PSpice™ based Examples

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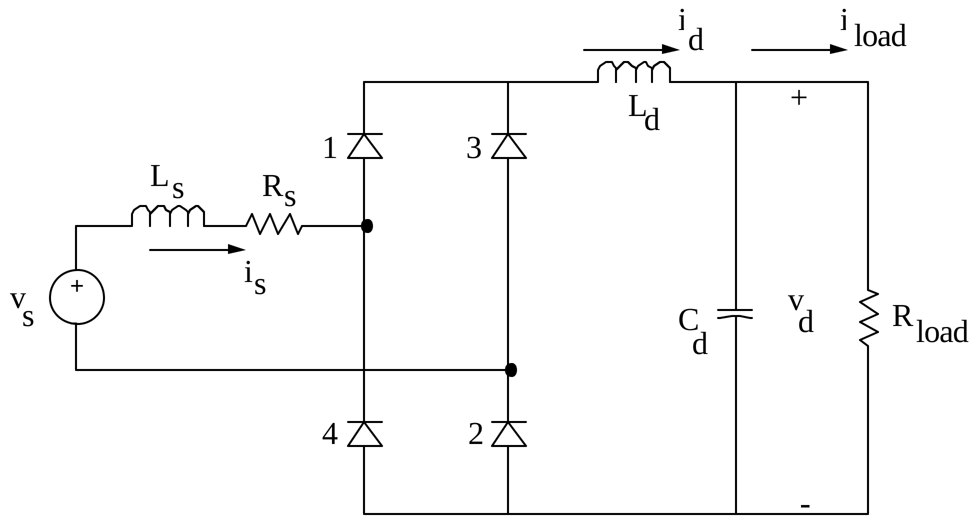
Example 1

1-Phase Diode Bridge Rectifier



Nominal Values: V_s(rms) = 120V at 60 Hz
L_s = 1 mH
R_s = 10 mΩ
L_d = 1μH
C_d = 1,000 μF
R_{load} = 20 Ω

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, d1, 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 ΔV_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 θ 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).

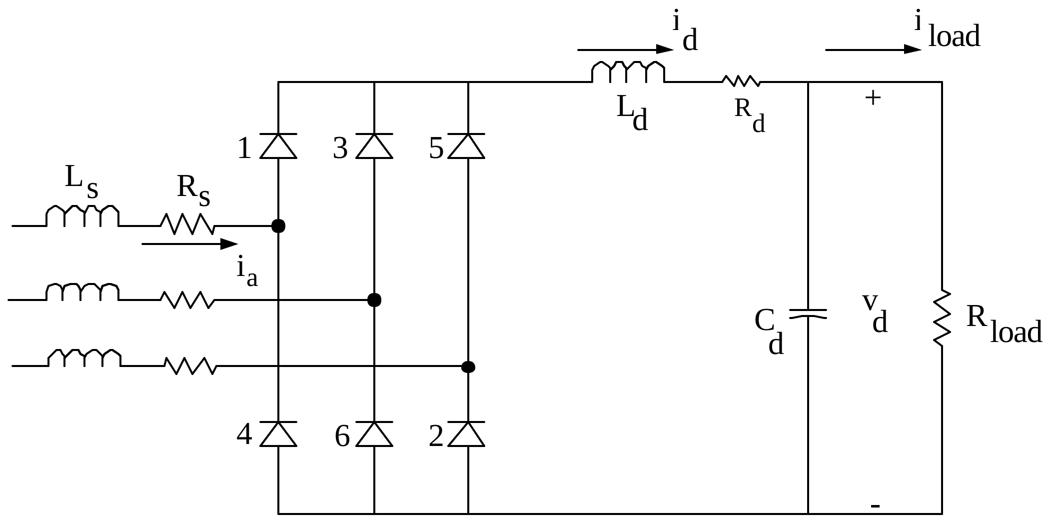
12. Make L_s = 3 mH in Problem 10 and obtain V_d(average), displacement power factor, power factor, %THD, and the current commutation interval.

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

PSpice Schematic: DBRECT1

EXAMPLE 2

3-Phase Diode Bridge Rectifier



Nominal Values:

V_{LL} (rms) = 208 V at 60 Hz
L_s = 0.1 mH
R_s = 1 mΩ
L_d = 0.5 mH
R_d = 5 mΩ
C_d = 500 μF
R_{load} = 16.5 Ω

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 ΔV_d (peak-to-peak)/V_d(average) as a function of C_d. Suggested range of C_d: 100 μF and 2,000 μF.

7. Investigate the influence of C_d on the input displacement power factor and the input power factor. Suggested range of C_d: 100 μF to 2,000 μF.

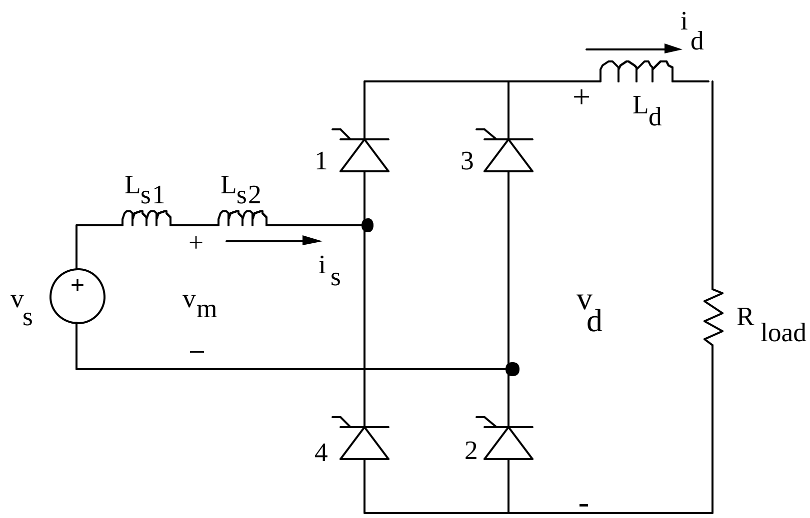
8. Plot the average dc voltage as a function of load. Suggested range of R_{load}: 50 Ω to 8 Ω.

Reference: Section 5-6, pages 103 112.

PSpice Schematic: Dbrect3

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 α = 45°

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 ρ(%)

(b) Line-notch area and,

(c) voltage %THD.

6. Obtain the average dc voltage V_d. Verify that

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

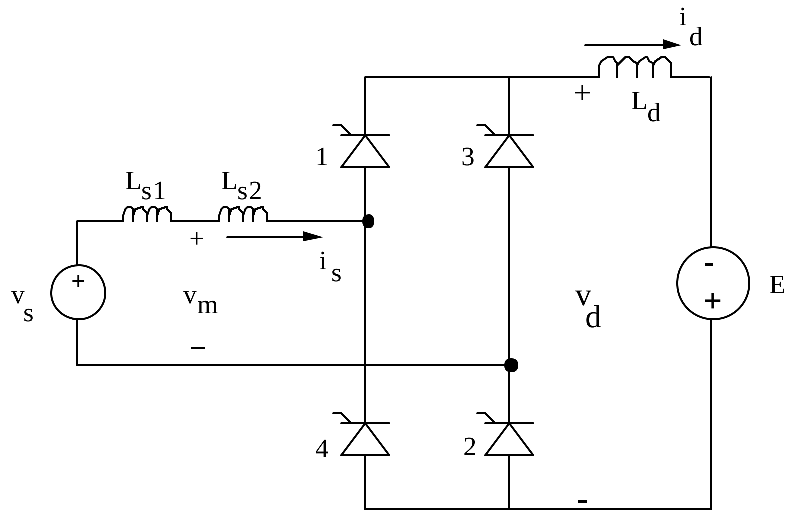
where first use the average value of i_d for I_d and then its value at the start of the commutation interval as calculated in Problem 2.

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

PSpice Schematic: Thyrect1

EXAMPLE 4

1-Phase Thyristor Inverter



Nominal Values: V_s(rms) = 120 V at 60 Hz
L_{s1} = 0.2 mH
L_{s2} = 1.0 mH
L_d = 20 mH
E = 88 V (dc)
delay angle α = 135°

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, %THD in the input current, the input displacement power factor and the input power factor.

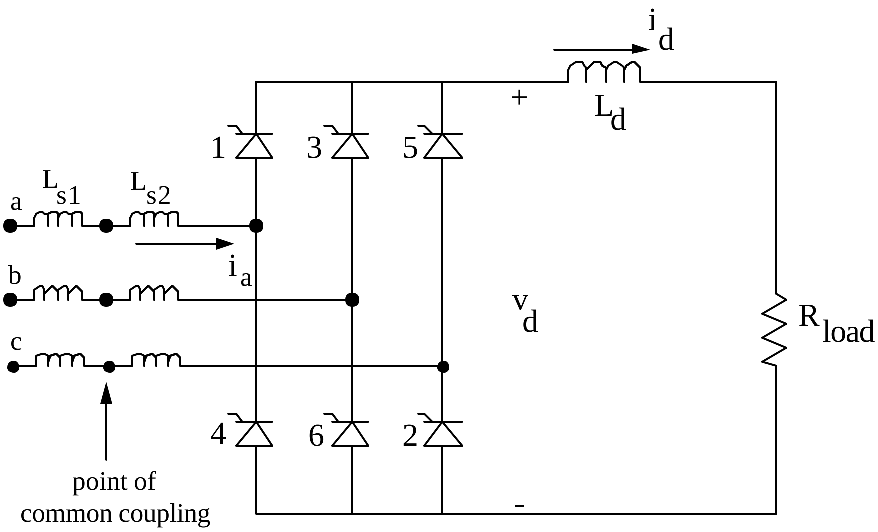
3. Study the startup of inverter operation. Increase the delay angle to a value close to 180° (for example, 150°) and look at the v_s, v_d and i_d waveforms. Repeat the above procedure by reducing α slowly to its nominal value of 135°. Plot the average dc current I_d versus α.

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

PSpice Schematic: Thyinv1

EXAMPLE 5

3-Phase Thyristor Rectifier Bridge



Nominal Values: V_{LL}(rms) = 208 V at 60 Hz
L_{s1} = 0.2 mH
L_{s2} = 1.0 mH
L_d = 16 mH
R_{load} = 8 Ω
delay angle = 45°

Problems

1. (a) Obtain v_a, v_d and i_d 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 i_d 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, %THD in the input current, the input displacement power factor and the input power factor.

5. Verify the following equation:

Displacement power factor $\simeq \cos(\alpha + \frac{u}{2}) \simeq \frac{\cos\alpha + \cos(\alpha+u)}{2}$

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

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

7. Obtain the average dc voltage V_d. Verify that

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

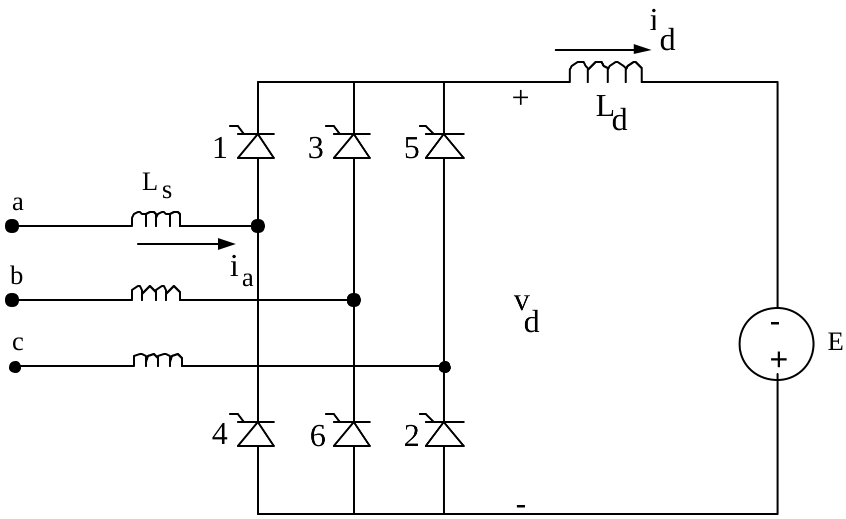
For I_d, use the average value of i_d or its value at the start of the commutation.

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

PSpice Schematic: Thyrect3

EXAMPLE 6

3-Phase Thyristor Inverter



Nominal Values: V_{LL}(rms) = 480 V at 60 Hz
L_s = 1.0 mH
L_d = 16 mH, R_d = 1 ohm
E = 630 V
delay angle α = 160°

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.

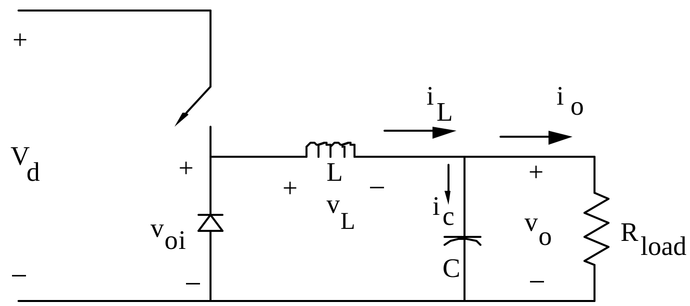
3. Study the startup of the inverter operation. Increase the delay angle to a value close to 180° and look at the v_a, v_d and i_d waveforms. Repeat the above procedure by reducing α slowly to its nominal value of 160°. Plot the average dc current I_d versus α.

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

PSpice Schematic Thyinv3

EXAMPLE 7

Step-down (BUCK) dc-dc Converter



Nominal Values:

$V_d = 8$ V (dc)
L = 5 μH
rL = 10 mΩ
C = 100 μF
$R_{load} = 0.5\ \Omega$
$f_s = 100$ 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 Ω. Obtain v_L and i_L waveforms in the discontinuous conduction mode [Hint: use V(0) = 5.8V and $I_L(0) = 0$]. Check if the results agree with the following equation:

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

where $$I_{LB,max} = \frac{V_d}{8Lf_s}\ .$$

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_o.

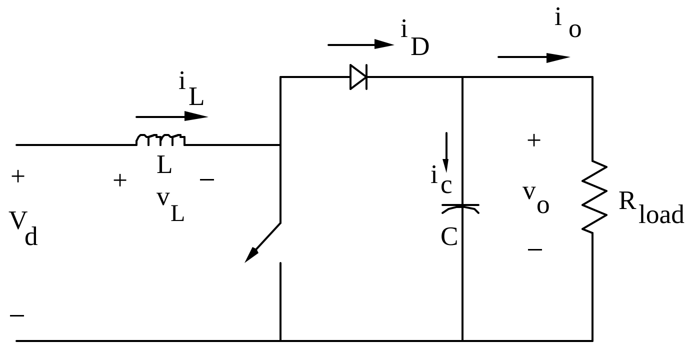
6. Calculate the peak-to-peak ripple in the output voltage in the presence of the output capacitor Equivalent Series Resistance (ESR) [Suggested ESR = 100 mΩ]. Plot the ripple across C, ESR and the total ripple in v_o.

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

PSpice Schematic: Buckconv

EXAMPLE 8

Step-Up (Boost) dc-dc Converter



Nominal Values:

$V_d = 9$ V
$L = 10$ μH
$rL = 10$ mΩ
$C = 50$ μF
$R_{load} = 5$ Ω
$f_s = 100$ 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_o.

3. Increase the load resistance to 50 Ω. Obtain v_L and i_L waveforms in the discontinuous conduction mode [Hint: use $V_o(0) = 28$ 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 Ω to 50 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 the analytical calculations.

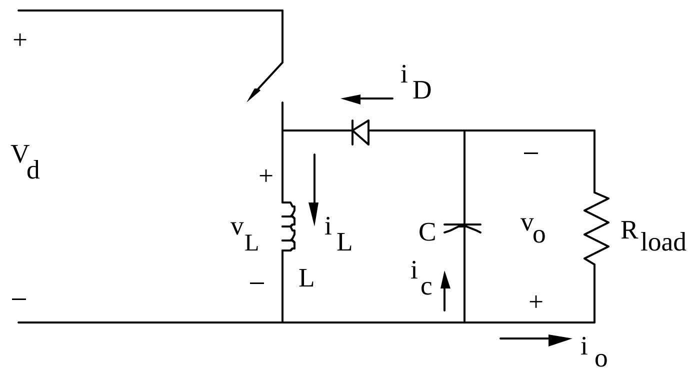
6. Calculate the rms value of the current through the output capacitor as a ratio of the average load current I_o.

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

PSpice Schematic: Boost

EXAMPLE 9

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



Nominal Values:
- V_d = 8.5 V
- L = 10 μH
- rL = 10 mΩ
- C = 100 μF
- R_{load} = 8 Ω
- f_s = 100 kHz
- 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 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.

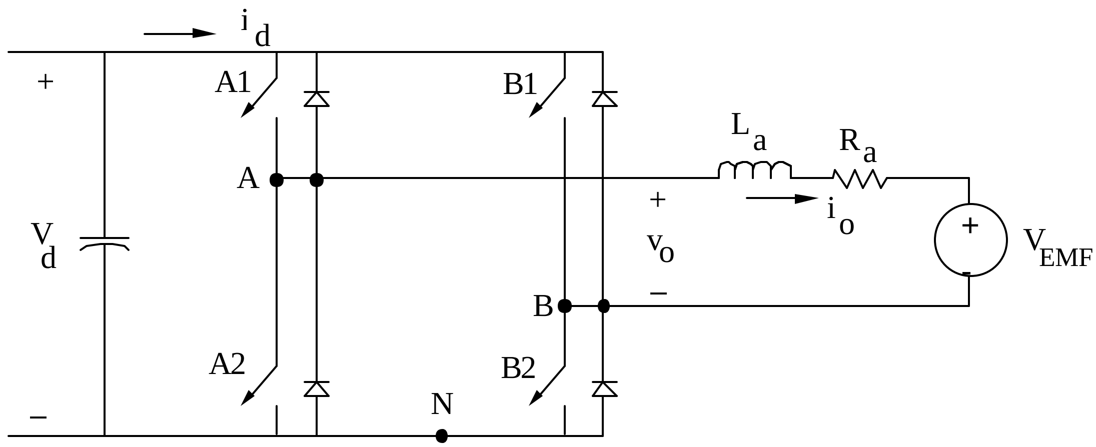
6. Calculate the rms value of the current through the output capacitor as a ratio of the average load current I_O.

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

PSpice Schematic: Buck-Boost

EXAMPLE 10

Full-Bridge, Bipolar-Switching dc-dc Converter



Nominal Values: $V_d = 200$ V
$V_{EMF} = 79.5$ V
$R_a = 0.37\ \Omega$
$L_a = 1.5$ mH
$I_o(avg) = 10$ A
$f_s = 20$ kHz
duty-ratio D_1 of T_{A1} and $T_{B2} = 0.708$
($\therefore$ $v_{control} = 0.416$ V with $\hat{V}_{tri} = 1.0$ 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_{EMF} = 0 and I_a(avg) = 0, V_o(avg) = 0 V. Therefore, $V_{control}$ = 0. Calculate the following [Hint: use $I_o(0) = -1.67A$]:
   (a) v_o, i_o and $p_o(t)$ waveforms.
   (b) peak-to-peak ripple in i_o. 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_{EMF}= 79.5V, I_a(avg) = 10A in the reverse direction, and V_o(avg) = 79.5 - 0.37x10 = 75.8V. Therefore,

$$V_{control} = \frac{75.8}{200} \times 1.0 = 0.379.$$

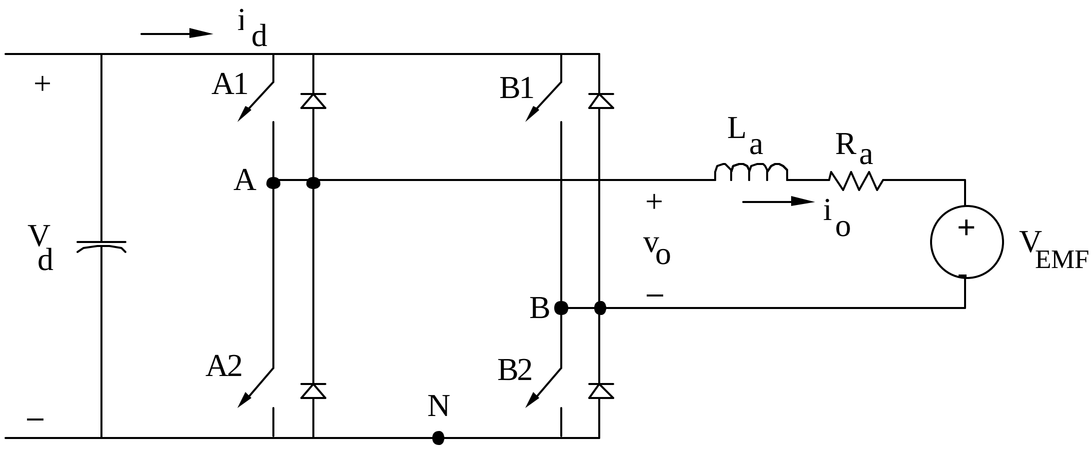
Calculate parts (a) through (c) of Problem 5 [Hint: use $I_o(0) = -11.67$ A].

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

PSpice Schematic: FBBSDCDC

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.

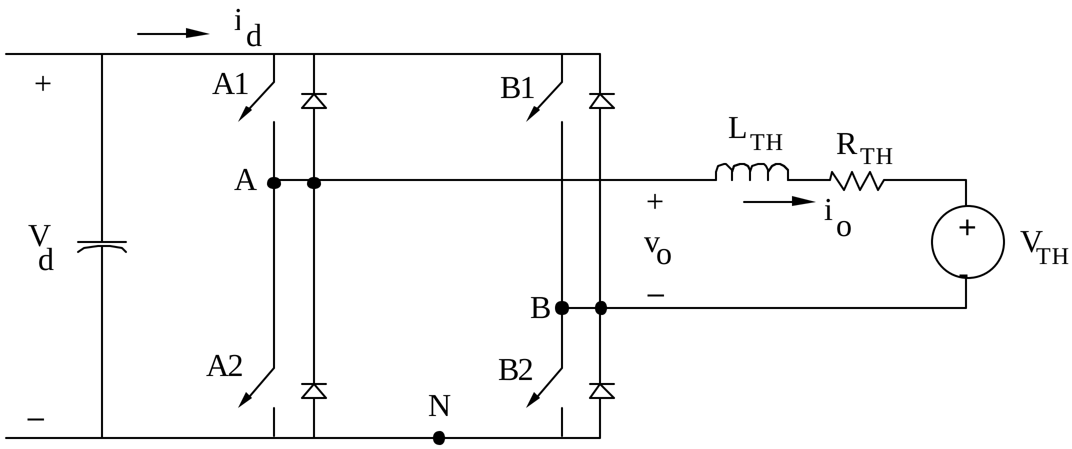
4. Obtain the rms value of the ripple in v_o. Check it with its analytical value and compare it with Problem 3 of Example 10.

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

PSpice Schematic: FBUSDCDC

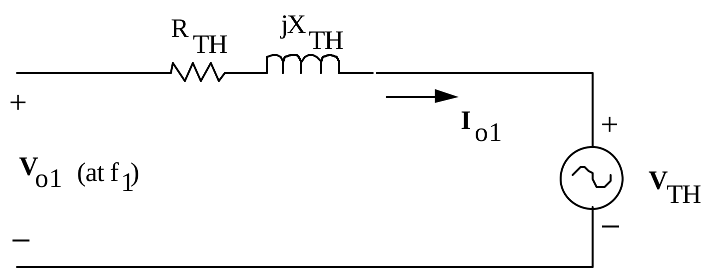
EXAMPLE 12

1-Phase, Bipolar-Voltage Switching Inverter



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

Phasor Diagram:



Therefore, $\mathbf{V}_{TH}$ (rms) = 124.1 $\underline{/-5.39^o}$ V

and v_{TH} = 175.5 sin (2πx40xt - 5.39^o).

Inverter and Controller for Sinusoidal PWM:

Switching frequency f_s = 1 kHz ,
Frequency modulation ratio m_f = 1000 / 40 = 25,
Amplitude modulation ratio m_a = 0.8.
Therefore, $V_d = V_{o1,peak} / m_a$ = 271 V and,
$v_{control}$ = 0.8 sin (2πx40t).

Problems

1. Obtain the following waveforms using 1Phbsinv:
   (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_{ripple} waveform in the output voltage.

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_{ripple} in the output current.

6. Obtain I_d(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.

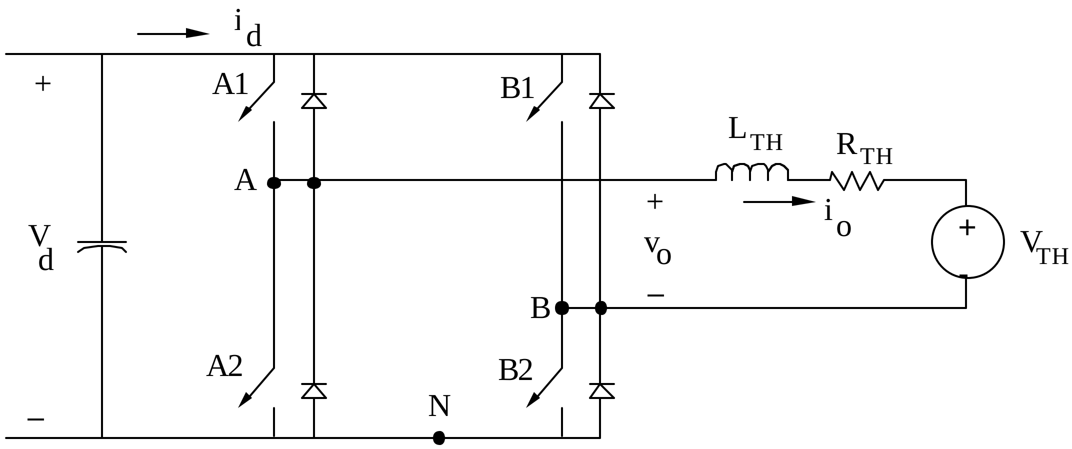
Reference: Section 8-3-2-1, pages 212 - 215.

PSpice Schematic: 1Phbsinv

Based on $\mathbf{I}_{o1}$(rms) = 10 $\underline{/-30^o}$ A, the initial value $I_o(o)$ = -7 A.

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_{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_{ripple} in the output current. Compare the peak-to-peak ripple to that in the bipolar-voltage switching inverter.

6. Obtain I_d(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

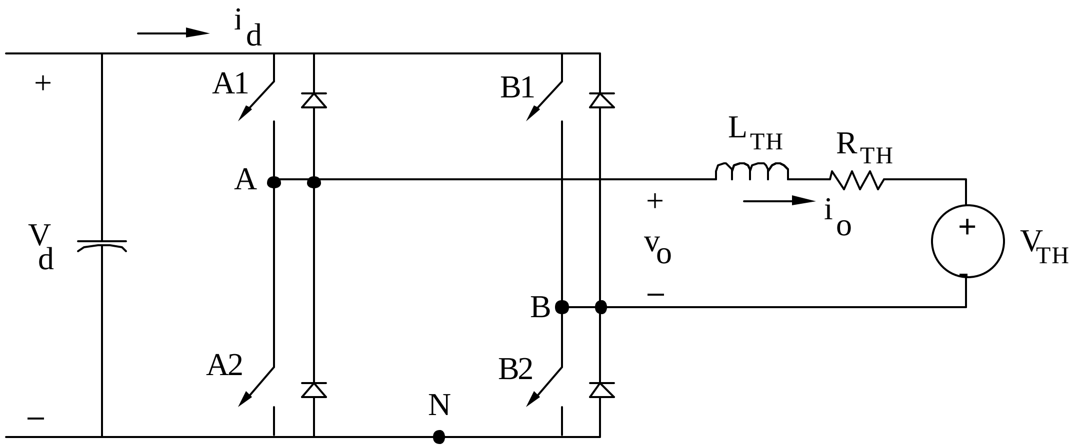
Based on $\mathbf{I}_{o1}$(rms) = 10 /-30º A, the initial value $I_o(o)$ = -7 A.

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 vcontrol, whereas the switches in the converter-leg B depend on (- vcontrol).

EXAMPLE 14

1-Phase, Square-Wave Inverter



Nominal Values: Same as in Example 12 except,

$$V_d = \frac{\pi}{4} \; V_{01,peak} = 216.8 \; \frac{\pi}{4} \; = 170.27 \text{ V}$$

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

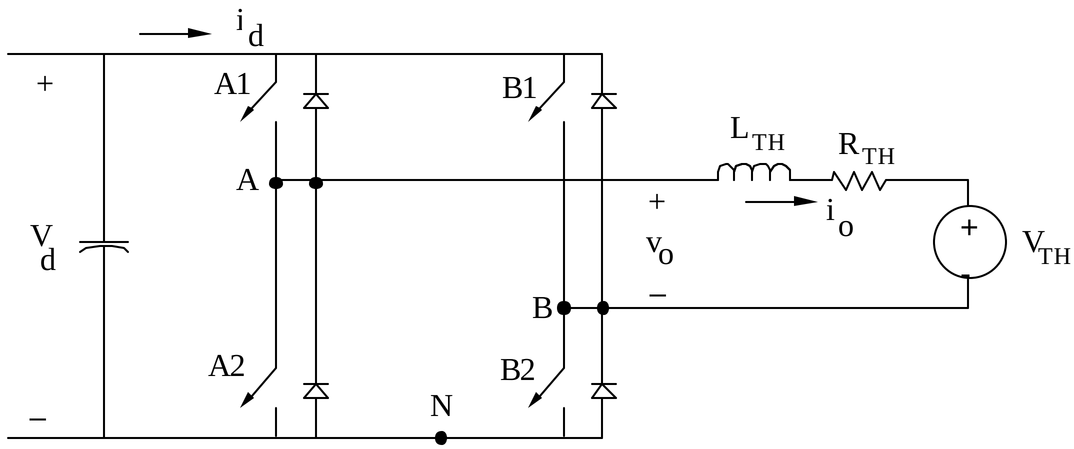
Based on $\mathbf{I}_{o1}$(rms) = 10 $\underline{/-30}^o$ A, the initial value $I_o(o)$ = -7 A.

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 $\hat{V}_{01}$ = 216.8V, at h = 1

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

$$\therefore\ \beta = 38.9° \quad \text{and} \quad \alpha = 180 - 2\beta = 102.2°$$

$$\frac{a}{2} = 51.1^0$$

Problems

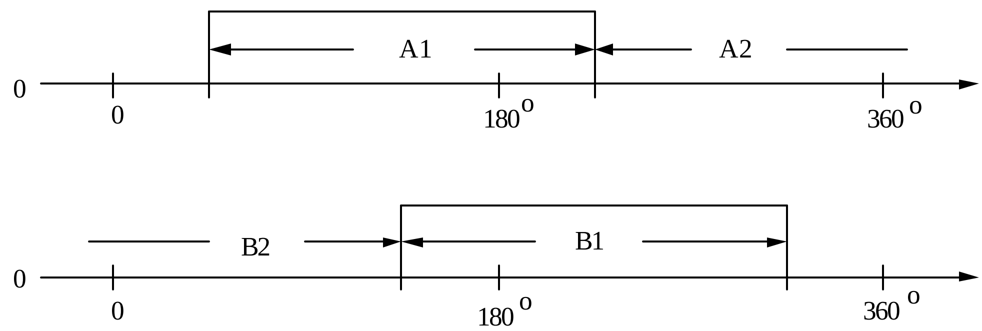
Same as in Example 14.

Reference: Section 8-3-2-4, pages 218 - 219. See the definitions of α and β.

PSpice Schematic: 1Phvcinv

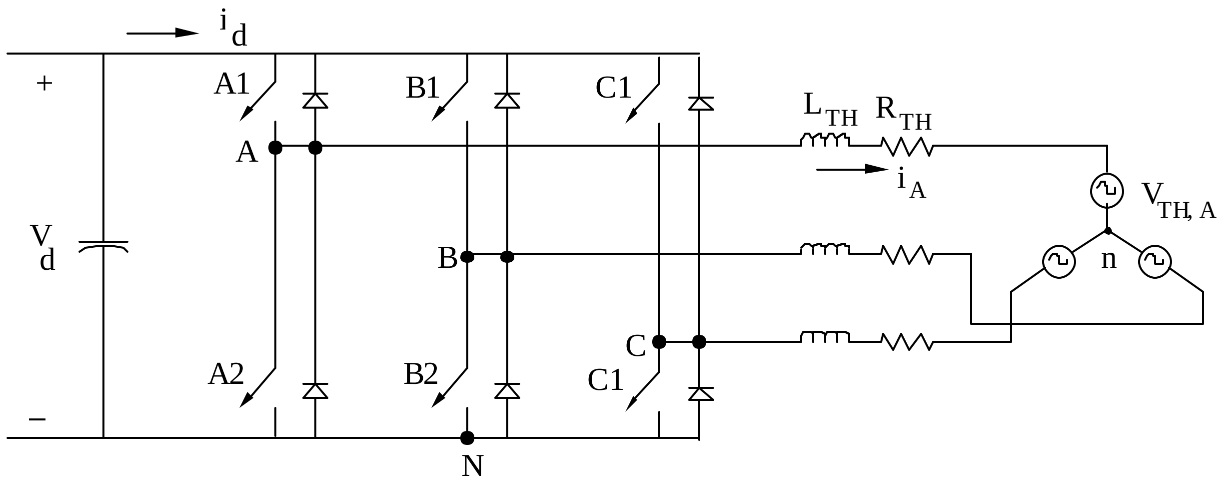
Based on $\mathbf{I}_{o1}$(rms) = 10 /-30° A, the initial value $I_o(o)$ = -7 A.

Controller:



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,

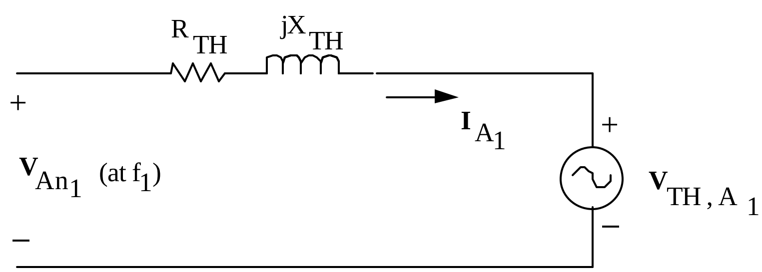
$$V_{LL_1}^{rms} = \frac{47.619}{60} \times 230 = 182.54 \text{ V.}$$

$$V_{An_1}^{rms} = \frac{V_{LL_1}^{rms}}{\sqrt{3}} = 105.39 \text{ V} = 105.39\angle\underline{0}°.$$

$I_{A_1}^{rms}$ = 10 A at a lagging power factor of 0.866 = 10 $\angle\underline{-30}°$ A. R_s = 2Ω , L_s = 10 mH,

$\therefore$ $X_s = 2\pi x 47.619 x 10 x 10^{-3} = 3\Omega$.

Phasor Diagram:



$\therefore$ $(\mathbf{V}_{TH,A})_1$ = 74.76 $\angle\underline{-12.36}°$ V (rms)

Inverter and Sinusoidal PWM Controller:

Switching frequency f_s = 1 kHz.

Amplitude modulation ratio m_a = 0.95 .

$\therefore$ $V_d = \dfrac{V_{LL_1}^{rms}}{0.612\, m_a}$ = 313.97 V. With $\hat{V}_{tri}$ = 1.0 V

$v_{control,A} = 0.95 \cos(2\pi f_1 t - 90°)$ V.

Problems

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

2. Obtain v_{An_1} by means of Fourier analysis of the v_{An} waveform. Compare v_{An_1} with its precalculated nominal value.

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

4. Obtain i_{A_1} by means of Fourier analysis of i_A waveform. Compare i_{A_1} with its precalculated nominal value.

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

6. Obtain I_d(avg) by means of Fourier analysis and obtain the high frequency ripple $i_{d,ripple} = i_d - I_d$(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

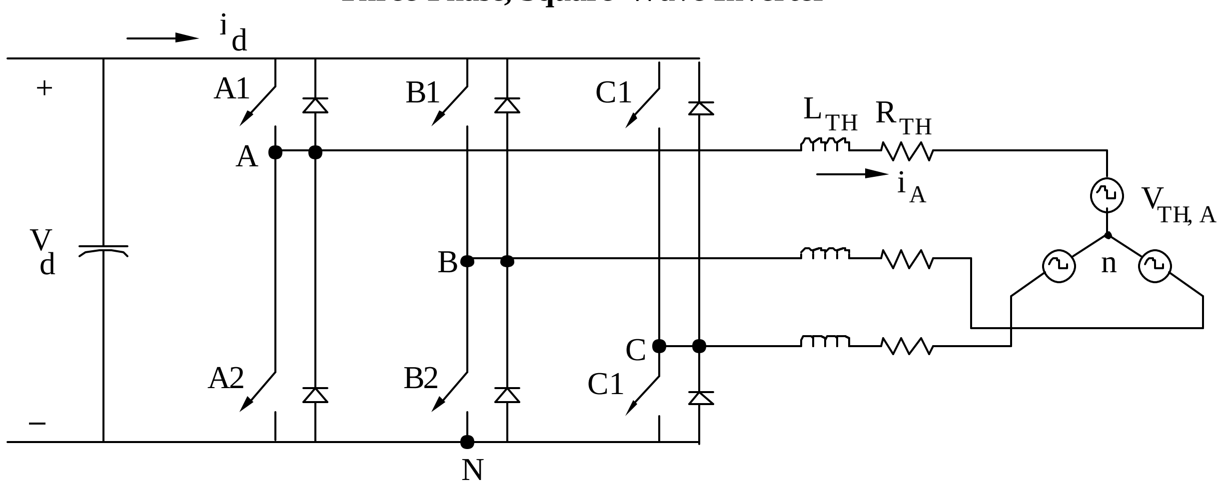
Based on $\mathbf{I}_{A1}$(rms) = 10 $\underline{/-30^o}$ A, the initial value $I_{A1}(o) = -7.07$ A.

Controller:

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

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 $V_{LL_1}^{rms} = 182.54$ V.

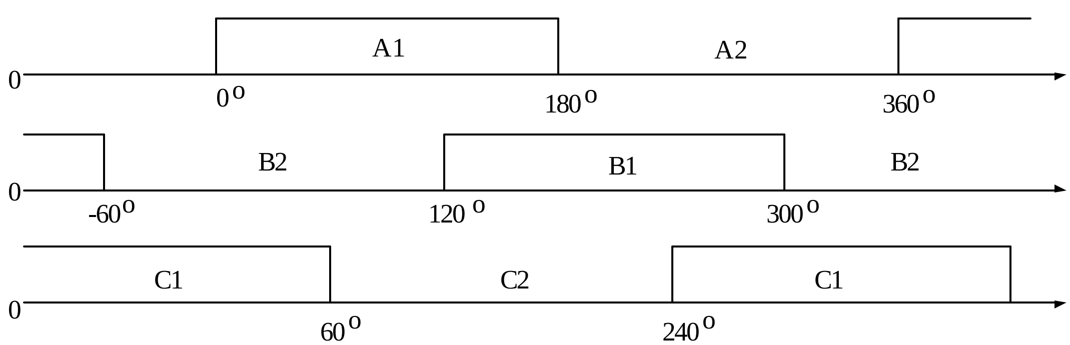
Problems

Same as in Example 16.

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

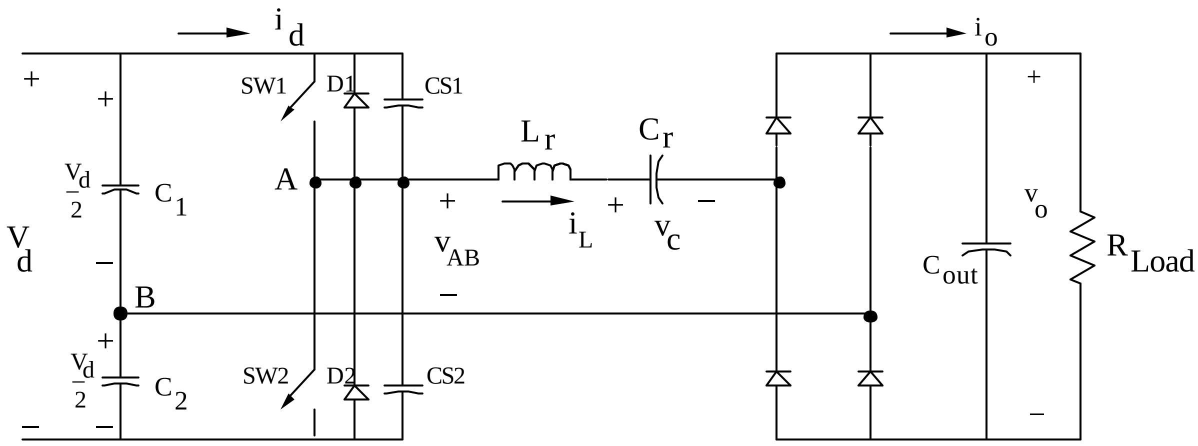
PSpice Schematic: SQINV3

Controller:



EXAMPLE 18

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



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

$L_r = 45.5\ \mu$H, $C_r = 96.9$ nF

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

C_1, C_2 = Large, $C_{out} = 50\ \mu$F, $R_{Load} = 50\ \Omega$.

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_{cs1} and i_{cs2} 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 μs to 5.8 μs in Problems 3 and 4.

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

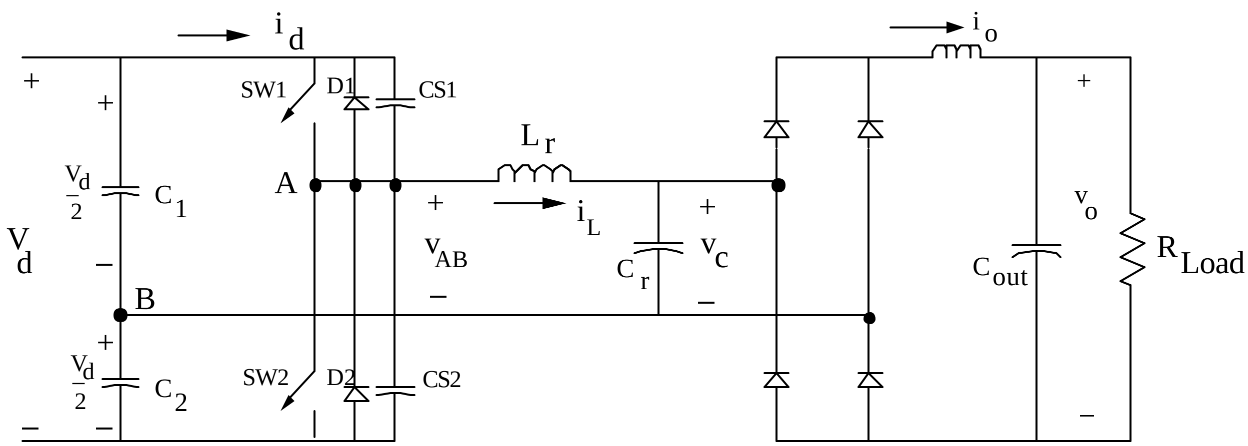
7. Without changing the circuit parameters, change the switching frequency to f_s = 80 kHz. Obtain I_o(avg) and compare the normalized v_c and i_L / I_o(avg) with those in Problem 3. Hint: Estimate the output voltage and use it as initial condition in the simulation.

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

PSpice Schematic: SLRCM2

EXAMPLE 19

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



Nominal Values:

V_d = 155 V, f_s = 300 kHz

L_r = 37.96 μH, C_r = 8.97 nF

∴ f_o = 272.74 kHz, f_s / f_o = 1.1 .

I_o = 0.9926 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?

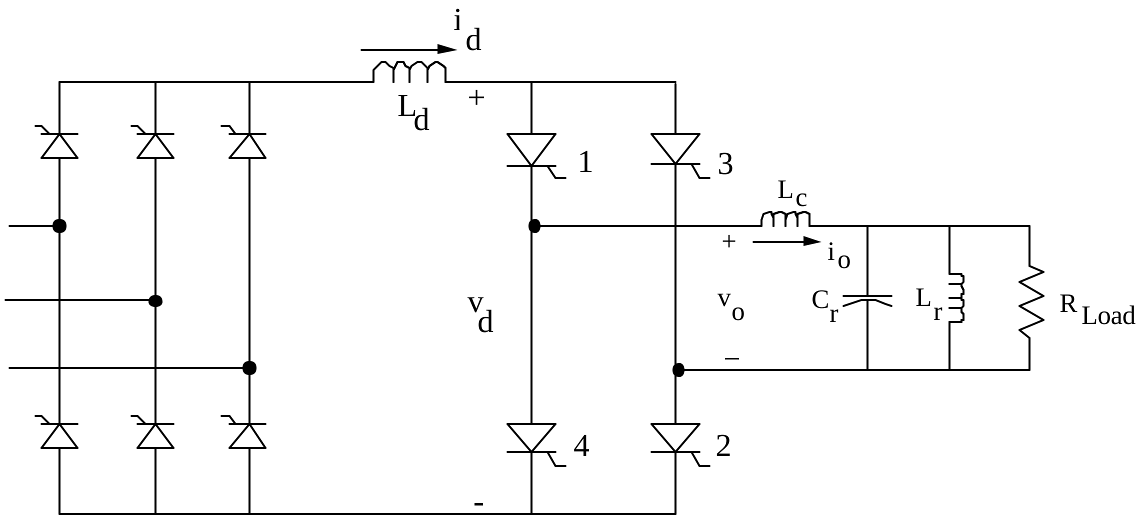
5. In a time range of 6.5 μs to 7.5 μs, plot the currents i_{cs1} and i_{cs2} through the snubber capacitors, i_{D1}, i_L, i_{sw1} and the gate signals to switches 1 and 2 (all on the same plot).

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

PSpice Schematic: PLRCM2

EXAMPLE 20

Current-Source, Parallel-Resonant Inverter for Induction Heating



Nominal values: $f_s = 4$ kHz

$L_r = 78\ \mu H$, $L_c = 20\ \mu H$

$C_r = 25\ \mu F$, $R_{load} = 20\ \Omega$.

$f_o = 3.6$ kHz, $\frac{f_s}{f_o} = 1.11$.

$i_d \simeq I_d = 25$ 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.

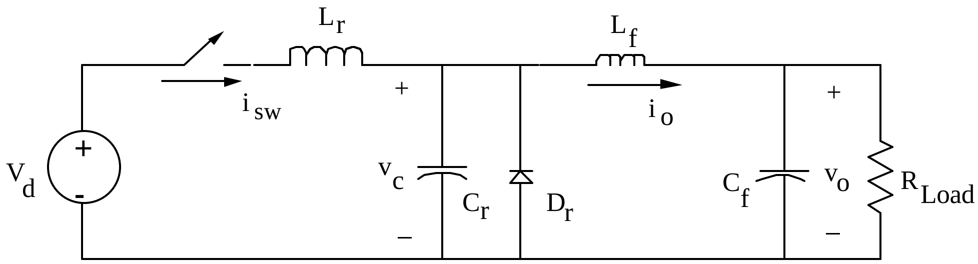
5. Plot the voltage across one of the thyristors and calculate the reverse recovery time (= γ/ω_S) in μs available to the thyristors.

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

PSpice Schematic: CSINV

EXAMPLE 21

Zero-Current-Switching, Quasi-Resonant Buck Converter



Nominal Values: $V_d = 15$ V, $V_o = 10$ V,

$i_o = I_o = 1$ A,

$$f_o = \frac{1}{2\pi\sqrt{L_r C_r}} = 1 \text{ MHz}$$

$$Z_o = \sqrt{\frac{L_r}{C_r}} = 10\ \Omega$$

$\therefore$ $L_r = 1.59$ µH, $C_r = 15.9$ nF

$f_s = 0.614$ MHz $\therefore$ $T_s = 1.624$ µs

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.

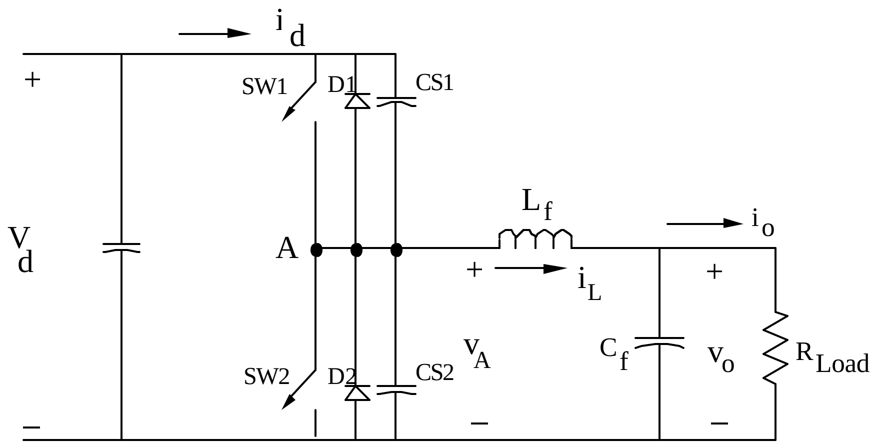
PSpice Schematic ZCSconv:

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.

EXAMPLE 22

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



Nominal Values:

V_d = 21 V, V_o = 10 V
f_s = 100 kHz, L_f = 20 μH
$C_{s1} = C_{s2}$ = 5 nF
C_f = 1000 μF, R_{load} = 10 Ω.

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?

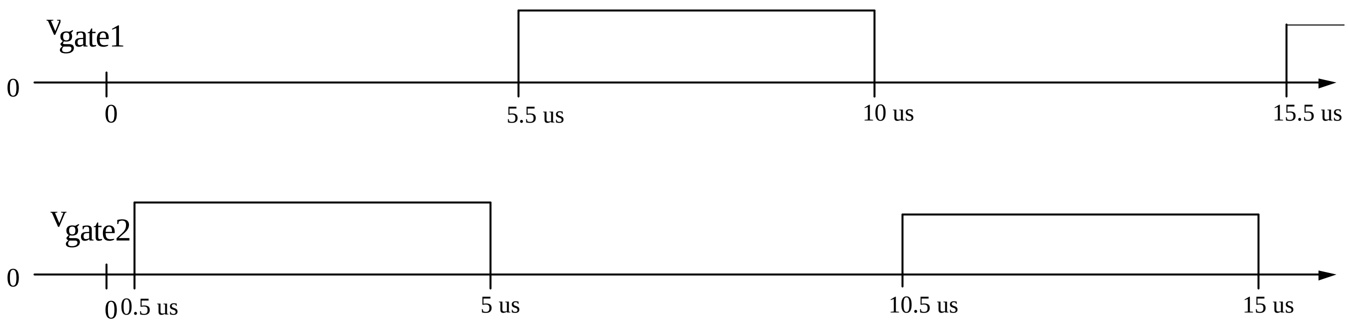
5. Calculate the peak-to-peak ripple in the inductor current as a ratio of the average inductor current. What should its value be to provide zero voltage switching?

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.

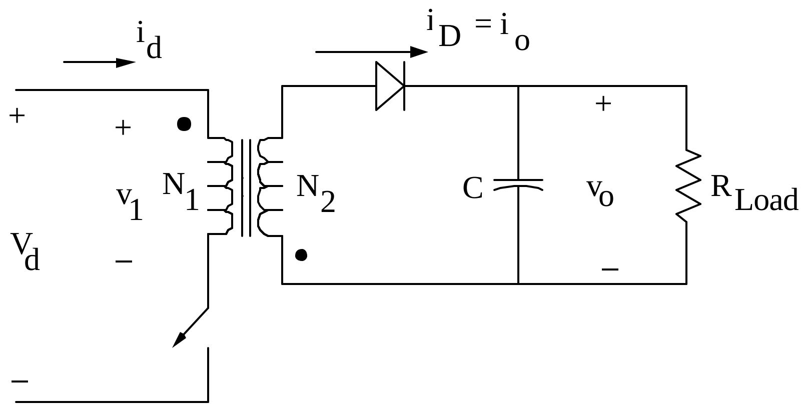
PSpice Schematic: ZVSCV

Controller:



EXAMPLE 23

Flyback dc-dc Converter



Nominal Values:

V_d = 32 V, $V_o \simeq$ 4 V
switch duty-ratio D = 0.4, f_s = 200 kHz,
C = 100 μF, R_{load} = 1 Ω
Transformer: N_1/N_2 = 4,
Magnetizing inductance L_m = 30 μH,
Neglect the leakage inductances.

Problems:

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

2. Plot v_1, i_{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

$$\frac{I_d}{I_o} = \frac{V_o}{V_d} \quad .$$

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

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

5. Change the load resistance to 50 Ω 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,

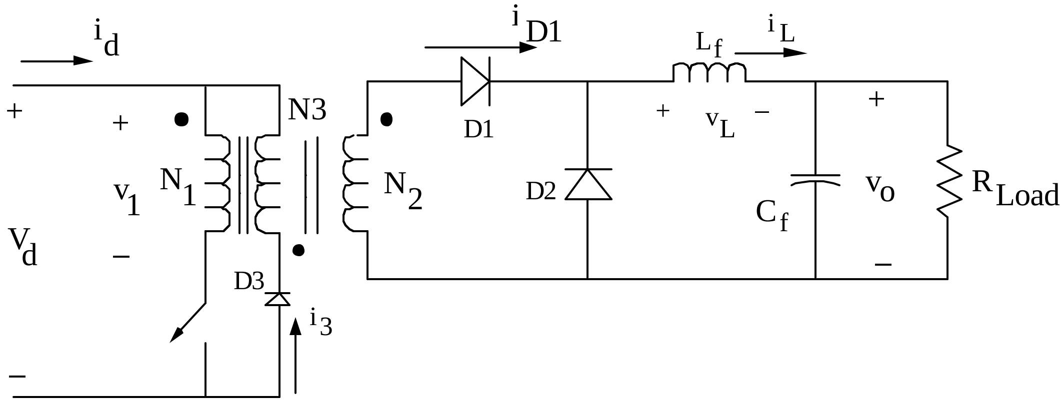
$$L_1 = 30\ \mu H, \text{ and } L_2 = L_1 / (N_1/N_2)^2 = 1.875\ \mu H.$$

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.

EXAMPLE 24

Forward dc-dc Converter



Nominal Values:

$V_d = 50$ V, $V_o \simeq 4.5$ V, $\frac{N_1}{N_2} = 4$, $\frac{N_1}{N_3} = 1$

$f_s = 200$ kHz, $L_m = 100\ \mu$H, $L_f = 7.5\ \mu$H

$C_f = 100\ \mu$F, $R_{Load} = 1\ \Omega$,

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

$$\frac{t_m}{T_s} = \frac{N_3}{N_1} D$$

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

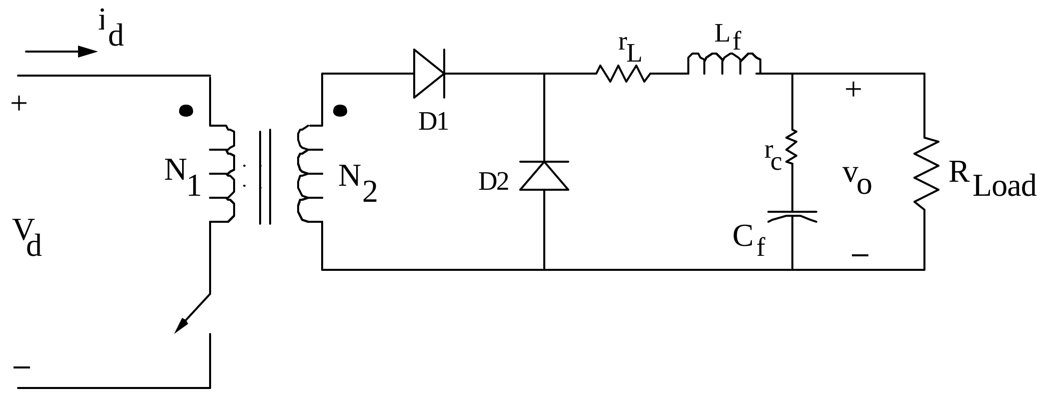
Notes:

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.

EXAMPLE 25

Forward Converter: Voltage-Mode Controlled



Nominal Values:

r_c = 10 mΩ, C_f = 2,000 µF, R_{Load} = 200 mΩ,
V_d = 24 V, V_o = 4 V, r_L = 10 mΩ (ignore), L_f = 5 µH,
f_s = 200 kHz, N_1 / N_2 = 3.

PWM Modulator: $T_m(s)$ = 0.34 (-9.37 dB)

Voltage-Mode Controller: Designed with crossover frequency $w_c = 10^5$ rad/s and phase margin $f_{pm} = 45^o$.

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 µs. Observe the system response.

2. Repeat Problem 1 by applying an additional load resistance of 800 mΩ 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.

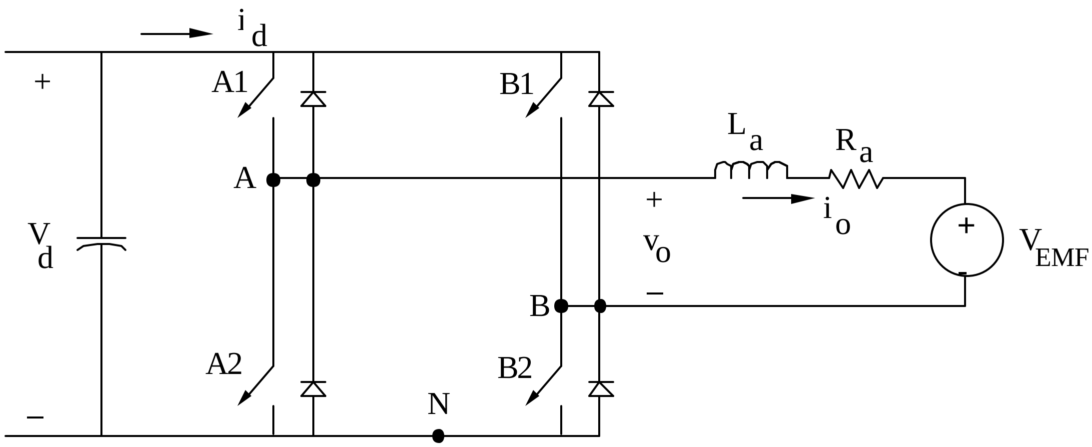
5. Repeat Problems 1 through 4 with a Type-3 controller which provides a phase boost of 60^o with the same crossover frequency as before.

Reference: Section 10-5, pages 322 - 336.

PSpice Schematic: For_Cntl

EXAMPLE 26

Ripple in the DC Motor Armature Current



Nominal Values: V_d = 200 V

R_a = 0.37 Ω

L_a = 1.5 mH

f_s = 10 kHz, Unipolar Voltage Switching

$K_E = K_T = 0.75$

duty-ratio D_1 of T_{A1} and T_{B2} = 0.708

($v_{control}$ = 0.416 V with $\hat{V}_{tri}$ = 1.0 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

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 rs = 1mΩ). 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_{stray}.

Problems

1. Look at the MOSFET switching waveforms.

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

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

PSpice Schematic: MOSFET