CHAPTER 9

Resonant Converters

9.1 Introduction

The switching devices in converters with a pulse width modulation (PWM) control can be gated to synthesize the desired shape of output voltage or current. However, the devices are turned-on and off at the load current with a high *di*/*dt* value. The switches are subjected to a high voltage stress, and the switching power loss of a device increase linearly with the switching frequency. The turn-on and turn-off loss could be a significant portion of the total power loss. The electromagnetic interference is also produced due to high *di*/*dt* and *dv*/*dt* in the converter waveforms.

The disadvantages of PWM control can be eliminated or minimized if the switching devices are turned "on" and "off" when the voltage across a device or its current become zero. The voltage and current are forced to pass through zero crossing by creating an LC resonant circuit, thereby called a resonant pulse converter.

Series Resonant Inverters

The series resonant inverters are based on resonant current oscillation. The resonating components and switching device are placed in series with the load to form an underdamped circuit. The current through the switching devices falls to zero due to the natural characteristics of the circuit. If the switching element is a thyristor, it is said to be self-commutated. This type of inverter produces an approximately sinusoidal waveform at a high output frequency, ranging from 200 to 100 kHz, and is commonly used in relatively fixed output applications (e.g. induction heating, sonar transmitter, fluorescent lightening, or ultrasonic generators). Due to the high switching frequency, the size of resonating components is small.

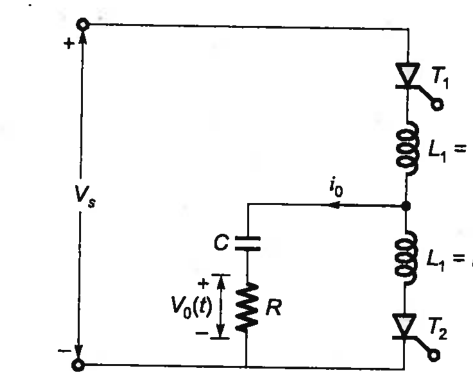
Series-Resonant Inverters with Unidirectional Switches

The circuit diagram of a simple series inverter using two unidirectional thyristor of switches. When thyristor T_1 is fired, a resonant pulse of current flows through the load and the current falls to zero at $t = t_{1m}$ and T_1 is self commutated. Firing of thyristors T_2 causes a reverse resonant current through the load and T_2 is also self-commutated. The circuit operation can be divided into three modes and the equivalent circuits are shown in figure below. The gating signals for thyristors and the waveform for the load current and capacitor voltage are shown.

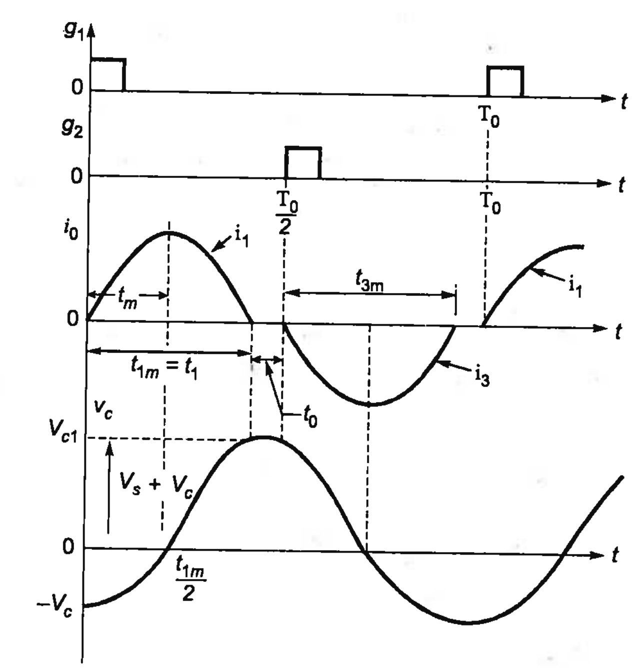
The series resonant circuit formed by *L*, *C* and load (assumed resistive) must be underdamped.

i.e., $$R^2 < \frac{4L}{C}$$

The resonant frequency, $$\omega_r = \left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)^{1/2}$$



(a) Circuit



(b) Waveforms

$$\frac{\pi}{\omega_0} - \frac{\pi}{\omega_r} = t_{off} > t_q$$

$$f_0 \le f_{max} = \frac{1}{2\left(t_q + \frac{\pi}{\omega_r}\right)}$$

The resonant inverter circuit shown above is very simple. However, it gives the basic concept and described the characteristic equations, which can be applied to other types of resonant inverters.

9.2 Zero-Current-Switching Resonant Converters

The switches of a zero-current-switching (ZCS) resonant converter turn on and off at zero current. The resonant circuit that consists of switch S_1, inductor L, and capacitor C is shown in figure. Inductor L is connected in series with a power switch S_1 to achieve ZCS. It is classified into two types: L type and M type. In both types, the inductor L limits the di/dt of the switch current, and L and C constitute a series-resonant circuit. When the switch current is zero, there is a current $i = C_j \frac{dv_T}{dt}$ flowing through the internal capacitance C_j due to a finite slope of the switch voltage at turn-off. This current flow causes power dissipation in the switch and limits the high switching frequency.

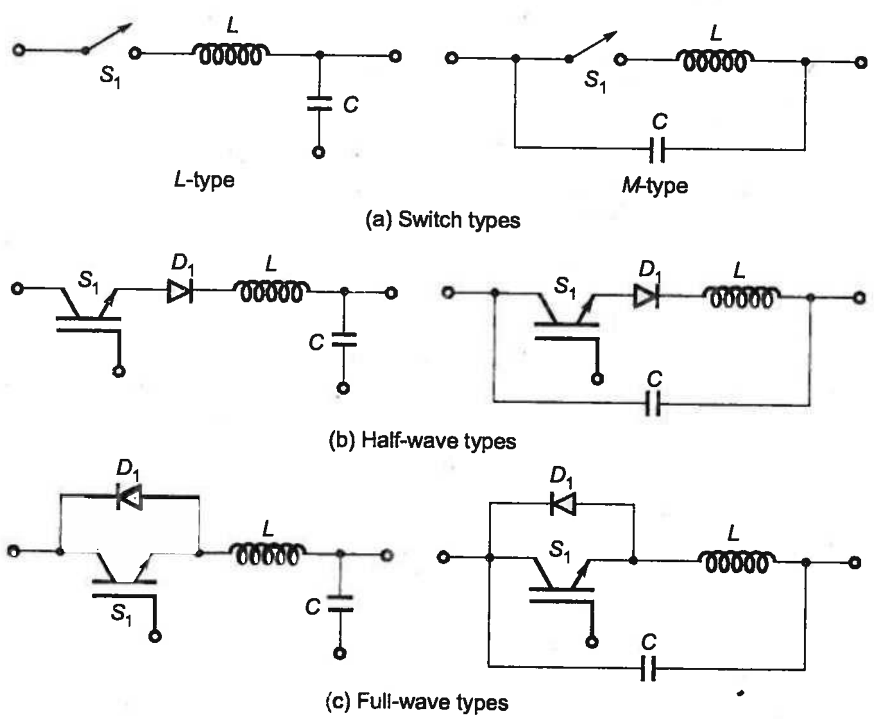


Figure: Switch configuration for ZCS resonant converters

9.3 L-Type ZCS Resonant Converter

An L-type ZCS resonant converter is shown in Fig. (a). The circuit operation can be divided into five modes, whose equivalent circuits are shown in Fig. (b). We shall redefine the time origin, $t = 0$, at the beginning of each mode.

Mode-1: This mode is valid for $0 \le t \le t_1$. Switch S_1 is turned on and diode D_m conducts. The inductor current i_L, which rises linearly, is given by

$$i_L = \frac{V_s}{L} t$$

This mode ends at time $t = t_1$ when $i_L(t = t_1) = I_0$. That is, $t_1 = \frac{I_0 L}{V_s}$.

Mode-2: This mode is valid for $0 \le t \le t_2$. Switch S_1 remains on, but diode D_m is off. The inductor current i_L is given by

$$i_L = I_m \sin \omega_0 t + I_0$$

where $I_m = V_s\sqrt{C/L}$, and $\omega_0 = 1\sqrt{LC}$. The capacitor voltage v_c is given by

$$v_c = V_s(1 - \cos \omega_0 t)$$

The peak switch current, which occurs at $t = (\pi/2)\sqrt{LC}$, is

$$I_p = I_m + I_0$$

The peak capacitor voltage is

$$V_{c(pk)} = 2\,Vs$$

This mode ends at $t = t_2$ when $i_L(t = t_2) = I_0$, and $v_c(t = t_2) = V_{c2} = 2V_s$.

Therefore,

$$t_2 = \pi\sqrt{LC}$$

Mode-3: This mode is valid for $0 \le t \le t_3$. The inductor current that falls from I_0 to zero is given by

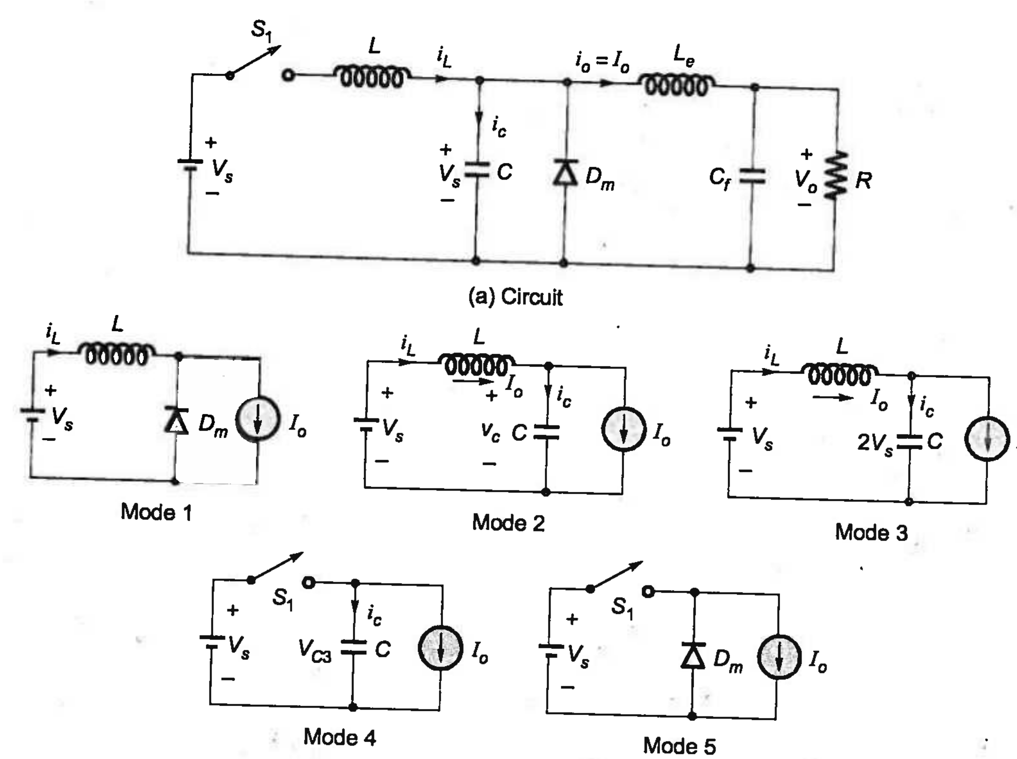
$$i_L = I_0 - I_m \sin \omega_0 t$$

The capacitor voltage is given by

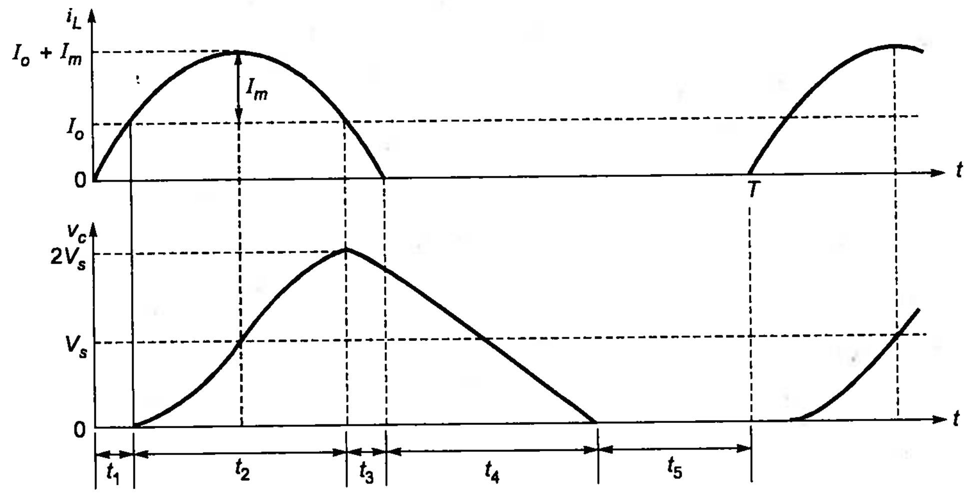
$$v_c = 2V_s \cos \omega_0 t$$

This mode ends at $t = t_3$ when $i_L(t = t_3) = 0$ and $v_c(t = t_3) = V_{c3}$.

Thus, $t_3 = \sqrt{LC}\sin^{-1}\left(\frac{1}{x}\right)$ where $x = \frac{I_m}{I_0} = \left(\frac{V_s}{I_0}\right)\sqrt{\frac{C}{L}}$.



(b) Equivalent circuits



(c) Waveforms

L-type ZCS resonant converter

Mode-4: This mode is valid for $0 \le t \le t_4$. The capacitor supplies the load current I_0, and its voltage given by

$$v_c = V_{c3} - \frac{I_0}{C}t$$

This mode ends at time $t = t_4$ when $v_c(t = t_4) = 0$.

Thus, $$t_4 = \frac{V_{c3}C}{I_0}$$

Mode-5: This mode is valid for $0 \le t \le t_5$. When the capacitor voltage tends to be negative, the diode D_m conducts. The load current I_0 flows through the diode D_m. This mode ends at time $t = t_5$ when the switch S_1 is turned on again, and the cycle is repeated. That is, $t_5 = T - (t_1 + t_2 + t_3 + t_4)$.

The waveforms for i_L and v_c are shown in Fig. (c). The peak switch voltage equal to the dc supply voltage V_s. Because the switch current is zero at turn-on and turn-off, the switching loss, which is product of v and i, becomes very small. The peak resonant current I_m must be higher than the load current I_0, and this sets a limit on the minimum value of load resistance R. However, by placing an antiparallel diode across the switch, the output voltage can be made insensitive to load variations.

9.4 M-Type ZCS Resonance Converter (DC–DC)

An *M*-type ZCS resonant converter is shown in figure a. The circuit operation can be divided into five modes, whose equivalent circuits are shown in figure b. We shall redefine the time origin, $t = 0$, at the beginning of each mode. The mode equations are similar to those of an *L*-type converter, except the following.

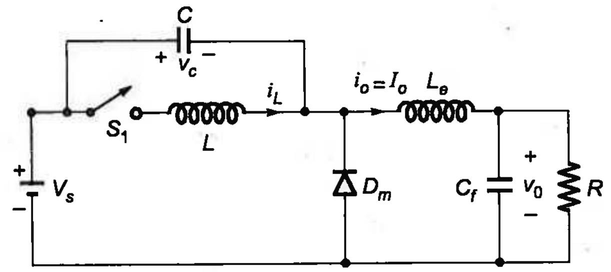
Mode-2: The capacitor voltage v_c is given by

$$v_c = V_s \cos\omega_0 t$$

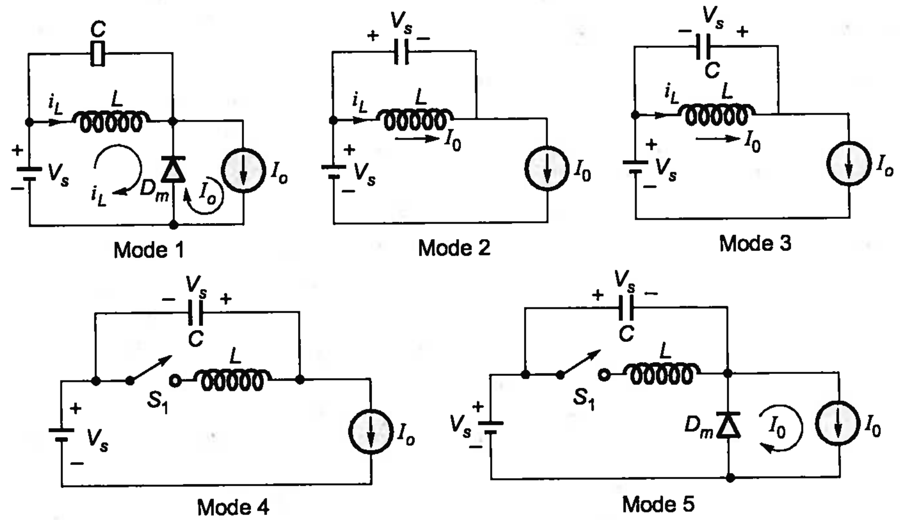
The peak capacitor voltage is $V_{c(pk)} = V_s$. At the end of this mode at $t = t_2$, $v_c(t = t_2) = V_{c2} = -V_s$.

Mode-3: The capacitor voltage is given by

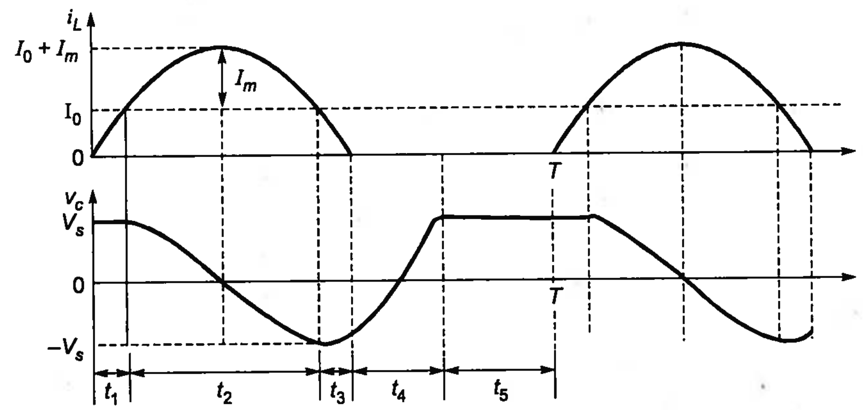
$$v_c = -V_s \cos\omega_0 t$$



(a) Circuit



(b) Equivalent circuits



(c) Waveforms

M-type ZCS resonant converter

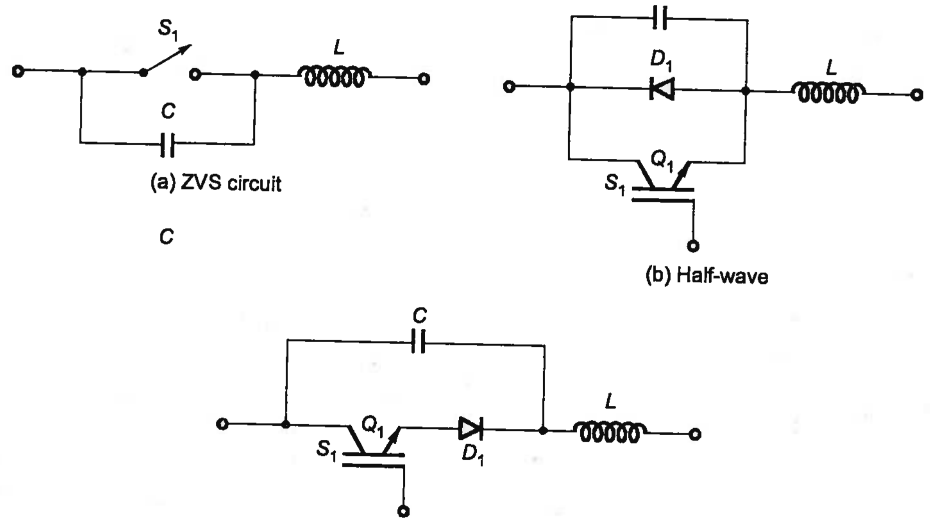
At the end of this mode at $t = t_3$, $v_c(t = t_3) = V_{c3}$. It should be noted that V_{c3} can have a negative value.

Mode-4: This mode ends at $t = t_4$ when $v_c(t = t_4) = V_s$. Thus, $t_4 = (V_s - V_{c3})C/I_0$. The waveforms for i_L and v_c are shown in figure c.

A zero current (Z_C) switch shapes the switch current waveform during its conduction time to create a Z_C condition for the switch to turn-off.

9.5 Zero-Voltage Switching Resonant Converters (DC-DC)

The switches of a ZVS resonant converter turn on and off at zero voltage. The resonant circuit is showing in figure a. The capacitor C is connected in parallel with the switch S_1 to achieve ZVS. The internal switch capacitance C_j is added with the capacitor C, and it affects the resonant frequency only, thereby contributing no power dissipation in the switch. If the switch is implemented with a transistor Q_1 and an antiparallel diode D_1, as shown in figure b, the voltage across C is clamped by D_1, and the switch is operated in a half-wave configuration. If the diode D_1 is connected in

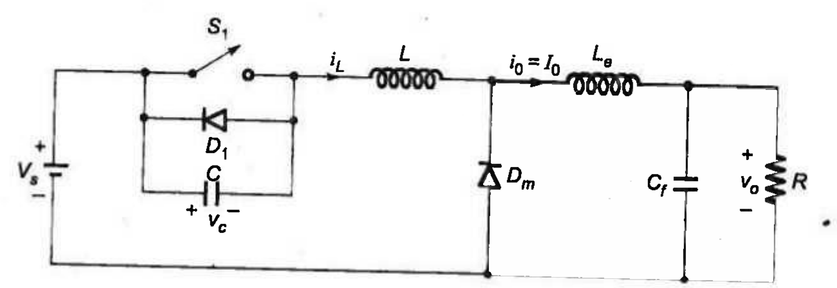


(a) ZVS circuit

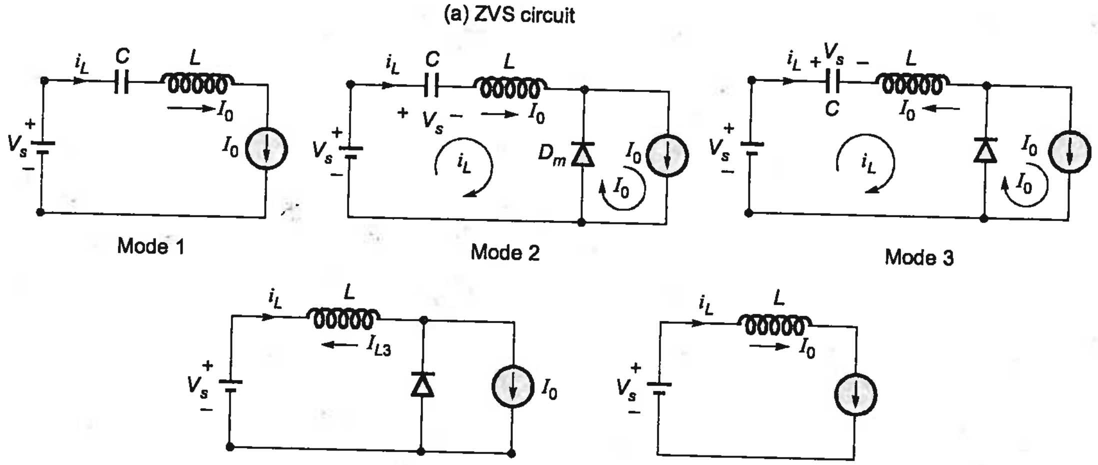
C

(b) Half-wave

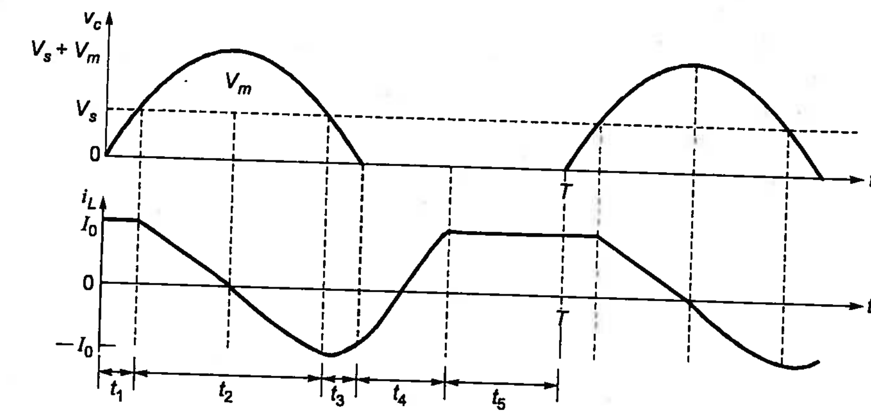
(c) Full-wave



(a) ZVS circuit



(b) Equivalent circuits



(c) Waveforms

ZVS resonant converter

series with Q_1, as shown in figure c, the voltage across C can oscillate freely, and the switch is operated in a full-wave configuration. A ZVS resonant converter is shown in figure a. A ZVS resonant converter is the dual of the ZCS resonant converter. Equations for the *M*-type ZCS resonant converter can be applied if i_L is replaced by v_c and vice versa, L by C and vice versa, and V_s by I_0 and vice versa. The circuit operation can be divided into five modes whose equivalent circuits are shown in figure b. We shall redefine the time origin, $t = 0$, at the beginning of each mode.

Mode-1: This mode is valid for $0 \le t \le t_1$. Both switch S_1 and Diode D_m are off. Capacitor C charges at a constant rate of load current I_0. The capacitor voltage v_c, which rises, is given by

$$v_c = \frac{I_0}{C}t$$

This mode ends at time $t = t_1$ when $v_c(t = t_1) = V_s$. That is, $t_1 = \frac{V_s C}{I_0}$.

Mode-2: This mode is valid for $0 \le t \le t_2$. The switch S_1 is still off, but diode D_m turns on. The capacitor voltage v_c is given by

$$v_c = V_m \sin\omega_0 t + V_s$$

where, $V_m = I_0\sqrt{L/C}$. The peak switch voltage, which occurs at $t = \left(\frac{\pi}{2}\right)\sqrt{LC}$, is

$$V_{T(pk)} = V_{C(pk)} = I_0\sqrt{\frac{L}{C}} + V_s$$

The inductor current i_L is given by

$$i_L = I_0 \cos\omega_0 t$$

This mode ends at $t = t_2$ when $v_c(t = t_2) = V_s$, and $i_L(t = t_2) = -I_0$.

Therefore,

$$t_2 = \pi\sqrt{LC}$$

Mode-3: This mode is valid for $0 \le t \le t_3$. The capacitor voltage that falls from V_s to zero is given by

$$v_c = V_s - V_m \sin\omega_0 t$$

The inductor current i_L is given by

$$i_L = -I_0 \cos\omega_0 t$$

This mode ends at $t = t_3$ when $v_c(t = t_3) = 0$, and $i_L(t = t_3) = I_{L3}$. Thus,

$$t_3 = \sqrt{LC}\sin^{-1}x$$

where, $x = \frac{V_s}{V_m} = \frac{V_s}{I_0}\sqrt{\frac{C}{L}}$.

Mode-4: This mode is valid for $0 \le t \le t_4$. Switch S_1 is turned on, and diode D_m remains on. The inductor current, which rises linearly from I_{L3} to I_0, is given by

$$i_L = I_{L3} + \frac{V_s}{L}t$$

This mode ends at time $t = t_4$ when $i_L(t = t_4) = 0$. Thus, $t_4 = (I_0 - I_{L3})(L/V_s)$. Note that I_{L3} is a negative value.

Mode-5: This mode is valid for $0 \le t \le t_5$. Switch S_1 is on, but D_m is off. The load current I_0 flows through the switch. This mode ends at time $t = t_5$, when switch S_1 is turned off again and the cycle is repeated. That is, $t_5 = T - (t_1 + t_2 + t_3 + t_4)$.

The waveforms for i_L and v_c are shown in figure c. Equation shows that the peak switch voltage $V_{T(pk)}$ is dependent on the load current I_0. Therefore, a wide variation in the load current results in a wide variation of the switch voltage. For this reason, the ZVS converters are used only for constant-load applications. The switch must be turned on only at zero voltage. Otherwise, the energy stored in C can be dissipated in the switch. To avoid this situation, the antiparallel diode D_1 must conduct before turning on the switch.

A ZVS shapes the switch voltage waveform during the off time to create a zero voltage condition for the switch to turn on.

9.6 Comparisons between ZCS and ZVS Resonant Converters

ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on. Because a relatively large capacitor is connected across the diode D_m, the inverter operation becomes insensitive to the diode's junction capacitance. When power MOSFETs are used for ZCS, the energy stored inthe device's capacitance is dissipated during turn-on. This capacitive turn-on loss is proportional to the switching frequency. During turn-on, a high rate of change of voltage may appear in the gate drive circuit due to the coupling through the Miller capacitor, thus increasing switching loss and noise. Another limitation is that the switches are under high-current stress, resulting in higher conduction loss. It should, however, be noted that ZCS is particularly effective in reducing switching loss for power devices (such as IGBTs) with large tail current in the turn-off process.

By the nature of the resonant tank and ZCS, the peak switch current is much higher than that in a square wave. In addition, a high voltage becomes established across the switch in the off-state after the resonant oscillation. When the switch is turned on again, the energy stored in the output capacitor becomes discharged through the switch, causing a significant power loss at high frequencies and high voltages. This switching loss can be reduced by using AVS.

ZVS eliminates the capacitive turn-on loss. It is suitable for high-frequency operation. Without any voltage clamping, the switches may be subjected to excessive voltage stress, which is proportional to the load.

For both ZCS and ZVS, the output voltage control can be achieved by varying the frequency. ZCS operates with a constant on-time control, whereas ZVS operates with a constant off-time control.