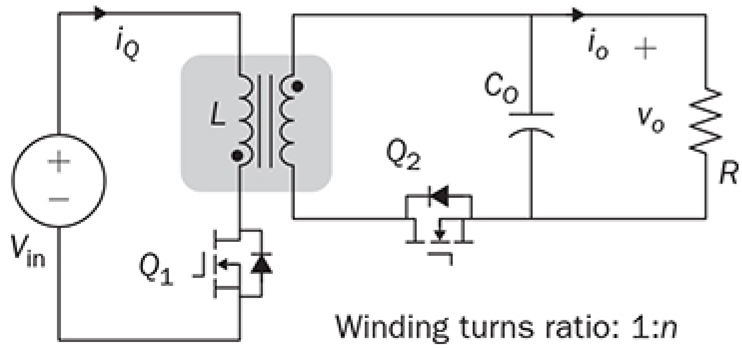


FIGURE 7.22 Flyback converter with synchronous rectifier.

Figure 7.23 shows the synchronous switching implementation for the forward topologies. The diode D_2 remains in the circuit since its conduction loss does not weigh high in the distribution when $V_{in} > 100$ V. The conduction loss of the MOSFETs, Q_3 and Q_4, is expected to be low in comparison to the diode implementation for ELV applications.

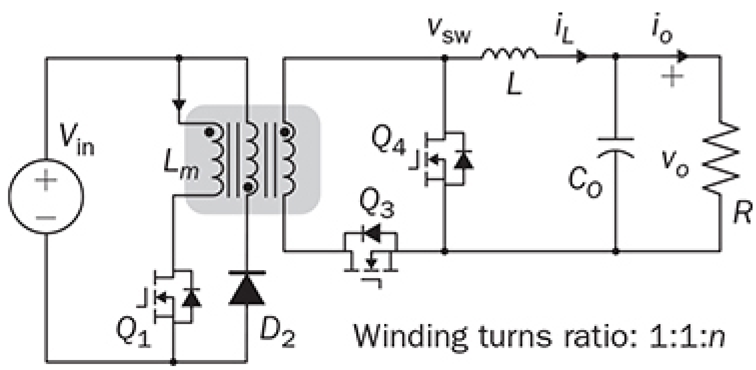
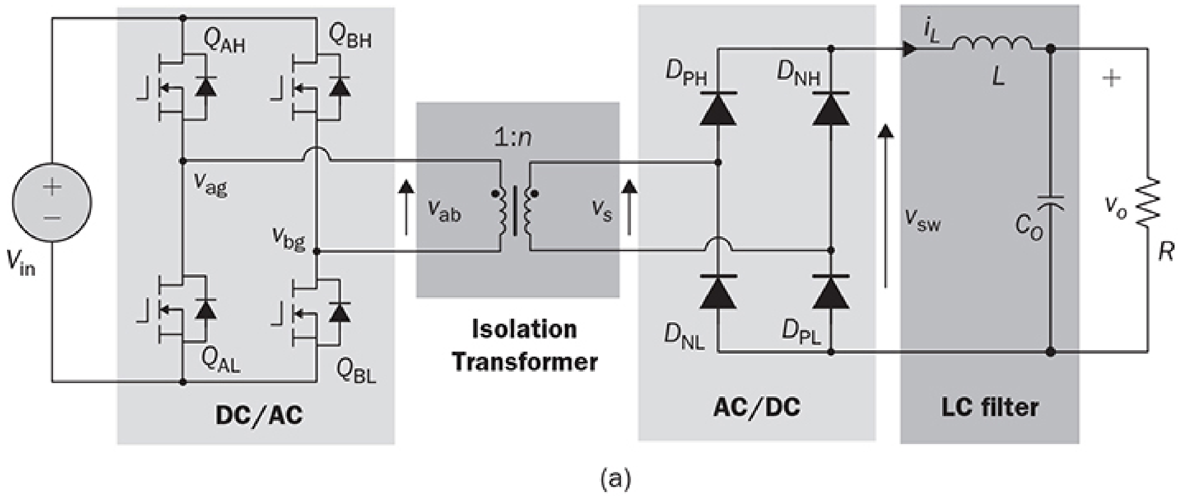


FIGURE 7.23 Synchronous switching solution for forward converter.

7.5 Full Bridge for DC/AC Stage

An isolated DC/DC topology is called the full-bridge isolated DC/DC converter, as shown in Fig. 7.24*a*. Different from the forward converter, the isolation transformer directly passes AC from one terminal to another. The term "full bridge" refers to the utilization of the active four-switch bridge for the DC/AC conversion, and the passive four-switch bridge for the AC/DC conversion. Even though the circuitry is more complicated than the topologies introduced earlier, the converter follows a simple design concept, as demonstrated in Fig. 7.24*b*. Power passes from the source to the load via the path of DC/AC, AC/AC, AC/DC, and filtering. The voltage transformer naturally performs the AC/AC voltage conversion from one winding to others. The magnetic flux density in the transformer swings two quadrants of its B-H curve, as illustrated in Fig. 7.24*b*.



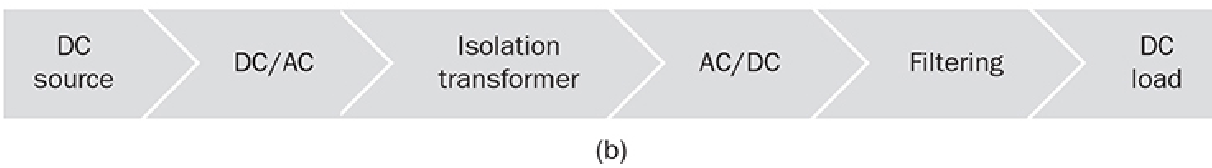


FIGURE 7.24 Full-bridge isolated DC/DC converter: (*a*) schematics; (*b*) concept illustration of power flow.

The DC/AC stage can be modulated and controlled to output the desired pulse width and frequency of AC, as discussed in Chap. 5. The diode bridge is a full-wave rectifier that has been discussed and analyzed in Chap. 6. The key components also include the isolation transformer and the LC circuit for low-pass filtering. The active four-switch bridge can produce the AC signal, v_{ab}, in high frequency. It is an effective way to minimize the size and cost of the isolation transformer. The high switching frequency also appears at the DC signal, v_{sw}, which lowers the size of L and C_O. For the four-switch active bridge, the complication of sine-triangle modulation is unnecessary since the power quality of the interlinking AC is not a concern. The modulation should produce chopped-square waveforms in v_{ab} to represent the amplitude and frequency of AC. As discussed in Sec. 5.1, the phase-shift technique can produce the desired pulse width through the modulation process.

7.5.1 Steady-State Analysis

Figure 7.25 illustrates the key waveforms of the converter in the CCM and steady state. The pulse width of v_{ab} appears the same as that in the waveforms of v_s and v_{sw}. The AC signals pass the transformer, which is expressed by $v_s = nv_{ab}$ corresponding to the winding turns ratio. The signal of v_s is rectified into DC as v_{sw}. From the point of v_{sw}, the operation follows the same principle as the nonisolated buck converter regarding the steady-state analysis. Figure 7.26 illustrates the equivalent circuit of the output stage of the isolated converter. The duty ratio of v_{sw} determines the averaged value of the output voltage and current.

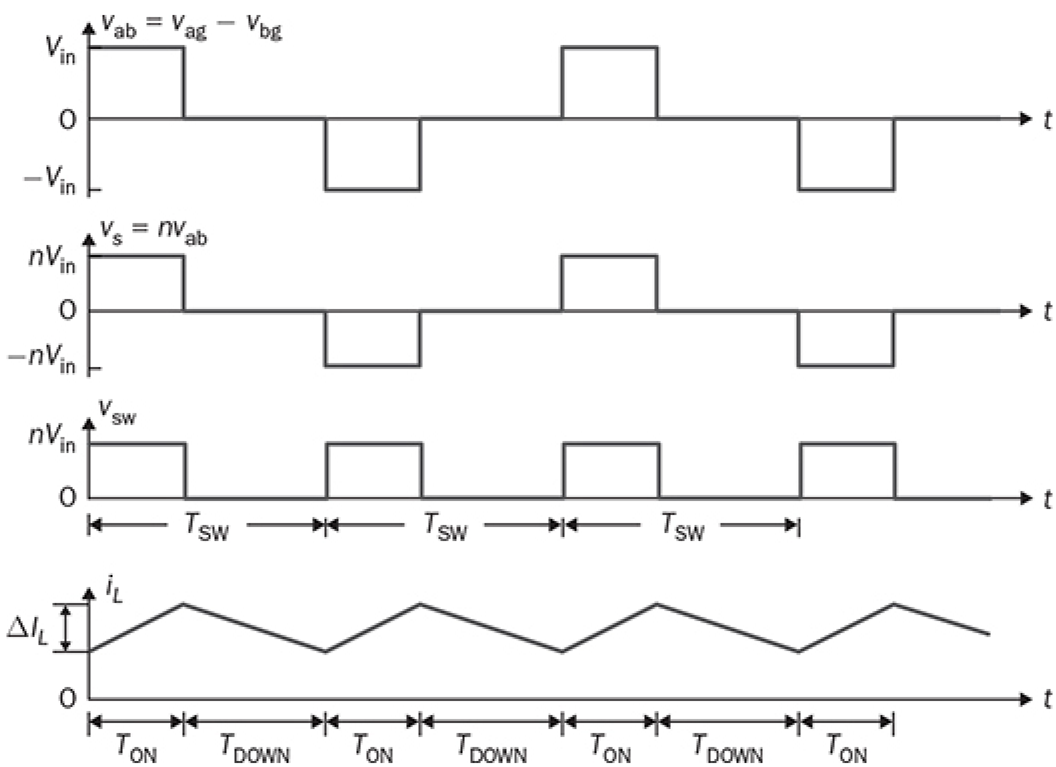


FIGURE 7.25 Steady-state waveforms of isolated buck converter.

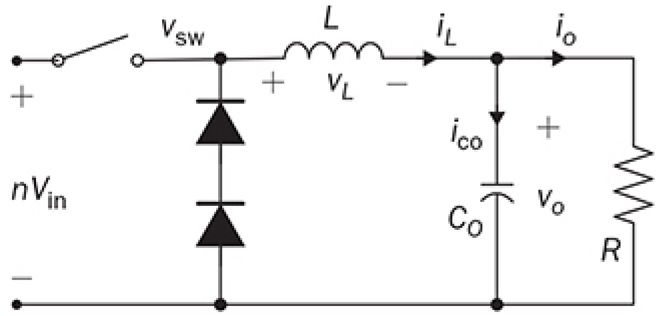


FIGURE 7.26 Equivalent circuit of the output stage of full-bridge isolated converter.

Following the waveforms in Fig. 7.25, the voltage conversion ratio in steady state can be derived as in (7.28). The voltage conversion ratio becomes as in (7.29) since $T_{ON} + T_{DOWN} = T_{SW}$ in CCM. The duty ratio, D_{ON}, refers to the signal of v_{sw} expressed

$$\frac{V_O}{nV_{\text{in}}} = \frac{T_{\text{ON}}}{T_{\text{ON}} + T_{\text{DOWN}}} \tag{7.28}$$

$$\frac{V_O}{V_{\text{in}}} = nD_{\text{ON}} \tag{7.29}$$

The modulation is performed by the active four-switch bridge at the DC/AC stage. According to the phase-shift modulation in Sec. 5.1.2, the phase delay angle, Φ, is the control variable to determine the pulse width of v_{ab}, v_s, and v_{sw}. The relation between Φ and D_{ON} is proportional and expressed in (7.30). Therefore, the output voltage of the full-bridge isolated DC/DC converter can be determined by the applied phase angle, Φ, as shown in (7.31).

$$D_{\text{ON}} = \frac{\Phi}{\pi} \tag{7.30}$$

$$V_O = nV_{\text{in}}\frac{\Phi}{\pi} \tag{7.31}$$

where V_O represents the averaged value of the output voltage. It should be noted that the switching frequency of the DC/AC stage is expressed by

$\frac{1}{2T_{SW}}$, as shown in the waveform of v_{ab} in Fig. 7.25. The difference is caused by the rectification from the single-phase AC to DC.

Following the equivalent circuit in Fig. 7.26, the diode bridge serves as the freewheeling purpose of the inductor current, i_L. Thus, the discontinuous conduction mode (DCM) results when the inductor current, i_L, is saturated to zero for a certain time during the periodic cycle in steady state. The output voltage cannot be predicted by the CCM in (7.31). However, the steady-state analysis for the DCM can follow the same procedure for the nonisolated buck converter and refers to the equivalent circuit in Fig. 7.26.

7.5.2 Circuit Specification and Design

The design of the full-bridge isolated DC/DC converter is mainly based on the CCM operation. The value of f_{sw} is referred to as the switching frequency of the active swtiches. According to the nominal operating condition, the following procedure can be followed for design:

1. Determine the winding turns ratio of the isolation transformer according to the ratio of the input voltage and output voltage and the constraint of D_{ON} and Φ.
2. Calculate on-state duty cycle and on-state time at steady state: $D_{ON} = \frac{V_O}{nV_{in}} \frac{D_{ON}}{2f_{sw}}$, $T_{DOWN} = 1 - T_{ON}$, and $\Phi = D_{ON}\pi$.
3. Calculate the inductance: $L = \frac{V_O}{\Delta I_L} T_{DOWN}$ following the same measure for the nonisolated buck converter.
4. Calculate the capacitance of C_O following the same procedure as in (3.15) for the buck converter.
5. Determine the critical load condition in terms of the averaged output current and the resistance.

Following the circuit in Fig. 7.24, the specifications for a case study are shown in Table 7.3. Thus, the converter can be designed step by step.

Symbol	Description	Value
P_{norm}	Nominal power rating	4.8 kW
V_{in}	Nominal input voltage	380 V
V_o	Nominal output voltage	48 V
f_{SW}	Switching frequency of the active switches	20 kHz
ΔI_L	Nominal peak-to-peak ripple of inductor current	20 A
ΔV_O	Nominal peak-to-peak ripple of capacitor voltage	0.5 V

TABLE 7.3 Specifications of Forward Converter

1. The winding turns ratio is assigned to be $n = 0.25$, following the nominal conversion ratio of 48/380 and the upper limit of D_{ON}.
2. On-state duty cycle at the CCM: $D_{ON} = \dfrac{V_O}{nV_{in}} = 50.53\%$; $T_{ON} = \dfrac{D_{ON}}{2f_{SW}} = 12.63\ \mu s$; $T_{DOWN} = 12.37\ \mu s$; $\Phi = 1.59$.
3. Calculate the inductance: $L = \dfrac{V_O}{\Delta I_L} T_{DOWN} = 29.68\ \mu H$.
4. Calculate the capacitor: $C_O = \dfrac{\Delta I_L}{8 \Delta V_O f_{sw}} = 125\ \mu F$.
5. BCM: BCM: $I_{O,crit} = \dfrac{\Delta I_L}{2} = 10\ A$; $R_{crit} = \dfrac{V_O}{I_{O,crit}} = 4.8\ \Omega$.

7.5.3 Simulation for Concept Proof

Based on the previous discussion for DC/AC, AC/DC, and buck converters, the simulation model for the full-bridge isolated DC/DC conversion can be built by integrating the individual functional blocks, as shown in Fig. 7.27. The DC/AC block follows the same development described in Sec. 5.4.1, as shown in Fig. 5.23. The functional block of phase-shift modulation has been developed and shown in Fig. 5.24. The operations of the ideal transformer and the AC/DC conversion are simplified by the mathematical computation of scaling and absolution, respectively. The model takes the inputs of the phase-shift angle, Φ, and the input voltage, V_{in}. It outputs the