• converters for soft switching
Why resonant converters

• Hard switching is based on on/off
  – Switching losses
  – Electromagnetic Interference (EMI) because of high \( \frac{du}{dt} \) and \( \frac{di}{dt} \)

• SMPS size decreases with increasing switching frequency
  – Target is to use as high \( f_s \) as possible
  – Switching losses are reduced if voltage and/or current are zero during switching
One Inverter Leg

*The output current can be positive or negative*
Chapter 9 Resonant Converters

Hard Switching Waveforms

Figure 9-2  Switch-mode inductive current switchings.

- The output current can be positive or negative
Change over

- **T-** conducts $I_0$ and it is turned off
  - Voltage over it increases and when it is $U_d$ diode D+ starts to conduct
  - Because of parasitic inductances voltage exceeds $U_d$
- **D+** conducts $I_0$ and **T-** is turned on
  - Current increases and exceeds $I_0$ because of diode reverse recovery current
  - After recovery of the diode voltage over T- drops to nearly zero
Turn-on and Turn-off Snubbers

- Turn-off snubbers are used, turn-on very seldom

Figure 9-3 Dissipative snubbers: (a) snubber circuits; (b) switching loci with snubbers.
Switching Trajectories

- Comparison of Hard versus soft switching

Figure 9-4 Zero-voltage-/zero-current-switching loci.
Switching losses

• Voltage and current stresses of the switches can be reduced by snubber circuits (Finnish kytkentäsuojapiiri)
  – Losses are transferred from the switch to the R of the RC-snubber
  – C discharges through R when switch is turned on
  – Total losses do not necessarily decrease, requires careful dimensioning

• In resonant circuit switching losses in theory can be even zero
Basics of resonant circuits

Series resonance
Lossless parallel resonant circuit
Undamped Series-Resonant Circuit

Figure 9-5  Undamped series-resonant circuit; $i_L$ and $v_c$ are normalized: (a) circuit; (b) waveforms with $I_{LO} = 0.5$, $V_{c0} = 0.75$.

- The waveforms shown include initial conditions
Series resonance

- Equations
  \[ L_r \frac{di_L}{dt} + u_C = U_d \]
  \[ C_r \frac{du_C}{dt} = i_L \]

- Solution from time \( t = 0 \)
  \[ i_L = I_{L0} \cos \omega_0 t + \frac{V_d - V_{C0}}{Z_0} \sin \omega_0 t \]
  \[ v_C = V_d - (V_d - V_{C0}) \cos \omega_0 t + Z_0 I_{L0} \sin \omega_0 t \]

- Resonance frequency and impedance
  \[ \omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}} \]
  \[ Z_0 = \sqrt{\frac{L_r}{C_r}} \]

- Often per unit values are used
  \[ V_{\text{base}} = V_d \]
  \[ I_{\text{base}} = \frac{V_d}{Z_0} \]
Series-Resonant Circuit with Capacitor-Parallel Load

Figure 9-6 Series-resonant circuit with capacitor-parallel load ($i_L$ and $v_c$ are normalized): (a) circuit; (b) $V_{c0} = 0$, $I_{L0} = I_o = 0.5$.

- The waveforms shown include initial conditions
Series-Resonant Circuit with Capacitor-Parallel Load

- Equations
- Derivation

\[ v_C = V_d - L_r \frac{di_L}{dt} \quad i_L - i_C = I_o \]

\[ i_C = C_r \frac{dv_C}{dt} = - L_r C_r \frac{d^2 i_L}{dt^2} \]

- And using

\[ \frac{d^2 i_L}{dt^2} + \omega_0^2 i_L = \omega_0^2 I_o \]

- Solution is

\[ i_L = I_o + (I_{L0} - I_o) \cos \omega_0 t + \frac{V_d - V_{C0}}{Z_0} \sin \omega_0 t \]

\[ v_C = V_d - (V_d - V_{C0}) \cos \omega_0 t + Z_0 (I_{L0} - I_o) \sin \omega_0 t \]
Impedance of a Series-Resonant Circuit

- Quality factor

\[ Q = \frac{\omega_0 L_r}{R} = \frac{1}{\omega_0 C_r R} = \frac{Z_0}{R} \]

- The impedance is capacitive below the resonance frequency

Figure 9-7 Frequency characteristics of a series-resonant circuit.
Undamped Parallel-Resonant Circuit

\[ i_L + C_r \frac{dv_C}{dt} = I_d \]
\[ v_C = L_r \frac{di_L}{dt} \]
\[ i_L = I_d + (I_{L0} - I_d) \cos \omega_0 t + \frac{V_{C0}}{Z_0} \sin \omega_0 t \]
\[ v_C = V_{C0} \cos \omega_0 t + Z_0 (I_d - I_{L0}) \sin \omega_0 t \]

\[ \omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}} \]
\[ Z_0 = \sqrt{\frac{L_r}{C_r}} \]

**Figure 9-8** Undamped parallel-resonant circuit.
Impedance of a Parallel-Resonant Circuit

\[ Q = \frac{\omega_0 R C_r}{\omega_0 L_r} = \frac{R}{Z_0} \]

- The impedance is inductive below the resonant frequency
- At resonance frequency imaginary part of admittance is zero, i.e. impedance is infinite

Figure 9-9  Frequency characteristics of a parallel-resonant circuit.
Load resonant converters

• **Series Load Resonant (SLR) Converter**
  - Discontinuous area $\omega_s < \omega_0/2$
  - Continuous area $\omega_0/2 < \omega_s < \omega_0$
  - Continuous area $\omega_s > \omega_0$
  - Steady state characteristics
  - Control of SLR

• **Parallel Load Resonant (PLR) Converter**
  - Discontinuous area
  - Continuous area $\omega_s < \omega_0$
  - Continuous area $\omega_s > \omega_0$
  - Steady state characteristics

• **Hybrid-resonant converter**
Load resonant converters

• Converter has LC-resonant circuit and load current goes through it
  – Both series and parallel resonance

• Voltages and current in the resonant circuit are introducing zero voltage or current switching

• Load power is controlled by adjusting switching frequency in relation to resonance frequency
  – Impedance of the resonant circuit changes
Series Load Resonant (SLR) Converter

The transformer is ignored in this equivalent circuit.

Figure 9-10  SLR dc–dc converter: (a) half-bridge; (b) equivalent circuit.

- The transformer is ignored in this equivalent circuit
Principle

• Full-bridge and transformer connection are also possible
• Current of the resonant circuit is rectified in the diode bridge
• Output voltage $U_o$ is assumed to be constant and its polarity depends on the sign of current $i_L$ of the resonant circuit
Polarity of voltages

• Positive current

\[ T_+ \text{ conducts } \quad u_{AB} = \frac{U_d}{2} \quad u_{AB}' = \frac{U_d}{2} - U_o \]

\[ D_- \text{ conducts } \quad u_{AB} = -\frac{U_d}{2} \quad u_{AB}' = -\frac{U_d}{2} - U_o \]

• Negative current

\[ T_- \text{ conducts } \quad u_{AB} = -\frac{U_d}{2} \quad u_{AB}' = -\frac{U_d}{2} + U_o \]

\[ D_+ \text{ conducts } \quad u_{AB} = \frac{U_d}{2} \quad u_{AB}' = \frac{U_d}{2} + U_o \]
SLR Waveforms, DCM, $\omega_s < \omega_0/2$

Figure 9-11  SLR dc–dc converter; discontinuous-conduction mode with $\omega_s < \frac{1}{2} \omega_0$. 

Chapter 9 Resonant Converters
Operation

• Current of $T+$ is zero
  – Turned on at $\omega_0 t_0$

• At $\omega_0 t_1$ current of resonant circuit turns and $D+$ conducts, because $T-$ is not turned on yet ($\omega_s < \omega_0/2$)

• After 180°, at $\omega_0 t_2$ current goes to zero
  – Because of symmetry, capacitor voltage is $2U_o$

• Because $2U_o < U_d/2 + U_o$ inductor current is not increasing but it is discontinuous

• At $\omega_0 t_3$ control is given to $T-$ and negative half cycle starts
Remarks

• Switches are turning off naturally as current goes to zero
  – Even thyristors could be used

• Switches are turning on when current is zero but voltage not

• Peak value of current in the resonant circuit is much higher than the average of output current
SLR Waveforms, CCM, $\omega_0/2 < \omega_s < \omega_0$

Figure 9-12  SLR dc–dc converter; continuous-conduction mode with $\frac{1}{2} \omega_0 < \omega_s < \omega_0$. 

Chapter 9 Resonant Converters
Operation

• Switch T+ current ≠ 0
  – It is turned on at $\omega_0 t_0$, voltage is $U_d$
  – Switch conducts less than 180°
  – At $\omega_0 t_1$ current $i_L$ becomes negative and D+ conducts

• T- is turned on at $\omega_0 t_2$
  – This is earlier than in the previous DCM operating area $\omega_s < \omega_0/2$
  – D+ conducts less than 180°
Devices

• Turning on
  – Current and voltage are not zero => losses

• Turning off
  – Current and voltage are zero
  – Even thyristors could be used

• Reverse recovery current of the diodes must be small
SLR Waveforms, CCM, $\omega_s > \omega_0$

Figure 9-13  SLR dc–dc converter; continuous-conduction mode with $\omega_s > \omega_0$. 

Chapter 9 Resonant Converters

9-28
Operation

• Current of T+ is zero and it is turned on at $\omega_0 t_0$
• T+ is turned on at $\omega_0 t_1$
  – This is before the current has become zero
  – D- starts to conduct
  – Voltage over the LC-circuits is high and diode current goes rapidly to zero
• T- is turned on immediately as D- starts to conduct
  – T- can conduct as the polarity of the current changes
Switches

- Turn-on at zero current and voltage
- Turning off takes place close to the peak of the resonant current
  - Turn-off losses
- Before the switch starts to conduct the antiparall diode has conducted
  - Voltage over switch is ≈ 0
  - It is possible to use lossless snubbers, i.e. only snubber capacitor in the circuit as there is no discharge current when the switch is turned on
Lossless Snubbers in SLR Converters

- The operating frequency is above the resonance frequency.

Figure 9-14 Lossless snubbers in an SLR converter at $\omega_s > \omega_0$. 

Chapter 9 Resonant Converters
SLR Converter Characteristics

- Output Current as a function of operating frequency for various values of the output voltage

Figure 9-15  Steady-state characteristics of an SLR dc–dc converter; all parameters are normalized.
SLR Converter Control

• The operating frequency is varied to regulate the output voltage.

• In full-bridge converters frequency can also be constant and voltage is controlled phase-shifting leg voltages, \((D = 50\%)\).

Figure 9-16 Control of SLR dc–dc converter.
Parallel Load Resonant (PLR) Converter

Figure 9-17  PLR dc–dc converter: (a) half-bridge; (b) equivalent circuit.

- The transformer is ignored in this equivalent circuit.
Principle

- Voltage of $C_r$ is rectified and filtered
- Output current is assumed to be constant during switching cycle
- Voltage over the resonant circuit

\[
{u_{AB}} = \frac{{{U_d}}}{{2}} \quad T_+ \quad \text{or} \quad D_+ \quad \text{conducts}
\]

\[
{u_{AB}} = -\frac{{{U_d}}}{{2}} \quad T_- \quad \text{or} \quad D_- \quad \text{conducts}
\]

- Operation depends on $i_L$ and $u_C$
• The current is in a discontinuous conduction mode
Operation (1/2)

- T+ is turned on at $\omega_0 t_0$, $i_L = u_C = 0$
- Constant output current flows through the diode bridge and keeps capacitor voltage as zero
  - After $\omega_0 t_1$ current difference charges resonant capacitor
- $LC$-circuit current $i_L$ goes to zero at $\omega_0 t_2$ and becomes negative
  - D+ conducts as T- is not turned on
Operation (2/2)

- Gate of T+n is removed before $\omega_0 t_3$: a
  - $i_L$ remains zero
  - Cr discharges in time $\omega_0 (t_3 - t_4)$ with $I_o$
  - After this we are in the beginning
- Output voltage average is adjusted with time $t_5 - t_4$
- No turn-on or turn-off losses in diodes
PLR Waveforms, CCM, $\omega_s < \omega_0$

- The operating frequency is below the resonance frequency.

Figure 9-19  PLR dc–dc converter in a continuous mode with $\omega_s < \omega_0$. 

Chapter 9 Resonant Converters
The operating frequency is above the resonance frequency.
PLR, CCM

• No trun-on losses
• Turn-off with current
  – Losses
  – Losses can be reduced with lossless snubber as in SLR
PLR Converter Characteristics

- Output voltage as a function of operating frequency for various values of the output current

Figure 9-21  Steady-state characteristics of a PLR dc–dc converter. All quantities are normalized.
PLR Characteristics

- **DCM**
  - Output voltage doesn’t depend on current
    - Many parallel outputs are possible
  - Output voltage depends linearly from switching frequency
- Output voltage can be higher than input
- Maximum current and voltage much higher than $I_o$ and $U_d$
PLR versus SLR

• PLR
  – Acts as voltage source
    • Fits for multiple output SMPS
  – No built-in overload protection
  – Both step up and step down operation
Hybrid-Resonant DC-DC Converter

- Combination of series and parallel resonance

Figure 9-22 Hybrid-resonant dc–dc converter.
Parallel-Resonant Current-Source Converter

Figure 9-23  Basic circuit for current-source, parallel-resonant converter for induction heating: (a) basic circuit; (b) phasor diagram at \( \omega_s = \omega_0 \); (c) phasor diagram at \( \omega_s > \omega_0 \).

- Basic circuit to illustrate the operating principle at the fundamental frequency
Parallel-Resonant Current-Source Converter

- Using thyristors; for induction heating

Figure 9-24  Current-source, parallel-resonant inverter for induction heating: (a) circuit; (b) waveforms.
Chapter 9 Resonant Converters

Class-E Converters

\[ i_d = i_d \]

\[ V_d \]

\[ R_{\text{load}} \]

\[ C_r \]

\[ L_r \]

\[ i_c1 = i_d + i_o \]

\[ V_T \]

\[ V_d \]

\[ i_c1 = i_d + i_o \]

\[ i_T = i_d + i_o \]

\[ \hat{I}_T \]

\[ \hat{V}_T \]

\[ i_o \]

\[ I_d \]

\[ I_o \]

\[ t \]

\[ t \]

\[ t \]

\[ t \]

\[ (a) \]

\[ (b) \]

\[ (c) \]

\[ (d) \]

**Figure 9-25** Class E converter (optimum mode, \( D = 0.5 \)).
Class-E Converters

Figure 9-26  Class E converter (nonoptimum mode).
Resonant Switch Converters

Classifications

**Figure 9-27** Resonant-switch converters: (a) ZCS dc–dc converter (step-down); (b) ZVS dc–dc converter (step-down); (c) ZVS-CV dc–dc converter (step-down).
Resonant Switch Converters

• Similar ideas was used before gate turn-off devices
  – Thyristors were used in dc-dc converters and dc-ac inverters => additional LC circuit used to turn-off conduction thyristor (e.g. McMurray-circuit)

• Nowadays also in power supplies

• Transformer parasitic inductances and other parasitics can be used in LC-circuits
Classification

- **ZCS, zero-current-switching**
  - Switch turns on and off without current

- **ZVS, zero-voltage-switching**
  - Switch turns on and off without voltage

- **ZVS-CV, zero-voltage-switching, clamped voltage**
  - As before but at least two switches
  - Voltage over switch is limited to the supply voltage
ZCS Resonant-Switch Converter

Figure 9-28  ZCS resonant-switch dc–dc converter.
Operation principle

- Current $I_o$ goes through the diode
  - $C_r$ is charged to the supply voltage $U_d$
- Switch is turned on
  - Diode D conducts until at $t_1$ current is equal to the load current
- $L_rC_r$ is a resonant circuit discharging $C_r$
  - At $t_2$ current goes to zero and switch turns off
- Output current $I_o$ charges $C_r$ to the supply voltage
  - At $t_3$ diode starts to conduct
ZCS Resonant-Switch Converter

Figure 9-29 $v_{oi}$ waveform in a ZCS resonant-switch dc–dc converter.

- Waveforms; voltage is regulated by varying the switching frequency, time interval $t_4 - t_3$
Properties

- Resonant frequency in MHz area
  resonanssitaajuus valitaan MHz-alueelle

- Switch turns on and off without current
  - At turn-off switch voltage is $U_d$ => turn-off losses

- Output current
  $$I_o < V_o/Z_0, Z_0 = \sqrt{L_r/C_r}$$

- When output current increases output voltage decreases
  - Switching frequency is increased

- Antiparallel connected diode
  - At low load resonant circuit energy can be supplied back to the supply
Electromagnetic Interference, EMI

• Losses and EMI due to the converter are reduced when soft switching is used

• Peak current of switch
  – High when compared to the output current
  – Conduction losses are higher than in hard switching
  – EMI increases???
ZCS Resonant-Switch Converter

• A practical circuit
• Capacitor is in parallel with the diode

Figure 9-30  ZCS resonant-switch dc–dc converter; alternate configuration.
Operation

• When switch is turned on its current increases linearly until $i_T = I_o$
  – Diode turns off

• Current $i_T - I_o$ charges capacitor after $t_1$

• At $t_2$ current $i_T$ goes to zero and switch turns off

• Capacitor is discharged with output current
ZVS Resonant-Switch Converter

- Capacitor is connected in parallel with the switch => limits voltage changes
- Serious limitations

Figure 9-31 ZVS resonant-switch dc–dc converter.
Operation

- **Switch is turned off when it conducts** $I_o$
  - Capacitor $C_r$ charges with constant current

- **At $t_1$ $u_C = U_d$**
  - Diode D conducts, $C_r L_r$ resonant circuit

- **At $t_2$ $C_r$ voltage becomes zero**
  - $D_r$ starts to conduct, gate control is given to switch and current $i_L$ increases linearly
  - A $t_2$ current is positive and it goes through the switch

- **At $t_3$ $i_L$ is equal to $I_o$ and D stops to conduct**
ZVS Resonant-Switch Converter

Output voltage

Figure 9-32  The $v_{oi}$ waveform in a ZVS resonant-switch dc–dc converter.
Comparison of ZCS and ZVS

- **ZCS**
  - Switch maximum current: \( I_o + V_d / Z_0 \)
  - Output current limited: \( I_o < V_o / Z_0 \), \( Z_0 = \sqrt{L_r / C_r} \)

- **ZVS**
  - Switch maximum voltage: \( V_d + I_o Z_0 \)
  - Output current must be larger than: \( V_d / Z_0 \)
  - High voltage switch is needed if output power variation is large
MOSFET Internal Capacitances

- These capacitances affect the MOSFET switching
- ZVS is better for MOSFET
- ZCS good e.g. for IGBT’s because of tail current

Figure 9-33  Switch internal capacitances.
Zero-voltage-switching, clamped-voltage, ZVS-CV

- The inductor current must reverse direction during each switching cycle.

Figure 9-34 ZVS-CV dc–dc converter.
ZVS-CV

- Switch turn on and off with zero voltage
  - Maximum voltage is clamped to input voltage
- $L_f$ is small when compared to hard switching
  - Its current is both positive and negative
- $T^+$ conduct current and it is turned off
  - Voltage over it is zero because of $C_+$
ZVS-CV DC-DC Converter

- One transition is shown
- In Fig c) \( C_+ = C_- = C/2 \)
- \( i_L \) is not change much during \( t_0 - t_0' \).

Figure 9-35  ZVS-CV dc–dc converter; \( T_+, T_- \) off.
Operation (1/2)

• Condensator $C_-$ has discharged at $t_0$´
  – Inductor’s current decreases linearly as D- conducts and $u_L = -U_o$.
  – At the same time gate control to T-
  – When current polarity changes at $t_0$´´ switch starts to conduct

• T- is turned of at $t_1$ with zero voltage ($u_{C-} = 0$)
  – When $C_-$ is charged to $U_d$ and $C_+$ has discharged, negative current flows through diode D+
Operation (2/2)

- After $t_1$ voltage over inductor is positive
  - Its current is positive after $t_2$ when $T+$ conducts
- For ZVS capacitor is connected parallel to the switch
  - Capacitor must be discharged when switch is turned on
  - It is discharged if antiparallel diode has been conducting
  - Therefore current $i_L$ has to have both polarities
Control of output voltage

- Constant frequency PWM can be used
  - Durations $t_0 - t_0'$ and $t_1' - t_1$ can be assumed short
  - Output voltage is square wave $\Rightarrow U_o \approx D U_d$

- $L_f$ must be dimensioned so that
  - Even with smallest $U_d$ and highest load current instantaneous value of $i_L$ is also negative
ZVS-CV Principle Applied to DC-AC Inverters

- Even in dc-dc converter inductor current had negative values, now both polarities are equal
- Very large ripple in the output current
Control of output voltage

- In full bridge delay between pole voltages can be adjusted.
Three-Phase ZVS-CV DC-AC Inverter

Figure 9-37  Three-phase, ZVS-CV dc-to-ac inverter.

- Very large ripple in the output current
ZVS-CV with Voltage Cancellation

- Commonly used
- $L_m$ is magnetizing inductance of transformer
Inverter

- The dc-link voltage is made to oscillate

Figure 9-40 Resonant-dc-link inverter, basic concept: (a) basic circuit; (b) lossless $R_t = 0$; (c) losses are present.
Three-Phase Resonant DC-Link Inverter

Figure 9-41  Three-phase resonant-dc-link inverter.

- Modifications have been proposed.
High-Frequency-Link Inverter

- Basic principle for selecting integral half-cycles of the high-frequency ac input

Figure 9-42 High-frequency-link integral-half-cycle inverter.
High-Frequency-Link Inverter

- Low-frequency ac output is synthesized by selecting integral half-cycles of the high-frequency ac input.

Figure 9-43  Synthesis of low-frequency ac output.
High-Frequency-Link Inverter

Figure 9-44 High-frequency ac to low-frequency three-phase ac converter.

• Shows how to implement such an inverter