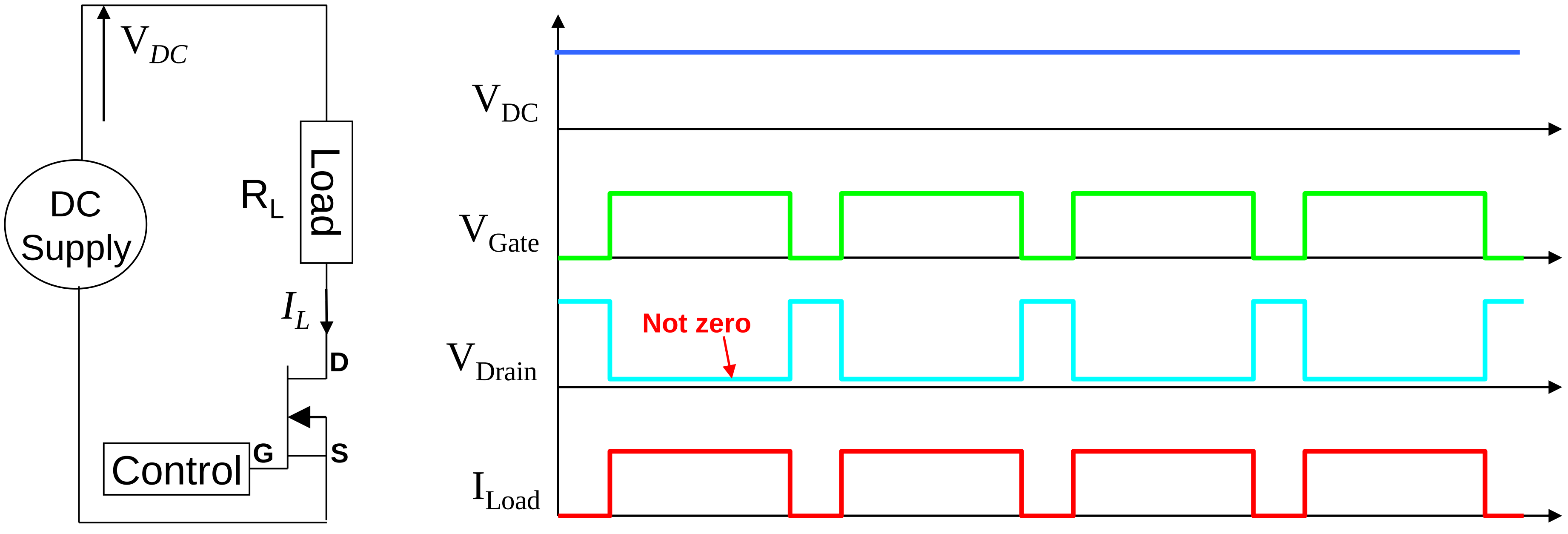
Power Electronics
电力电子

PWM & Lab 1 Tutorial

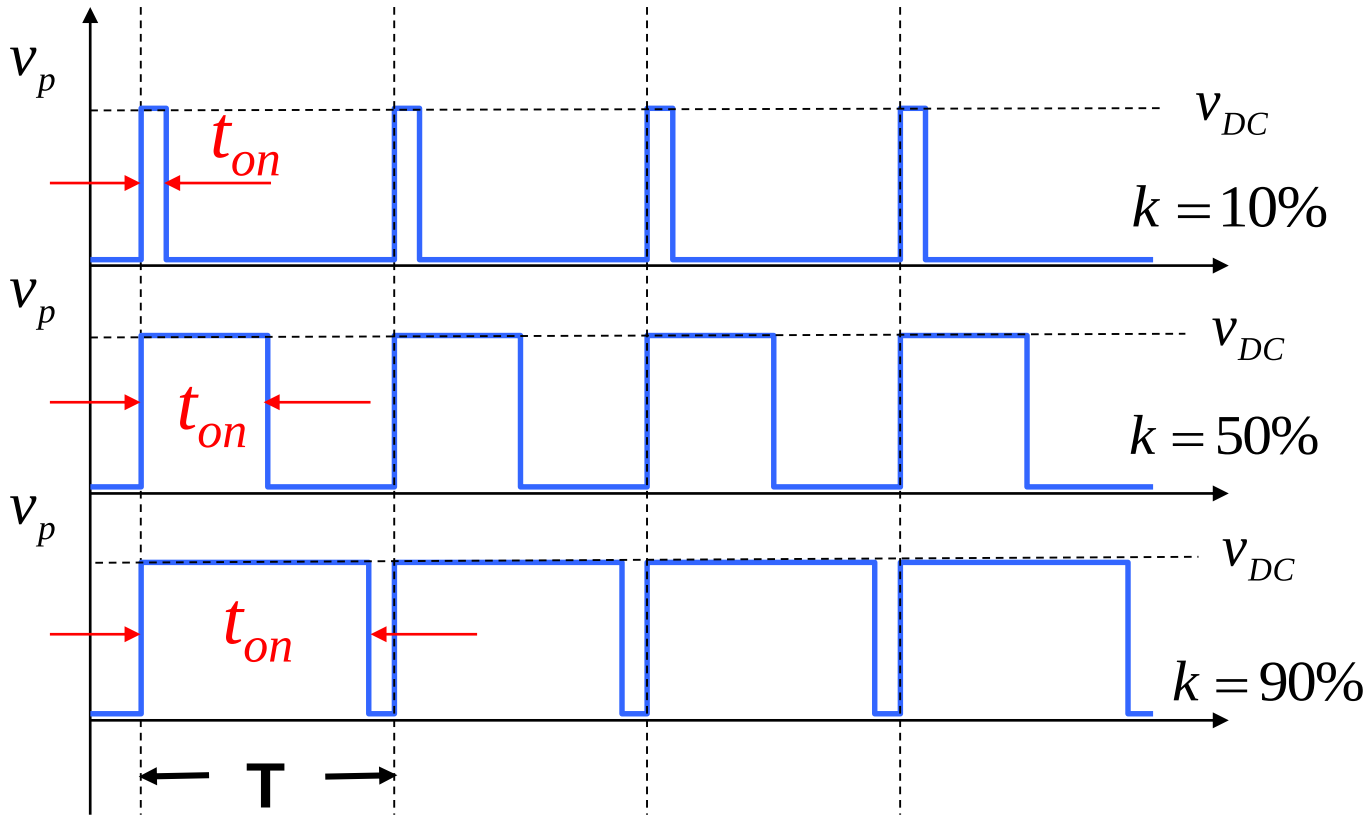
PWM Switching



Pulse Width Modulation (PWM). By changing the width (or duty cycle) of the gate pulse in relation to the operating frequency we can linearly change the average voltage value on the load.

PWM is actually developed for fully-controlled switches e.g. MOSFET, IGBT,…

Periodic PWM Waveforms



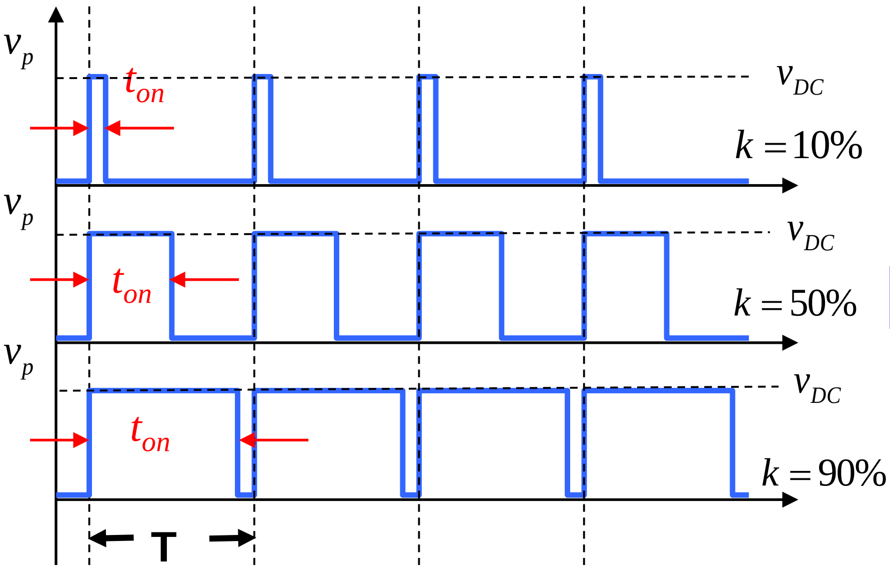
Duty Cycle: $k = \dfrac{\text{On time}}{\text{Period}} = \dfrac{t_{on}}{T}$

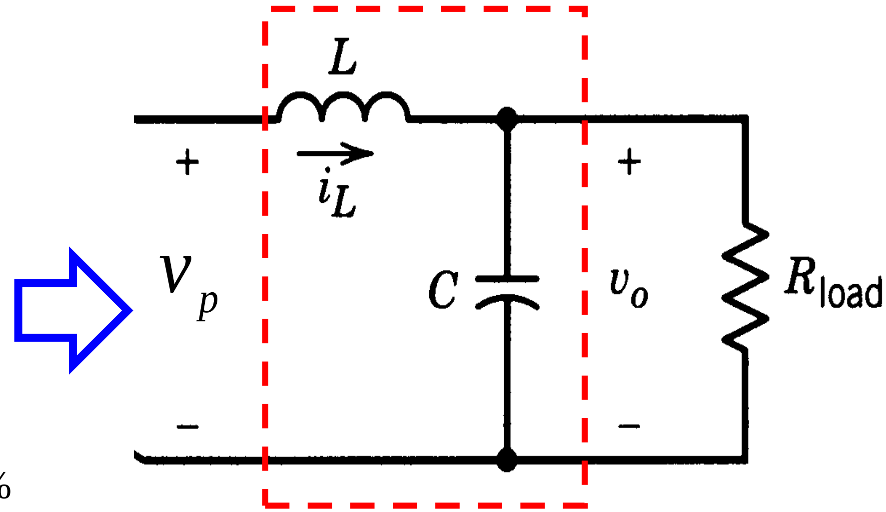
Average Load Voltage

$$v_{p(avg)} = k v_{DC}$$

High frequency (e.g. > 20kHz) voltage pulse train is ok for heating or even lighting, but is unacceptable for constant DC power supplies.

Smoothed PWM Output

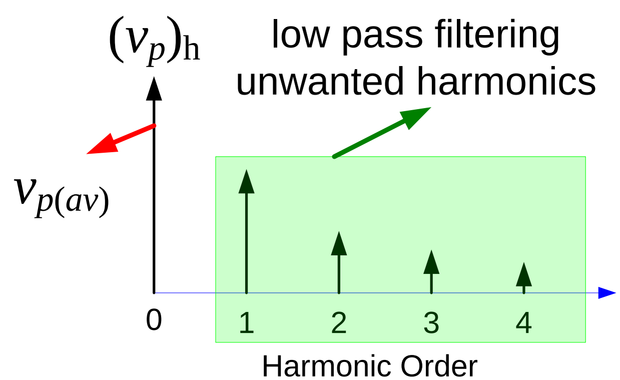




low-pass filter

Low pass LC filter smoothed the pulse voltage v_p into a constant dc voltage v_o

$$\boxed{v_o \approx v_{p(avg)} = k v_{dc}}$$



The higher the switching frequency is, the smaller the size and weight of low pass filter LC can be, and more smoothed the output dc voltage v_o is.

Fourier Series

Fourier Series: Any periodic signal $f(x)$ can be decomposed into the sum of a (possibly infinite) set of harmonics (*i.e.* sines and cosines) plus its dc mean value.

$$f(x) = \underbrace{\tfrac{1}{2} a_0}_{\text{Mean value}} + \underbrace{\sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx)}_{\text{Harmonics}},$$

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)\, dx$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(nx)\, dx$$

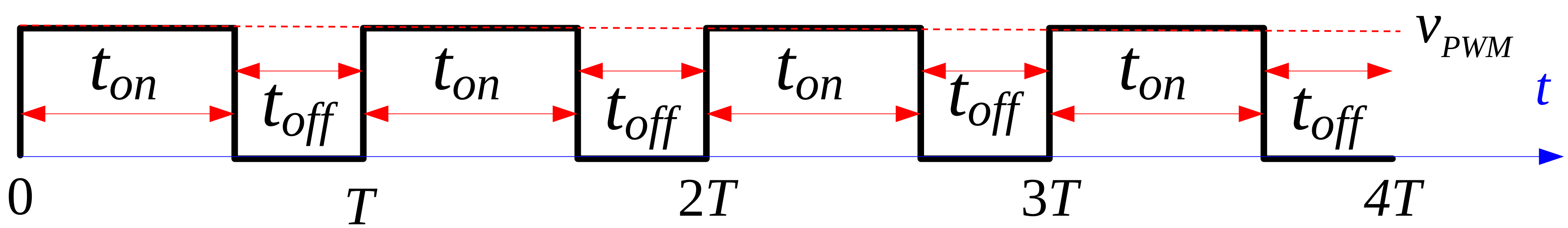
$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin(nx)\, dx$$

A low pass filter can easily remove harmonics. Thus the output voltage can be conveniently regulated by tuning duty cycle k. It is simple and easy-implementation.

Switching Strategies

How to generate duty-cycle-controllable rectangular pulse train for switching ON/OFF?

1. Constant switching frequency with variable ON time and OFF time (i.e. *variable duty ratio*)



$$\text{switching period}: \quad T = t_{on} + t_{off}$$

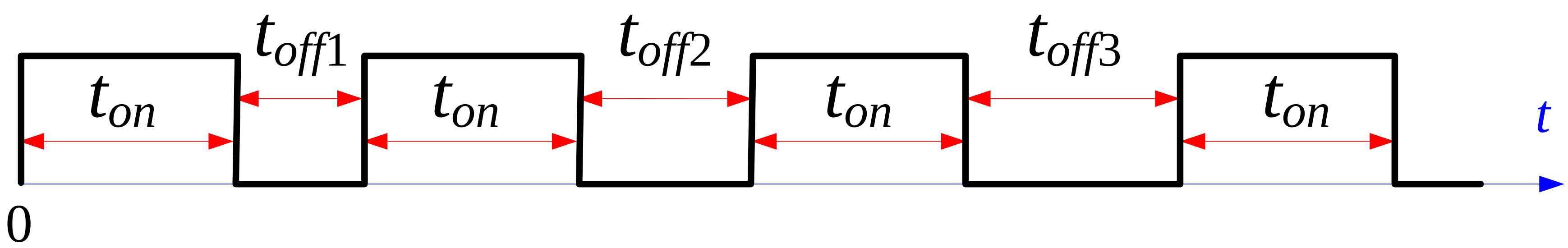
$$\text{duty ratio}: \quad k = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}$$

It is called Pulse-Width-Modulation (**PWM**). PWM signal has constant amplitude v_{PWM}.

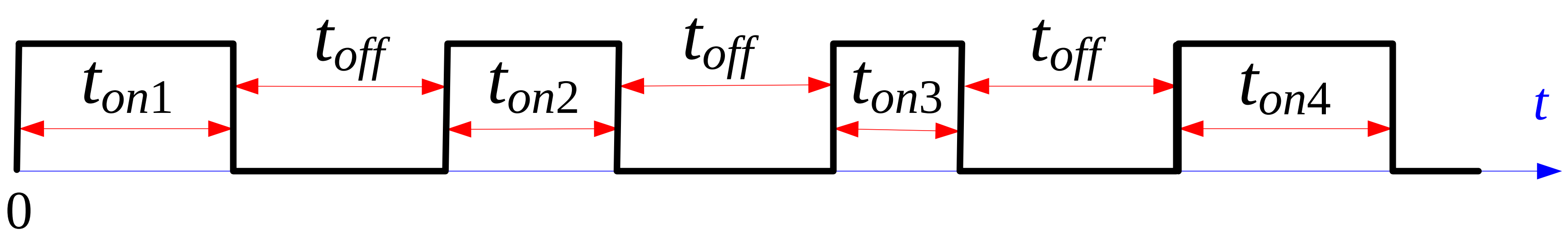
Variable Frequency Switching

2. Non-constant switching frequency, but either ON time or OFF time is held constant

Constant ON time

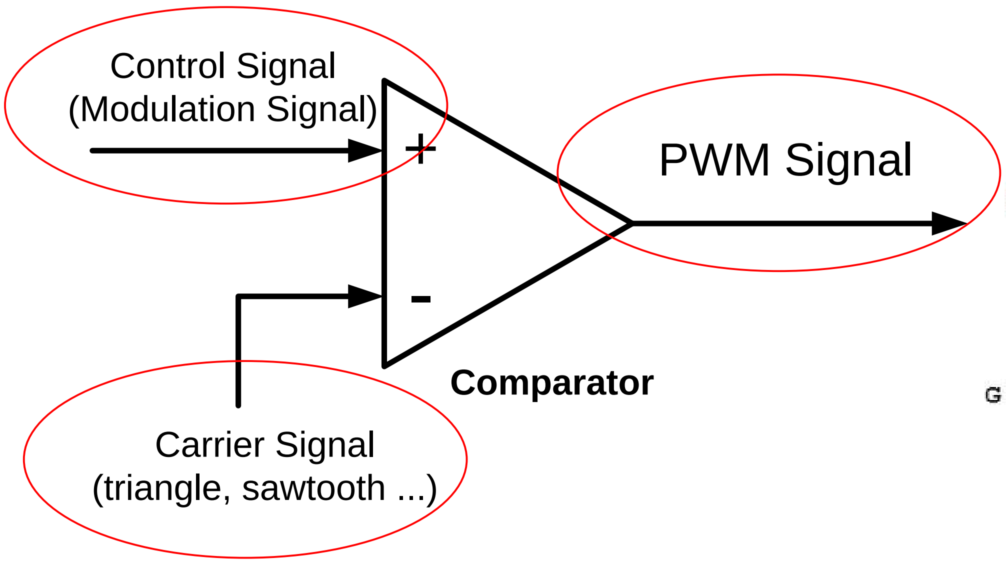


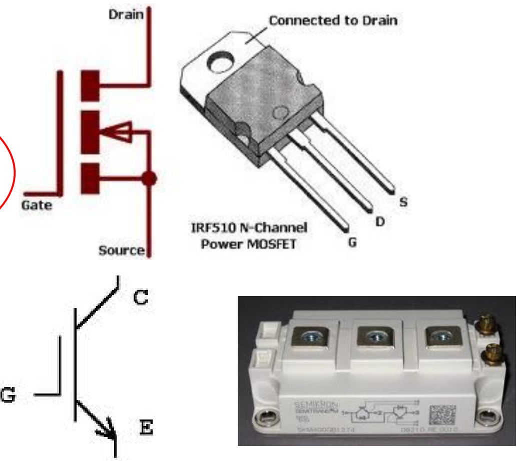
Constant OFF time



However, variable switching frequency leads to difficulty in designing filters to remove switching harmonics.

PWM Signal Generation





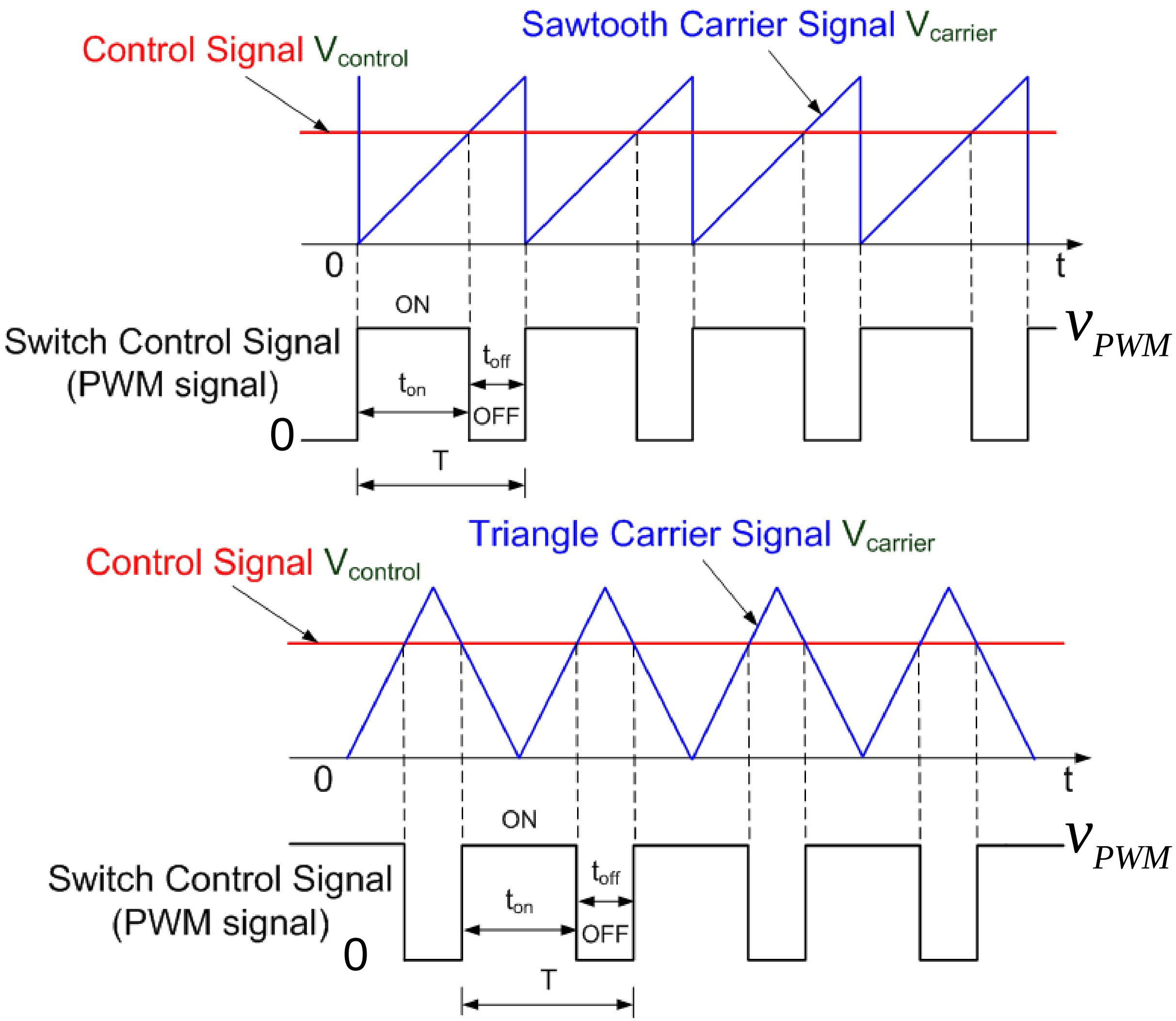
Switch

Pulse Width Modulation (PWM)

1. Constant (high) Switching (Carrier) Frequency
2. Carrier Frequency >> Control Signal Frequency
3. Control Signal Peak <= Carrier Signal Peak
4. Output Pulse Width is proportional to input control signal

Unipolar PWM Signal

Within one switching period, PWM signal is either positive or zero; or PWM is either negative or zero.



switching frequency:

$$f_s = \frac{1}{T_s};$$

duty cycle:

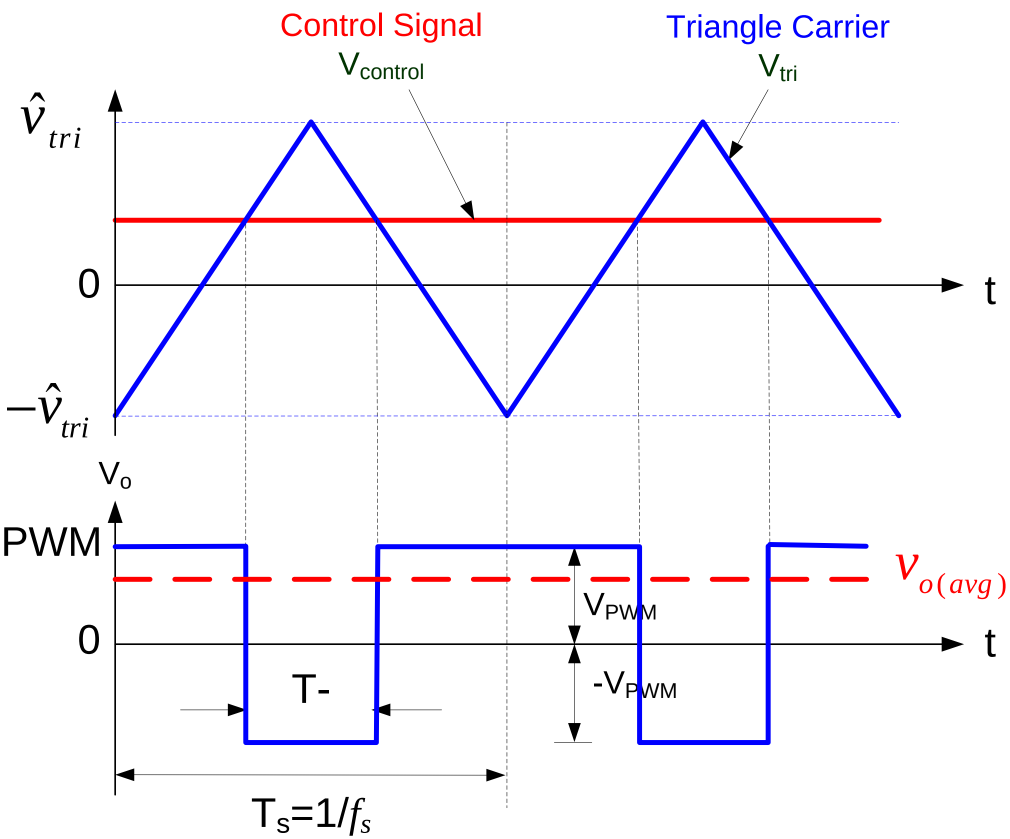
$$k = \frac{t_{on}}{T_s} = \frac{V_{control}}{\hat{V}_{carrier}}$$

average output:

$$v_{o(avg)} = k v_{PWM}$$

Bipolar PWM Signal

Within one switching period, PWM signal is either positive or negative.



$$T_s = \frac{1}{f_{tri}}, T_+ + T_- = T_s$$

$$v_{o(avg)} = \frac{T_+}{T_s} v_{PWM} - \frac{T_-}{T_s} v_{PWM}$$

$$= \frac{2T_+ - T_s}{T_s} v_{PWM} = \frac{v_{control}}{\hat{v}_{tri}} v_{PWM}$$

$$= k v_{PWM}$$

Duty Cycle :

$$k = \frac{2T_+ - T_s}{T_s} = \frac{v_{control}}{\hat{v}_{tri}}$$

PWM Amplifier

$$v_{o(avg)} = k v_{PWM} = \left(\frac{V_{control}}{\hat{V}_{carrier}} \right) v_{PWM} = \left(\frac{v_{PWM}}{\hat{V}_{carrier}} \right) V_{control}$$

1. Neglecting high order harmonics, PWM conversion is a linear amplifier. The mean value of output PWM signal for each switching period is equivalent to an amplified control signal with amplifier gain of $v_{PWM}/V_{carrier(peak)}$.

2. In fact, control signal $V_{control}$ can be either a sinusoidal signal for DC-AC PWM conversion and a dc signal for DC-DC PWM conversion.

PWM will be further discussed in late lectures !!!

MOSFET Gate Drive Circuit

Fast, Efficient, Reliable and Cost-Effective

[Chapter 2 and Chapter 28 Mohan]

General Functionality of Gate Drive Circuit

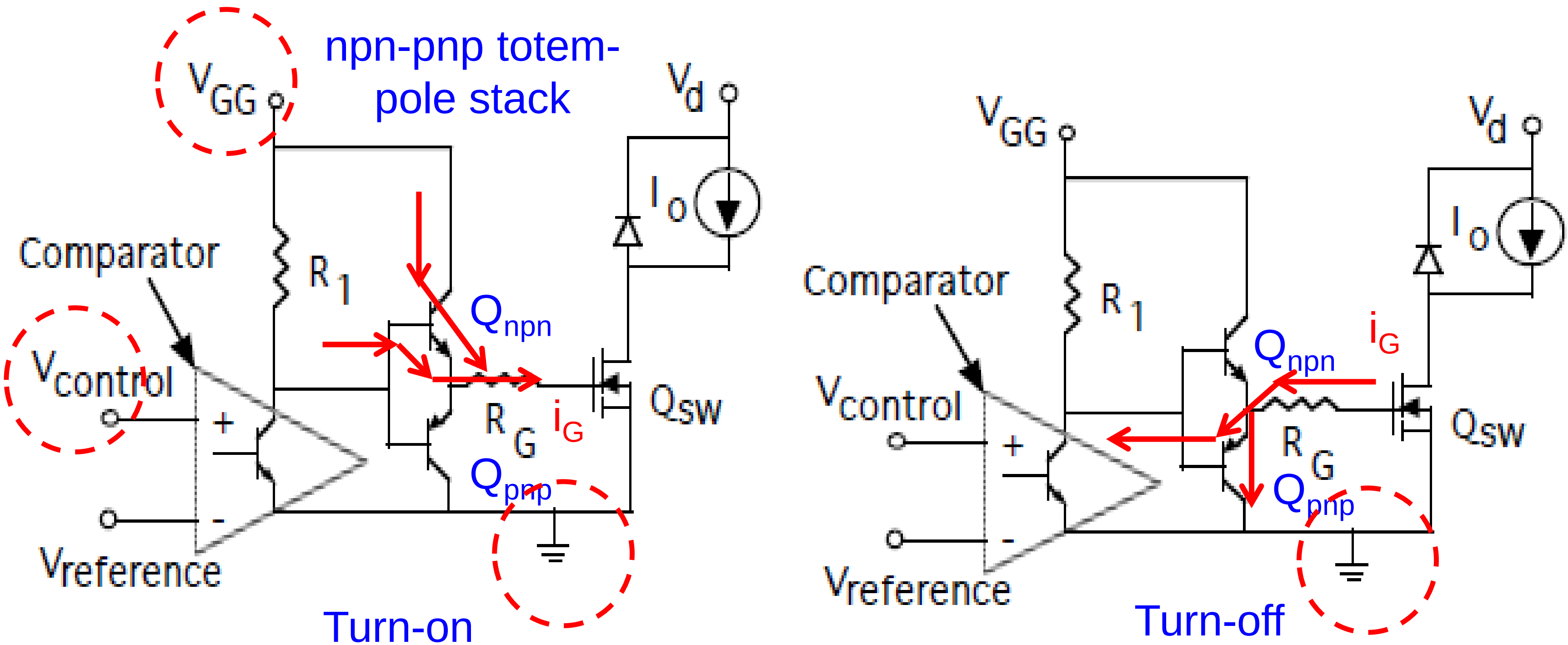
1. Provide adequate power for driving switch
2. Turn power switch from off-state to on-state
   - Minimize turn-on time to reduce switching-on power loss
   - Provide adequate drive power to keep power switch in on-state
3. Turn power switch from on-state to off-state
   - Minimize turn-off time to reduce switching-on power loss
   - Provide bias to insure that power switch remains off

- Advanced Function
  - Provide overvoltages or overcurrents protection
  - Provide electrical isolation between power switch and logic level signal processing/control circuits

Gate Drive for MOSFETs

- The current sinking and sourcing capabilities of the drive circuit will determine the switching time and switching losses of the power device. As a rule, the higher the gate charging and discharging current at turn-on and turn-off, the faster the switching speed.
- However, fast drive circuits may produce ringing in the gate circuit and drain circuits. To prevent this occurrence, a damping resistor may be added to limit gate charging current.

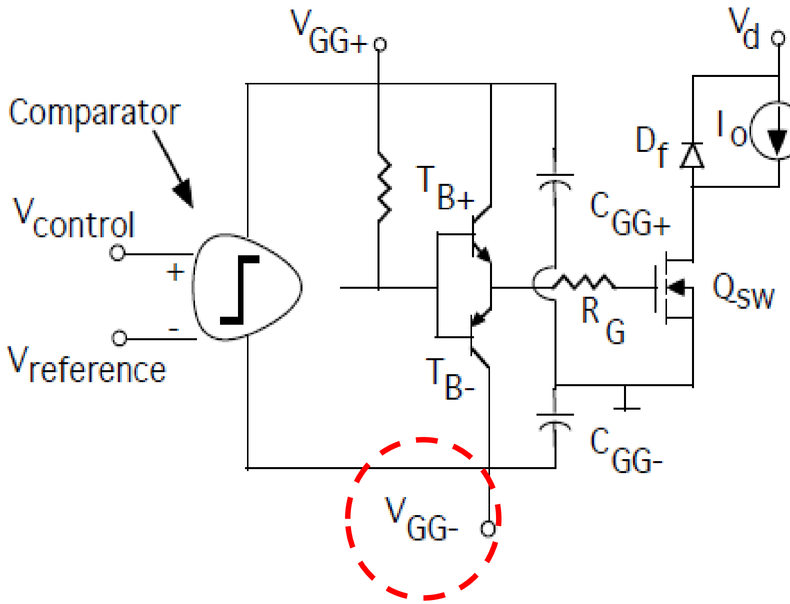
Typical Unipolar MOSFET Drive Circuit

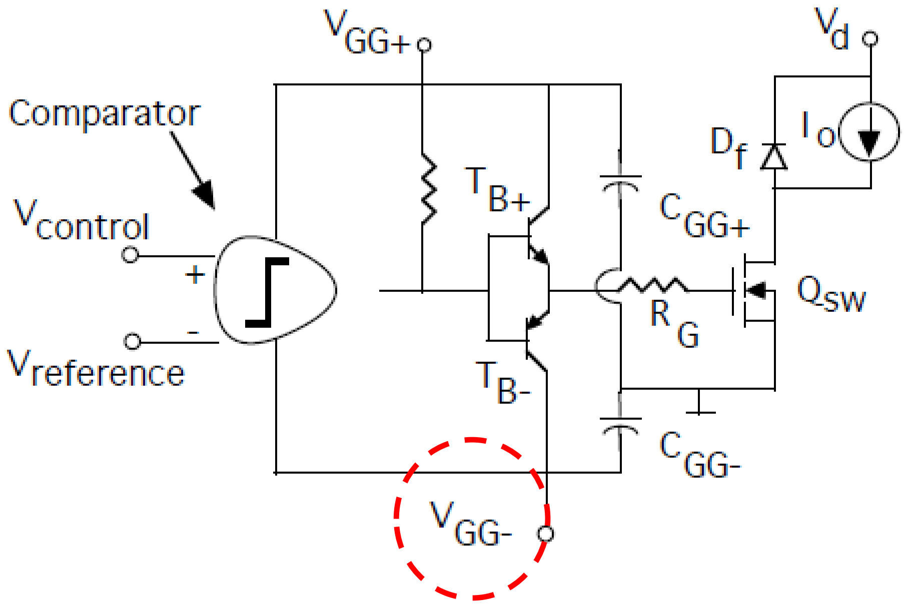


- $V_{GG} > V_{control}$ provides adequate power to drive MOSFET rapidly.
- A small gate resistor R_G is used to damp the switching ringings.

Unipolar Driver: very Simple

Bipolar MOSFET Drive Circuit

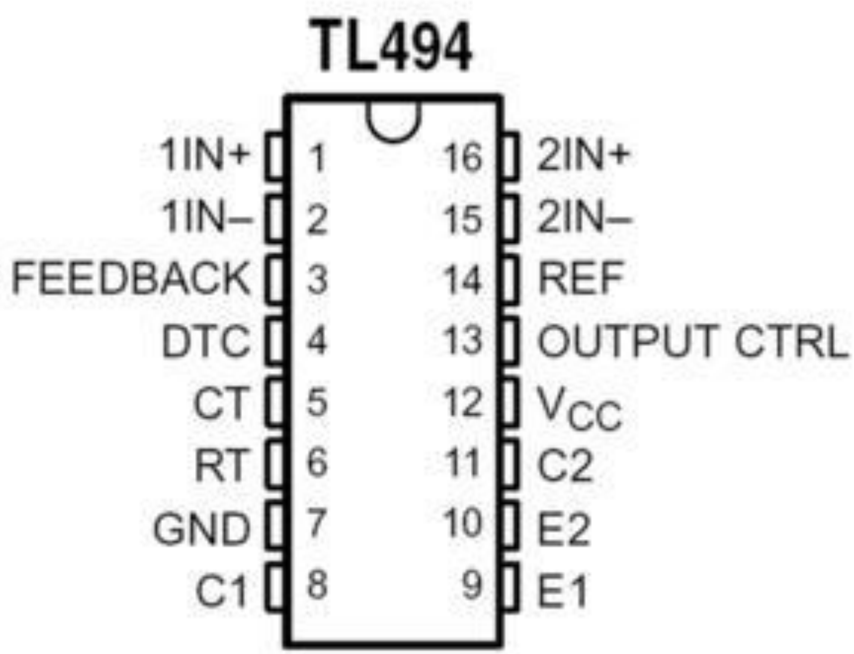




- $V_{GG-}<0$ enables MOSFETs to be turned off more rapidly

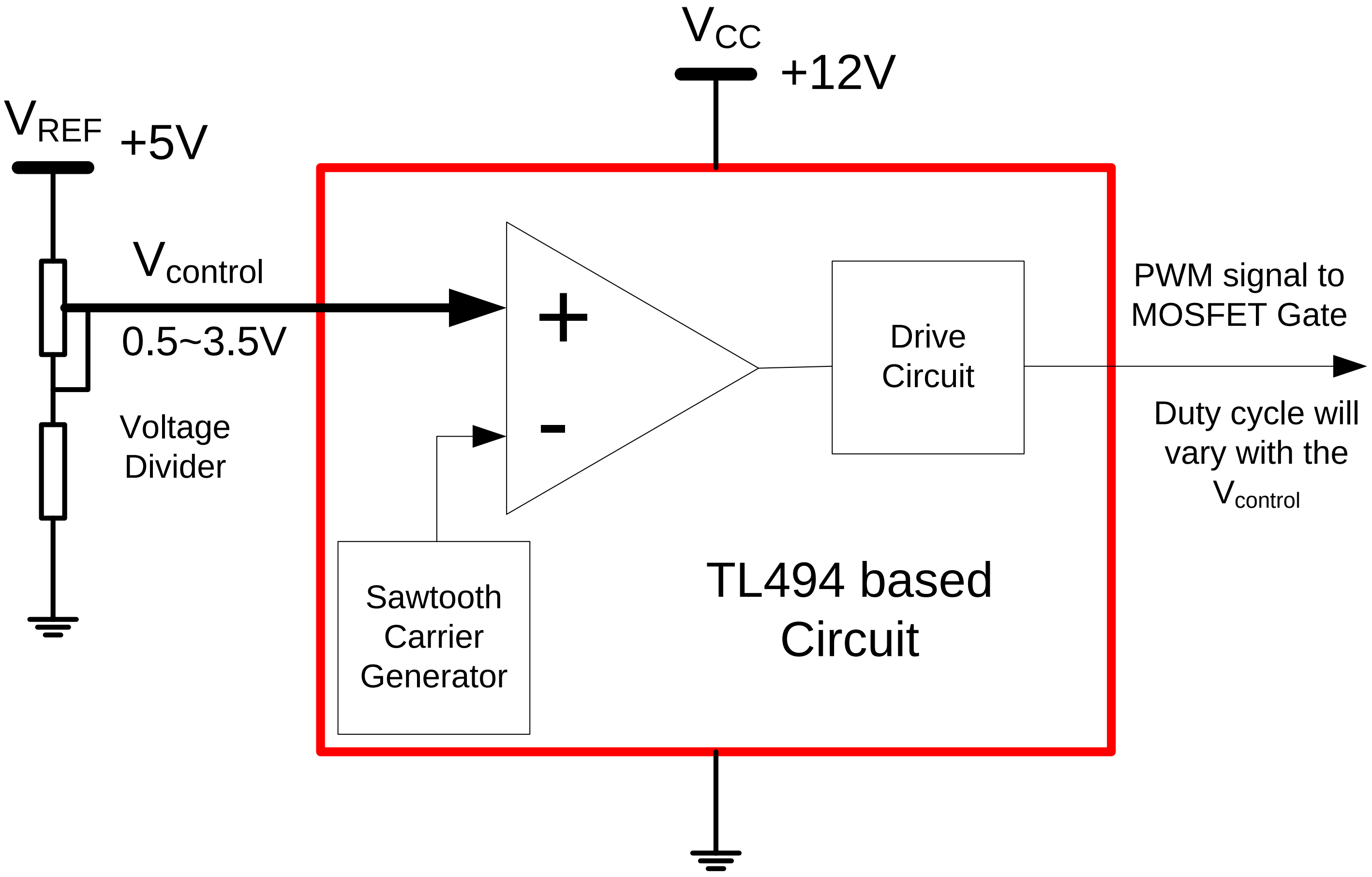
Bipolar: Rapid turn-on and turn-off

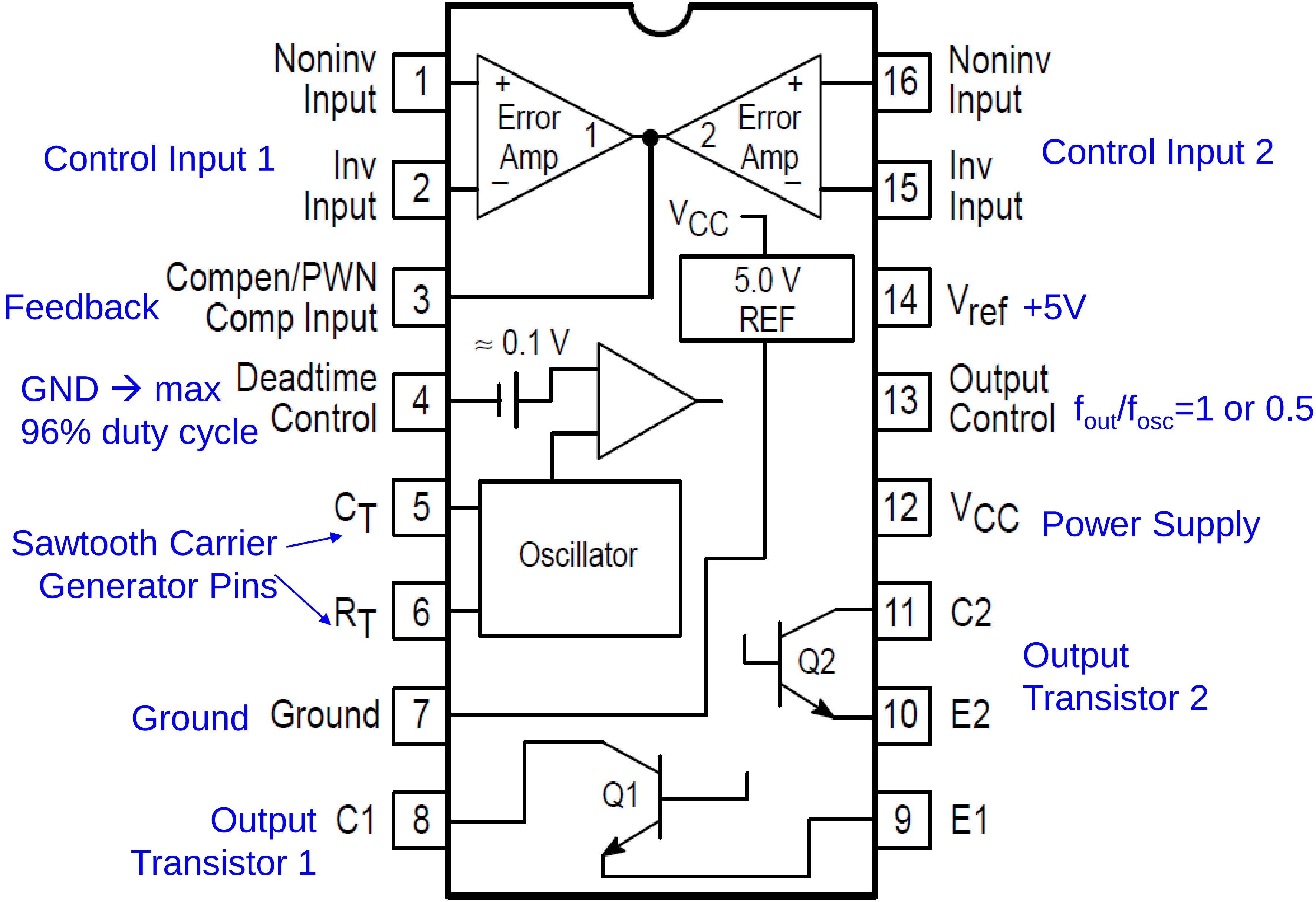
IC TL494 Based PWM Generator



Please carefully read the datasheet file TL494_MOTO.pdf

Lab 1-Task 2: Construct a TL494-based adjustable duty cycle PWM Generation Drive Circuit with switching frequency 30kHz~60kHz



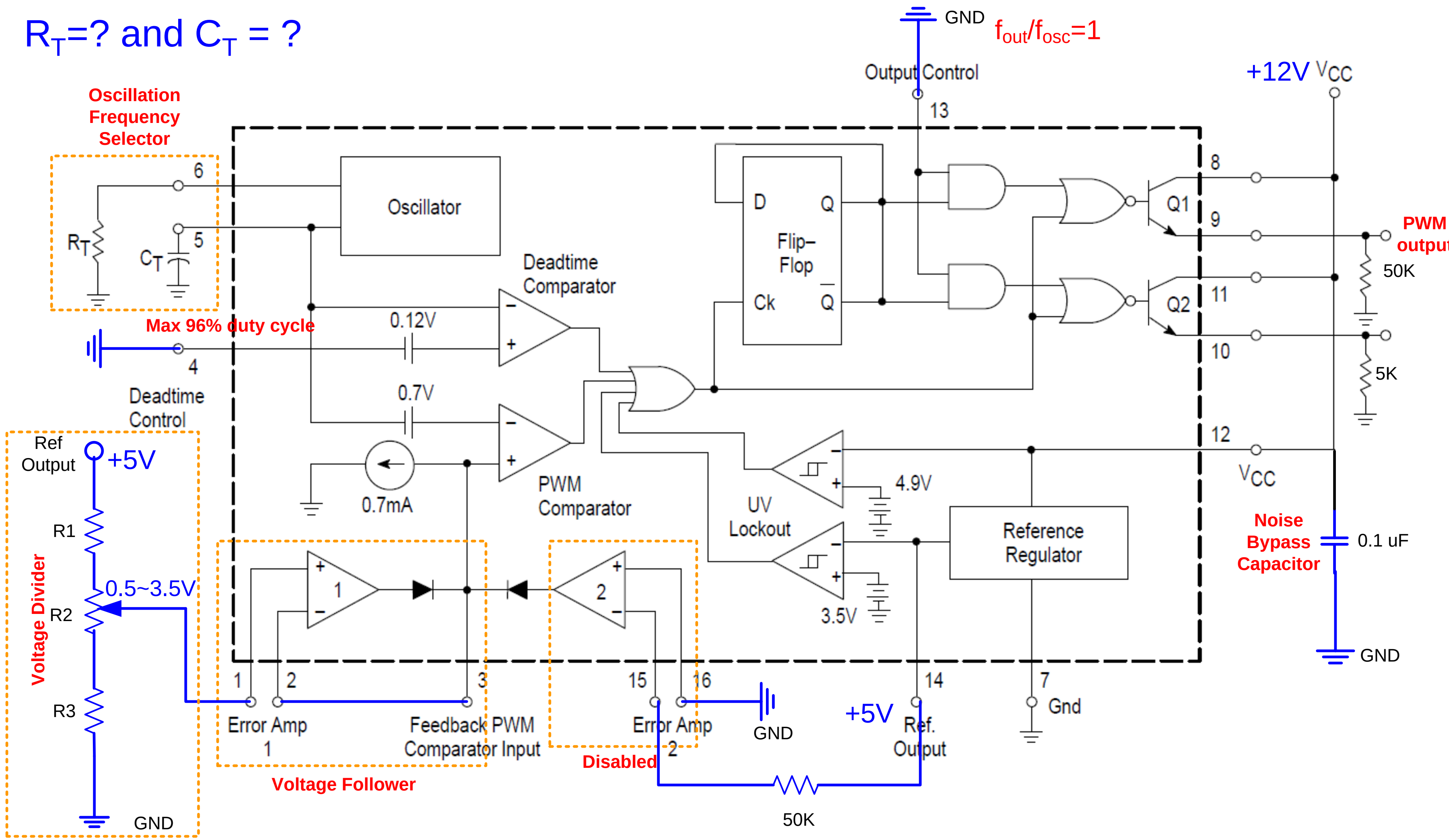


Noninv Input
Control Input 1
Inv Input
Compen/PWN Comp Input
Feedback
Deadtime Control
GND → max 96% duty cycle
C_T
Sawtooth Carrier Generator Pins
R_T
Ground
Ground
Output Transistor 1
C1
1
2
3
4
5
6
7
8
+
Error Amp 1
−
≈ 0.1 V
Oscillator
Q1
Q2
2
Error Amp
+
−
V_{CC}
5.0 V REF
16
15
14
13
12
11
10
9
Noninv Input
Inv Input
Control Input 2
V_{ref} +5V
Output Control
f_{out}/f_{osc}=1 or 0.5
V_{CC}
Power Supply
C2
Output Transistor 2
E2
E1

(Top View)

TL494-based PWM Generator

R_T=? and C_T = ?



R_1=?, R_2=? and R_3= ?