ECEN 4517/5517

Power Electronics and Photovoltaic Power Systems Laboratory

Lecture 10

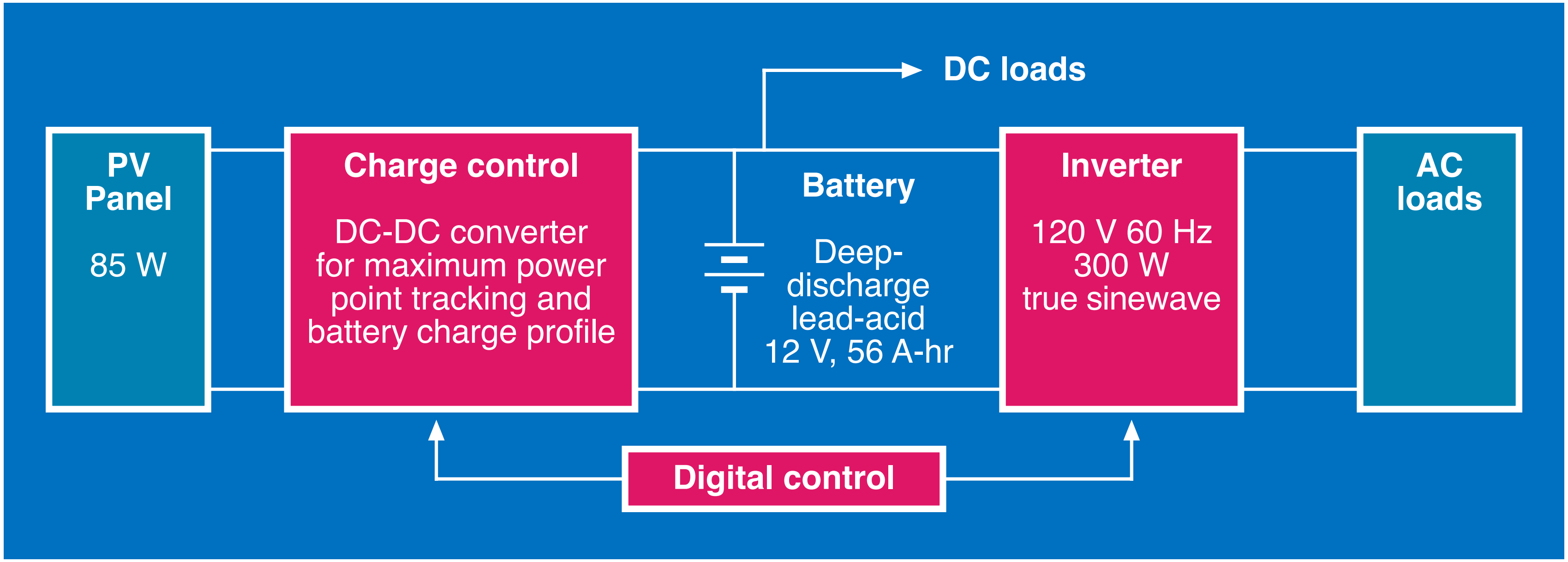
True Sine Wave Inverter

And Other Inverter Modulation Techniques

Announcements

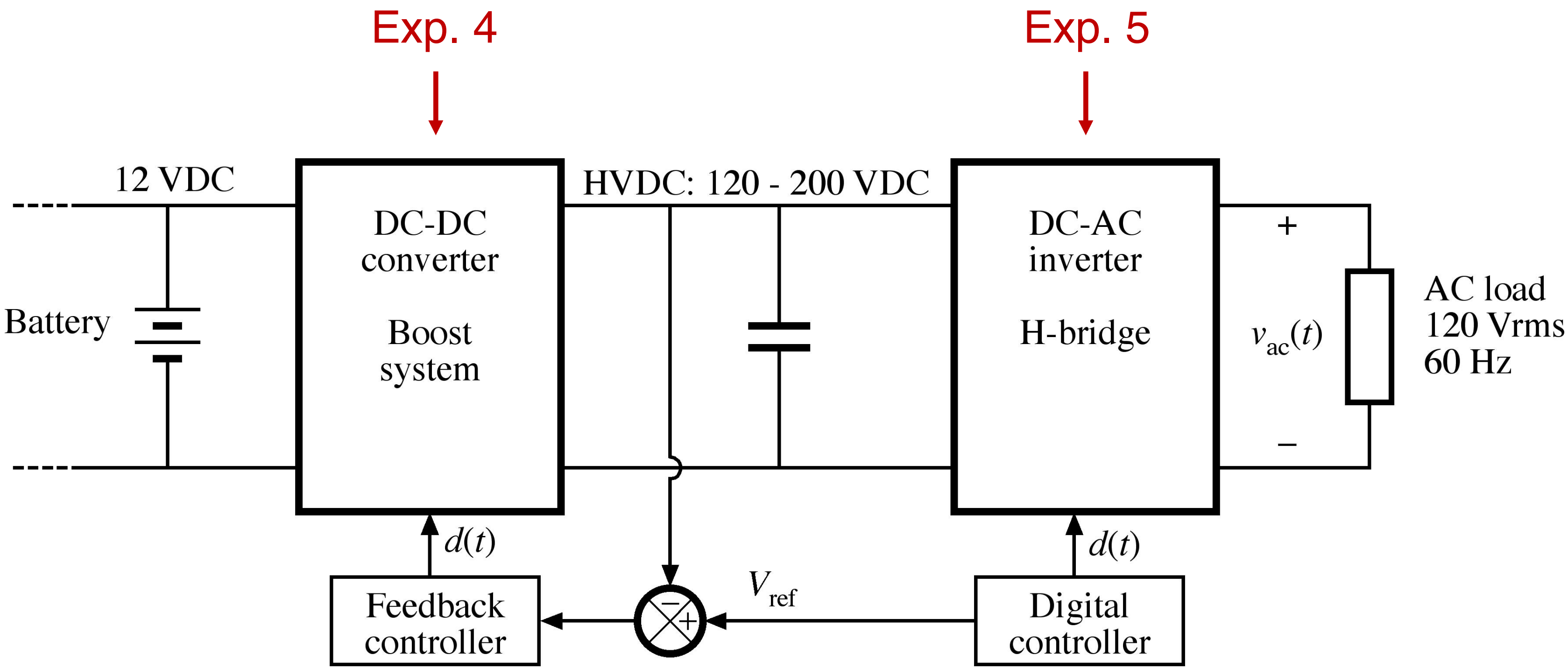
- Exp 4 Lab Report due by 11:59 pm (MT) on Friday April 7, 2017
- This week's lab: Experiment 5
  - Have 2 weeks to work on Experiment 5
  - Exp 5 Lab Report due by 11:59 pm (MT) on Friday April 21, 2017
- After that: Assemble Complete System
- Quiz 2 on Monday April 24, 2017
  - In-class 40-minute quiz administered during lecture time
  - Closed book/notes, calculator allowed
  - Will cover Experiment 4 and 5 material
- Expo (Final Demo) on Thursday May 4, 2017

Experiments



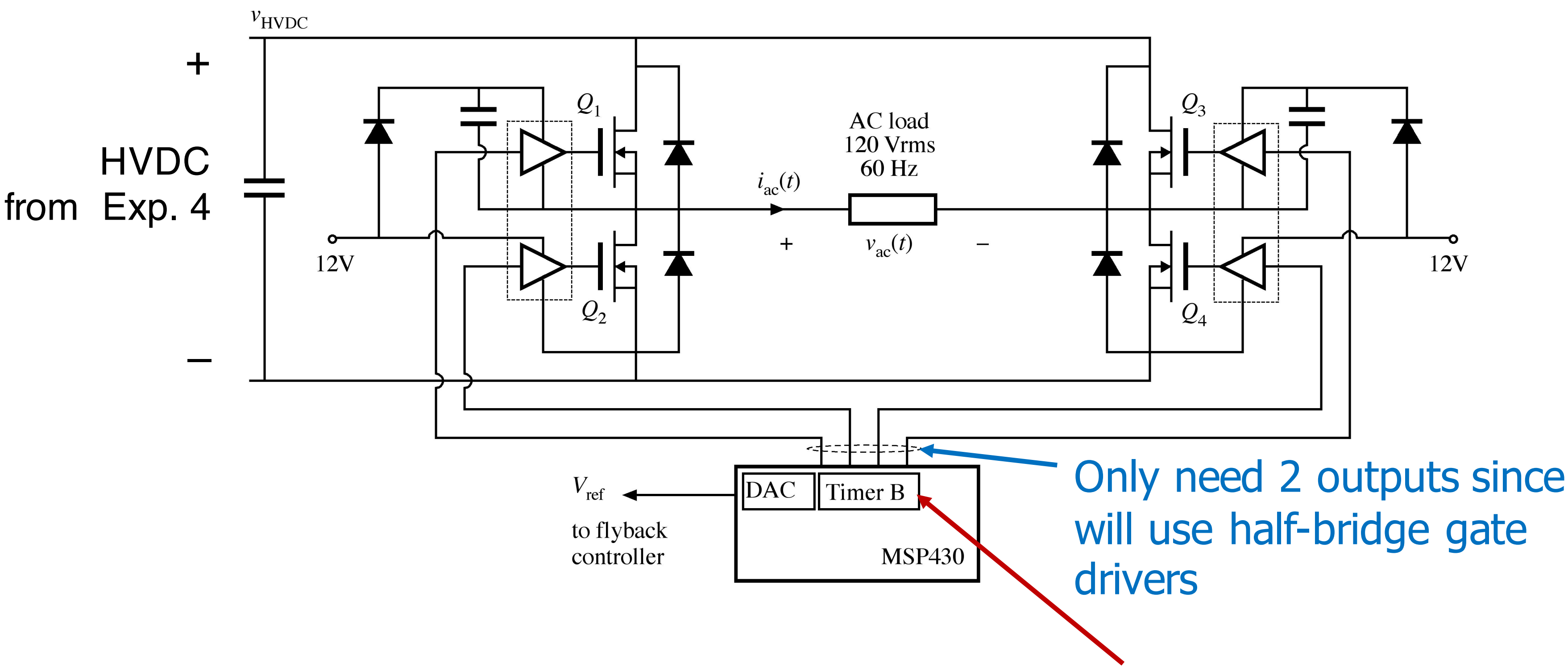
- Exp 1 – PV panel and battery characteristics and direct energy transfer
- Exp 2 – TI MSP430 microcontroller introduction
- Exp 3-1, 3-2 – Buck dc-dc converter for PV MPPT and battery charge control
- Exp 4 – Step-up 12V-200V dc-dc converter
- Exp 5 – Single-phase dc-ac converter (inverter)
- Expo – Complete system demonstration

Experiment 5 – Off-Grid Inverter



- **Required**: Demonstrate modified sine-wave inverter
- **Extra Credit**: Demonstrate PWM inverter

Off-Grid H-Bridge Inverter

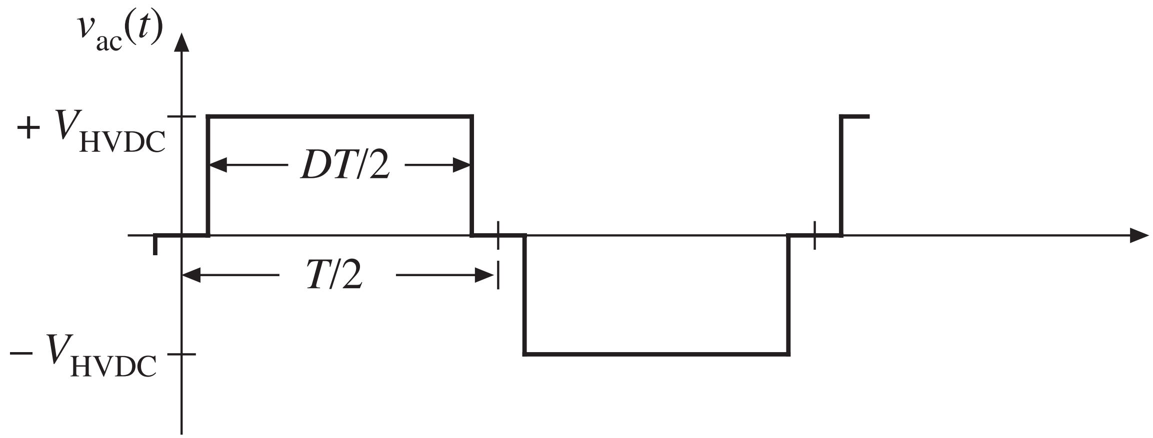


- Need MOSFETs and half-bridge gate drivers
- Filtering of ac output not explicitly shown
- Grid-tied: control $i_{ac}(t)$
- Off-grid: control $v_{ac}(t)$

“Modified Sine Wave” Inverter

$v_{ac}(t)$ has a rectangular waveform

Inverter transistors switch at 60 Hz, T = 16.66 msec



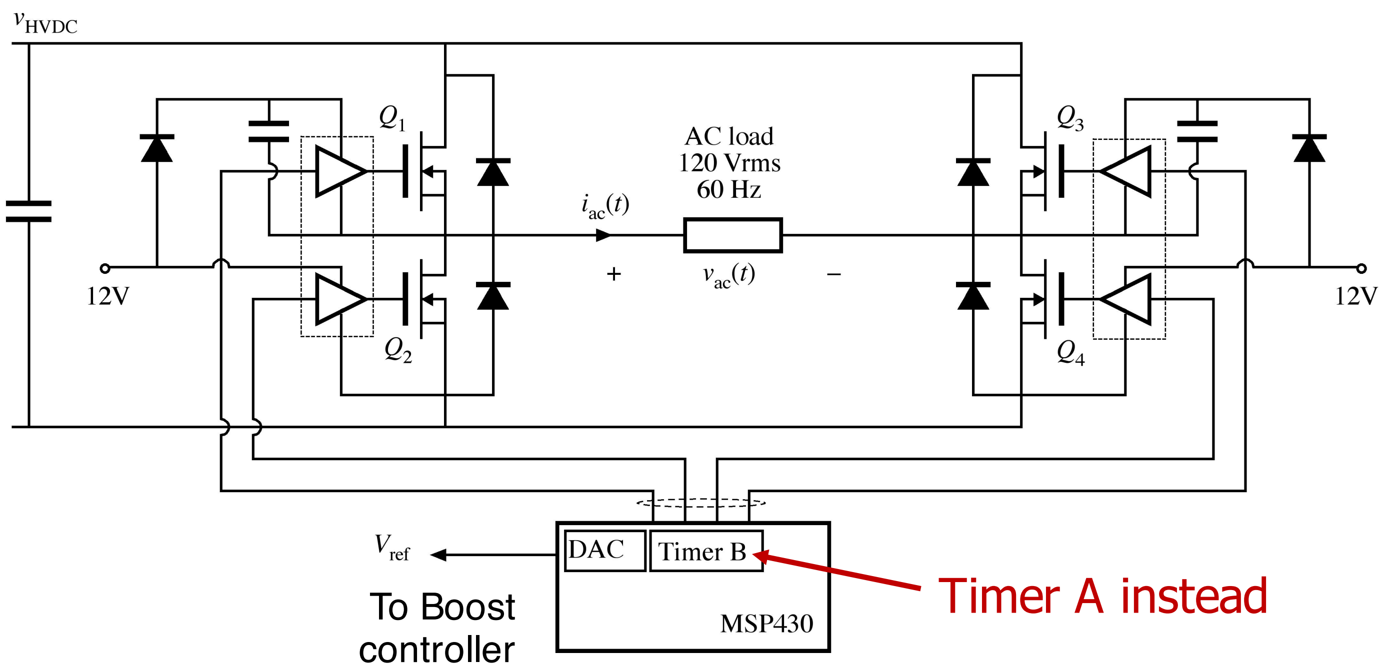
RMS value of $v_{ac}(t)$ is:

$$V_{ac,RMS} = \sqrt{\frac{1}{T}\int_0^T v_{ac}^2(t)\,dt} = \sqrt{D}\;V_{HVDC}$$

- Choose V_{HVDC} larger than desired $V_{ac,RMS}$
- Can regulate value of $V_{ac,RMS}$ by variation of D
- Waveform is highly nonsinusoidal, with significant harmonics

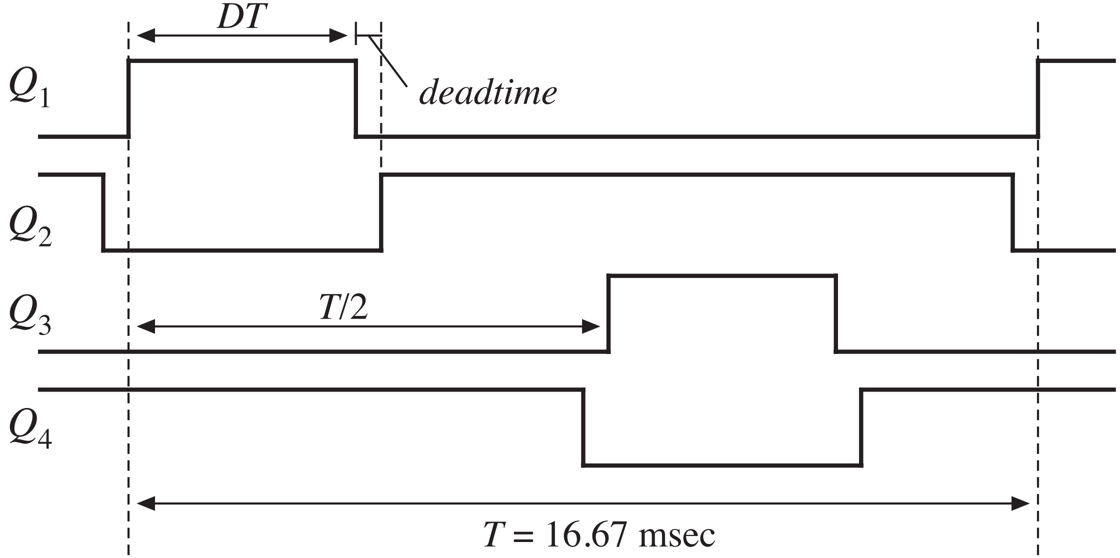
Inverter Control

- Use MSP430 to control the MOSFET gate drivers
  - Can use Timer A (or logic outputs) to generate drive signals



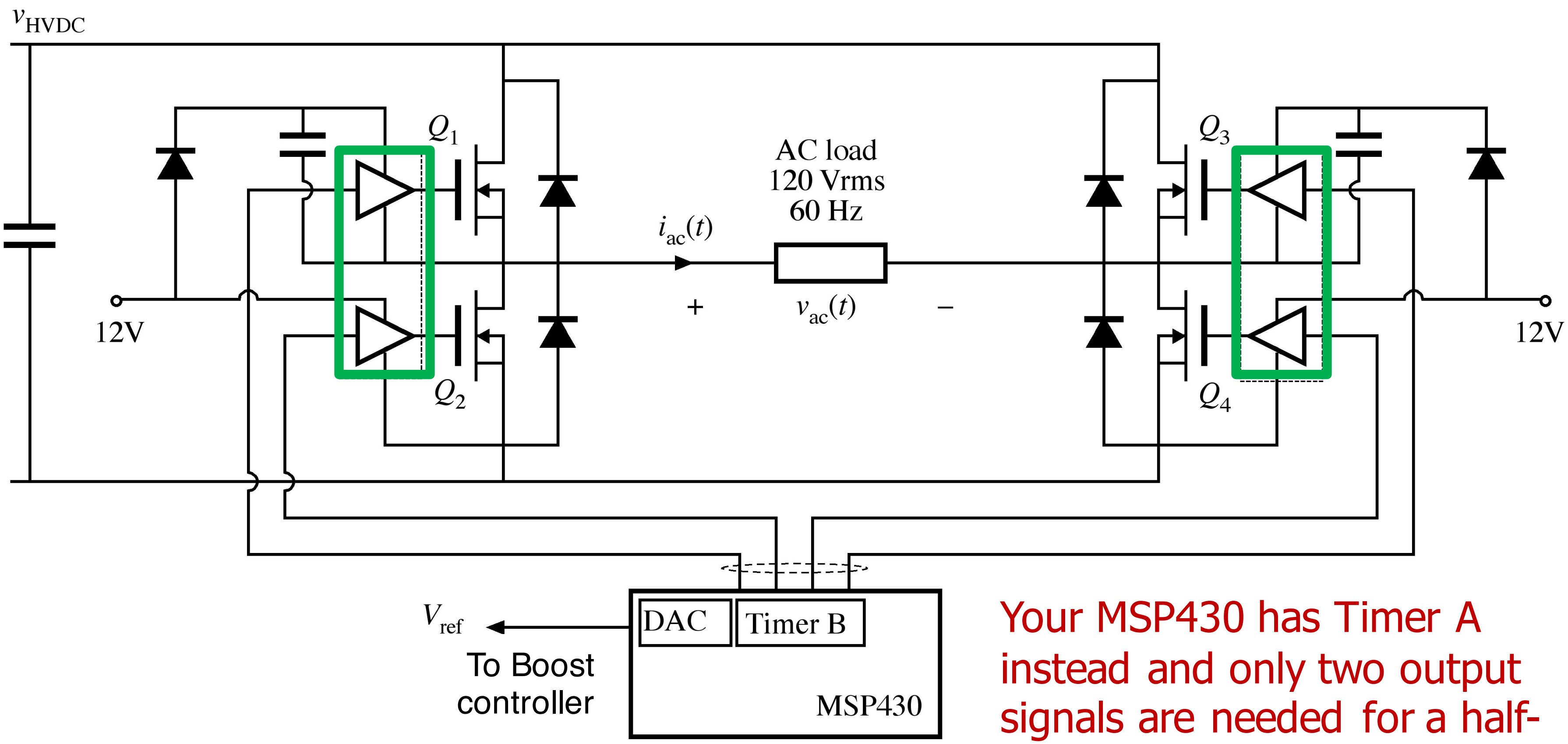
- Your goal: adjust V_{ref} and inverter duty cycle to obtain V_{ac} = 120 V rms

Gate Drive Timing



- For modified sine wave inverter: switch once per ac half cycle
- Adjust duty cycle to control rms voltage
- Require deadtime > (switching/delay times of MOSFETs plus gate drivers); otherwise, simultaneous conduction of Q_1 and Q_2 causes "shoot-through" current that can damage MOSFETs

Half-Bridge Gate Drivers



Your MSP430 has Timer A instead and only two output signals are needed for a half-bridge driver

Half-bridge gate driver examples: IR21094 and FAN 73832
(your parts kit has IR21094)

Half-Bridge Gate Driver Functionality

Contains two MOSFET drivers:
- Low side driver
- High side driver

High side driver includes
- Level-shifting circuitry
- Provisions for bootstrap power supply

Undervoltage lockout circuitry holds MOSFETs off when driver power supply is below threshhold

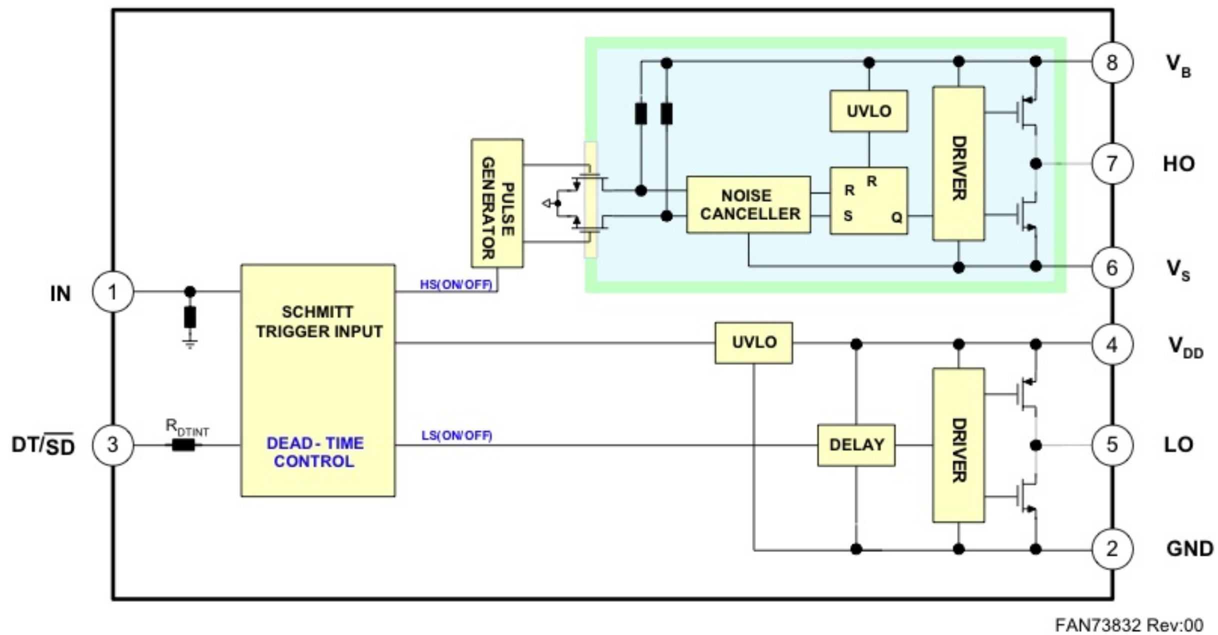
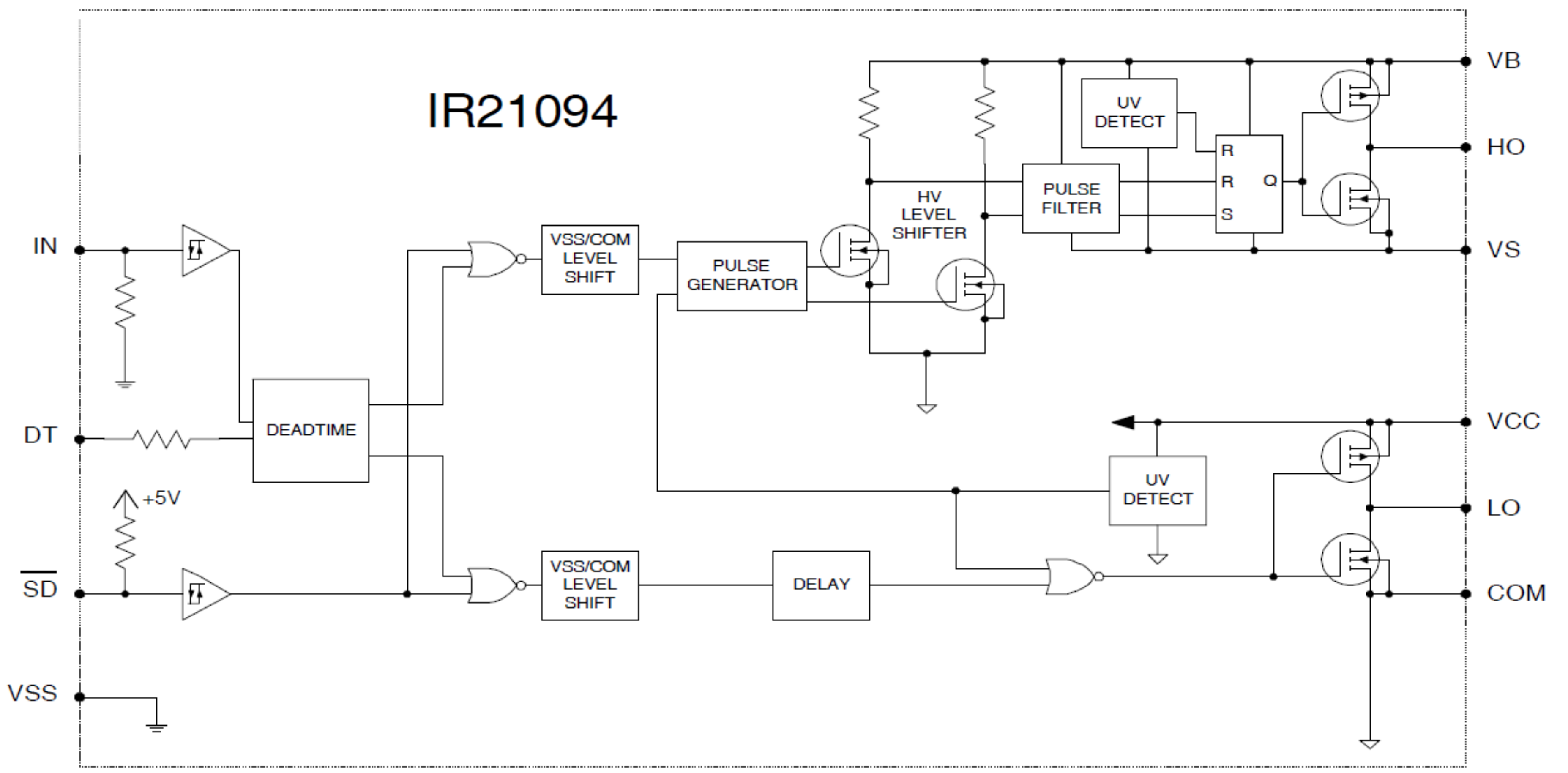
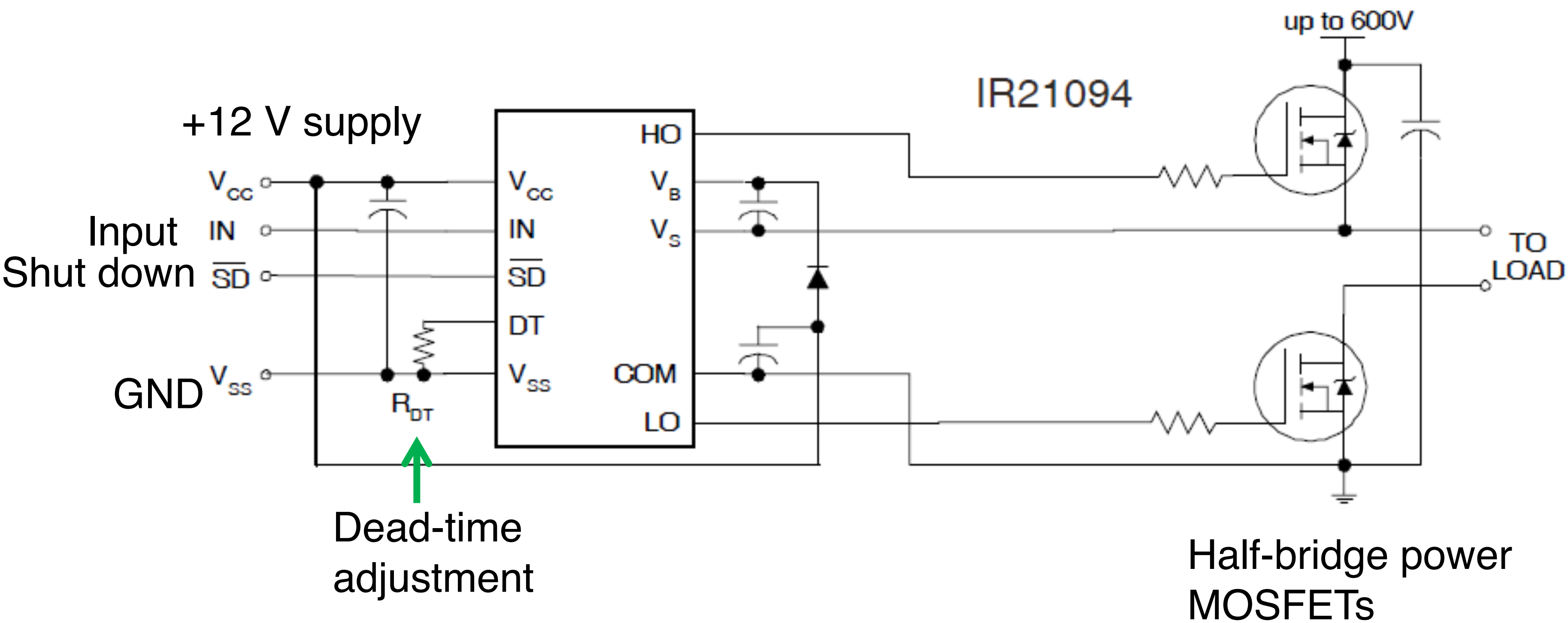


Figure 3. Functional Block Diagram of FAN73832

Half-Bridge Gate Driver - IR21094



Half-Bridge Gate Driver Circuit Example



Half-Bridge Gate Driver Circuit Example

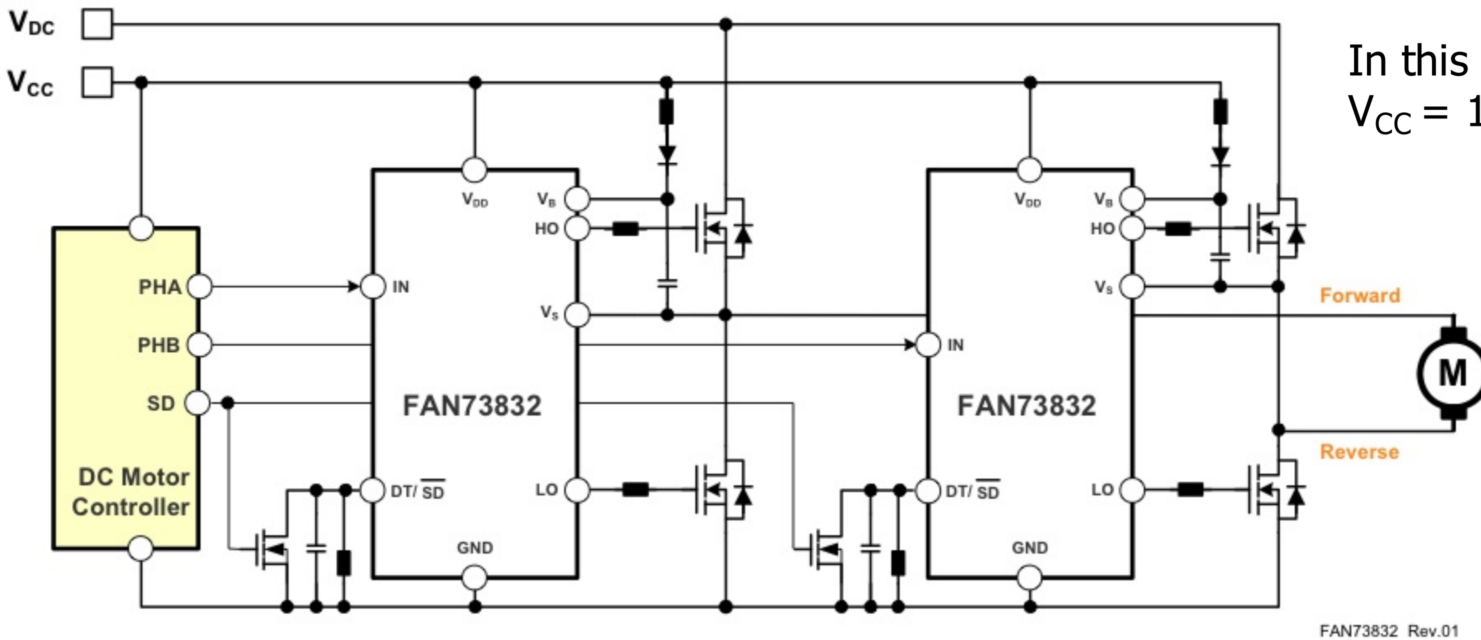


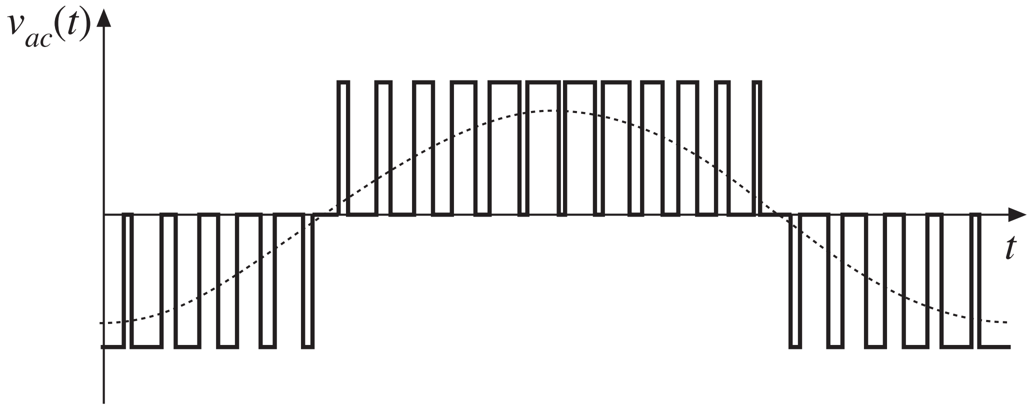
Figure 2. Application Circuit for Full-Bridge DC Motor Driver

In this example, V_{CC} = 12 V

- High side circuitry includes external diode and capacitor for bootstrap power supply
- To charge bootstrap capacitor, low side MOSFET must conduct

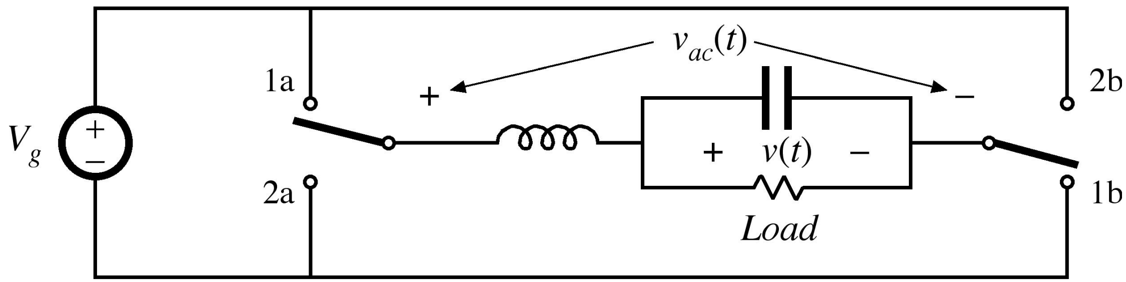
PWM Inverter

- Average $v_{ac}(t)$ has a sinusoidal waveform
- Inverter transistors switch at frequency substantially higher than 60 Hz



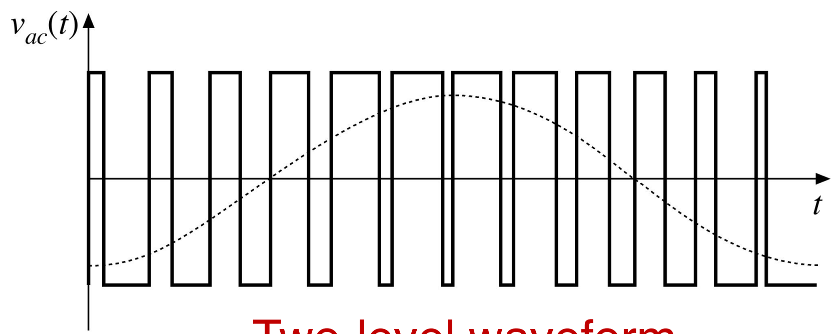
- Choose V_{HVDC} larger than desired $V_{ac,peak}$
- Can regulate waveshape and value of $V_{ac,RMS}$ by variation of d(t) (programming inside microcontroller)
- Can achieve sinusoidal waveform, with negligible harmonics
- Higher switching frequency leads to more switching loss and need to filter high-frequency switching harmonics and common-mode currents
- For the same $V_{ac,RMS}$, need larger V_{HVDC}

Alternate Ways to Generate PWM Sinusoid



(a) Operate left and right sides with same (complementary) gate drive signals

$$v(t) = (2d(t) - 1)\ V_g$$



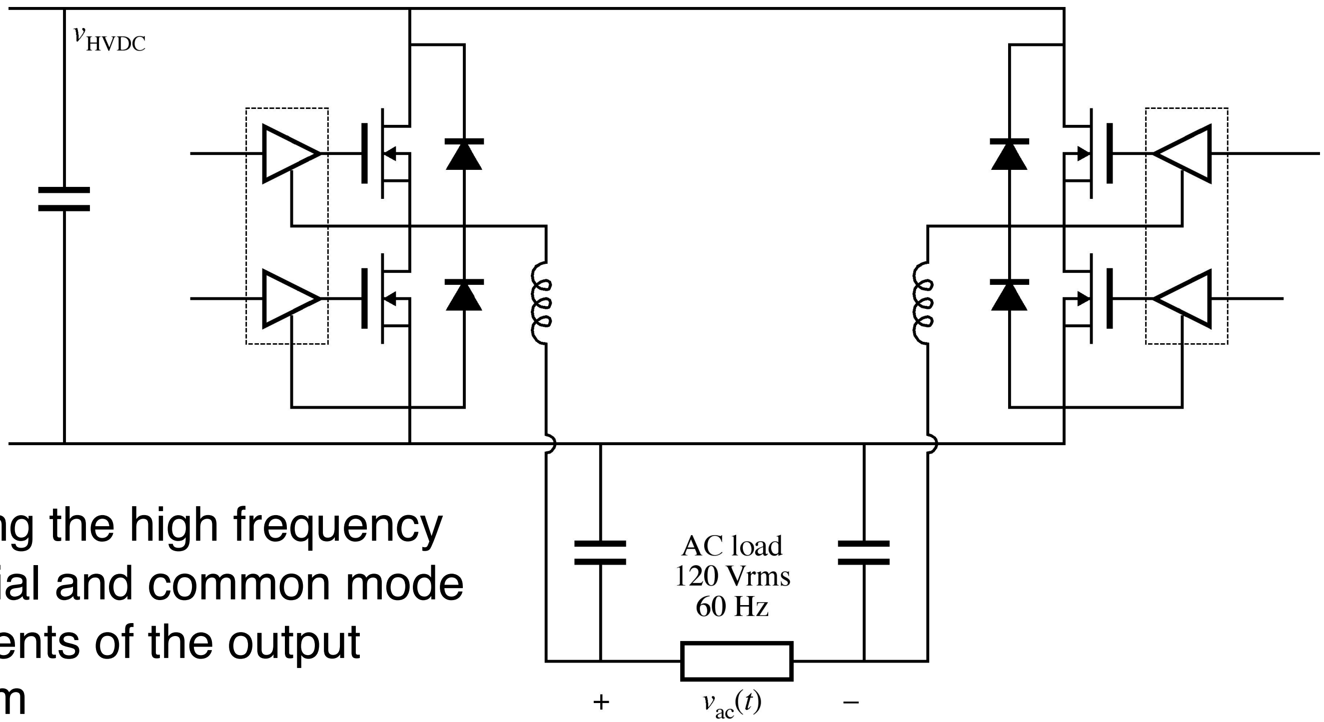
Two-level waveform

(b) PWM one side, while other side switches at 60 Hz

$$v(t) = \pm\ d(t)\ V_g$$

Three-level waveform

Filtering the AC Output



Removing the high frequency differential and common mode components of the output waveform

Note: the “Kill-a-Watt” power meters cannot tolerate high frequency components in the ac voltage waveform. Do not connect these meters to an unfiltered inverter output!

Review of Fourier Series

- Any periodic waveform f(t) can be expressed in terms of harmonically related sin() and cos() terms

$$f(t) = \frac{b_0}{2} + \sum_{n=1}^{\infty} \left[a_n \sin(n\omega_0 t) + b_n \cos(n\omega_0 t) \right]$$

where $\omega_0 = \frac{2\pi}{T}$ and T is period of $f(t)$

- The coefficients a_n and b_n can be calculated from:

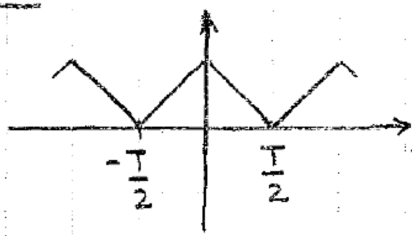
$$a_n = \frac{2}{T} \int_T f(t) \sin(n\omega_0 t)\, dt$$

$$b_n = \frac{2}{T} \int_T f(t) \cos(n\omega_0 t)\, dt$$

Classification of Waveforms

- Some waveforms have special characteristics

Even $x(t) = x(-t)$



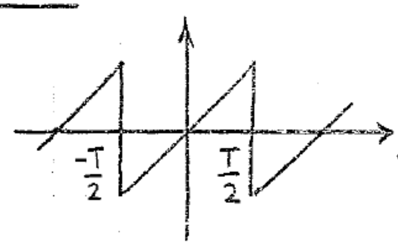
No Sin terms since Sin is Odd

$a_n = 0$ for all n

[Even func. × Odd func. = Odd func.

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} (\text{Odd func.})\,dt = 0$$]

Odd $x(t) = -x(-t)$



No Cos terms since Cos is Even

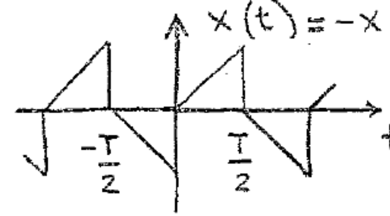
$b_n = 0$ for all n

[Odd func. × Even func. = Odd func.

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} (\text{Odd func.})\,dt = 0$$]

Half-wave Symmetric

$x(t) = -x\left(t - \frac{T}{2}\right)$



No Even Harmonics

$a_{2k} = 0$ & $b_{2k} = 0$ for all k

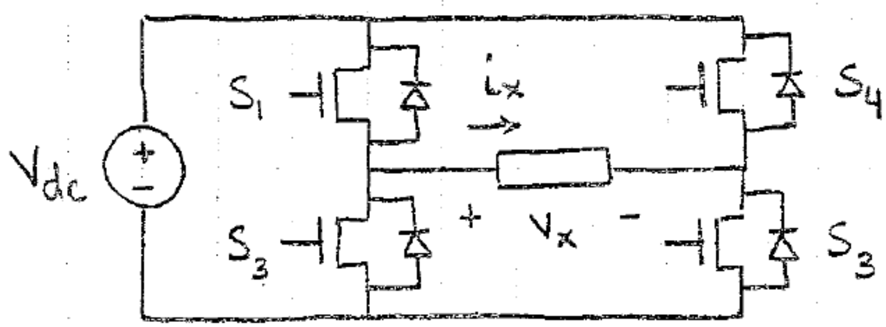
[For n Even

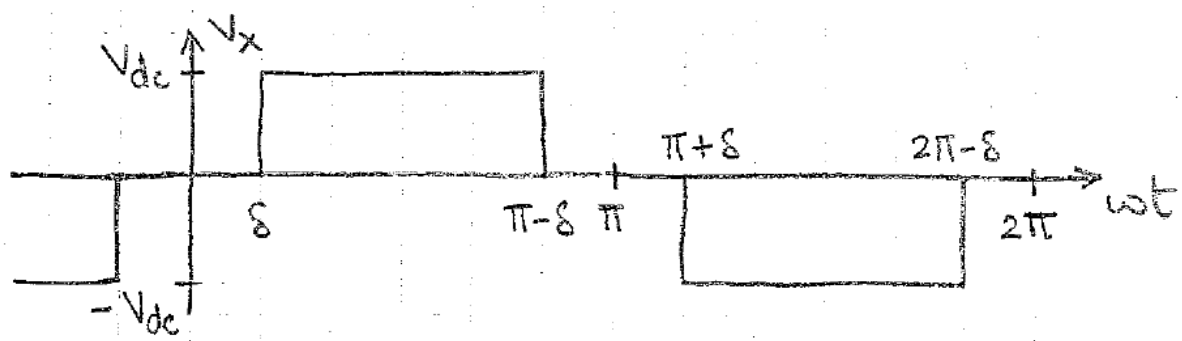
$$\int_{-T/2}^{0} (\quad)\,dt = -\int_{0}^{T/2} (\quad)\,dt$$

$\Rightarrow a_n = 0$ & $b_n = 0$ for n even]

$$f(t) = \frac{b_0}{2} + \sum_{n=1}^{\infty}\left[a_n \sin(n\omega_0 t) + b_n \cos(n\omega_0 t)\right]$$

Modified Sine-Wave Inverter



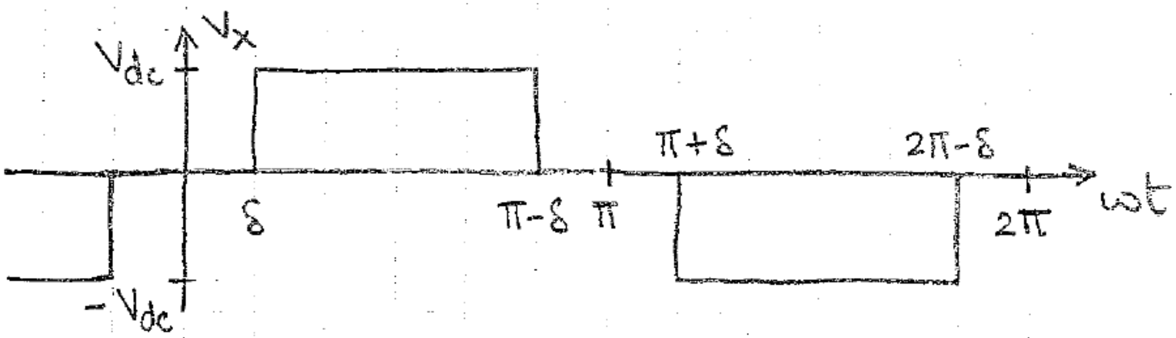


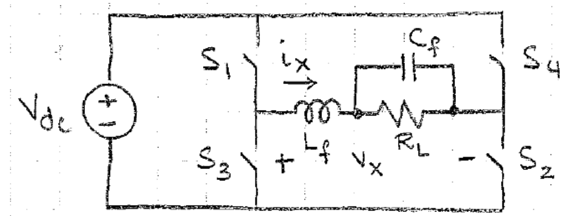
What is the frequency content of v_x

- v_x waveform is Odd ⟶ No cos terms, Only Sin terms
- v_x waveform is Half-wave Symmetric ⟶ No even harmonics

$$\therefore \quad \boxed{v_x(t) = \sum_{n \text{ odd}} V_n \sin(n\omega_0 t)}$$

Frequency Content of Modified Sine-Wave





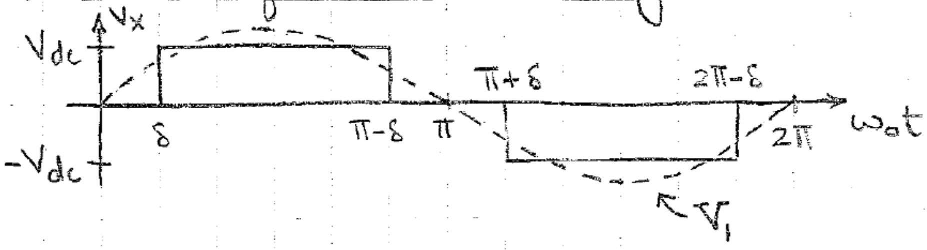
<u>If $\delta = 0$</u> $\Rightarrow$ v_x is a square wave $\Rightarrow$ $v_x(t) = \sum\limits_{n\ odd} \frac{4V_{dc}}{n\pi} \sin(n\omega_o t)$

Frequency content: Fundamental, $\underbrace{3^{rd}, 5^{th}, 7^{th}, \ldots}_{\text{harmonics}}$

- If we can filter out the harmonics, load voltage will be more sinusoidal than v_x
- However, difficult to filter because the frequencies to be rejected $(3\omega_o, 5\omega_o, \ldots)$ are close to the frequency we want to keep (ω_o)
- Would like to find another way to eliminate harmonics

Impact of Change of δ

(A) Control of Fundamental Magnitude



$$v_x(t) = \sum_{n\ \text{odd}} V_n \sin(n\omega_o t)$$

$$\omega_o = \frac{2\pi}{T}$$

$$V_1 = \frac{2}{T}\int_T v_x(t)\sin(\omega_o t)\,dt = \frac{2}{2\pi}\int_{2\pi} v_x(\omega_o t)\sin(\omega_o t)\,d(\omega_o t)$$

$$V_1 = \frac{4}{2\pi}\int_{\delta}^{\pi-\delta} V_{dc}\sin(\omega_o t)\,d(\omega_o t) = \frac{4V_{dc}}{2\pi}\Big[-\cos(\omega_o t)\Big]_{\delta}^{\pi-\delta}$$

$$V_1 = \frac{4V_{dc}}{2\pi}\Big[-\overbrace{\cos(\pi-\delta)}^{=\,-\cos\delta} + \cos(\delta)\Big] \Rightarrow \boxed{V_1 = \frac{4V_{dc}}{\pi}\cos(\delta)}$$

- Hence we can control the magnitude of the fundamental by controlling δ
- Can be useful if we want to regulate the output voltage of an inverter when the input voltage is changing (e.g., in a UPS when battery voltage is drooping as it discharges)

Impact of Change of δ (Cont.)

(B) Control of Harmonics' Magnitude

$$V_n = \frac{2}{T}\int_T v_x(t)\,\sin(n\omega_o t)\,dt = \frac{2}{2\pi}\int_{2\pi} v_x(\omega_o t)\,\sin(n\omega_o t)\,d(\omega_o t)$$

$$V_3 = \cancel{2}\cdot\frac{2}{\cancel{2}\pi}\int_{\delta}^{\pi-\delta} V_{dc}\,\sin(3\omega_o t)\,d(\omega_o t) = \frac{2}{\pi}\,\frac{V_{dc}}{3}\Big[-\cos(3\omega_o t)\Big]_{\delta}^{\pi-\delta}$$

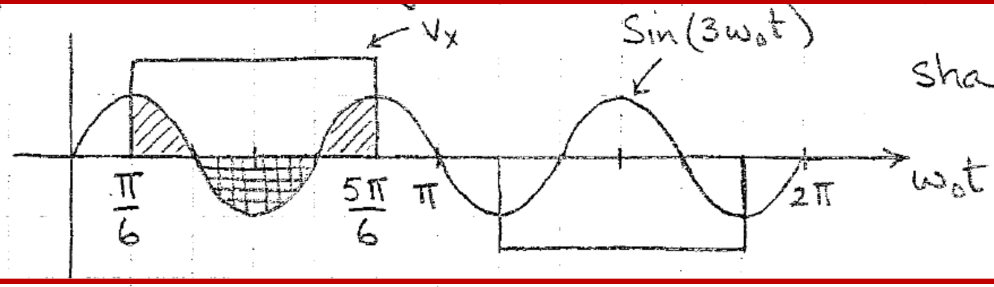
$$V_3 = \frac{2V_{dc}}{3\pi}\Big[\overbrace{-\cos(3\pi-3\delta)}^{=\,-\cos(3\delta)} + \cos(3\delta)\Big] \Rightarrow \boxed{V_3 = \frac{4V_{dc}}{3\pi}\cos(3\delta)}$$

- So as we change δ, the magnitude of the 3rd harmonic also changes
- If $\delta = 30°$ $\Rightarrow$ $3\delta = 90°$ $\Rightarrow$ $V_3 = 0$

  Hence we can kill the 3rd harmonic by setting $\boxed{\delta = 30°}$

Harmonic Elimination

- Easy to visualize why 3rd harmonic is killed by $\delta = 30^\circ$



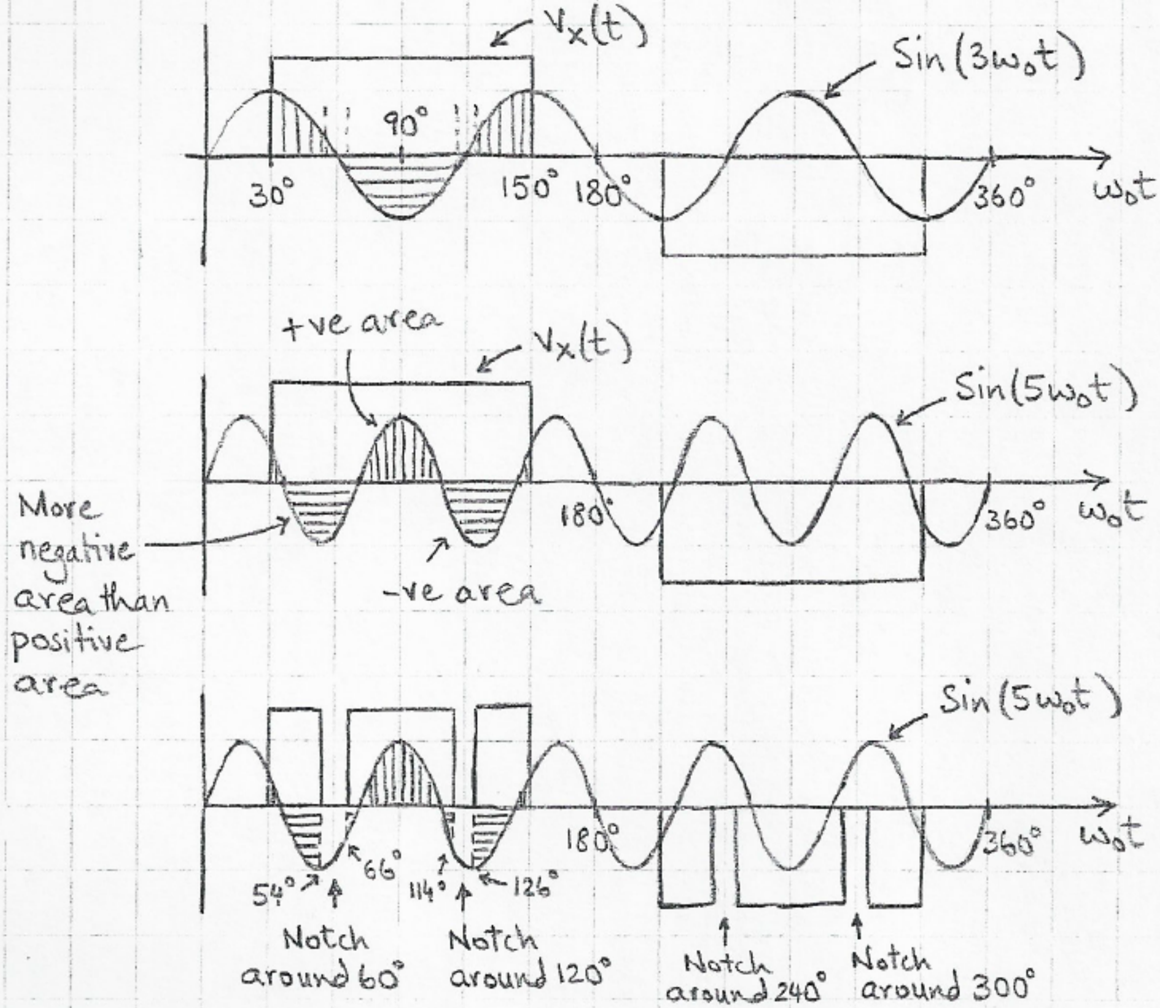
Can use same technique to see what happens to other harmonics

- Hence the lowest harmonic we are left with is the 5th, so filtering becomes easier

- Note $\delta = 30^\circ$, eliminates all triple-n (3n) harmonics (i.e., 9th, 15th are also killed).

- However, when we fix δ to kill harmonics, we can not use it to regulate the magnitude of the fundamental

Elimination of 3rd and 5th Harmonic



3rd harmonic free $v_x(t)$
(+ve and -ve areas cancel)

Need to take a bite out of the negative area while keeping 3rd harmonic areas in balance

5th & 3rd harmonic free $v_x(t)$
(+ve and -ve areas cancel)

These notches don't disturb the 3rd harmonic content as they take equal +ve & -ve area out the 3rd harmonic waveform