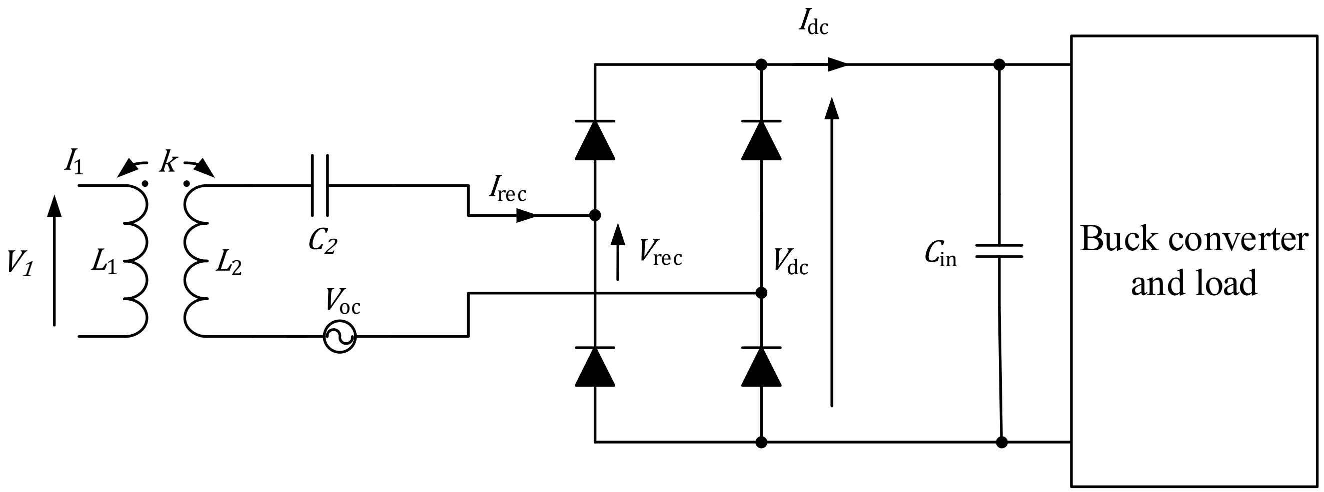

Buck Converter




Boost Converter

# The series compensated system - Assumptions

- A buck converter is used for a series compensated system with a constant current sourced primary
  - Constant voltage source IPT system
- Certain assumptions are made:
  - $C_{in}$ is sufficiently large to ensure that $V_{in}$ is a dc waveform
  - The system is operated in a state where the full bridge rectifier is always in conduction
  - There is no voltage drop across the diodes in the full bridge rectifier
  - The DC/DC converter is 100% efficient so $P_{out} = V_{dc}I_{dc}$
  - The full bridge rectifier is 100% efficient so $V_{rec}I_{rec} = V_{dc}I_{dc}$
  - The magnetic and compensation system is 100% efficiency so $V_{oc}I_{rec} = V_{dc}I_{dc}$

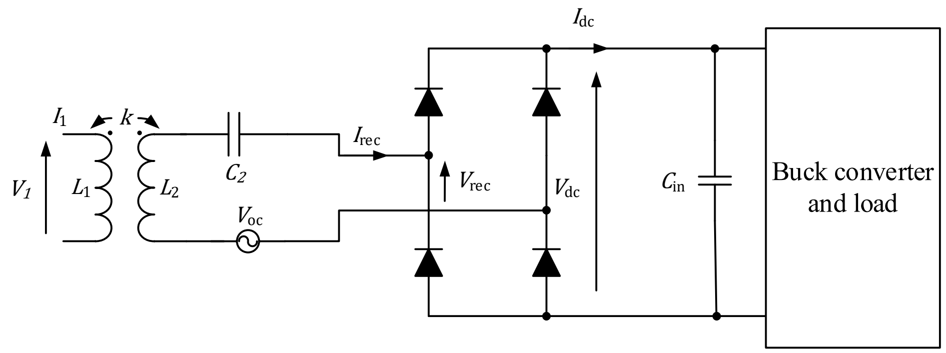


# The series compensated system - $V_{dc}$

- Due to $C_{in}$, $V_{in}$ **must** be a dc voltage
  - $V_{rec}$ must be a square wave with amplitude $\pm V_{in}$
  - Therefore, $V_{rec}$ can be described by the fourier series:

$$V_{rec} = \frac{4}{\pi} V_{dc} \sum_{n=1,3\ \ldots}^{\infty} \frac{1}{n} \sin(n\omega t)$$

  - Since the rectifier is assumed to have 100% efficiency:
    - RMS value of $V_{rec}$ is equal to the RMS value of $V_{dc}$




- Since the LC network is tuned to $\omega$, the fundamental component of $V_{rec}$ is equal to $V_{oc}$

$$V_{oc} = V_{rec,n=1} = \frac{4V_{dc}}{\pi\sqrt{2}} = \frac{2\sqrt{2}V_{dc}}{\pi} \approx 0.9\ V_{dc}$$

$$V_{dc} = \frac{\pi}{2\sqrt{2}} V_{oc} \approx 1.1\ V_{oc}$$

- The maximum dc output voltage from a series compensated secondary with a constant current sourced primary is $\frac{2\sqrt{2}}{\pi} * V_{oc}$

# The series compensated system - $I_{dc}$

- We have assumed a 100% efficient rectifier and buck converter so:

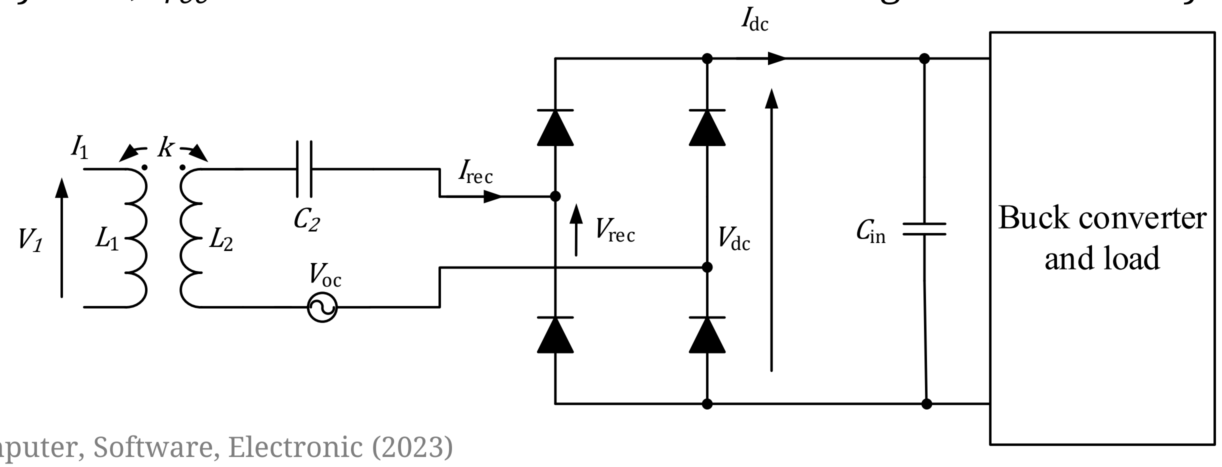
$$V_{oc}I_{rec} = V_{rec}I_{rec} = V_{dc}I_{dc}$$

$$\frac{2\sqrt{2}V_{dc}}{\pi}I_{rec} = V_{dc}I_{dc}$$

$$I_{rec} = \frac{\pi}{2\sqrt{2}}I_{dc}$$

$$I_{dc} = \frac{2\sqrt{2}}{\pi}I_{rec}$$

- For the series compensated system, $I_{rec}$ is also the current that flows through the secondary coil



# The series compensated system – with a boost converter

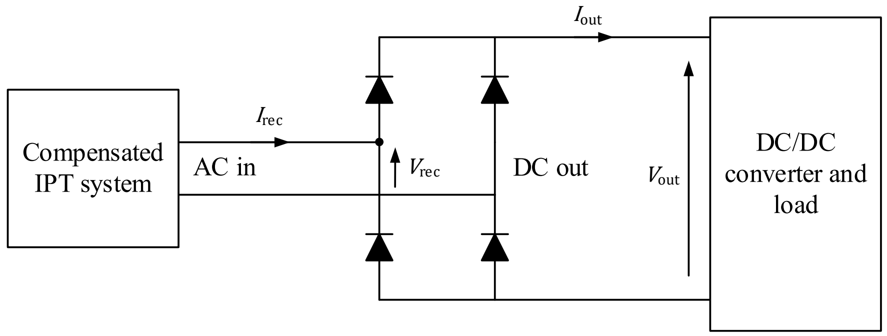
- What happens if we put a boost converter here?
- The boost converter has a dc inductor on the input stage
- This dc inductor forces the current to be a dc waveform
- Due to how the rectifier works, this forces $I_{rec}$ to be a square wave
- If $I_{rec}$ is square:

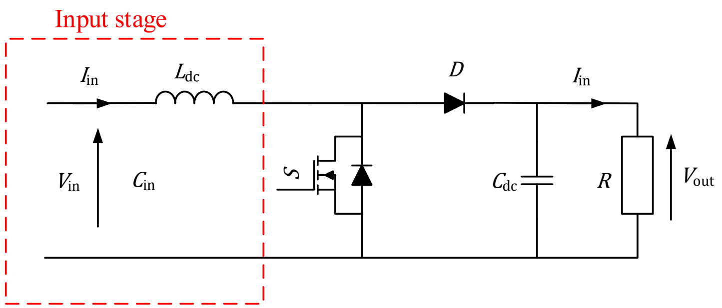
$$v_L = L\frac{di_L}{dt}$$

Where $v_L$ is the voltage across the secondary coil inductor

$i_L = I_{rec}$, and $dt$ is the change in time

- Square waves will have a very small $dt$ on the switching edges
    - High induced voltages across the pick-up coil




Boost Converter

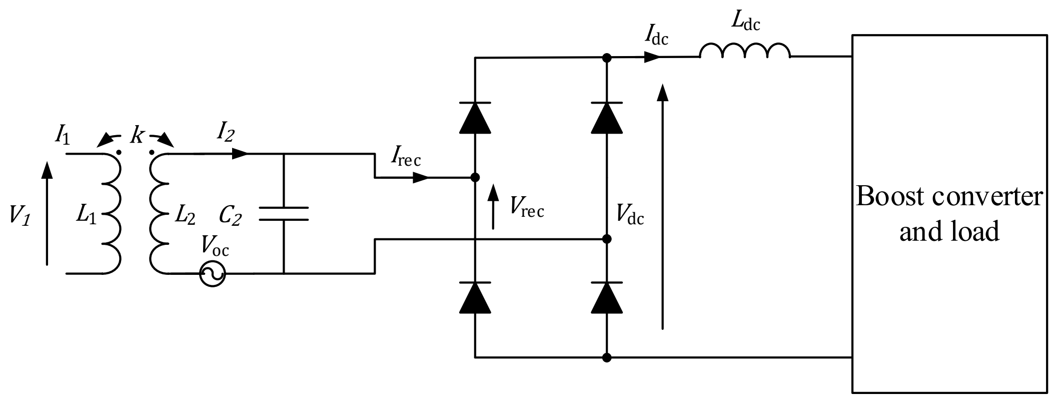
# The series compensated system – summary

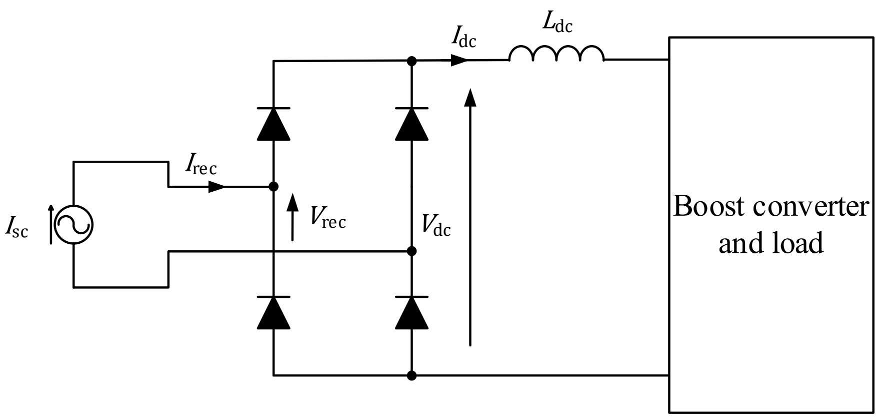
- The series compensated secondary is a voltage source
- A DC/DC converter with a capacitive input must be used (doesn't have to be a buck) for the series compensated secondary
  - An inductor-based input will cause large $di/dt$ across the pick-up inductor
- A full bridge rectifier for a series compensated secondary boosts the dc voltage ($V_{dc}$) by approximately 1.1 times
- A full bridge rectifier for a series compensated secondary decreases the dc current ($I_{dc}$) by approximately 1.1 times

- More detail will be taught later on in this course

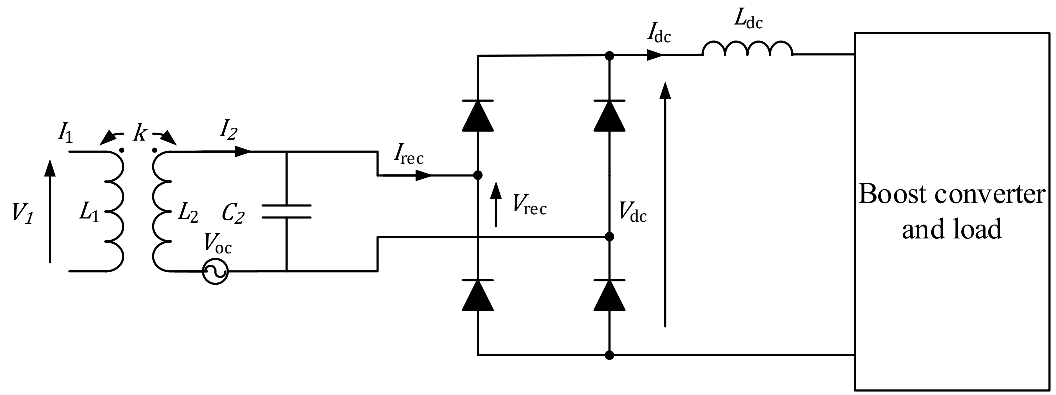
# The parallel compensated system

- A boost converter is used for a parallel compensated system with a constant current sourced primary
- Certain assumptions are made:
  - The parallel tuned system is perfectly compensated
  - $L_{dc}$ is sufficiently large to ensure that $I_{dc}$ is a dc waveform
  - The system is operated in a state where the full bridge rectifier is always in conduction
  - There is no voltage drop across the diodes in the full bridge rectifier
  - The DC/DC converter is 100% efficient so $P_{out} = V_{dc}I_{dc}$
  - The full bridge rectifier is 100% efficient so $V_{rec}I_{rec} = V_{dc}I_{dc}$
  - The magnetic and compensation system is 100% efficiency so $V_{rec}I_{sc} = V_{rec}I_{rec}$



# The parallel compensated system - $I_{dc}$




- Due to $L_{dc}$, $I_{dc}$ **must** be a dc current
  - $I_{rec}$ must be a square wave with amplitude $\pm I_{dc}$
  - Therefore, $V_{rec}$ can be described by the fourier series:

$$I_{rec} = \frac{4}{\pi} I_{dc} \sum_{n=1,3\,\ldots}^{\infty} \frac{1}{n} \sin(n\omega t)$$

  - Since the rectifier is assumed to have 100% efficiency:
    - RMS value of $V_{rec}$ is equal to the RMS value of $V_{dc}$

- Since the LC network is tuned to $\omega$, the fundamental component of $I_{rec}$ is equal to $I_{sc}$

$$I_{sc} = I_{rec,n=1} = \frac{4 I_{dc}}{\pi\sqrt{2}} = \frac{2\sqrt{2} I_{dc}}{\pi} \approx 0.9\ I_{dc}$$

$$I_{dc} = \frac{\pi}{2\sqrt{2}} I_{sc} \approx 1.1\ I_{sc}$$

- The maximum dc output current from a parallel compensated secondary with a constant current sourced primary is $\frac{2\sqrt{2}}{\pi} * I_{sc}$

# The parallel compensated system – with a buck converter

- What happens if we design a parallel tuned system with a buck converter?
- The output capacitor holds $V_{dc}$ constant
- $V_{rec}$ must be a square wave
  - Voltage across the tuning capacitor must be square
  - $i_c = C\frac{dv_c}{dt}$
  - Large currents may be induced in the parallel capacitor

# Practical considerations

- In practice:
  - System efficiencies will degrade the performance of the system, therefore the ratios between $V_{rec}$ and $V_{dc}$, as well as $I_{rec}$ and $I_{dc}$ will be different
- Additional losses in the $R_{esr}$ of the inductors and capacitors
- Forward voltage drops ($V_f$) across diodes will also cause additional losses
- Diodes may not always be conducting
  - Operating in discontinuous mode will affect the efficiency of the rectifier

# Active rectifiers

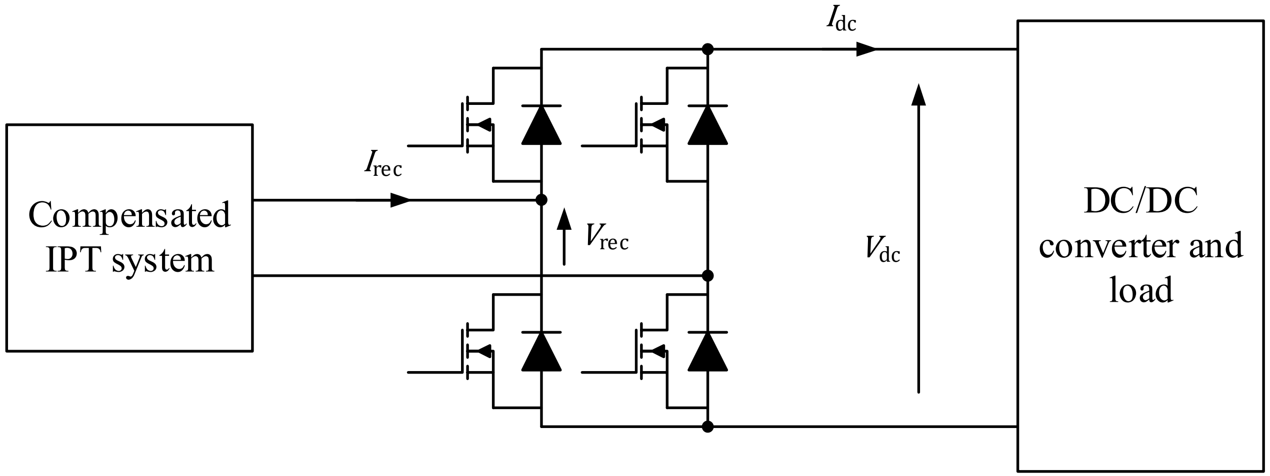
- One source of loss in any rectifier is caused by the forward voltage drop of the diodes

$$P_{loss,vf} = V_f I_f \text{ per diode}$$

- Active rectifiers replace the diodes with actively switching MOSFETs
  - MOSFET on resistance loss is much lower than forward voltage drop loss

$$P_{loss,on} = I_f^2 R_{ds,on} \text{ per diode}$$

- Need to control the switches so they turn on at the right time
- Can be achieved using a simple Schmitt trigger circuit or more complex digital controller applications



# AC/DC converters summary

- AC/DC converters are critical for all IPT applications
  - To transform the coupled ac energy into a useful dc form (battery charging, dc motor driving)
- Passive full bridge rectifiers are the most common method
  - Cheapest (only need four diodes)
  - Simplest (no control needed)
- Can go discontinuous
- Not the best efficiency (dependent on $V_f$ drops)
  - Can be improved by using active rectifiers
- Certain secondary compensation topologies can only be used with certain types of DC/DC converters
  - Limited by the input stage of the required DC/DC converter and the compensation topology
  - Series compensated secondaries need a capacitor after the full bridge rectifier
  - Parallel compensated secondaries need an inductor after the full bridge rectifier