PSpice™ based Examples

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Example 1

1-Phase Diode Bridge Rectifier

![Diode Bridge Rectifier Diagram]

Nominal Values:
- $V_s\text{rms} = 120V$ at 60 Hz
- $L_s = 1\, \text{mH}$
- $R_s = 10\, \text{m}\Omega$
- $L_d = 1\, \mu\text{H}$
- $C_d = 1,000\, \mu\text{F}$
- $R_{load} = 20\, \Omega$

Problems

1. Execute DBRECT1 to obtain $v_s$, $i_s$ and $v_d$ waveforms.

2. From the results of the Fourier analysis contained in the output file DBRECT1.OUT, calculate the input power factor and the displacement power factor.

3. Make use of the Fourier analysis in DBRECT1.OUT to plot $i_s$, $i_{s1}$, $i_{s3}$ and $i_{s5}$. Superimpose the distortion current component $i_{distortion} = i_s - i_{s1}$ on the above plot.

4. Calculate $I_{cap}$ (the rms current though the filter capacitor) as a ratio of the average load current $I_{load}$.

5. Plot the current and voltage associated with one of the diodes, for example, $d_1$, and obtain the average and the rms values of the current as a ratio of the average load current.
6. Vary $L_s$ as a parameter to investigate its influence on the input displacement power factor, the input power factor, %THD, and the peak-peak ripple in the dc voltage $v_d$.

7. Vary the filter capacitor $C_d$ to investigate its influence on the percentage ripple in $v_d$, input displacement power factor and %THD. Plot the percentage $\Delta V_d$ (peak-to-peak)/$V_d$(average) as a function of $C_d$.

8. Vary the load power to investigate its influence on the average dc voltage.

9. In the nominal circuit input file, remove the limit on the maximum time step during the simulation and observe its influence on the circuit waveforms.

10. Obtain the $v_S$, $i_S$ and $v_d$ waveforms during the startup transient when the filter capacitor is initially not charged. Obtain the peak inrush current as a ratio of the peak current in steady state. Vary the switching instant by simply varying the phase angle $\theta$ of the source $v_S$.

11. Replace the dc side of the diode bridge by a current source $I_d = 10$ A, corresponding to a very large $L_d$. Make $L_s$ almost equal to zero. Obtain $V_d$(average).

12. Make $L_s = 3$ mH in Problem 10 and obtain $V_d$(average), displacement power factor, power factor, %THD, and the current commutation interval.

**Reference:** Section 5-3-4, pages 95 - 99.

**PSpice Schematic:** DBRECT1

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EXAMPLE 2

3-Phase Diode Bridge Rectifier

Nominal Values:
- $V_{LL} \text{ (rms)} = 208 \text{ V at } 60 \text{ Hz}$
- $L_s = 0.1 \text{ mH}$
- $R_s = 1 \text{ m\Omega}$
- $L_d = 0.5 \text{ mH}$
- $R_d = 5 \text{ m\Omega}$
- $C_d = 500 \text{ \mu F}$
- $R_{load} = 16.5 \text{ \Omega}$

Problems

1. (a) Obtain $v_{ab}$, $v_d$ and $i_d$ waveforms.
   (b) Obtain $v_a$ and $i_a$ waveforms

2. By means of Fourier analysis of $i_a$, calculate its harmonic components as a ratio of $I_{a1}$.

3. Calculate $I_a$, $I_{a1}$, $I_{dis}$, %THD in the input current, input displacement power factor and the input power factor. How do the results compare with the 1-phase diode-bridge rectifier of Example 1.

4. Calculate $I_{cap}$ (the rms current through the filter capacitor) as a ratio of the average load current $I_{load}$. Compare the results with that in Example 1.

5. Investigate the influence of $L_d$ on the input displacement power factor, the input power factor and the average dc voltage $V_d$. Suggested range of $L_d$: 0.1 mH to 10 mH.
6. Investigate the influence of \( C_d \) on the percent ripple in \( v_d \). Plot the percentage \( \Delta V_d \) (peak-to-peak)/\( V_d(\text{average}) \) as a function of \( C_d \). Suggested range of \( C_d \): 100 \( \mu \)F and 2,000 \( \mu \)F.

7. Investigate the influence of \( C_d \) on the input displacement power factor and the input power factor. Suggested range of \( C_d \): 100 \( \mu \)F to 2,000 \( \mu \)F.

8. Plot the average dc voltage as a function of load. Suggested range of \( R_{\text{load}} \): 50 \( \Omega \) to 8 \( \Omega \).

Reference: Section 5-6, pages 103 112.

PSpice Schematic: Dbrect3

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EXAMPLE 3

1-Phase Thyristor Rectifier Bridge

Nominal values:  
- $V_s$(rms) = 120 V at 60 Hz
- $L_{s1} = 0.2$ mH
- $L_{s2} = 1.0$ mH
- $L_d = 20$ mH
- $R_{load} = 5$ Ω
- delay angle $\alpha = 45^\circ$

Problems

1. (a) Obtain $v_s$, $v_d$ and $i_d$ waveforms.
   (b) Obtain $v_s$ and $i_s$ waveforms.
   (c) Obtain $v_m$ and $i_s$ waveforms.

2. From the plots, obtain the commutation interval $u$ and the dc-side current at the start of the commutation.

3. By means of Fourier analysis of $i_s$, calculate its harmonic components as a ratio of $I_{s1}$.

4. Calculate $I_s$, %THD in the input current, the input displacement power factor and the input power factor.

5. At the point of common coupling, obtain the following from the voltage $v_m$ waveform:
   (a) Line-notch depth $\rho(\%)$
(b) Line-notch area and,
(c) voltage \%THD.

6. Obtain the average dc voltage \( V_d \). Verify that

\[
V_d = 0.9 \, V_s \cos \alpha - \frac{2 \omega L_s}{\pi} \, I_d.
\]

where first use the average value of \( \bar{I}_d \) for \( I_d \) and then its value at the start of the commutation interval as calculated in Problem 2.

Reference: Section 6-3, pages 126 - 134.

PSpice Schematic: Thyrect1

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EXAMPLE 4

1-Phase Thyristor Inverter

![Thyristor Inverter Circuit Diagram]

Nominal Values:  
- \( V_s \text{(rms)} = 120 \text{ V at 60 Hz} \)
- \( L_{s1} = 0.2 \text{ mH} \)
- \( L_{s2} = 1.0 \text{ mH} \)
- \( L_d = 20 \text{ mH} \)
- \( E = 88 \text{ V (dc)} \)
- delay angle \( \alpha = 135^\circ \)

Problems

1. (a) Obtain \( v_s, v_d \) and \( i_d \) waveforms using Thyinv1.
   (b) Obtain \( v_s \) and \( i_s \) waveforms.

2. Calculate \( I_s, \% \text{THD} \) in the input current, the input displacement power factor and the input power factor.

3. Study the startup of inverter operation. Increase the delay angle to a value close to \( 180^\circ \) (for example, \( 150^\circ \)) and look at the \( v_s, v_d \) and \( i_d \) waveforms. Repeat the above procedure by reducing \( \alpha \) slowly to its nominal value of \( 135^\circ \). Plot the average dc current \( I_d \) versus \( \alpha \).

Reference: Section 6-3-4, pages 135 - 138.

PSpice Schematic: Thyinv1

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EXAMPLE 5

3-Phase Thyristor Rectifier Bridge

Nominal Values: \( V_{LL} \, \text{(rms)} = 208 \, \text{V at 60 Hz} \)
\( L_{s1} = 0.2 \, \text{mH} \)
\( L_{s2} = 1.0 \, \text{mH} \)
\( L_d = 16 \, \text{mH} \)
\( R_{load} = 8 \, \Omega \)
\( \text{delay angle} = 45^\circ \)

Problems

1. (a) Obtain \( v_a, v_d \) and \( id \) waveforms using Thyrect3.
   (b) Obtain \( v_a \) and \( i_a \) waveforms.
   (c) Obtain \((v_a)_{pcc}, (v_{ab})_{pcc}\) and \( i_a \) waveforms.

2. From the plots, obtain the commutation interval \( u \) and \( id \) at the start of the commutation.
   Verify the following commutation equation:

\[
\cos(\alpha+u) = \cos \alpha - \frac{2\omega L_s}{\sqrt{2} V_{LL}} I_d
\]

where \( L_s = L_{s1} + L_{s2} \). For \( I_d \), use the average value of \( i_d \) or its value at the start of the commutation.

3. By means of Fourier analysis of \( i_s \), calculate its harmonic components as a ratio of \( I_{s1} \).

4. Calculate \( I_s, \% \text{THD} \) in the input current, the input displacement power factor and the input power factor.
5. Verify the following equation:

\[ \text{Displacement power factor } \approx \cos(\alpha + \frac{u}{2}) \approx \frac{\cos \alpha + \cos(\alpha + u)}{2} \]

6. At the point of common coupling, obtain the following from the voltage \( v_{pcc} \) waveform:

(a) Line-notch depth \( \rho(\%) \)
(b) Line-notch area and,
(c) voltage THD%

7. Obtain the average dc voltage \( V_d \). Verify that

\[ V_d = 1.35 \, V_{LL} \cos \alpha - \frac{3 \omega L_s}{\pi} \, I_d. \]

For \( I_d \), use the average value of \( i_d \) or its value at the start of the commutation.

**Reference:** Section 6-4, pages 138 - 148.

**PSpice Schematic: Thyrect3**

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EXAMPLE 6

3-Phase Thyristor Inverter

Nominal Values:  

\[ V_{LL}(\text{rms}) = 480 \text{ V at 60 Hz} \]  
\[ L_s = 1.0 \text{ mH} \]  
\[ L_d = 16 \text{ mH}, R_d = 1 \text{ ohm} \]  
\[ E = 630 \text{ V} \]  
\[ \text{delay angle } \alpha = 160^\circ \]

Problems:

1. (a) Obtain \(v_a\), \(v_d\) and \(i_d\) waveforms using Thyinv3.  
   (b) Obtain \(v_a\) and \(i_a\) waveforms

2. Calculate \(I_s\), \%THD in the input current, the input displacement power factor and the input power factor.

3. Study the startup of the inverter operation. Increase the delay angle to a value close to \(180^\circ\) and look at the \(v_a\), \(v_d\) and \(i_d\) waveforms. Repeat the above procedure by reducing \(\alpha\) slowly to its nominal value of \(160^\circ\). Plot the average dc current \(I_d\) versus \(\alpha\).

Reference: Section 6-4-4, pages 148 - 150.

PSpice Schematic Thyinv3

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EXAMPLE 7

Step-down (BUCK) dc-dc Converter

![Diagram of the Buck converter](image)

Nominal Values:  
- $V_d = 8$ V (dc)  
- $L = 5$ $\mu$H  
- $rL = 10$ m$\Omega$  
- $C = 100$ $\mu$F  
- $R_{load} = 0.5$ $\Omega$  
- $f_s = 100$ kHz  
- Switch duty ratio $D = 0.75$

Problems

1. In steady state, obtain the following waveforms using Buckconv:
   (a) $v_L$ and $i_L$ waveforms.
   (b) $v_o$, $i_L$ and $i_c$ waveforms

2. Obtain $v_{oi}$ waveform and by means of Fourier analysis, obtain its harmonic components as a ratio of its average value $V_o$.

3. Increase the load resistance to 10 $\Omega$. Obtain $v_L$ and $i_L$ waveforms in the discontinuous conduction mode [Hint: use $V(0) = 5.8$V and $I_L(0) = 0$]. Check if the results agree with the following equation:

$$\frac{V_o}{V_d} = \frac{D^2}{D^2 + \frac{1}{4} \left( \frac{I_o}{I_{LB,\text{max}}} \right)}$$

where $I_{LB,\text{max}} = \frac{V_d}{8Lf_s}$. 
4. Obtain the peak-to-peak ripple in the output voltage and check to see if the results agree with the analytical calculations.

5. Calculate the rms value of the current through the output capacitor as a ratio of the average load current $I_0$.

6. Calculate the peak-to-peak ripple in the output voltage in the presence of the output capacitor Equivalent Series Resistance (ESR) [Suggested ESR = 100 mΩ]. Plot the ripple across C, ESR and the total ripple in $v_0$.

**Reference:** Section 7-3, pages 164 - 168.

**PSpice Schematic:** Buckconv

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EXAMPLE 8

Step-Up (Boost) dc-dc Converter

Nominal Values:
- \( V_d = 9 \, \text{V} \)
- \( L = 10 \, \mu\text{H} \)
- \( r_L = 10 \, \text{m\Omega} \)
- \( C = 50 \, \mu\text{F} \)
- \( R_{\text{load}} = 5 \, \Omega \)
- \( f_s = 100 \, \text{kHz} \)
- switch duty ratio \( D = 0.625 \)

Problems
1. In steady state obtain the following waveforms using Boost:
   (a) \( v_L \) and \( i_L \) waveforms
   (b) \( v_o, i_D \) and \( i_C \) waveforms

2. Obtain \( i_D \) waveform and by means of Fourier analysis, obtain its harmonic components as a ratio of its average value \( I_0 \).

3. Increase the load resistance to 50 \( \Omega \). Obtain \( v_L \) and \( i_L \) waveforms in the discontinuous conduction mode [Hint: use \( V_o(0) = 28 \, \text{V} \) and \( I_L(0) = 0 \)]. Check if the results agree with the analytical calculations.

4. After 10 ms, change the load resistance as a step from its nominal value of 5 \( \Omega \) to 50 \( \Omega \). Obtain \( v_L, i_L \) and \( v_o \) waveforms as they reach their new steady state values.

5. Obtain the peak-to-peak ripple in the output voltage and check to see if the results agree with the analytical calculations.

6. Calculate the rms value of the current through the output capacitor as a ratio of the average load current \( I_0 \).

Reference: Section 7-4, pages 172 - 178.

PSpice Schematic: Boost

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EXAMPLE 9

Step-down/Up dc-dc (Buck-Boost) Converter

\[ V_d \sim \text{Block-Boost} \]

Nominal Values:
- \( V_d = 8.5 \text{ V} \)
- \( L = 10 \mu \text{H} \)
- \( r_L = 10 \text{ m} \Omega \)
- \( C = 100 \mu \text{F} \)
- \( R_{\text{load}} = 8 \text{ } \Omega \)
- \( f_S = 100 \text{ kHz} \)
- \( \text{switch duty ratio } D = 0.75 \)

Problems

1. In steady state, obtain the following waveforms using Buck-Boost:
   (a) \( v_L \) and \( i_L \)
   (b) \( v_o, i_o \) and \( i_c \).

2. Obtain \( i_D \) waveform and by means of Fourier analysis, obtain its harmonic components as a ratio of its average value \( I_o \).

3. Increase the load resistance to 80 Ω. Obtain \( v_L \) and \( i_L \) waveforms in the discontinuous conduction mode [Hint: use \( V(o) = 28 \text{ V} \) and \( i_L(0) = 0 \)]. Check if the results agree with the analytical calculations.

4. After 10 ms, change the load resistance as a step from its nominal value of 8 Ω to 80 Ω. Obtain \( v_L, i_L \) and \( v_o \) waveforms as they reach their new steady state values.

5. Obtain the peak-to-peak ripple in the output voltage and check to see if the results agree with analytical calculations.
6. Calculate the rms value of the current through the output capacitor as a ratio of the average load current $I_0$.

**Reference:** Section 7-5, pages 178 - 184.

**PSpice Schematic: Buck-Boost**

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EXAMPLE 10

Full-Bridge, Bipolar-Switching dc-dc Converter

Nominal Values:

- \( V_d = 200 \text{ V} \)
- \( V_{EMF} = 79.5 \text{ V} \)
- \( R_a = 0.37 \Omega \)
- \( L_a = 1.5 \text{ mH} \)
- \( I_o(\text{avg}) = 10 \text{ A} \)
- \( f_s = 20 \text{ kHz} \)
- Duty-ratio \( D_1 \) of \( T_{A1} \) and \( T_{B2} = 0.708 \)
  \( \therefore \, V_{\text{control}} = 0.416 \text{ V} \) with \( V_{\text{tri}} = 1.0 \text{ V} \)

Problems

1. Obtain the following waveforms using FBBSDCDC:
   (a) \( v_o, i_o \) and \( p_o(t) = v_o i_o \)
   (b) \( v_o \) and \( i_d \)

2. Calculate peak-to-peak ripple in \( i_o \).

3. By means of Fourier analysis, calculate the average value and the harmonic components in \( v_o \). Obtain the rms value of the ripple in \( v_o \) and check it with the analytical calculations.

4. By means of Fourier analysis, calculate the average value of \( i_d \) and the rms value of the ripple.
5. With \( V_{\text{EMF}} = 0 \) and \( I_a(\text{avg}) = 0 \), \( V_o(\text{avg}) = 0 \) V. Therefore, \( V_{\text{control}} = 0 \). Calculate the following [Hint: use \( I_0(0) = -1.67 \text{A} \)]:
   (a) \( v_o \), \( i_o \) and \( p_o(t) \) waveforms.
   (b) peak-to-peak ripple in \( i_b \). Compare it with its analytical value, and that in Problem 2.
   (c) In part (a), label the intervals during which various devices are conducting.

6. In the regenerative mode, the power flows from the load to the dc-bus at \( V_d \). Let \( V_{\text{EMF}} = 79.5 \text{V} \), \( I_a(\text{avg}) = 10 \text{A} \) in the reverse direction, and \( V_o(\text{avg}) = 79.5 - 0.37 \times 10 = 75.8 \text{V} \). Therefore, \( V_{\text{control}} = \frac{75.8}{200} \times 1.0 = 0.379 \).
   Calculate parts (a) through (c) of Problem 5 [Hint: use \( I_0(0) = -11.67 \text{A} \)].

Reference: Section 7-7-1, pages 190 - 192.

PSpice Schematic: FBBSDCDC

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EXAMPLE 11

Full-Bridge, Unipolar Switching dc-dc Converter

Nominal Values: Same as that in Example 10 except for unipolar-voltage switchings.

Problems

1. Obtain the plot of \( v_A \), \( v_B \) and \( v_o \) using FBUSDCDC.

2. Obtain the plot of \( v_o \) and \( i_o \)

3. Obtain the peak-peak ripple in \( i_o \). Check it with its analytical value and compare it with Problem 2 of Example 10.

4. Obtain the rms value of the ripple in \( v_o \). Check it with its analytical value and compare it with Problem 3 of Example 10.

Reference: Section 7-7-2, pages 192 - 194.

PSpice Schematic: FBUSDCDC

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EXAMPLE 12

1-Phase, Bipolar-Voltage Switching Inverter

Nominal Values: Frequency $f_1 = 40 \text{ Hz}$, $V_{o1\text{rms}} = 153.33 \text{ V}$, $V_{o1\text{peak}} = 216.8 \text{ V}$. $R_{TH} = 2 \Omega$, $L_{TH} = 10 \text{ mH}$. $I_{o1\text{rms}} = 10 \text{ A}$ at a 0.866 pf (lagging).

Phasor Diagram:

Therefore, $V_{TH \text{rms}} = 124.1 /-5.39^\circ \text{ V}$
and $v_{TH} = 175.5 \sin (2\pi \times 40t - 5.39^\circ)$.

Inverter and Controller for Sinusoidal PWM:

Switching frequency $f_s = 1 \text{ kHz}$,
Frequency modulation ratio $m_f = 1000 / 40 = 25$,
Amplitude modulation ratio $m_a = 0.8$.
Therefore, $V_d = V_{o1\text{peak}} / m_a = 271 \text{ V}$ and,
$v_{\text{control}} = 0.8 \sin (2\pi \times 40t)$. 
Problems

1. Obtain the following waveforms using 1Phbsinv:
   (a) \( v_0 \) and \( i_0 \).
   (b) \( v_0 \) and \( i_d \).
   (c) \( v_0, i_0 \) and \( p_0 \).

2. Obtain \( v_{01} \) by means of Fourier analysis of the \( v_0 \) waveform. Compare \( v_{01} \) with its precalculated nominal value.

3. Using the results of Problem 2, obtain the ripple component \( v_{\text{ripple}} \) waveform in the output voltage.

4. Obtain \( i_{01} \) by means of Fourier analysis of the \( i_0 \) waveform. Compare \( i_{01} \) with its precalculated nominal value.

5. Using the results of Problem 4, obtain the ripple component \( i_{\text{ripple}} \) in the output current.

6. Obtain \( I_d(\text{avg}) \) and \( i_d^2 \) (the component at the 2nd harmonic frequency) by means of the Fourier analysis of the \( i_d \) waveform. Compare them with their precalculated nominal values.

7. Using the results of Problem 6, obtain the high frequency ripple component \( i_d_{\text{ripple}} \) in the input dc current. Calculate its rms value.

Reference: Section 8-3-2-1, pages 212 - 215.

PSpice Schematic: 1Phbsinv

Based on \( I_{01}(\text{rms}) = 10 \sqrt{30} \) A, the initial value \( I_0(\phi) = 7 \) A.

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EXAMPLE 13

1-Phase, Unipolar-voltage Switching Inverter

Nominal Values: Similar to Example 12.

Problems

1. Obtain the following waveforms using 1Phusinv:
   (a) $v_o$ and $i_o$.
   (b) $v_o$ and $i_d$.
   (c) $v_o$, $i_o$ and $p_o$.

2. Obtain $v_{01}$ by means of Fourier analysis of the $v_o$ waveform. Compare $v_{01}$ with its precalculated nominal value.

3. Using the results of Problem 2, obtain the ripple component $v_{\text{ripple}}$ waveform in the output voltage. Compare the peak-to-peak ripple to that in the bipolar-voltage switching inverter.

4. Obtain $i_{01}$ by means of Fourier analysis of the $i_o$ waveform. Compare $i_{01}$ with its precalculated nominal value.

5. Using the results of Problem 4, obtain the ripple component $i_{\text{ripple}}$ in the output current. Compare the peak-to-peak ripple to that in the bipolar-voltage switching inverter.

6. Obtain $I_d(\text{avg})$ and $i_{d2}$ (the component at the 2nd harmonic frequency) by means of the Fourier analysis of the $i_d$ waveform. Compare them with their precalculated nominal values.
7. Using the results of Problem 6, obtain the high frequency ripple component $i_{d,ripple}$ in the input dc current. Calculate its rms value. Compare the rms value of the dc-side current ripple to that in the bipolar-voltage switching inverter.

**Reference:** Section 8-3-2-2, pages 215 - 218.

**PSpice Schematic: 1Phusinv**

Based on $I_{o1}(\text{rms}) = 10/30^\circ$ A, the initial value $I_o(\text{o}) = -7$ A.

**Controller:**

The same controller PWM_TRI, as in Example 12 is used. The difference is that the switches in the converter-leg A depend on the control voltage $v_{\text{control}}$, whereas the switches in the converter-leg B depend on (- $v_{\text{control}}$).

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EXAMPLE 14

1-Phase, Square-Wave Inverter

Nominal Values: Same as in Example 12 except,

\[ V_d = \frac{\pi}{4} \quad V_{01, peak} = 216.8 \times \frac{\pi}{4} = 170.27 \text{ V} \]

Problems

Similar to Example 12 but compare the results with both Examples 12 and 13. Also, obtain the lower order harmonics in \( v_o \) as a ratio of \( V_{01} \).

Reference: Section 8-3-2-3, page 218.

PSpice Schematic: 1Phsqinv

Based on \( I_{01}(\text{rms}) = 10 \angle -30^\circ \text{ A}, \) the initial value \( I_o(0) = -7 \text{ A}. \)

Controller:

Switches (A1, B2) and (B1, A2) form two switch pairs, each of which is gated on for alternate half periods.
EXAMPLE 15

1-Phase, Voltage-Cancellation Inverter

Nominal values: Same as in Example 14.

For $V_d = 271$ V and $\hat{V}_{01} = 216.8$ V, at $\theta = 1$

$$216.8 = \frac{4}{\pi} 271 \sin \beta$$

$\beta = 38.9^\circ$ and $\alpha = 180 - 2\beta = 102.2^\circ$

$$\frac{\alpha}{2} = 51.1^\circ$$

Problems

Same as in Example 14.

Reference: Section 8-3-2-4, pages 218 - 219. See the definitions of $\alpha$ and $\beta$.

PSpice Schematic: 1Phvcinv

Based on $I_{o1}(\text{rms}) = 10 \ltsim 30^\circ$ A, the initial value $I_o(\alpha) = -7$ A.
Controller:

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EXAMPLE 16

Three-Phase PWM Inverter

Nominal Values:

**Load:** A 230 V, 60 Hz, 3-phase motor is operating at a frequency $f_1 = 47.619$ Hz. Therefore,

$$V_{LL_1}^{ms} = \frac{47.619}{60} \times 230 = 182.54 \text{ V}.$$  

$$V_{An_1}^{ms} = \frac{V_{LL_1}^{ms}}{\sqrt{3}} = 105.39 \text{ V} = 105.39/0^\circ.$$

$$I_{A_1}^{ms} = 10 \text{ A} \text{ at a lagging power factor of } 0.866 = 10/-30^\circ \text{ A.}$$

$$R_S = 2\Omega, \quad L_S = 10 \text{ mH},$$

$$\therefore \quad X_S = 2\pi \times 47.619 \times 10 \times 10^{-3} = 3\Omega.$$  

**Phasor Diagram:**

$$\therefore \quad (V_{TH,A})_1 = 74.76/-12.36^\circ \text{ V (rms)}$$

**Inverter and Sinusoidal PWM Controller:**

Switching frequency $f_s = 1 \text{ kHz}.$

Amplitude modulation ratio $m_a = 0.95.$

$$\therefore \quad V_d = \frac{V_{LL_1}^{ms}}{0.612 \ m_a} = 313.97 \text{ V.} \quad \text{With } V_{tri} = 1.0 \text{ V}$$
\[ v_{\text{control}, A} = 0.95 \cos (2\pi f_1 t - 90^\circ) \text{ V}. \]

**Problems**

1. Obtain the following waveforms using:
   (a) \( v_{AN} \) and \( i_A \).
   (b) \( v_{\text{AN}} \) and \( i_A \).
   (c) \( v_{\text{AN}} \) and \( i_d \).

2. Obtain \( v_{An} \) by means of Fourier analysis of the \( v_{An} \) waveform. Compare \( v_{An} \) with its precalculated nominal value.

3. Using the results of Problem 2, obtain the ripple component \( v_{\text{ripple}} \) waveform in the output voltage.

4. Obtain \( i_{A1} \) by means of Fourier analysis of \( i_A \) waveform. Compare \( i_{A1} \) with its precalculated nominal value.

5. Using the results of Problem 4, obtain the ripple component \( i_{\text{ripple}} \) in the output current.

6. Obtain \( I_d(\text{avg}) \) by means of Fourier analysis and obtain the high frequency ripple \( i_d,\text{ripple} = i_d - I_d(\text{avg}) \) in the input current.

7. Obtain the load neutral voltage with respect to the mid-point of the dc input voltage.

**Reference:** Section 8-4, pages 225 - 236.

**PSpice Schematic: PWMINV3**

Based on \( I_{A1}(\text{rms}) = 10 \left/ -30^\circ \right. \text{ A}, \) the initial value \( I_{A1}(0) = -7.07 \text{ A}. \)

**Controller:**

Three sinusoidal control voltages, one for each phase, are compared with a switching-frequency triangular waveform in PWM_Tri_3PH_Subcircuit.

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EXAMPLE 17

Three-Phase, Square-Wave Inverter

Nominal values: The same as in Example 16, except

\[ V_d = \frac{182.54}{0.78} = 234.03 \text{ V} \]

where \( V_{\text{LL}} = 182.54 \text{ V} \).

Problems

Same as in Example 16.

Reference: Section 8-4-2, pages 229 - 230.

PSpice Schematic: SQINV3

Controller:

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EXAMPLE 18

Series-Loaded Resonant (SLR) dc-dc Converter Operating Above the Resonant Frequency

Nominal Values: $V_d = 155$ V, $f_s = 100$ kHz,

$L_r = 45.5$ µH, $C_r = 96.9$ nF

$\therefore f_o = 132$ kHz, $f_s/f_o = 1.32$.

$C_1, C_2 = \text{Large}$, $C_{out} = 50$ µF, $R_{Load} = 50$ Ω.

Snubber Capacitors $C_{s1} = C_{s2} = 0.1$ nF

$V_o(0) = 69.75$ V

Problems

1. Obtain $v_{AB}$ and $i_L$ waveforms.

2. By Fourier analysis, obtain and plot $v_{AB1}$ and $i_{L1}$. Note that the current lags in phase with respect to the voltage.

3. Obtain the voltage across and the current through the lower switch. Check for zero voltage/current switchings.

4. In a time range of 4.8µs to 5.8µs, plot the currents $i_{s1}$ and $i_{s2}$ through the snubber capacitors, $i_D2$, $i_L$, $i_{SW2}$ and the gate signals to switches 1 and 2 (all on the same plot).
5. Remove both the snubber capacitors and reexamine the switching interval between 4.8\,\mu s to 5.8\,\mu s in Problems 3 and 4.

6. Obtain the voltage $v_c$ and the current $i_L$ waveforms. Normalize the results by $V_{\text{base}} = V_d$ and $I_{\text{base}} = V_d / z_0$, respectively.

7. Without changing the circuit parameters, change the switching frequency to $f_s = 80$ kHz. Obtain $I_o(\text{avg})$ and compare the normalized $v_c$ and $i_L / I_o(\text{avg})$ with those in Problem 3. Hint: Estimate the output voltage and use it as initial condition in the simulation.

References: Section 9-4-1-3, pages 261 - 262.

PSpice Schematic: SLRCM2

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EXAMPLE 19

Parallel-Loaded Resonant (PLR) dc-dc Converter Above the Resonant Frequency

Nominal Values:  
\[ V_d = 155 \text{ V}, \quad f_s = 300 \text{ kHz} \]
\[ L_r = 37.96 \mu \text{H}, \quad C_r = 8.97 \text{ nF} \]
\[ \therefore f_o = 272.74 \text{ kHz}, \quad f_s / f_o = 1.1 \]
\[ I_o = 0.9926 \text{ A}. \]

Problems

1. Obtain \( v_{AB} \) and \( i_L \) waveforms.

2. Obtain the voltage across and the current through the bottom switch. Check for zero voltage/current switchings.

3. Obtain \( v_C \) and \( i_L \) waveforms.

4. Plot the fundamental frequency components of the inverter voltage \( v_{AB} \) and the current \( i_L \). Does the current lag the voltage? If so, by how many degrees and why?

5. In a time range of 6.5 \( \mu \text{s} \) to 7.5 \( \mu \text{s} \), plot the currents \( i_{CS1} \) and \( i_{CS2} \) through the snubber capacitors, \( i_{D1}, i_{Lr}, i_{SW1} \) and the gate signals to switches 1 and 2 (all on the same plot).

Reference: Section 9-4-2-3, pages 266 - 267.
PSpice Schematic: PLRCM2

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EXAMPLE 20

Current-Source, Parallel-Resonant Inverter for Induction Heating

Nominal values: \( f_s = 4 \text{ kHz} \)

\[ L_r = 78 \, \mu\text{H}, \quad L_c = 20 \, \mu\text{H} \]

\[ C_r = 25 \, \mu\text{F}, \quad R_{\text{load}} = 20 \, \Omega \]

\[ f_o = 3.6 \text{ kHz}, \quad \frac{f_s}{f_o} = 1.11 \]

\[ i_d \approx I_d = 25 \text{ A} \]

Problems

1. Obtain \( v_o \) and \( i_o \) waveforms.

2. Obtain the fundamental frequency components of the output voltage \( v_o \) and the output current \( i_o \). Calculate the angle by which the current leads the voltage. Compare this value with the phase angle of the impedance (at the switching frequency) seen from the output of the converter.

3. Obtain the waveform of the voltage across the dc input to the inverter. Calculate its average value \( V_d \) and the average power input \( V_d I_d \).

4. Obtain the voltage across the load and the average power supplied to the load. Compare with the average power input \( (V_d I_d) \) calculated in Problem 3.
5. Plot the voltage across one of the thyristors and calculate the reverse recovery time (= \( \gamma / \omega_b \)) in \( \mu s \) available to the thyristors.

Reference: Section 9-4-4, pages 269 - 270.

PSpice Schematic: CSINV

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EXAMPLE 21

Zero-Current-Switching, Quasi-Resonant Buck Converter

\[ V_d \]

\[
\begin{align*}
L_r & \\
L_r & \\
C_r & \\
D_r & \\
f_s & \\
R_{Load} & \\
V_d & \\
V_c & \\
C_r & \\
D_r & \\
V_o & \\
i_{sw} & \\
i_o & \\

\end{align*}
\]

Nominal Values:

\[
V_d = 15 \text{ V}, \quad V_o = 10 \text{ V,}
\]

\[
i_o = I_o = 1 \text{ A,}
\]

\[
fo = \frac{1}{2\pi \sqrt{L_rC_r}} = 1 \text{ MHz}
\]

\[
Z_o = \sqrt{\frac{L_r}{C_r}} = 10 \Omega
\]

\[
\therefore \quad L_r = 1.59 \mu\text{H, } C_r = 15.9 \text{ nF}
\]

\[
f_s = 0.614 \text{ MHz} \quad \therefore \quad T_s = 1.624 \mu\text{s}
\]

Problems:

1. Obtain \( v_c, i_{sw} \) and \( i_{diode} \) waveforms.

2. Plot the voltage across and the current through the switch. Check for zero voltage/current switchings.

3. Obtain the average value of the voltage across the switch to check if \( V_o \) equals 10 V as the specified nominal value.

4. Change \( I_o \) in the PSpice circuit to 0.5 A. Obtain \( V_o/V_d \) and the corresponding \( R_{load}/Z_o \). Compare the results and comment on how the switching frequency should be changed to bring \( V_o \) back to its nominal value.

5. Change \( I_o \) in the PSpice circuit to 2.0 A. Look at the first switching frequency cycle and discuss the need for turning off a finite amount of current by the switch rather than the zero-current switching obtained earlier.
6. Obtain the voltage $v_C$ and the inductor current $i_L$ by putting a diode in anti-parallel with the switch. Obtain $V_o/V_d$.

**Reference:** Section 9-5-1, pages 274 - 278.

**PSpice Schematic ZCSconv:**

**Controller:**

At the beginning of each cycle, a short pulse of 0.05 µs is produced. The switch is turned off when the current through it tries to reverse direction.

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EXAMPLE 22

Zero-Voltage-Switching, Clamped-Voltage dc-dc Converter

![Diagram of the converter circuit]

Nominal Values:

- \( V_d = 21 \text{ V} \), \( V_o = 10 \text{ V} \)
- \( f_s = 100 \text{ kHz} \), \( L_f = 20 \mu\text{H} \)
- \( C_{S1} = C_{S2} = 5 \text{ nF} \)
- \( C_f = 1000 \mu\text{F} \), \( R_{\text{load}} = 10 \Omega \)

Problems:

1. Obtain \( v_A \) and \( i_L \) waveforms.

2. Obtain the voltage across and the current through one of the switches. Comment on the zero voltage/current switchings.

3. Around the blanking time, obtain the currents through one of the switches and through its associated diode and the snubber capacitors.

4. Obtain the average value of \( v_A \). How much lower is it compared to the nominal value of 10 V for \( V_o \)?

5. Calculate the peak-to-peak ripple in the inductor current as a ratio of the average inductor current. What should its value be to provide zero voltage switching?

6. Change \( C_{S1} \) and \( C_{S2} \) to be 2.5 nF. Repeat Problems 1 through 4.

Reference: Section 9-6-1, pages 280 - 283.
PSpice Schematic: ZVSCV

Controller:

\[ \text{\( v_{\text{gate1}} \)} \]

\[ \begin{array}{c}
0 & 0 & 5.5 \text{ us} & 10 \text{ us} & 15.5 \text{ us} \\
\end{array} \]

\[ \text{\( v_{\text{gate2}} \)} \]

\[ \begin{array}{c}
0 & 0.5 \text{ us} & 5 \text{ us} & 10.5 \text{ us} & 15 \text{ us} \\
\end{array} \]

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EXAMPLE 23

Flyback dc-dc Converter

Nominal Values:

- $V_d = 32 \text{ V}$, $V_o \approx 4 \text{ V}$
- switch duty-ratio $D = 0.4$, $f_s = 200 \text{ kHz}$
- $C = 100 \mu \text{F}$, $R_{\text{load}} = 1 \Omega$
- Transformer: $N_1/N_2 = 4$,
  Magnetizing inductance $L_m = 30 \mu \text{H}$,
  Neglect the leakage inductances.

Problems:

1. Obtain waveforms for $v_1$, $i_d$, and $i_D$.

2. Plot $v_1$, $i_{\text{sw}}$, and $i_D$ during a switching transition.

3. Calculate the average values of $i_d$ and $i_D$ in Problem 1 and verify that

$$\frac{I_d}{I_0} = \frac{V_o}{V_d}.$$

4. Obtain the waveform for the switch voltage $v_{\text{sw}}$. Verify the results with the following equation:

$$v_{\text{sw}} = \frac{V_d}{1-D}.$$

5. Change the load resistance to 50 $\Omega$ and repeat Problems 1 and 2 after a steady state is reached.
**Reference:** Section 10-4-2, pages 308 - 310.

**PSpice Schematic Flyback**

**NOTE:**

1. The transformer of the Flyback converter is represented by a component XFRM_Linear in the Analog library. Since the leakage inductances are ignored, the coefficient of coupling (k) is assumed to be nearly 1. Therefore,

   \[ L_1 = 30 \, \mu\text{H}, \text{ and } L_2 = L_1 / (N_1/N_2)^2 = 1.875 \, \mu\text{H}. \]

2. An R-C snubber is included across the switch.

3. A 1 MEG resistor is connected to ground at the output to satisfy connectivity requirements.

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EXAMPLE 24

Forward dc-dc Converter

Nominal Values:

\[ V_d = 50 \, \text{V}, \quad V_o \approx 4.5 \, \text{V}, \quad \frac{N_1}{N_2} = 4, \quad \frac{N_1}{N_3} = 1 \]
\[ f_s = 200 \, \text{kHz}, \quad L_m = 100 \, \mu\text{H}, \quad L_f = 7.5 \, \mu\text{H} \]
\[ C_f = 100 \, \mu\text{F}, \quad R_{\text{Load}} = 1 \, \Omega, \quad \text{Switch duty-ratio } D = 0.4. \]

Problems:

1. Obtain the waveforms for \( i_L \) and the voltage input to the output stage (i.e., the voltage across diode D2).

2. Obtain \( v_1 \), \( i_{SW} \) and \( i_3 \) waveforms.

3. In problem 2, show that the average value of \( v_1 \) equals zero.

4. From the results of Problem 2, verify that

\[ \frac{t_m}{T_s} = \frac{N_3}{N_1} \cdot D \]

where \( t_m \) is the time interval during which \( i_3 \) flows, and \( T_s \) is the switching time period.

Reference: Section 10-4-3, pages 311 - 314.

PSpice Schematic: Forward
Notes:

1. The 1-MEG resistor is for satisfying the connectivity requirement.

2. The 3-winding transformer is represented by three inductors L1, L2 and L3 with almost perfect magnetic coupling. It is represented by a component XFRM_3W.

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EXAMPLE 25

Forward Converter: Voltage-Mode Controlled

![Forward Converter Circuit](image)

Nominal Values:

\[ \begin{align*}
  r_c &= 10 \text{ m}\Omega, \quad C_f = 2,000 \mu\text{F}, \quad R_{\text{Load}} = 200 \text{ m}\Omega, \\
  V_d &= 24 \text{ V}, \quad V_o = 4 \text{ V}, \quad r_L = 10 \text{ m}\Omega \text{ (ignore)}, \quad L_f = 5 \mu\text{H}, \\
  f_s &= 200 \text{ kHz}, \quad N_1 / N_2 = 3.
\end{align*} \]

PWM Modulator: \( T_m(s) = 0.34 \ ( -9.37 \text{ dB} ) \)

Voltage-Mode Controller: Designed with crossover frequency \( \omega_c = 10^5 \text{ rad/s} \) and phase margin \( \phi_{pm} = 45^\circ \).

Problems:

1. Using the switching model in For_Cntl, apply a step increase of 0.05 V in the nominal value of the output voltage \( V_o \) equal to 4 V at 200 \( \mu \text{s} \). Observe the system response.

2. Repeat Problem 1 by applying an additional load resistance of 800 m\( \Omega \) in parallel with the nominal load resistance.

3. Repeat Problem 1 by applying a step increase of 1 V in the nominal value of the input voltage \( V_d \).

4. Repeat Problems 1 through 4 with a Type-3 controller which provides a phase boost of \( 60^\circ \) with the same crossover frequency as before.


PSpice Schematic: For_Cntl

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EXAMPLE 26

Ripple in the DC Motor Armature Current

Nominal Values: \( V_d = 200 \text{ V} \)
- \( R_a = 0.37 \Omega \)
- \( L_a = 1.5 \text{ mH} \)
- \( f_s = 10 \text{ kHz}, \text{ Unipolar Voltage Switching} \)
- \( K_e = K_f = 0.75 \)

- Duty-ratio \( D_1 \) of \( T_{A1} \) and \( T_{B2} = 0.708 \)
- \( V_{\text{control}} = 0.416 \text{ V} \) with \( V_{\text{tri}} = 1.0 \text{ V} \)

The motor-load is as represented in the schematic DC_Motor.

Problems:

1. Obtain the armature current waveform.
2. Calculate peak-to-peak ripple in \( i_a \).
3. Repeat Problems 1 and 2 using a Bi-polar-voltage switching scheme. Compare the results with the unipolar-voltage switching scheme here.
4. Apply a step increase in the control voltage to 0.6V at 0.5 ms and observe the system response.

Reference: Section 13-6-3, pages 388 - 389.

PSpice Schematic: DC_Motor

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EXAMPLE 27

MOSFET Switching Characteristics

In the schematic of MOSFET, the MOSFET is represented by IRF150 MOSFET in EVAL library of PSpice. The diode model within PSpice is used (where all its parameters have default values and $r_s = 1\text{m} \Omega$). A pulse voltage is applied to the gate of the MOSFET where the rise and fall times are specified as 100 ns. The stray inductance is represented by $L_{\text{stray}}$.

Problems

1. Look at the MOSFET switching waveforms.

2. Vary $L_{\text{stray}}$ in a range of 20 nH to 200 nH and observe its effect on the switching waveforms.

3. Vary $R_{\text{gate}}$ in a range of 10 Ω to 200 Ω and observe its effect on the switching waveforms.

PSpice Schematic: MOSFET

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