3b Fundamental of switching power converters and EMT

Modules for Maturing HVDC Electric Transmission Knowledge

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Prerequisite Competencies:	1. HVDC converter types and basics (Modules 1a, 1b, 1c) 2. VSC-HVDC converter station technologies (Module 2b)
Module Objectives:	Three one-hour lectures 1. Understand basics of power electronics converters 2. Analyze AC/DC converters 3. Simulate AC/DC converters in EMT simulation software tools

Abstract

HVDC is primarily a power electronics technology that processes power from one form of AC or DC to another. Therefore, understanding how this is done via power electronic converters is paramount to understanding HVDC technology. Power electronics operation is based on operation of switches and therefore inherently nonlinear---which is a major departure from the common mode of operation of the power system. However, their understanding can be greatly facilitated using the concept of voltage averaging to discuss technologies for achieving this conversion. Considering the fast timeline involved in converters, electromagnetic transient simulation of converters, different from phasor-based transient simulation, is important to understand.

This module provides an introduction to power electronics, emphasizing applications in HVDC technology and discusses how they can be analyzed and simulated. This module contains the following sections:

- Section 3b.1 provides an introduction and relevant references.
- Section 3b.2 introduces switching circuits and the concept of time averaging of voltages using a simple DC-DC example.
- Section 3b.3 takes the DC-DC example in the previous section and extends to create our very first DC-AC converter.
- Section 3b.4 discusses pulse width modulation (PWM) techniques for three-phase converters.
- Section 3b.5 provides example simulation results for a VSC system in PSCAD.

- Section 3b.6 summarizes the learning points of the module and concludes.

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Acronyms

AC	Alternating current
DC	Direct current
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistor
LCC	Line commutated converter
MVAr	Mega-volt-ampere-reactive
MW	Megawatt
PI	Proportional integral
PLL	Phase locked loop
VSC	Voltage source converter

3b-1 Introduction

High-voltage direct current (HVDC) transmission is a crucial technology for long-distance bulk power transfer, for offshore/underwater power transfer (e.g., offshore wind integration), and for interconnecting asynchronous grids. Power electronics lies at the heart of HVDC systems, enabling the conversion between AC and DC at high and even medium voltage levels, depending on the application. Modern HVDC links rely on power electronics converters that use high-power semiconductor switches (e.g., IGBTs, thyristors), as well as diodes and filter circuits (capacitors, inductors) and control systems to manage power flow by controlling current or voltage.

Power electronics converters can convert AC to DC and vice versa. When a converter performs AC to DC conversion, it operates in the rectification (rectifier) mode; when it performs DC to AC conversion, it operates in the inversion (inverter) mode. Note that the same converter hardware can operate in both modes depending on the direction of current or polarity of voltage, even when unidirectional switches are used.

Power electronic converters for HVDC can handle enormous power levels – individual units rated up to 2 GW and 1000 kV have been built, e.g., the 2,000 MW England–France interconnector linking the British and French transmission systems, the 1,000 MW BritNed interconnector between Britain and The Netherlands, Bipolar ±450 kV HVDC link (2,000 MW) underground/overhead from Quebec to Massachusetts, 8,000 MW ±800 kV UHVDC line over 2,000 km transmitting hydropower to eastern China. Multiple converters are often combined in series and/or parallel combinations to achieve even high ratings if the application warrants it.

HVDC links depend entirely on converter stations at each end to exchange power. These stations use line-commutated thyristor converters in classical HVDC or self-commutated transistor-based converters in modern voltage-sourced converter (VSC) HVDC. The choice of power electronic technology defines the HVDC system's characteristics. For example:

- **Line-Commutated Converters (LCC HVDC):** Use thyristors that turn on based on the grid's voltage and a firing signal and turn off when their current drops to zero. LCC systems are a mature technology and are very efficient at high power but require strong AC grids to (i) provide their reactive power demand, and (ii) ensure a high-quality line voltage, for commutation. Due to their operation at the network frequency (50 Hz or 60 Hz), they also produce harmonics, which requires filters to mitigate.
- **Voltage-Sourced Converters (VSC HVDC):** Use fully controllable switches like IGBTs, which can turn on/off based on a command signal (also called gating or firing signal). VSC-based HVDC (introduced in the late 1990s) enables independent control of real and reactive power, black-start capability, and better power quality due to high-frequency pulse-width modulation (PWM). This makes VSC suitable for connecting weak grids, offshore wind farms, and multi-terminal HVDC networks. ABB-Hitachi called VSC HVDC the HVD Light product. Siemens call is HVDC PLUS.

Both LCC and VSC stations incorporate similar passive components for filtering (although with different sizes and center frequencies), alongside the active switches:

- **Semiconductor switches:** High-power thyristors (LCC) or IGBTs (VSC) are arranged in valve groups. Modern devices can handle thousands of volts each; series-stacking allows operation up to hundreds of kV DC. Diodes are often connected anti-parallel to each transistor to carry current when the transistor is off; this also provides a freewheeling path for inductive loads as discussed later.

- **Transformers:** HVDC converters connect to AC systems via large transformers. These step up/down voltages and provide isolation. LCC stations use transformers, often in an indigenous 12-pulse configurations with phase-shifting windings, to reduce harmonics while operating at line frequency. VSC stations include converter transformers to match AC voltage and to provide a neutral ground reference (wye-delta connections).

- **Reactors and Inductors:** Converter reactors (series inductances) are used especially in VSC stations to limit fault currents and control the rate of current change. They also form part of the filter to reduce high frequency switching harmonics. Smoothing inductors on the DC side reduce DC current ripple, especially for reducing interference with telecommunication lines, for both LCC and VSC HVDC.

- **Capacitors:** On the DC side of VSC converters, large DC capacitors act as an energy reservoir to stabilize the DC voltage and provide ride-through capability. On the AC side, AC filter capacitors are used (particularly in LCC) to filter out high-order harmonics and to supply reactive power to the converter.

- **Filters:** Both AC and DC filters are employed. LCC HVDC requires extensive AC filters to absorb characteristic 12-pulse harmonics (e.g., 11th, 13th), whereas VSC HVDC (with PWM) generates higher frequency switching harmonics that are filtered with tuned filters targeting specific frequencies.

Key Texts and Standards: HVDC technology has a rich literature. Classic references include textbooks <include examples>. These texts provide foundational understanding of power electronic converters in HVDC. Additionally, industry standards and guides ensure best practices:

- *IEEE Std 1899-2017* – IEEE Guide for HVDC: Establishes basic requirements for protection and control of HVDC transmission systems. It covers standard definitions, equipment ratings, and design principles for HVDC control & protection equipment.

- *IEC/IEEE 60076-57-129:2017* – HVDC Converter Transformers: Specifies requirements for the special transformers used in HVDC converter stations (able to handle DC bias, harmonics). Other relevant IEC standards (e.g., IEC 61975 for HVDC system tests, IEC 60633 for HVDC definitions) standardize various aspects of HVDC engineering.

- *CIGRÉ Technical Brochures*: The international body CIGRÉ has published many guides on HVDC, e.g. a compendium of worldwide HVDC projects and best practices in converter design and testing. These provide practical insights and field experience which complement academic textbooks.

Advances in semiconductor devices and converter topologies have driven HVDC development – from mercury-arc valves in the 1940s, to thyristor LCC schemes (1970s onward), to today's VSC systems using IGBTs (since 1997). Considering that HVDC is primarily a power electronics technology that processes power from one form of AC or DC to another, understanding how this is done via power electronic converters is paramount to understanding HVDC technology.

Power electronics operation is based on operation of switches and therefore is inherently nonlinear---which is a major departure from the common mode of operation of the power system. However, their understanding can be greatly facilitated using the concept of voltage averaging to discuss technologies for achieving this conversion. Considering the fast timeline involved in converters, electromagnetic transient simulation of converters, which is different from phasor-based transient simulation, important to understand.

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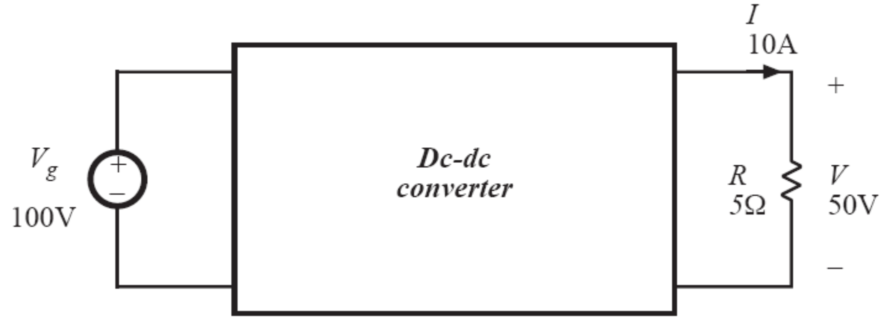
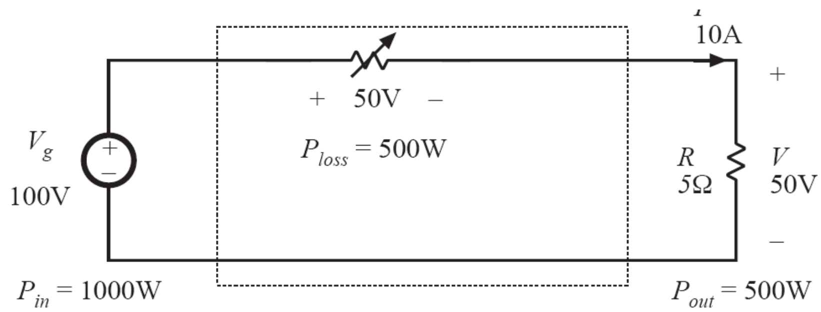
3b.2: Switching Circuits and Time-Averaging of Voltage

At the core of all power electronic converters is the principle of high-frequency switching. By turning semiconductor devices on and off rapidly, a converter can modulate an output voltage or current. The time-average of this switched waveform (filtered by inductors/capacitors) produces a desired DC or AC value. This section introduces switching converters using a simple DC-DC example and explains how time-averaged output voltages are determined by the switch duty cycle. Understanding this lays the groundwork for more complex converters used in HVDC.

Realization of a DC-DC Converter



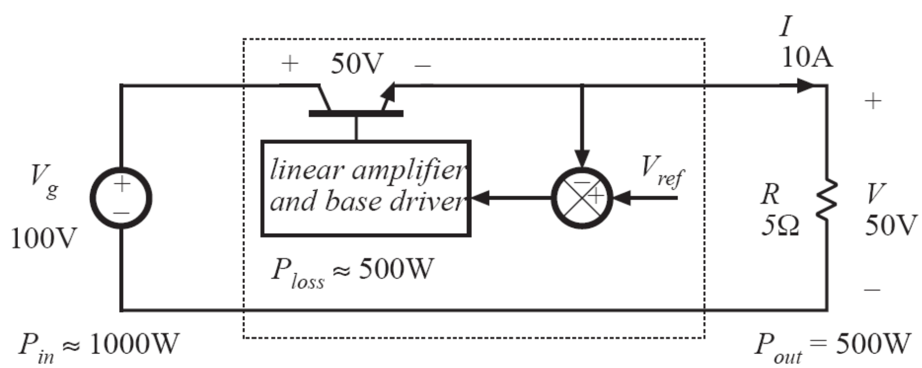
7a-1.1 Solution 1: Resistive Voltage Divider



This is a good, simple, and workable solution, but there are drawbacks:

1. Voltage is out easily adjustable
2. Losses are high (50% in this example)
3. Output voltage changes as more loads are added.

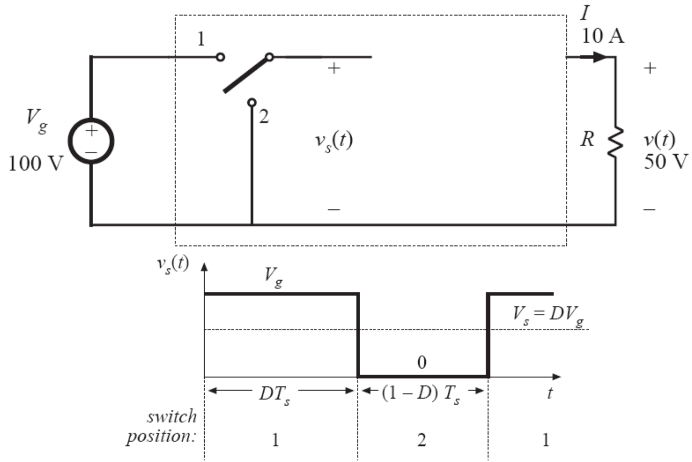
7a-1.2 Solution 2: Microelectronics (transistor in active region)



This can be a better solution as now the voltage is more easily adjustable but

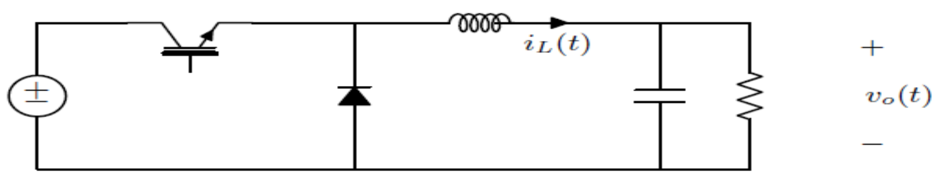
1. Losses are still high (50% in this example).

7a-1.3 Solution 3: Power electronics



This solves the problems mentioned above but needs further analysis as the circuit is now nonlinear.

DC-DC Buck Converter Example: A buck converter (step-down converter) is a basic circuit that converts a DC input voltage Vin to a lower DC output voltage Vout. It consists of a high-speed power electronics switch that connects and disconnects the input to an inductor, a diode, and output capacitor/filter feeding the load.



When the transistor switch is on, current flows from the DC source through the switch and inductor to the load, energizing the inductor. When the switch turns off, the inductor's current continues to flow through the diode into the load, and the inductor discharges its energy into the load and capacitor. In the buck converter:

- In the on state, the switch (S) is closed, applying Vin across the inductor-load series combination. The inductor current iL rises as energy is stored in the inductor's magnetic field. The output capacitor also charges and helps supply the load.
- In the off state, the switch opens, disconnecting the input. The inductor's current cannot change instantaneously, so it commutates through the diode (D) into the load. The inductor releases energy, sustaining current flow. The output capacitor also discharges slightly, supporting the load voltage.

By adjusting the fraction of time the switch is on (the duty cycle D = ton/T, where T is the switching period), we control the average output voltage. In the steady state (continuous conduction mode), the average output voltage is

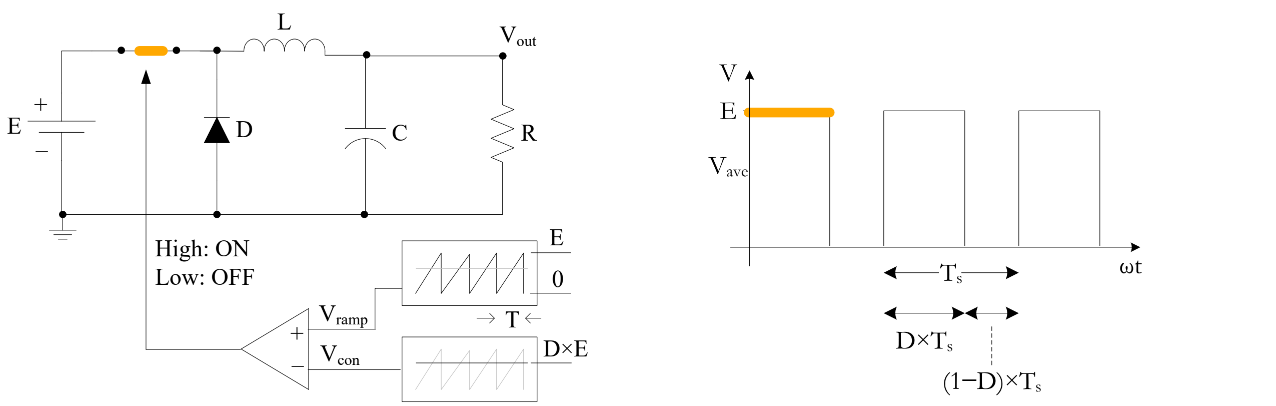
Vo = D Vin,

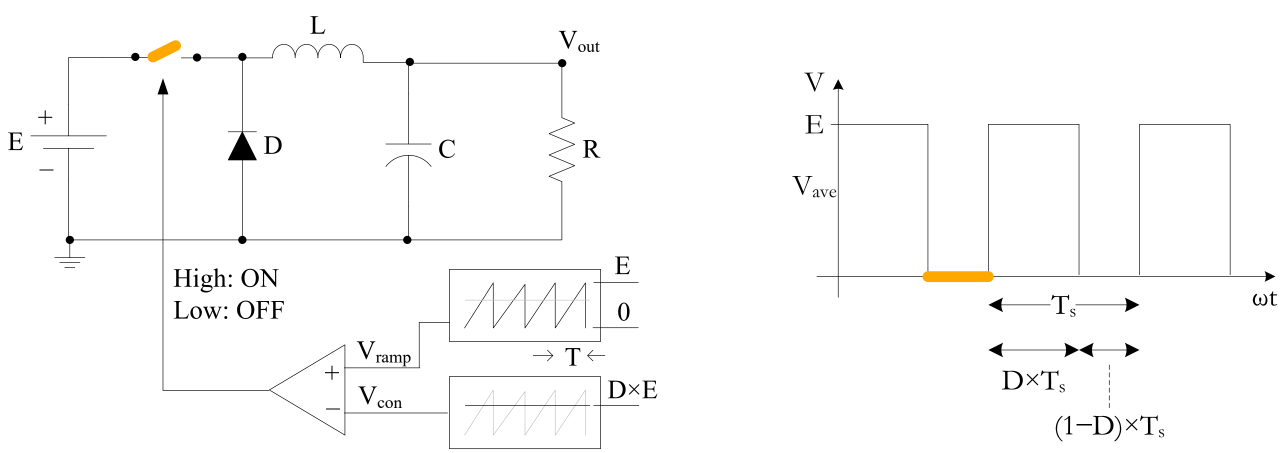
for an ideal buck converter. In a real buck converter, the voltage is slightly lower because of switching delays, conduction losses across the switch and inductor, and other stray losses. Therefore, for example, 50% duty cycle yields roughly 0.5·Vin at the output. The output filter (inductor and capacitor) smooths the pulsating waveform, so the load sees a nearly DC voltage with small ripple. Essentially, the fast ON/OFF switching, when averaged over time (assuming the switching frequency is much higher than the load's response), behaves like a variable DC voltage source but on average.

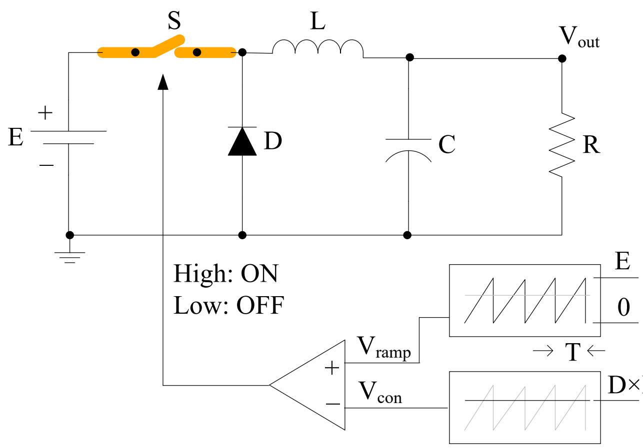
Time-Averaged Voltage and Waveforms: The output of the switching converter is a pulse-width modulated waveform. The inductor acts as an energy buffer, converting the chopped DC into a smoother current. In steady state, the inductor current ramps up during on (storing energy) and ramps down during off (releasing energy). Over one full cycle, the net change in inductor current is zero (periodic steady state).

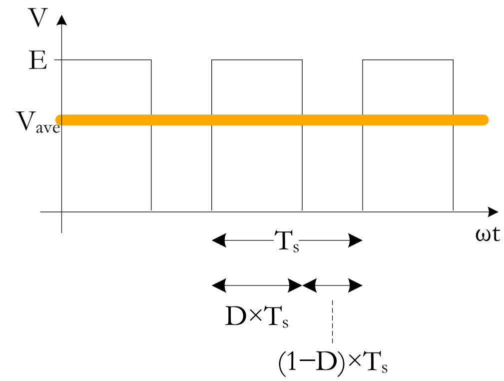
The capacitor filters the voltage by providing or absorbing current to limit the output voltage ripple. It supplies current to the load when the switch is off, and recharges when the switch is on.

The diode provides the return path for current when the switch is off, effectively clamping the inductor output to the load during the off phase (preventing the inductor from driving the voltage negative).









Example: Suppose Vin = 400 V and we desire Vout = 200 V. By setting D = 0.5, the switch is on half the time and off half the time, yielding an average of 200 V at the output (ignoring losses). During each switching cycle:

- For the on half-cycle, the inductor current increases as 400 V is applied.
- For the off half-cycle, the inductor current decays through the diode into the 200 V load.

If the switching frequency is high (e.g., several kHz or higher), the output capacitor filters the 400 V pulses into a near-DC 200 V with only a small triangular ripple (the magnitude of ripple depends on the switching frequency, inductor size, capacitor size, and load).

NOTE: A DC converter is not directly used in HVDC applications. This example is for illustration and to understand the basics of voltage conversion using power electronics circuits. However, DC converters can be thought of the building block of HVDC converters as discussed below.

Relevance to HVDC: DC converter principles are directly relevant to HVDC converter building blocks as we will see next by converting this buck converter to a VSC!

- In **VSC HVDC,** each phase-leg of a two-level VSC is essentially a high-power *bidirectional* buck or boost converter, generating a controlled AC waveform from a DC bus by alternating between connecting the phase to positive DC and negative DC (this is effectively two buck converters back-to-back forming an H-bridge, as discussed next).
- The concept of time-averaged switching is embodied in pulse width modulation (PWM), which we will explore in Section 3b.4. By controlling duty cycles, HVDC converters regulate their output voltages/currents and thus control power flow.

Example:

If an HVDC VSC station needs to generate a 1.0 pu AC voltage (say 1.0 pu = 320 kV line-to-line RMS) from a 640 kV DC link, the theoretical duty cycle for the fundamental component (in a two-level converter) would be 50% for each half-cycle to produce a square wave approximating the AC. Using modulation (e.g., sinusoidal PWM) the effective duty varies within each half-cycle sinusoidally to synthesize a near-sinusoidal output. But at the simplest level, the converter is rapidly switching each phase between +Vdc/2 and –Vdc/2, and the average over a half-cycle equals the desired AC half-cycle waveform.

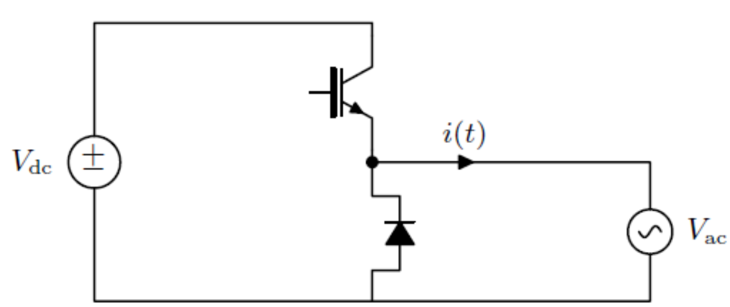
In summary, a switching DC-DC converter illustrates how controlled switching yields a desired average voltage. The buck converter's Vout = D Vin (ideal case) is a fundamental result. Similar analysis applies to other basic converters (boost, buck-boost), which use time averaging of switch states to step voltages up or down. Mastering this concept is essential before moving to DC-AC inverters and PWM control strategies in HVDC systems.

3b.3: Extending to DC-AC Converters (Half- and Full-Bridge Inverter Topology)

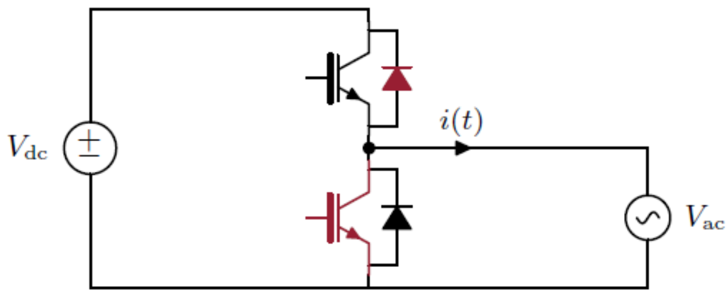
Using the principles from DC-DC converters, we can create DC-AC converters (inverters) by arranging switches to produce an AC output. The simplest inverter for single-phase AC is the half bridge topology. An H-bridge (full-bridge) topology is formed when the output of two H-bridges is used. This section builds from the DC-DC example to explain how an H-bridge generates AC from a DC source, and why this is important for HVDC (which ultimately must interface with AC systems).

Half Bridge Inverter Basics:

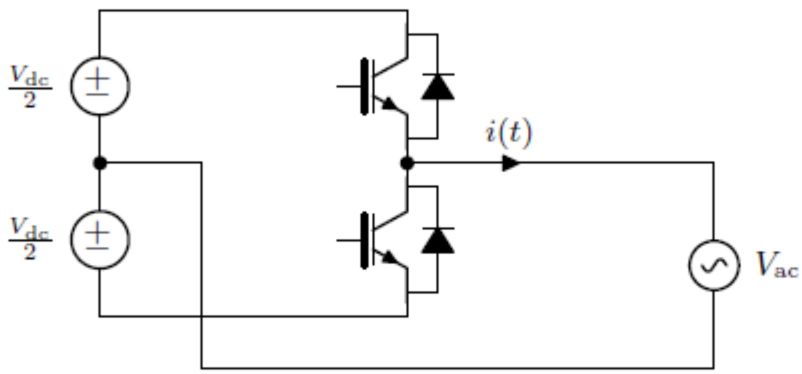
- Redraw our buck converter to make it easier to visualize



- Bidirectional Current. Need to add antiparallel switches to allow current to flow in both directions



- Bidirectional Voltage. Need to adjust the reference point of the voltage.



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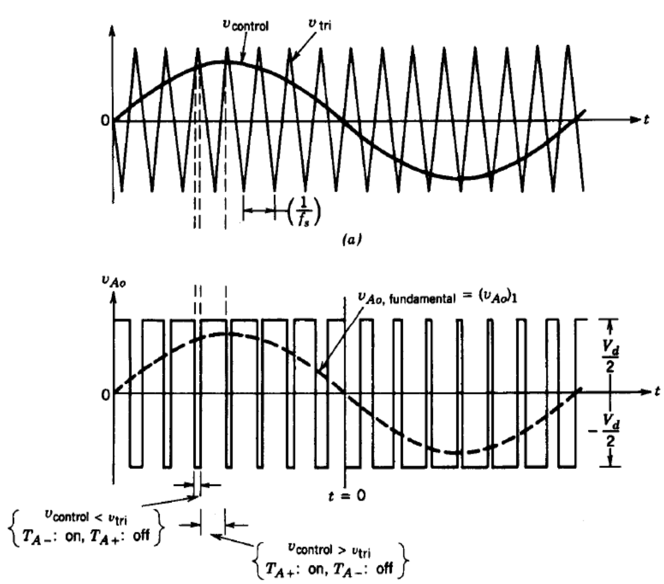
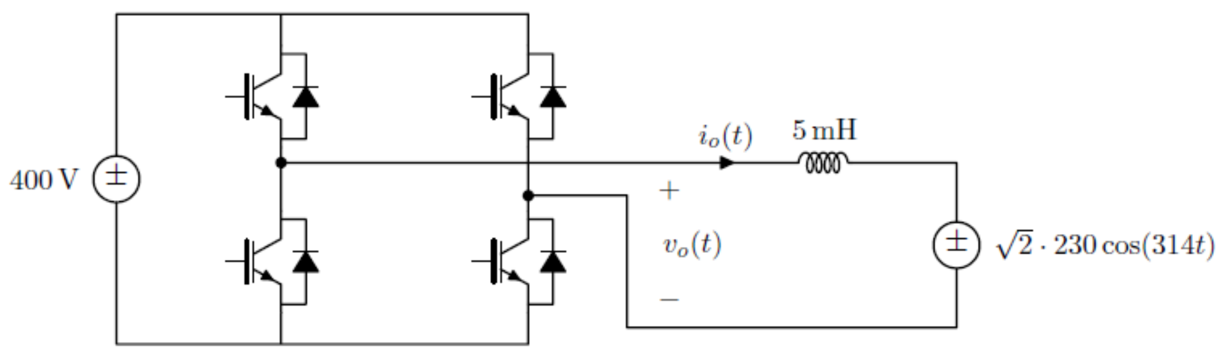
To generate a sinusoidal output, we change the constant duty cycle D to a sinusoidally changing duty cycle d(t) based on the concept of PWM as illustrated below.



H-Bridge Inverter Basics: An H-bridge consists of four switching devices in an H configuration. By closing two switches at a time, we can connect a DC source to a load in either polarity. Essentially, the H-bridge alternates the direction of current through the load, creating an AC voltage from a DC supply.



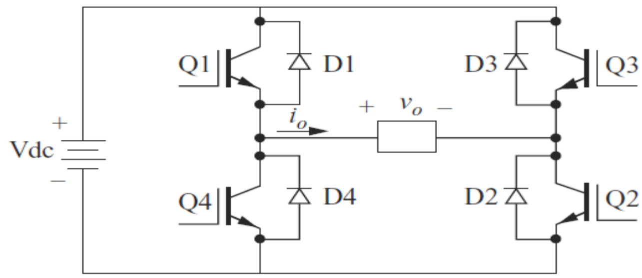
When the top-left and bottom-right switches are on, connecting the load to +Vdc/2 on the left and –Vdc/2 on the right, resulting in a positive output voltage across the load. Alternatively, when the top-right and bottom-left switches conduct, the polarity across the load reverses (–Vdc/2 on left, +Vdc/2 on right) to produce a negative output voltage. By toggling between these two states, a bipolar AC voltage is delivered to the load.

In an HVDC VSC station, each phase leg of the converter is equivalent to a half-bridge or full-bridge inverter:

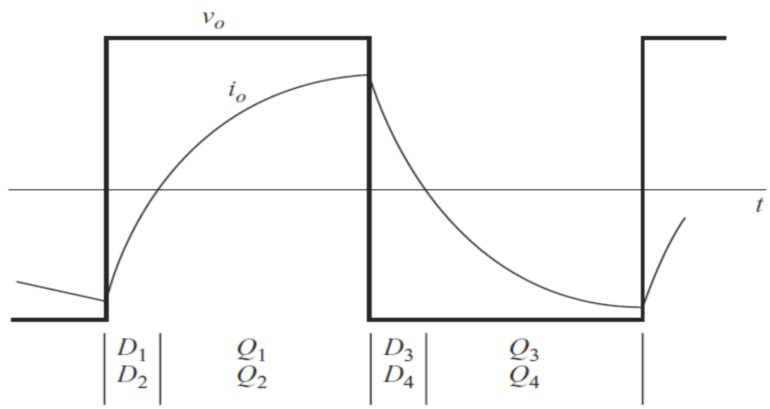
- A half-bridge has two switches and can create a two-level voltage (either +½Vdc or –½Vdc at output relative to mid-point).
- A full-bridge (H-bridge) per phase would use four switches and can apply +Vdc or –Vdc across the phase, effectively doubling the voltage range. Most three-phase VSCs use a configuration of three half-bridges (one per phase), but conceptually we can think of a phase leg as generating an AC waveform by switching the polarity of a DC voltage.

Operation of the H-Bridge: There are typically two active states (as discussed above) and states where all switches are off (or a pair of same-leg switches conduct to produce zero voltage as needed in certain modulation schemes):

- When switches S1 and S4 (top-left and bottom-right in the H pattern) are closed, and S2 and S3 are open, the load sees +Vdc across it (positive terminal at left, negative at right).
- When S2 and S3 (bottom-left and top-right) are closed instead, the load sees –Vdc (polarity reversed).
- By alternating between these two states, the inverter outputs a square-wave AC voltage: +Vdc during one half-cycle and –Vdc during the other half-cycle. This creates a bipolar voltage waveform.



(a)



(b)

If the H-bridge switches at the fundamental frequency (60 Hz in the United States), the output is a 60 Hz square wave. This contains the desired fundamental component (a sine wave of the same amplitude as the square wave's fundamental) plus odd harmonics. In practice, we usually switch much faster and use PWM to shape the waveform (next section), but even the basic two-state operation demonstrates the principle of DC-AC conversion.

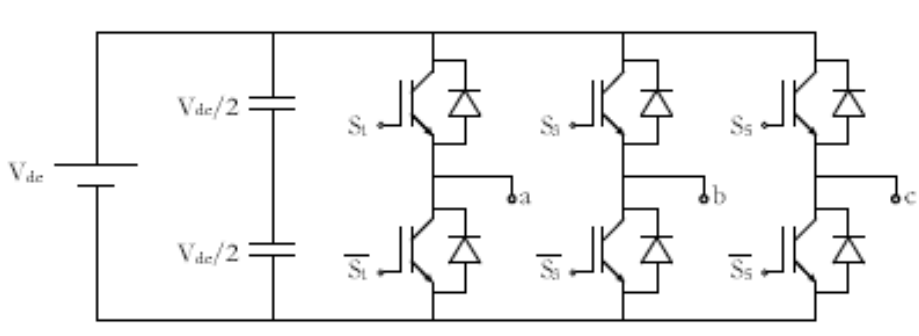
One thing worth noting for both the half and full-bridge circuits is the need for diodes to allow current to flow in a direction opposite to the applied voltage. The load may be inductive, and so it will continue moving current regardless. Without the diodes, we could damage our circuitry. In the waveform at the bottom, you can see how current still flows against its voltage level, even after the voltage switch has been applied by the control circuitry.

Output Filtering: The raw output of an H-bridge is a square wave (or a PWM-based waveform) that needs filtering to become a sinusoidal AC suitable for the grid or load. In HVDC converters:

- The AC filter (composed of inductors, capacitors, sometimes resistors) is connected at the converter output to absorb switching harmonics and smooth the waveform. For example, an LC filter can attenuate the high-frequency components, leaving a nearly sinusoidal 60 Hz voltage.

- In many VSC HVDC designs, the leakage inductance of the converter transformer and additional filter inductors serve to filter the output. Often, high-order harmonics (at multiples of the PWM frequency) are filtered by tuned filters or simply by the inductive reactance of the system at those frequencies.

Three-Phase Inverters: While the H-bridge illustration is single-phase, a three-phase inverter (as used in HVDC) consists of three phase legs, each similar to a half-bridge. Each phase leg connects one AC terminal of the converter to the positive or negative DC bus. By controlling the switching in each leg, three-phase AC output waveforms are generated. A basic three-phase two-level VSC uses six switches (IGBTs) – two per phase leg. For example, Phase A leg can connect the Phase A output either to +Vdc or –Vdc, producing a line-to-neutral voltage of +½Vdc or –½Vdc (assuming a neutral at mid-point of DC bus or using a split capacitor DC bus). Combining the switching of three legs with appropriate phase shifts (120° apart) yields a three-phase AC system output.



The H-bridge concept can also be extended: in modular multilevel converters (MMC), many submodule H-bridges are cascaded to synthesize a very fine-stepped waveform with very low harmonics, but the basic idea of each submodule is still to generate a piece of AC from DC by controlled switching.

Time Averaging in Inverters: Similar to the buck converter analysis, the inverter's output fundamental magnitude is related to the DC voltage and the effective duty cycle of how long the output is at +Vdc vs –Vdc. For a simple square wave inverter:

- The fundamental AC voltage (rms) is $V_{AC,rms}$ = Vdc/2 for a square wave (the fundamental of a ±Vdc square wave is 4/π times the DC half-value.
- Using PWM (next section) we can adjust the effective duty cycle within each half-cycle to control the fundamental amplitude smoothly (not just full ±Vdc). When the duty cycle (or modulation index) is less than 100%, the fundamental AC output is proportionally lower.

Relevance to HVDC: An HVDC converter station's core is a large three-phase inverter/rectifier. In rectifier mode, it takes AC and uses an H-bridge-like action (via phase-controlled thyristors or PWM IGBTs) to produce DC. In inverter mode, it takes DC and inverts to AC. Understanding the H-bridge helps explain:

- How VSC HVDC converters can create a controllable AC voltage in phase with the grid (to export power) or 180° out of phase (to import power).
- The need for commutation and dead-times: In a practical inverter, we never turn on both switches of one leg at the same time, and we include brief dead-time when switching to avoid shorting the DC bus. This is managed by gate drive timing in HVDC converters.
- Reactive power control: By adjusting the phase of the AC output relative to the grid, and the amplitude of the output (via modulation index, m), the converter can control not only real power (P) but also reactive power (Q). For example, if the converter's generated voltage is slightly higher magnitude than the grid and in phase, it will supply reactive power as well as real power.

In summary, the DC-AC inverter extends the concept of high-frequency switching to generate AC waveforms. The H-bridge provides the simplest conceptual template for how HVDC converters invert DC to AC. With this foundation, we can now discuss how pulse-width modulation is used to finely control the output waveform and achieve high power quality in HVDC applications.

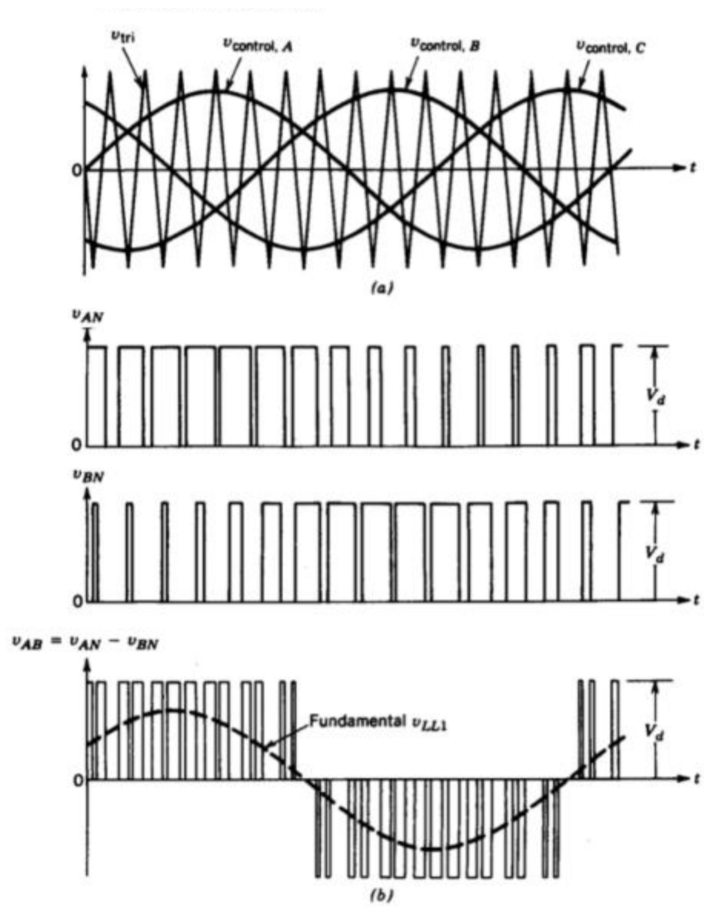
7a-2 Pulse Width Modulation (PWM) for Waveform Generation in VSCs

Simply switching an inverter at the line frequency (producing a square wave) is inadequate for most applications due to poor waveform quality and high harmonic content. Pulse width modulation (PWM) is a fundamental technique that modulates the duty cycle of switching devices within each cycle to synthesize a desired waveform (typically sinusoidal) at the output. This section discusses PWM strategies used in three-phase HVDC converters, focusing on sinusoidal PWM (SPWM) and space vector PWM (SVPWM). We will compare their principles, advantages/disadvantages, and include waveform illustrations.

Sinusoidal PWM (SPWM): This is the most straightforward PWM method. In SPWM, a sinusoidal reference waveform (the desired AC output voltage) is compared with a high-frequency triangular (carrier) waveform. The comparator generates switch gating signals: whenever the sinusoid (modulating signal) is above the triangle wave, one switch is turned on (output = +Vdc/2 for that leg), and when below, the other complementary switch is on (output = –Vdc/2). By doing this for each phase with 120° phase-shifted sinusoidal references, a three-phase PWM output is obtained.

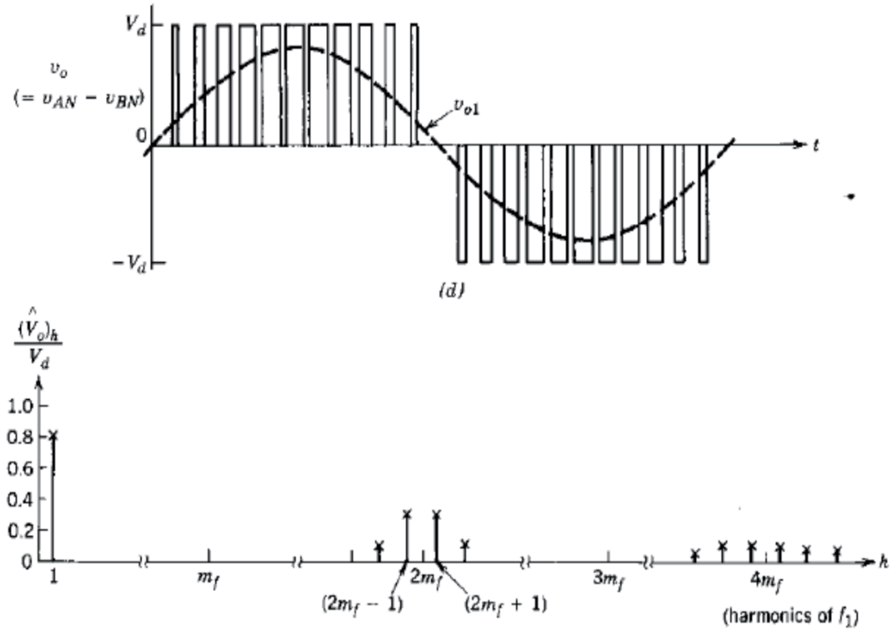
- The ratio of the reference amplitude to the carrier amplitude is the modulation index (m). When m=1.0 (reference peak equals carrier peak), the fundamental output voltage is maximized (just before pulse dropping occurs).

- The carrier frequency is typically many times the fundamental (e.g. a PWM frequency of several hundred to a few hundred Hz for HVDC converters, versus 60 Hz fundamental). A higher carrier frequency results in more but thinner pulses each half-cycle, reducing lower-frequency harmonic distortion at the expense of higher switching losses.
- SPWM is easy to implement and understand. It can be done with analog circuits (voltage-controlled oscillators and comparators) or digitally by calculating the intersection instants.



The top plot shows the sinusoidal reference and the high-frequency triangular carrier. The bottom three plots show the resulting PWM output voltage for phase A, for phase B, and for a full H-bridge leg, switching between +Vdc and –Vdc. The duty ratio of the output pulses within each 60 Hz cycle varies in proportion to the reference sine wave, producing an effective sinusoidal voltage after filtering.

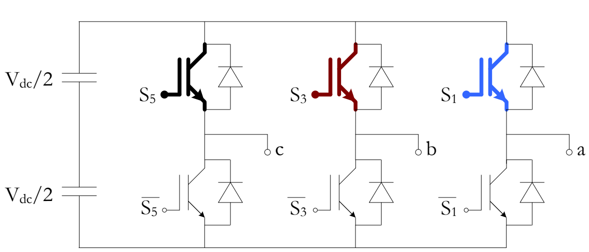
As seen above, near the zero-crossings of the reference sine, the pulses are narrow (low duty cycle), and near the peaks of the sine, the pulses are wide (high duty cycle). After filtering, the fundamental of this PWM waveform is a sine wave. The unwanted switching harmonics will cluster around the carrier frequency (and its multiples). In a well-designed system the PWM frequency is chosen to shift significant harmonics to a range easily filtered by small filters (e.g., several kHz, where inductors and capacitors can attenuate). The THD (total harmonic distortion) of the output can be very low (a few percent) if the modulation index is kept in the linear range (below overmodulation) and if filtering is adequate.

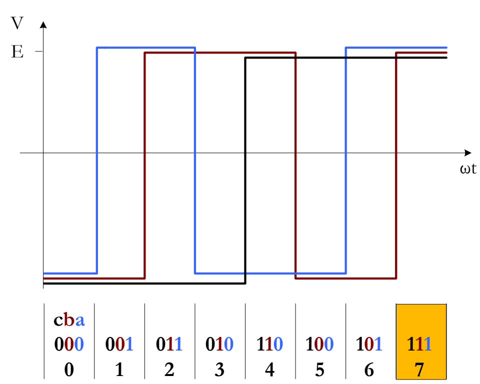


Space Vector PWM (SVPWM): Space Vector Modulation is a more advanced digital technique that treats the three-phase inverter as one unit and calculates the exact switching times to synthesize a desired three-phase voltage vector. Instead of modulating each phase independently with a sine wave, SVPWM considers the space vector representation of the three-phase AC voltages.

$$\mathbf{V} = \frac{2}{3}\left(v_{\mathrm{a}}(t) + v_{\mathrm{b}}(t)e^{j2\pi/3} + v_{\mathrm{c}}(t)e^{-j2\pi/3}\right)$$

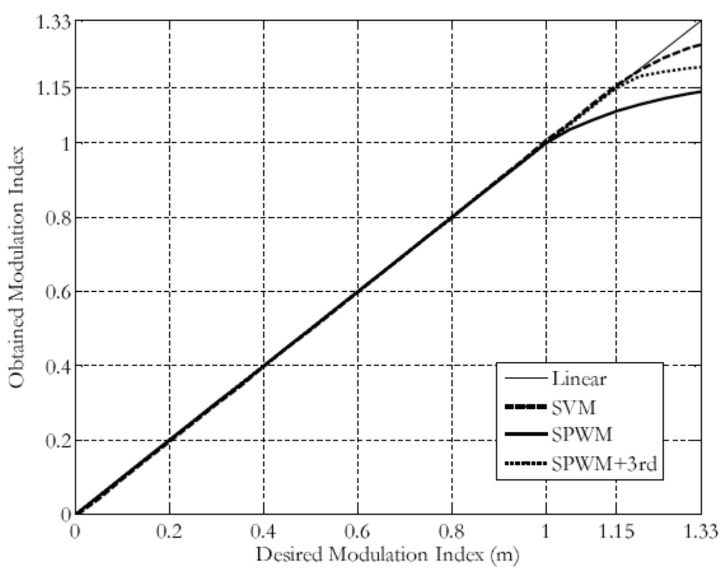
In a two-level inverter, there are 8 possible switch states (2^3): 6 active states (each produces a non-zero voltage space vector) and 2 zero states (both upper or both lower switches on, producing zero voltage vector). SVPWM works by determining which two active vectors the desired reference vector lies between, and how long to apply each, plus the zero vectors, within each PWM period.





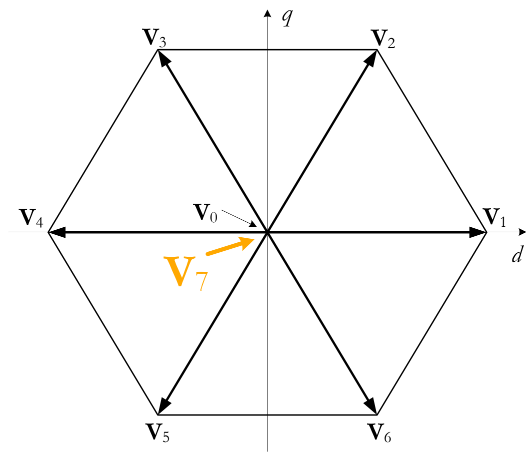
State	c, b, a	**V**	Pole Voltage, multiply by $V_{dc}/2$			Phase Voltage		
			V_{az}	V_{bz}	V_{cz}	V_{an}	V_{bn}	V_{cn}
0	**000**	0	-1	-1	-1	0	0	0
1	**001**	$2V_{dc}/3e^{j0}$	1	-1	-1	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
2	**011**	$2V_{dc}/3e^{j\pi/3}$	1	1	-1	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$
3	**010**	$2V_{dc}/3e^{j2\pi/3}$	-1	1	-1	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$
4	**110**	$2V_{dc}/3e^{j\pi}$	-1	1	1	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$
5	**100**	$2V_{dc}/3e^{j4\pi/3}$	-1	-1	1	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$
6	**101**	$2V_{dc}/3e^{j5\pi/3}$	1	-1	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$
7	**111**	0	1	1	1	0	0	0

SPWM achieves a higher utilization of DC voltage than SPWM. The maximum line-to-line voltage amplitude with SPWM is ~0.78 Vdc (sinusoidal modulation limit, for m = 1), whereas SVPWM can reach ~0.90 Vdc (for m = 1.15 (about 15% higher) for the same DC bus. In practical terms, SVPWM can produce a given AC voltage with a lower DC voltage, or for a given DC, deliver more AC voltage before reaching the limit.



Switching events are optimized: SVPWM minimizes the number of switch transitions per cycle by using the zero states optimally and sequencing the vectors to avoid unnecessary switching. This can reduce switching losses slightly or balance thermal loading on devices.

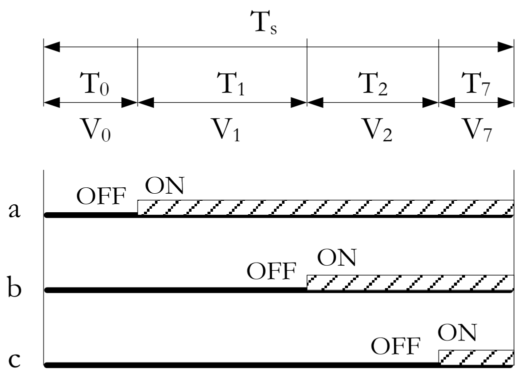
In SPWM, each phase is treated separately, whereas in SVPWM, the three-phase voltages are treated as a vector in a 2D plane (with 120° separated axes). The converter can output only certain discrete vectors (the six active states form six vectors spaced 60° apart in the complex plane, making a hexagon). The reference (desired) vector rotates to create the AC output. SVPWM at each small-time step applies the nearest two vectors that "surround" the reference vector, plus zeros, to average out to the reference.

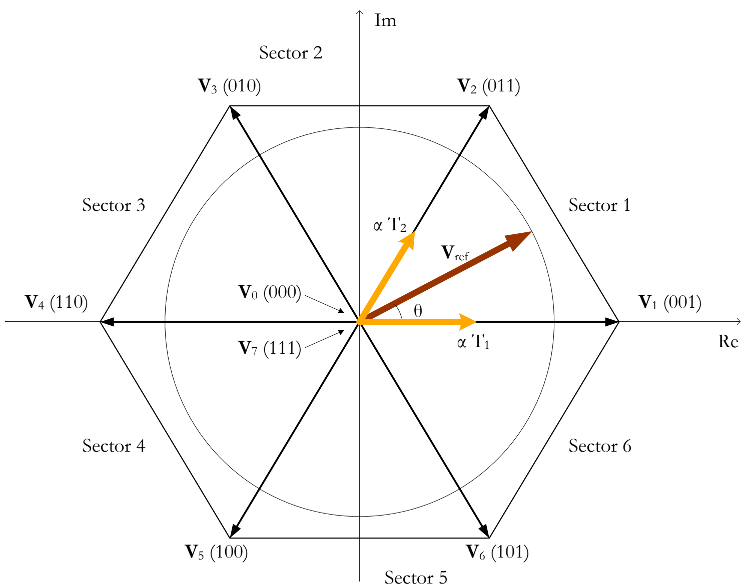


For example, if the reference is 30° from the horizontal axis inside the hexagon, SVPWM will spend a portion of time on the two adjacent active states (at 0° and 60°) proportional to how close the reference is to each, and the remainder of the time in a zero state. Over the PWM period, the average is the desired vector.

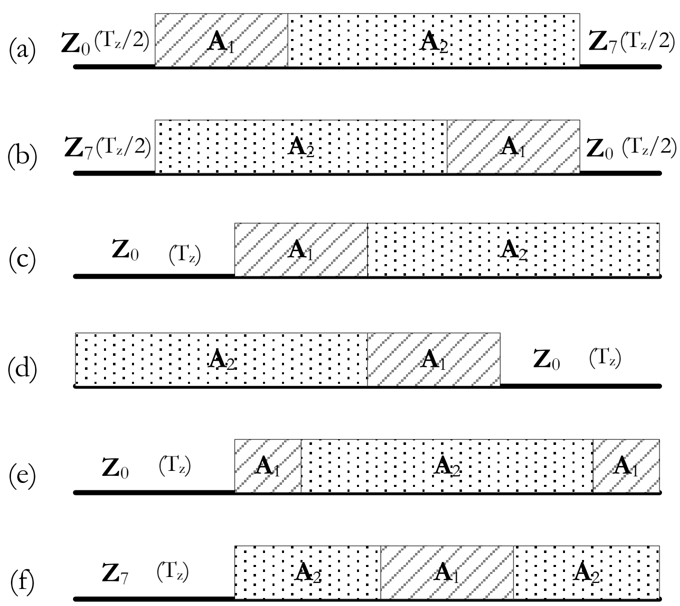
$$T_1 = \frac{\sqrt{3}}{2} \times T_s m \sin(\pi/3 - \theta)$$
$$T_2 = \frac{\sqrt{3}}{2} \times T_s m \sin(\theta)$$

$$T_0 + T_7 = T_z = T_s - T_1 - T_2$$





A degree of freedom in SVM is the individual shares of Z0, Z7 as well as placement of SVs within the sampling period. These can be decided based on the different harmonic performance requirements, number of switchings allowed, and losses.



7a-2.1 Other Modulation Methods

Most VSC-HVDC systems use a form of sinusoidal PWM or space-vector PWM (which can be seen as an optimized form of PWM) to control the valves. Typical switching frequencies for HVDC converters are in the range of a few hundred Hz up to a couple of kHz (e.g., 1350 Hz in a

50 Hz system). This is much lower than low-voltage drives (which often use 5-20 kHz) because HVDC valves handle very high power and switching losses must be limited.

To achieve low harmonics, the converters rely on both PWM and filtering. For instance, a 27th harmonic filter might be used on the AC side, indicating a 27x PWM frequency relative to fundamental (in that case 27*50 = 1350 Hz switching).

The gating signals are determined by a digital controller (typically a DSP or FPGA) that calculates the PWM timings in real-time, using either SPWM (by comparing a reference and carrier) or SVPWM (by performing space-vector calculations). Modern HVDC control systems often use SVPWM for the slightly improved performance, but SPWM is conceptually still the foundation.

With PWM, the output line-to-line voltage waveform of a VSC HVDC converter is a series of pulses. The *line current* (after filtering by inductance of system) is nearly sinusoidal. The main unwanted by-products are:

- High-frequency switching components (around the PWM frequency and its multiples). These are typically filtered out by small AC filters and by the leakage inductance of the converter transformer.
- Some non-characteristic harmonics if the modulation is unbalanced or during transient states, but under steady balanced conditions, a well-implemented PWM yields very low low-order harmonics (the dominant are around the switching frequency).

PWM allows HVDC converters to regulate DC voltage and AC power flow smoothly. By adjusting the modulation index, the converter changes its AC output magnitude (thus controlling power or reactive exchange). By adjusting the relative phase between the converter's AC output and the grid, it controls the power direction and amount (e.g. if the converter's AC voltage leads the grid, it injects power into the grid; if it lags, it absorbs power). The combination of these is often implemented through a control scheme that commands a certain modulation index and phase to maintain DC voltage or power setpoints.

In summary, PWM is the backbone of VSC HVDC control. Sinusoidal PWM provides a conceptually simple way to generate gate signals, while space vector PWM provides a more advanced method that improves DC utilization and harmonic performance. Both techniques, however, achieve the same goal: using high-frequency switching to create a low-frequency (50/60 Hz) AC output with controllable magnitude and phase. The next section will illustrate these concepts with simulation results, solidifying how an HVDC converter operates under PWM control.

Examples of other PWM alternatives include the following:

60-degree modulation:

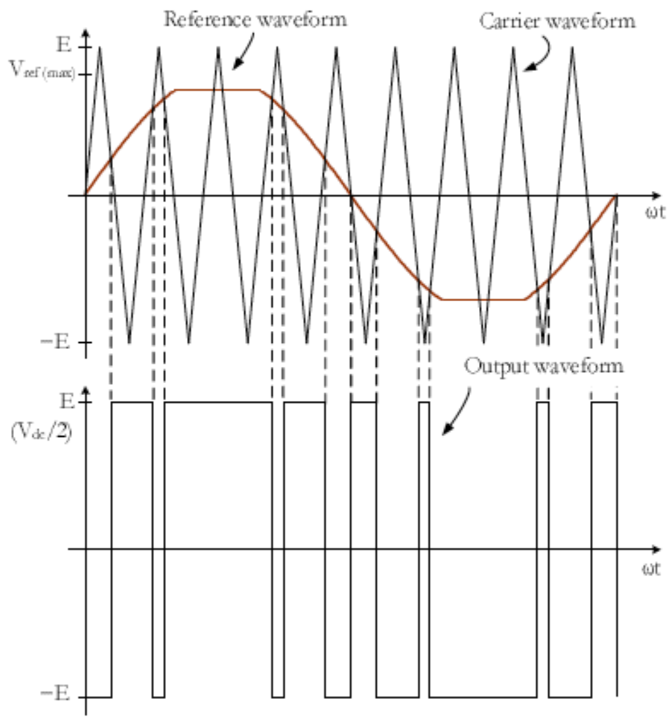


Fig. 3.3. 60-degree modulation.

Third-harmonic injection PWM:

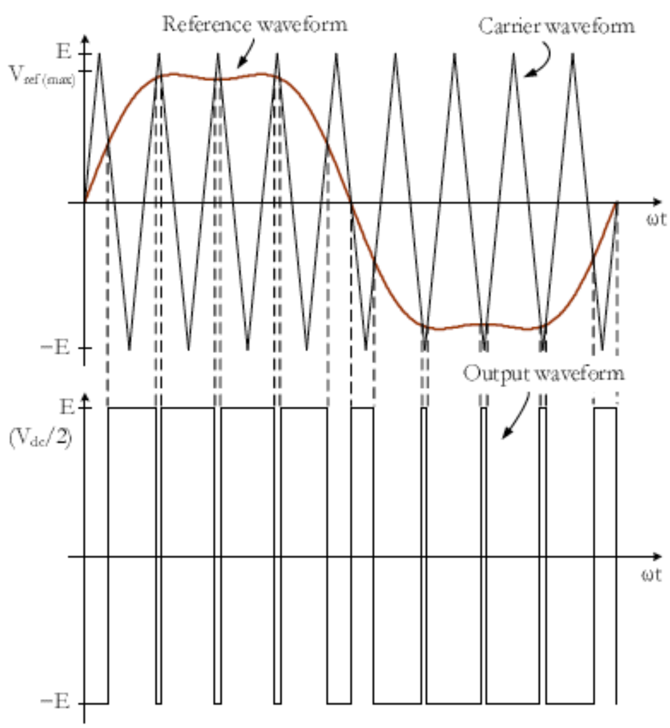


Fig. 3.5. Third-harmonic injection PWM.

Selection harmonic elimination (SHE): Bipolar

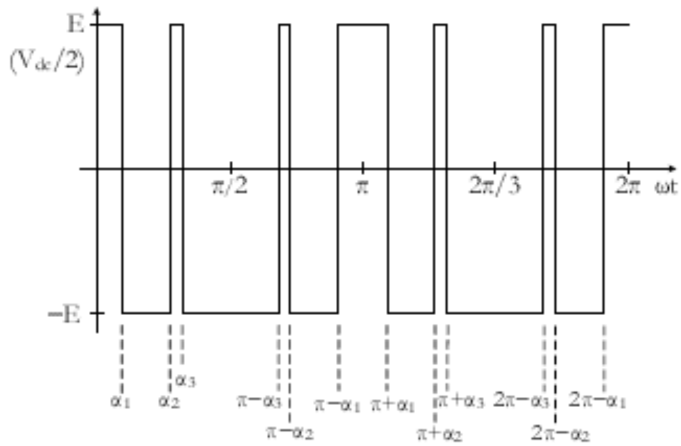


Fig. 3.7. Output voltage of a two-level, three–switching-angle SHE.

The equations governing bipolar SHE are as follows.

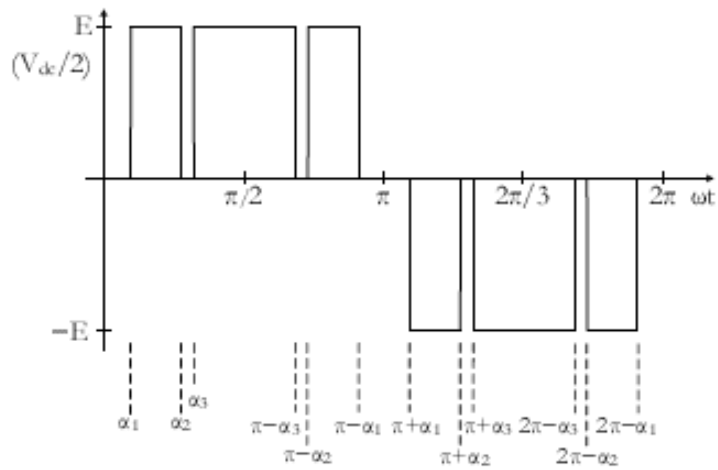
$$
\begin{aligned}
v(t) = \frac{2V_{dc}}{\pi}\Big\{&(1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 + \cdots)\sin\omega t \\
&+ (1 - 2\cos 3\alpha_1 + 2\cos 3\alpha_2 - 2\cos 3\alpha_3 + \cdots)\frac{\sin 3\omega t}{3} \\
&+ (1 - 2\cos 5\alpha_1 + 2\cos 5\alpha_2 - 2\cos 5\alpha_3 + \cdots)\frac{\sin 5\omega t}{5} + \cdots\Big\} \\
= \frac{2V_{dc}}{\pi}&\left\{\sum_{n=1,3,\ldots}^{\infty}\frac{\sin n\omega t}{n}\left[1 + 2\sum_{k=1}^{m}(-1)^k\cos n\alpha_k\right]\right\}
\end{aligned}
$$

$$
v_{1,\mathrm{rms}} = \frac{\sqrt{2}V_{dc}}{\pi}(1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3)
$$

$$
0 = (1 - 2\cos 5\alpha_1 + 2\cos 5\alpha_2 - 2\cos 5\alpha_3)
$$

$$
0 = (1 - 2\cos 7\alpha_1 + 2\cos 7\alpha_2 - 2\cos 7\alpha_3)
$$

Selection harmonic elimination (SHE): Unipolar



The equations governing unipolar SHE are as follows.

$$\begin{aligned} v(t) &= \frac{2V_{\text{dc}}}{\pi}\Big\{(\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3 + \cdots)\sin\omega t \\ &\quad + (\cos 3\alpha_1 - \cos 3\alpha_2 + \cos 3\alpha_3 + \cdots)\frac{\sin 3\omega t}{3} \\ &\quad + (\cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3 + \cdots)\frac{\sin 5\omega t}{5} + \cdots\Big\} \\ &= \frac{2V_{\text{dc}}}{\pi}\left\{\sum_{n=1,3,\ldots}^{\infty} \frac{\sin n\omega t}{n}\left[\sum_{k=1}^{m}(-1)^{k+1}\cos n\alpha_k\right]\right\} \end{aligned}$$

$$v_{1,\text{rms}} = \frac{\sqrt{2}V_{\text{dc}}}{\pi}(\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3)$$

$$0 = (\cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3)$$

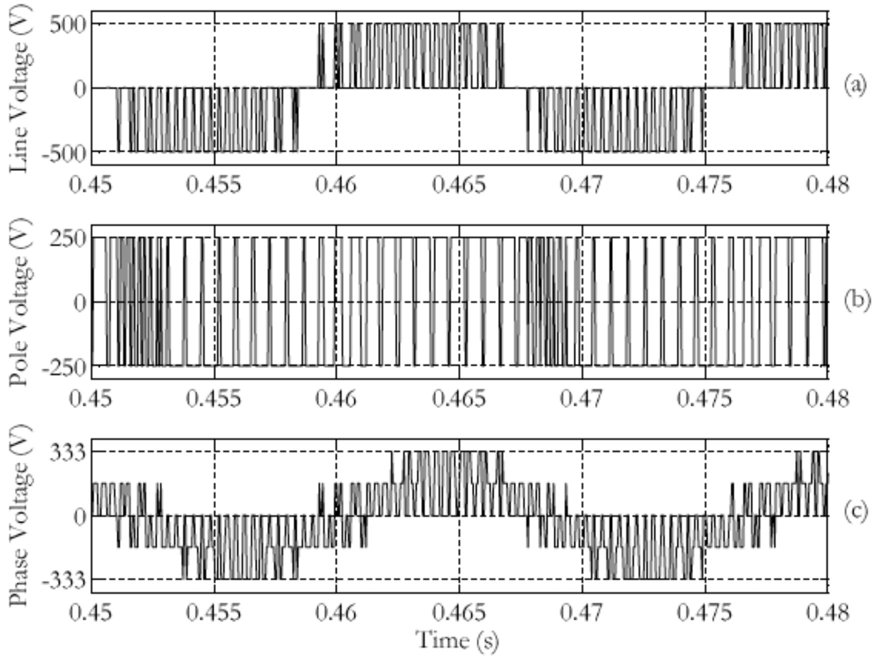
$$0 = (\cos 7\alpha_1 - \cos 7\alpha_2 + \cos 7\alpha_3)$$

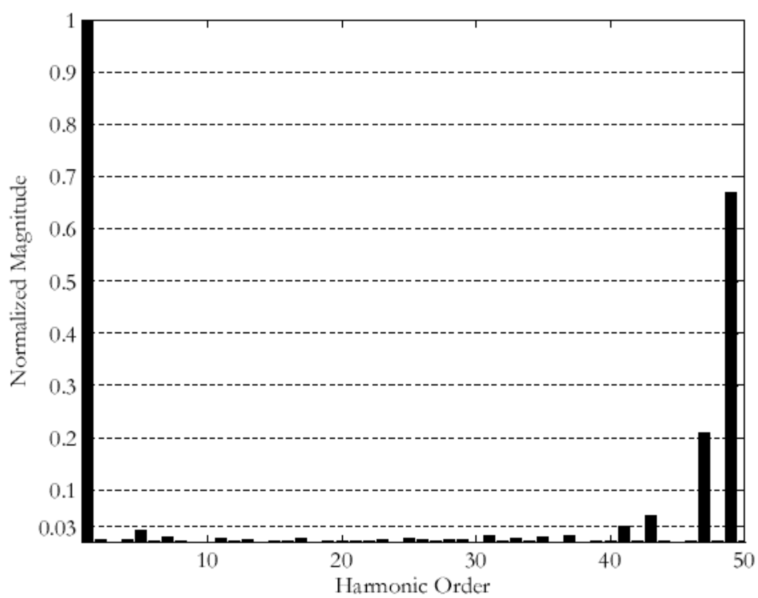
7a-3 Simulation Results of an HVDC System in PSCAD

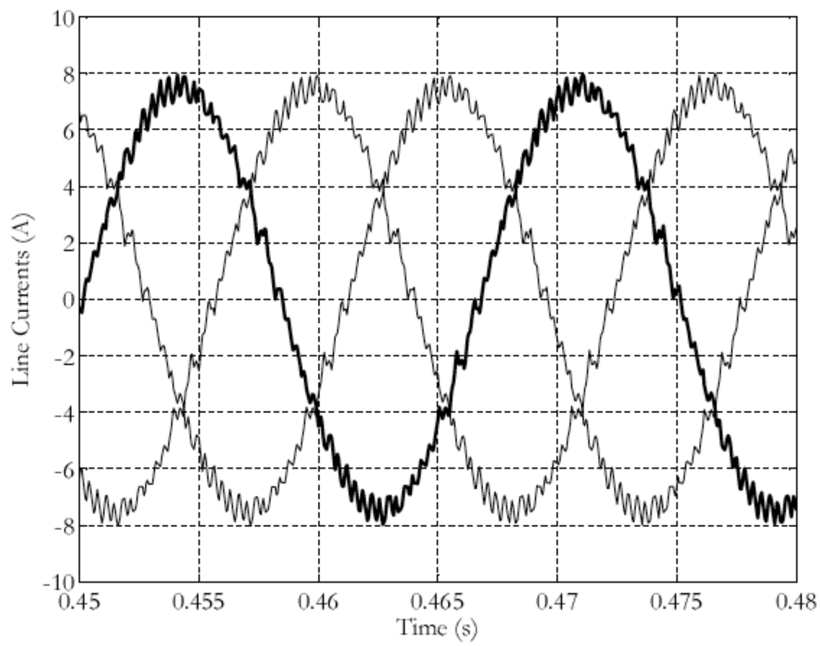
System Setup: Consider a simple point-to-point VSC-HVDC link:

- Station 1 (Rectifier): Connected to AC System A. Station 1 converts AC to DC, controlling the DC voltage. It consists of a three-phase two-level VSC using IGBTs with PWM, a phase-reactor and AC filter, and a step-up transformer to the AC network.

- Station 2 (Inverter): Connected to AC System B. Station 2 converts DC back to AC, controlling the power or DC current. Similar topology to Station 1, but operated as an inverter.
- DC Link: ±x kV DC bipolar link (for example) connecting the two stations, including smoothing reactors and a DC cable or line of a certain length.







Industry Insight: Why are dead-times important in practical inverter circuits?

In real-world inverter applications — including HVDC converter stations, motor drives, and uninterruptible power supplies — dead-times are essential to ensuring reliable and safe operation of power electronic switches. Dead-time refers to a brief, intentional delay introduced between the turn-off of one switch and the turn-on of its complementary switch within a half-bridge or full-bridge inverter leg. This delay is necessary because real switches (e.g., IGBTs and MOSFETs) do not turn off instantaneously. Without a dead-time, both switches in a leg could conduct simultaneously, creating a short circuit across the DC bus, damaging the equipment.

In industrial HVDC applications, *such as the 2,000 MW ±500 kV INELFE interconnection between France and Spain built by Siemens using VSC HVDC technology*, precise dead-time management is critical. At this scale, even a few microseconds of switch overlap can result in enormous fault currents. Siemens' HVDC PLUS platform incorporates adaptive dead-time control via digital signal processors (DSP) to ensure switching safety without excessive waveform distortion.

Industry-standard gate drivers use device-specific switching delay profiles and real-time feedback to set dead-times. Too long a dead-time causes waveform distortion and increased harmonic content; too short risks shoot-through. High-end converters also employ self-protective mechanisms and firmware-level interlock logic to enforce safe switching behavior.

7a-4 Summary of main learning points

We summarize the main learning points addressed in this module

- The concept of time averaging of voltages can be extended from DC-DC converters to DC-AC inverters that are used for HVDC applications. It is a great way to understand how DC waveform is converted to AC.
- DC-AC inverters employ PWM to craft the desired voltage waveform. It can be done using different techniques, but the most common PWM method is sinusoidal PWM.

Problems

Problem 1:

A buck converter has an input voltage of Vin=480 V and a duty cycle D=0.4.

1. Calculate the ideal average output voltage Vout .
2. How does increasing the inductance value affect the ripple and mode of operation?

Problem 2:

An H-bridge inverter connected to a 600 V DC source is used to generate an AC square wave at 60 Hz.

1. Sketch the output voltage waveform across the load.
2. Compute the RMS value of the output voltage.
3. List all possible switching combinations (S1–S4) that lead to positive, negative, and zero voltage output states.

Problem 3:

A VSC inverter uses sinusoidal PWM (SPWM) with a carrier frequency of 1.2 kHz and a fundamental output frequency of 60 Hz.

1. Define the modulation index and explain its effect on the output voltage.
2. Sketch how the PWM output for one phase would look when the modulation index is (a) 0.6 and (b) 1.0.
3. What happens when the modulation index exceeds 1.0? What is overmodulation?

Problem 4:

A two-level VSC inverter outputs a square wave voltage switching between +Vdc and −Vdc across the load.

1. Derive the fundamental (60 Hz) component of the square wave in terms of Vdc .
2. What is the RMS value of the fundamental?
3. Discuss how the use of PWM modifies the harmonic spectrum and how filters are selected accordingly.

Problem 5:

Use PSCAD or MATLAB/Simulink to simulate a basic buck converter with the following parameters: Vin=400 V, D=0.5, L=1 mH, C=100 μF, load R=10 Ω

1. Plot the inductor current and output voltage waveforms.
2. Measure the output voltage ripple.
3. Compare the simulation result with the theoretical value Vout=D·Vin.

Solutions:

Problem 1

1. Vout = D * Vin = 0.4 * 480 V = 192 V
2. A large ripple might indicate discontinuous mode; however, more information is needed (e.g., inductor size).
3. Increasing inductance reduces ripple and helps maintain continuous conduction.

Problem 2:

1. Square wave switching between +600 V and -600 V.
2. RMS = 600 V / √2 ≈ 424.3 V (for the fundamental component).
3. S1+S4: Positive output; S2+S3: Negative output; same-leg conduction: Zero.

Problem 3:

1. Modulation index (m) = reference peak / carrier peak; it controls the output voltage magnitude.
2. m = 0.6: lower output voltage; m = 1.0: max linear output voltage.
3. Overmodulation occurs when m > 1, leading to waveform distortion and square-wave operation.

Problem 4:

1. Fundamental component of square wave = (4/π) * V_dc.
2. RMS = V_dc / √2 for full square wave; fundamental RMS = (4/π) * V_dc / √2.
3. PWM reduces low-order harmonics; filters are selected based on switching frequency to attenuate high-frequency components.

Problem 5:

Theoretical Vout = 0.5 * 400 V = 200 V.