Unit-2

Resonant Converters

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Unit : 2
Resonant Converters

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• Zero-voltage switching dc-dc converters
• Zero current switching dc-dc converters
• Clamped voltage topologies
Need of Resonant Converters

- The switching devices in the converters with 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 high $di/dt$ value.
- The switches are subjected to a high voltage stress and the switching power loss of a device increases 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 $dv/dt$.
- The disadvantage of PWM control can be eliminated or minimized if the switching devices are turned “on” or “off” when the voltage across device or its current become zero.
- The voltage and current are forced to pass through zero crossing by creating LC resonant circuit, thereby called a resonant converter.
ZCS (Zero Current Switching) Resonant Converter

- A **step-down** DC-DC converter
- The L-C **resonant circuit** is built around the semiconductor switch to ensure ZCS.
- The $L_1 - C_1$ are sufficiently large to **filter the harmonic** current components.
- Current $I_0$ can be assumed to be constant in one switching cycle.

![Resonant Converter Diagram](image)
ZCS (Zero Current Switching) Resonant Converter

Mode-1

• **Switch ‘S’ is turned on** at instant \( t=0 \), diode \( D_m \) conducts during this interval.
• Because of output of converter is constant D.C. We can redefine output circuit equals to constant current source \( I_0 \).
• Current through output circuit is constant and it is \( I_0 \).
• Energy stored in the storage components at the output side *freewheels through diode \( D_m \).*
• The inductor current \( i_L \) *rises* linearly from 0 towards \( I_0 \).
• This mode ends at time \( t = t_1 \), when inductor current reaches to constant current \( I_0 \).
ZCS (Zero Current Switching) Resonant Converter

Mode-2

- When the inductor current reaches to value $I_0$; the diode $D_m$ stops conducting. By this time energy **freewheeling action gets completed**.
- Here the switch remains on and inductor current keeps on increasing.
- During this interval capacitor $C$ comes into the operation.
- Here $i_L$ is made up of two parts; $I_0$ and $I_m \sin \omega t$. Where, $I_0$ flows through the load. The remaining current flows through $C$ and voltage across $C$ gets developed.
- When current through inductor $I_0 + I_m$ maximum it **acts as short circuit** and entire voltage source appears across $C$ and hence $v_C = V_i$.
- After reaching to the maximum, current through $L$ decreases and **transfers its energy to $C$**.
- When current reduces to $I_0$, voltage appears across $C$ is the addition of $V_i$ & $V_L (=V_i)$ because both are in series.
ZCS (Zero Current Switching) Resonant Converter

Mode-3

- It starts when inductor current $i_L$ falls to $I_0$.
- Capacitor got charged up to $2V_i$ by the end of mode 2.
- In this mode $L$ continues to deliver its remaining energy. So, $i_L$ keeps on decreasing.
- But, to maintain $I_0$ through load; capacitor $C$ starts discharging & provides the constant $I_0$.
- This mode ends when $i_L$ falls to 0. At this instant voltage across $C$ is $V_{C3}$.

\[
\text{Mode - III, } i_L = I_0 - i_C
\]
ZCS (Zero Current Switching) Resonant Converter

Mode-4

- **In mode-3** to maintain $I_0$ constant, the output current is shared by $i_L$ and $i_C$ & at the end $i_L$ becomes 0.
- **In mode-4**; when $i_L=0$, the switch can be turned off as the current through it becomes 0.
- During this interval output current is maintained by discharging of capacitor $C$.
- By the end of mode 4; $C$ delivers its complete energy to the load.
ZCS (Zero Current Switching) Resonant Converter

Mode-5

- When capacitor voltage $v_C$ tends to be negative, the diode $D_m$ conducts.
- The load current flows through $D_m$ because it comes under forward bias condition due to polarity reversal across $C$. $I_0$ free wheels through $D_m$ in this interval.

![Diagram of L-type ZCS Converter]

Unit : 2 Resonant Converters
ZVS (Zero Voltage Switching) Resonant Converter

- As in ZCS converter, ZVS resonant converter has L, C as the resonant circuit components and L1, C1 as the filter circuit components.
- The function of resonant capacitor is to produce zero voltage across the switch S. Diode D2 provides freewheeling path to load current I0.
- As the name suggests, the switch S in ZVS resonant converter is turned on and off at zero voltage across the switch.
- Load current I0 is assumed constant and filter inductor current i0 is also taken to remain level at I0 as filter inductor is relatively large.
- Initially, (before t= 0 instant, in last mode of previous cycle operation) switch S is on and conducting I0. Therefore, iL = I0 and initial voltage across capacitor vC0=0.
**ZVS (Zero Voltage Switching) Resonant Converter**

**Mode-1**

- At \( t = 0 \), **switch S is turned off**.
- From the equivalent circuit diagram of mode I, it is seen that constant current \( I_0 \) flows through \( V_i, C \) and \( L \).
- As a result voltage across \( S \) or \( C \) builds up linearly from 0 to \( V_i \).
- Diode D2 is off.
- Also at \( t = 0 \), \( V_c = 0 \); therefore switch S is turned off at zero voltage as required.
ZVS (Zero Voltage Switching) Resonant Converter

Mode-2

• At the end of mode I, capacitor is somewhat overcharged i.e. \( v_c > V_i \), therefore diode D2 becomes forward biased.
• Now a resonant current \( i_L \) is set up in series circuit \( V_i, C, L, \) and D2. Where, \( i_L \) is given by \( i_L = I_0 \cos \omega_0 t \).
• The capacitor voltage, \( v_c \) is given by \( v_c = V_i + V_m \sin \omega_0 t \).
• It may be observed from the waveform that a ZVS resonant converter is the dual of ZCS resonant converter.
ZVS (Zero Voltage Switching) Resonant Converter

**Mode-3**

- At the beginning of this mode \( v_C = V_i \) and \( i_L = -I_0 \).
- In this mode capacitor voltage falls to zero from \( V_i \) that is given by \( v_C = V_i - V_m \sin \omega_0 t \) and inductor current is given by \( i_L = -I_0 \cos \omega_0 t \).
- As a result reverse bias across diode D1 vanishes and \( i_L \) begins to flow through D1.
ZVS (Zero Voltage Switching) Resonant Converter

Mode-4

- During this mode, capacitor voltage is **clamped to 0 by diode D1** conducting negative current $i_L$.
- As soon as anti-parallel diode begins to conduct the gate pulse is applied to switch S.
- The inductor current rises linearly from $-I_{L3}$ to zero.
- At this instant, reverse bias of D1 vanishes and already gated switch S turns on.
- This shows that S turns on at zero voltage and zero current.
- After this, current rises linearly to $I_0$ in the circuit formed by $V_i$, S, L and D2.
ZVS (Zero Voltage Switching) Resonant Converter

Mode-5

- At the end of mode 4, $i_L$ reaches to $I_0$ and therefore diode **D2 turns off**.
- Switch $S$ continues conducting $I_0$ as shown in fig
- **Mode 5 ends** at $t = t_5$ when switch $S$ is turned off again at zero voltage.
- The cycle now repeats as before.
## Comparison

<table>
<thead>
<tr>
<th>ZCS Resonant Converter</th>
<th>ZVS Resonant Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>The switch is required to conduct a peak current that is <strong>higher</strong> than the load current.</td>
<td>The switch is required to withstand a forward voltage that is <strong>higher</strong> than supply voltage.</td>
</tr>
<tr>
<td>It can be used for <strong>variable load</strong> application.</td>
<td>It is used for <strong>constant load application</strong>.</td>
</tr>
<tr>
<td>ZCS is used with comparatively <strong>less</strong> switching frequency.</td>
<td>ZVS is preferable over ZCS at <strong>high switching frequencies</strong>.</td>
</tr>
<tr>
<td>When the switch turns on at zero current but at a finite voltage, the charge on the internal capacitances is dissipated in the switch results into <strong>higher switching loss</strong>.</td>
<td>No such loss occurs if the switch turns on at a zero voltage.</td>
</tr>
<tr>
<td>Switching takes place when <strong>current through switch becomes zero</strong>.</td>
<td>Switching takes place when <strong>voltage across switch becomes zero</strong>.</td>
</tr>
<tr>
<td>Switching loss is eliminated <strong>during turn off</strong> operation of the switch.</td>
<td>Switching loss is eliminated <strong>during turn on</strong> operation of the switch.</td>
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</table>
The ZVS concept can be extended to a two-quadrant converter as shown where, the capacitors $C_+ = C_- = C/2$.

The inductance $L$ has such a value, so that it forms a resonant circuit.

The resonant frequency is $f_r$, and it is much larger than the switching frequency $f_s$.

Assuming the filter capacitance $C_e$ to be large, the load is replaced by a dc voltage $V_{dc}$.
Zero Voltage Switching - Clamped Voltage Topologies

- **Mode-1**

  - Switch $S_+$ is on. Assuming initial current of $I_{L0}=0$. The current linearly rises from 0.
  - This mode ends when the voltage on capacitor $C_+$ is zero and $S_+$ is turned off. The voltage on $C_-$ is $V_i$.

- **Mode-2**

  - Switches $S_+$ and $S_-$ both are off. This mode begins with $C_+$ having zero voltage and $C_-$ having $V_i$.
  - The equivalent mode can be simplified to a resonant circuit of $C$ and $L$ with an initial inductor current $I_{L1}$.
  - The voltage $v_0$ can be approximated to fall linearly from $V_i$ to 0. This mode ends when $v_0$ becomes zero and diode $D_-$ turns on.
Zero Voltage Switching - Clamped Voltage Topologies

- **Mode-3**
- Diode $D_-$ is turned on.
- Current $i_L$ falls linearly from $I_{L2} (= I_{L1})$ to 0.

- **Mode-4**
- Switch $S_-$ is turned on when $i_L$ and $v_0$ becomes zero. Inductor current $i_L$ continues to fall in the negative direction to $I_{L4}$ until the switch voltage becomes zero and $S_-$ is turned off.
Zero Voltage Switching - Clamped Voltage Topologies

- **Mode-5**
  - Switches $S_+$ and $S_-$ both are off. This mode begins with $C_-$ having zero voltage and $C_+$ having $V_i$, and is similar to mode 2.
  - The voltage $v_0$ can be approximated to rise linearly from 0 to $V_i$. This mode ends when $v_0$ tends to become more than $V_i$ and diode $D_+$ turns on.

- **Mode-6**
  - Diode $D_+$ is turned on; $i_L$ falls linearly from $I_{L5}$ to zero. This mode ends when $i_L=0$. $S_+$ is turned on and cycle repeated.
Key Points

- For ZVS, $i_L$ must **flow in either direction** so that a diode conducts before its switch is turned on.
- The output voltage can be **made almost square wave** by choosing the resonant frequency $f_0$ much larger than the switching frequency.
- The output voltage can be regulated by **frequency control**.
- The switch voltage is clamped to only $V_i$. However, the switches have to carry $i_L$, which has **high ripples and higher peak** than the load current $I_0$.
- The converter can be operated under a current – regulated mode to obtain the desired waveform of $i_L$. 

![Graph showing the key points of resonant converters](image)
Class E Resonant Inverter

- Uses only **one transistor** and has **low switching losses**, yielding a high efficiency of more than 95%.
- Normally used for low power applications requiring **less than 100 W**, particularly in high-frequency electronic lamp ballasts.
- The switching device has to **withstand a high voltage**.
Class E Resonant Inverter

- **Mode-1**
- During this mode transistor $Q_1$ is turned on
- The switch current $i_T$ consists of source current $i_S$ and load current $i_0$.
- To obtain an almost sinusoidal output current, the value of $L$ and $C$ are chosen to have a high quality factor ($Q \geq 7$), and a low damping ratio.
- The switch is turned off at zero voltage. When the switch is turned off, its current is immediately diverted through capacitor $C_e$. 

![Diagram of Class E Resonant Inverter](image)
**Class E Resonant Inverter**

- **Mode-2**
- During this mode transistor $Q_1$ is turned off. The capacitor current $i_c$ becomes the sum of $i_s$ and $i_0$. The switch voltage rises from zero to maximum value and falls to zero again.

- When the switch voltage falls to zero, $i_c = C_e \cdot \frac{dv}{dt}$ normally is negative.

- Thus, the switch voltage would tend to be negative. To limit this negative voltage, an anti-parallel diode is used.

- If the switch is MOSFET, its negative voltage is limited by its built-in diode to diode drop.
• **Mode-3**
  • This mode exists only if the switch voltage falls to zero with a finite negative slope.
  • The equivalent circuit is similar to that for mode 1 except the initial conditions.
  • The load current falls to zero at the end of mode 3.
  • However if the circuit parameters are such that the switch voltage falls to zero with a zero slope, there is no need of diode and this mode would not exist. That is $v_T = 0$ and $dv_T/dt = 0$. 

![Diagram of Class E Resonant Inverter](image-url)
### SLR (Series Loaded Resonant) Converter

- A half-bridge configuration of the SLR
- The series-resonant tank is formed by \( L_r \) and \( C_r \), and the current through the resonant tank circuit is full-wave rectified at the output, and feeds the output stage.
- Therefore, as the name suggests, the output load appears in series with the resonant tank.
- The filter capacitor \( C_f \) at the output is usually very large, and therefore the output voltage across the capacitor can be assumed to be a D.C. voltage without any ripple.
- The output voltage \( V_0 \), is reflected across the rectifier input as \( v_{BB'} \).
- Where, \( v_{BB'} = V_0 \) if \( i_L \) is positive and \( v_{BB'} = -V_0 \) if \( i_L \) is negative
- When \( i_L \) is positive, it flows through \( T_+ \) if it is on; otherwise it flows through the diode \( D_- \).
Similarly, when $i_L$ is negative, it flows through $T_-$ if it is on; otherwise it flows through the diode $D_+$. 

In the steady-state symmetrical operation, both the active switches are operated in a complementary manner.

Depending on the ratio between the switching frequency $\omega_s$ and the converter resonant frequency $\omega_0$, the converter has several possible operating modes.

At $t_0$, switch $T_+$ is turned on and the inductor current builds up from its zero value. The capacitor voltage builds up from its negative value $-2V_0$.

At $t_1$, 180° subsequent to $t_0$, the inductor current reverses and now must flow through $D_+$ since the other switch $T_-$ is not yet turned on.
SLR (Series Loaded Resonant) Converter

- After another 180° subsequent to $t_1$, with a smaller peak current in this half-cycle, the current goes to zero and remains zero as no switches are on.

- A symmetrical operation requires that $v_c$ during the discontinuous interval ($t_3 - t_2$) be negative $v_{c0}$, that is equal to $2V_0$.

- At $t_3$, the next switch $T_-$ is turned on and next half-cycle ensues.

- Note that in this mode of operation, the switches turn off naturally at zero current and at zero voltage, since the inductor current goes through zero.

- The switches turn on at zero current but not at zero voltage.

- Also, the diodes turn on at zero current and turn off naturally at zero current.
SLR (Series Loaded Resonant) Converter

• Since the switches turn off naturally in this mode of operation, it is **possible to use thyristors** in low-switching-frequency applications.

• The disadvantage of this mode is the relatively large peak current in the circuit and, therefore, **higher conduction losses**, compared with the continuous-conduction mode.

![Diagram of SLR Converter](image)
SLR (Series Loaded Resonant) Converter

Advantages

• Transformer saturation can be avoided since the series capacitor can block the dc component.
• The light load efficiency is high because the device current and conduction loss are low.

Disadvantages

• There is difficulty in regulating the output voltage under light load and no load conditions.
• Moreover, the output dc filter capacitor has to carry high ripple current, which could be a major problem in low-output voltage and high-output current applications.
Parallel resonant converters (PRCs) have their load connected in parallel with the resonant tank capacitor $C_r$.

SRC behaves as a current source, whereas the PRC acts as a voltage source.

For voltage regulation, PRC requires a smaller operating frequency range than the SRC to compensate for load variation.

During steady-state operation, initially both $i_L$ and $v_C$ are zero and $T_+$ is turned on at $t_0$. So long as $i_L < I_0$, the output current circulates through the rectifier bridge, which appears as a short circuit across $C_r$ and keeps its voltage at zero.

At $t_1$, $i_L$ exceeds $I_0$ and the difference $i_L - I_0$ flows through $C_r$ and $v_C$ increases.

Due to LC resonance, $i_L$ reverses at $t_2$ and flows through $D_-$, since $T_-$ is not turned on until some time later.
**PRC (Parallel Loaded Resonant Converter)**

- During the interval \((t_3 - t_2)\), \(i_L\) and \(v_C\) can be calculated using \(i_{L0} = I_0\) and \(v_{C0} = 0\) as the initial conditions at time \(t_0\).
- If the gate/base drive of \(T_+\) is removed prior to \(t_3\), \(i_L\) can no longer flow after \(t_3\) and stays at zero.
- With \(i_L = 0\), \(i_0\) flows through \(C_r\) and \(v_C\) decays linearly to zero during the interval \(t_3\) to \(t_4\).
- In this discontinuous mode of operation, both \(v_C\) and \(i_L\) stay at zero for an interval that can be varied in order to control the output voltage.
- Beyond this discontinuous interval, \(T_-\) is gated on at \(t_5\) and the next half-cycle ensues with identical initial conditions of zero \(i_L\) and \(v_C\), as for the first half-cycle.
Advantages

- The PRC has the advantages that the load can be short circuited and the circuit is suitable for low-output voltage, high-output current applications.

Disadvantages

- However, the major disadvantage of the PRC is the high device current. Moreover, since the device current does not decrease with the load, the efficiency drops with a decrease in the load.
References