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Quasi-Resonant Vs. Resonant Operation—Which Has Better Power Utilization?

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The power density of modern switching power supplies tends to increase rapidly. This means that despite the desperate efforts of power electronics engineers to improve efficacy of their devices and lower power loss, the heat removal problem is still there.

One of the wide-spread solutions is to implement resonant operation in a power supply or multi-resonant operation, as embodied in the LLC converter. An LLC converter has a pretty complicated control scheme associated with the converter operation below or above the resonant frequencies of the transformer module. The near-resonance mode is used to ensure a zero-current or zero-voltage mode of the LLC converter operation targeted at reducing the switching power dissipation.

The LLC converter also requires use of a gapped transformer design in which primary inductance is intentionally made low to incorporate a significant leakage resonant inductance. This adds to the complexity of the power stage and extra complexity (both in the control and the magnetics) generally adds cost.

However, there is an alternative to the resonant LLC, which offers simpler control and a simpler (ungapped) transformer design—the ZVT (zero-voltage transition) phase-shift converter. This type of converter is non-resonant but uses a resonant condition that occurs only during the switching process. This resonant mode is easy to achieve—it exists for just a portion of the resonance period, thus it's referred to as quasi-resonant—even for very light loads. (Both the resonant and quasi-resonant approaches can be implemented with either full or half bridges.)

Conceptually, the key difference between these two approaches is that the resonant LLC converters utilize a resonant circuit (formed by the transformer primary winding inductance, resonant capacitor and power MOSFETs) to ensure zero-voltage or zero-current switching of the power MOSFETs, while the phase-shifted converters are non-resonant but use a quasi-resonant mode of operation where resonance occurs at switching only. In the latter case, the resonance is created by the MOSFETs' total output capacitance and a small inductance (often the stray inductance of traces) in series with the transformer primary winding.

In this article, we will compare the efficacy of half- or full-bridge configurations when operating in resonant and quasi-resonant modes. Specifically, we will assess the power utilization of a resonant LLC converter versus an equivalent phase-shifted ZVT converter to see which one delivers more power under the same operating conditions.

Principles Of Resonant Switching

Ideally it is desirable to operate an active (resistive) load and transfer as much power to the resistive load as the load requires. In this case we usually apply rectangular pulsating voltage to the resistive load, and the load current follows this voltage exactly since there is no phase shift between the applied rectangular voltage and resulting rectangular load current.

The power transfer from the power supply to the load in this case is straightforward, and substantial power loss at switching occurs when the switching ramping up and down voltage and current cross producing switching loss, which in this case may be significant. The only reasonable way of reducing the switching power loss is shifting the current waveform to a somewhat later time.

This can be performed by adding some reactance in series with the load that would shift the current switching moment to a slightly later time and thus obtain the zero-current switching. This resonant component (inductor) has an optimal value that is defined by the load current and is hard to keep. Therefore, a complex resonance is used that causes many expected and unexpected difficulties.

Let's consider the effects of power transfer in power converters operating in the resonant mode, in which a sine wave current may have a phase shift with respect to the applied rectangular voltage, and converters operating in an active load mode that has no resonance but may have some phase shift (see the reference).

Resonant Vs Quasi-Resonant Operation

In the resonant mode, rectangular voltage pulses are applied to the resonant circuit placed at the power transformer primary side thus defining a sinusoidal primary current waveform. In this case the zero-current-switching mode occurs due to a slow-rising current waveform and subsequent low value of the product of the MOSFET voltage (rectangular) and almost zero MOSFET current defined by the sinusoidal current waveform.

In the non-resonant mode employed in the phase-shift converters, the power transformer primary winding is connected directly to the totem-pole connection of the MOSFETs, and zero-voltage switching is defined by the short period of time when the MOSFET drain-to-source voltage becomes zero due to the action of the quasi-resonant circuit.

We will analyze both schematics from the point of view of their capability to drive power to the load. To do so, we will calculate power for half a period that is handled by both schematics.

To begin, let's designate the following terms:

I_1 and V_1 are amplitudes of the current and voltage waveforms

ω is the cyclic frequency of the sinusoidal or rectangular waveforms

τ is the duration of the half-cycle sine wave or rectangular pulse at 50% duty cycle

τ_{01} is the fixed duration of the pulses' phase shift between the rectangular voltage pulse and current sine wave (in the case of the resonant LLC) or between the voltage and current rectangular waveforms (in the case of the phase-shift converter).

τ_1 is the continuous duration of the pulses' phase shift between the rectangular voltage pulse and current sine wave or between the voltage and current rectangular waveforms.

To begin our analysis, let's designate a current waveform through the MOSFET for half a period $f_1(t)$ using a phantom function $f_{ph}(t)$ for a sinusoidal current in the resonant converter:

$$f_{ph}(t) = I_1 \cdot \sin(\omega \cdot t)$$

This is the same function as the main one $f_1(t)$ but it does not participate in the target calculations. It is just used to facilitate calculations process.

$$f_1(t) = \begin{cases} I_1 \cdot \sin(\omega \cdot t) \text{ if } f_{ph}(t) > 0 \\ 0 \text{ otherwise} \end{cases}$$

Using the Heaviside step function, we'll designate the voltage across the MOSFET for both converters this way

$$f_2(t) = V_1 \cdot \left(\Phi(t - \tau_{01}) - \Phi(t - \tau - \tau_{01})\right)$$

Then, we'll designate current through the MOSFET in the non-resonant mode as:

$$f_3(t) = I_1 \cdot \left(\Phi(t) - \Phi(t - \tau)\right)$$

To illustrate the impact of these equations, we'll need some example values:

I_1 = 1.0 A

V_1 = 1 V

$\omega = 200\ \text{kHz} \cdot 2 \cdot \pi$

$\tau = \pi / \omega = 2.5 \times 10^{-6}$ s

$T_1 = 2 \cdot \tau$

$\tau_{01} = 0.0001\ \mu s$

Applying the equations above as numeric expressions in Mathcad 15, together with the example values just given, we can determine the power produced by the process for half a period.

$$f_{ph}(t) := I_1 \cdot \sin(\omega \cdot t)$$

$$f_1(t) := \begin{cases} I_1 \cdot \sin(\omega \cdot t) & \text{if } f_{ph}(t) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$f_2(t) := V_1 \cdot \left(\Phi(t - \tau_{01}) - \Phi(t - \tau - \tau_{01})\right)$$

$$f_3(t) := I_1 \cdot \left(\Phi(t) - \Phi(t - \tau)\right)$$

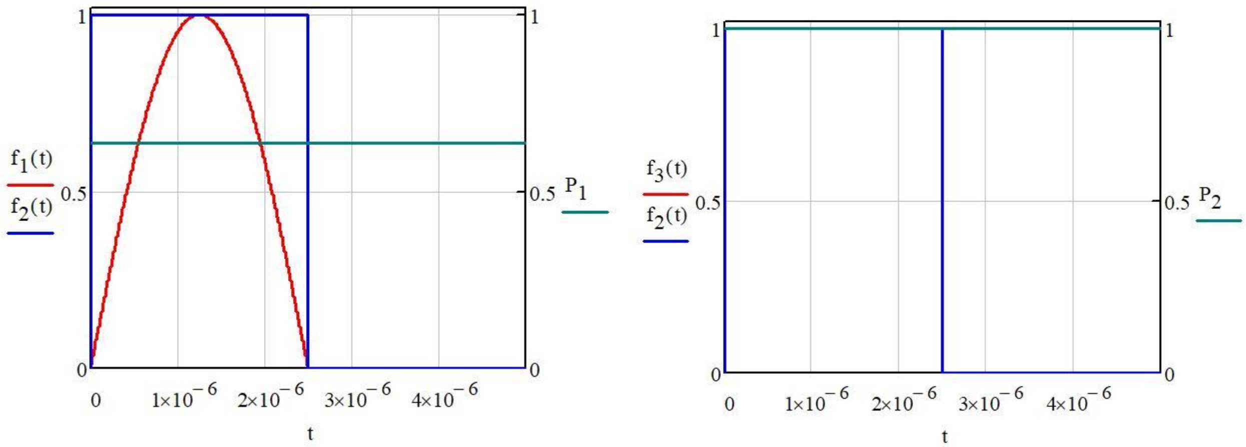
In the case of resonant–mode operation, where we have the sine wave and rectangle, the power delivered to the load is

$$P_1 = \frac{1}{\frac{T_1}{2}} \cdot \left(\int_0^{\frac{T_1}{2}} f_1(t) \cdot f_2(t)dt\right) = 0.637\ \text{W}$$

In the non-resonant mode of operation, where we have the two rectangular waveforms, the power delivered is

$$P_2 = \frac{1}{\frac{T_1}{2}} \cdot \left(\int_0^{\frac{T_1}{2}} f_3(t) \cdot f_2(t)dt\right) = 1\ \text{W}$$

We show the three functions and the two power equations graphically in Fig. 1.



(a) (b)

Fig. 1. Resonant-mode operation (a) allows for using just a portion of the power a phase-shift converter is capable of delivering, which is by 57% greater than that delivered, while the phase–shift converter (b) transfers its full power.

A pulse utilization coefficient gives us a measure of how much more efficient the non-resonant mode of operation is versus the resonant mode at one point of operation in the example case:

$$\delta = \frac{P_2}{P_1} = 1.571$$

While the above calculation tells us how the efficacies of the two modes of operation compare for a given value of displacement factor ($\tau_{01} = 0.0001$ µs), we'd also like to know how these modes compare across a range of values. The displacement factor represents a time shift between pulses that occurs in resonant switching schemes when reactances are present. These shift current waveforms with respect to voltage depending on the load resistance and rectangular pulses, which can also have some time delay with respect to each other due to the energy transfer along the long LC line.

Designating the displacement factor as τ_1, which is the same as τ_{01}, but not fixed, we obtain the following expressions for the power dependence on the displacement factor.

$$p_1(\tau_1) = \frac{1}{\frac{T_1}{2}} \cdot \int_0^{\frac{T_1}{2}} \left(f_1(t)\right) \cdot \left[V_1 \cdot \left(\Phi(t-\tau_1) - \Phi(t-\tau-\tau_1)\right)\right] dt$$

$$p_2(\tau_1) = \frac{1}{\frac{T_1}{2}} \cdot \int_0^{\frac{T_1}{2}} \left[I_1 \cdot \left(\Phi(t) - \Phi(t-\tau)\right)\right] \cdot \left[V_1 \cdot \left(\Phi(t-\tau_1) - \Phi(t-\tau-\tau_1)\right)\right] dt$$

If we graph these two expressions across the range of τ_1 = 0 to 3 x 10-6 s, which is just beyond a half period of the switching waveform, we obtain the following plots of $p_1(\tau_1)$ and $p_2(\tau_1)$ in Fig. 2.

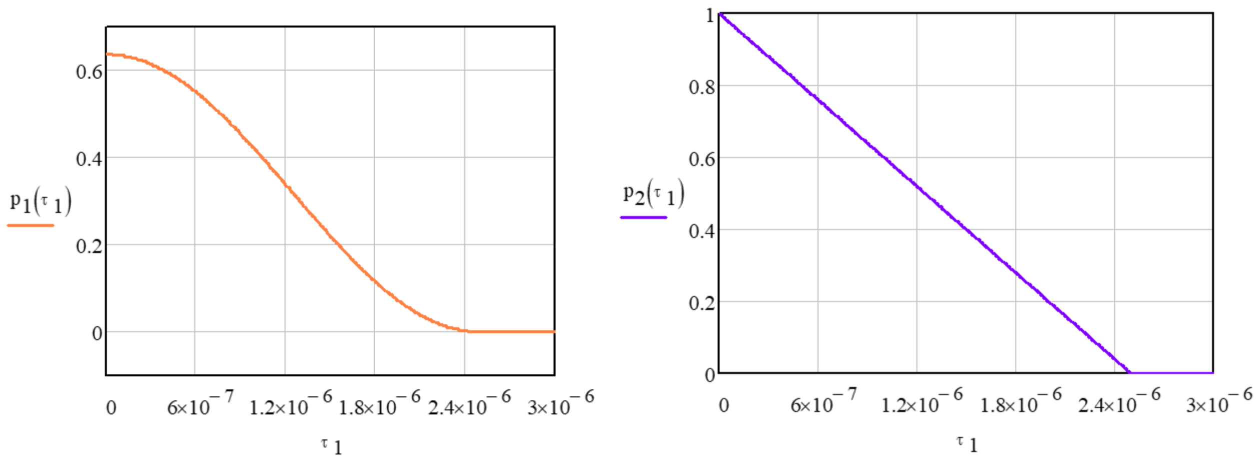


Fig. 2. Power produced by a half period of switching under resonant-mode operation (a) and non-resonant mode operation (b) as a function of displacement factor τ_1.

Going a step further, we can calculate a pulse utilization ratio for P1(τ_1) and P2 (τ_1):

$$\sigma(\tau_1) = \frac{P_2(\tau_1)}{P_1(\tau_1)}$$

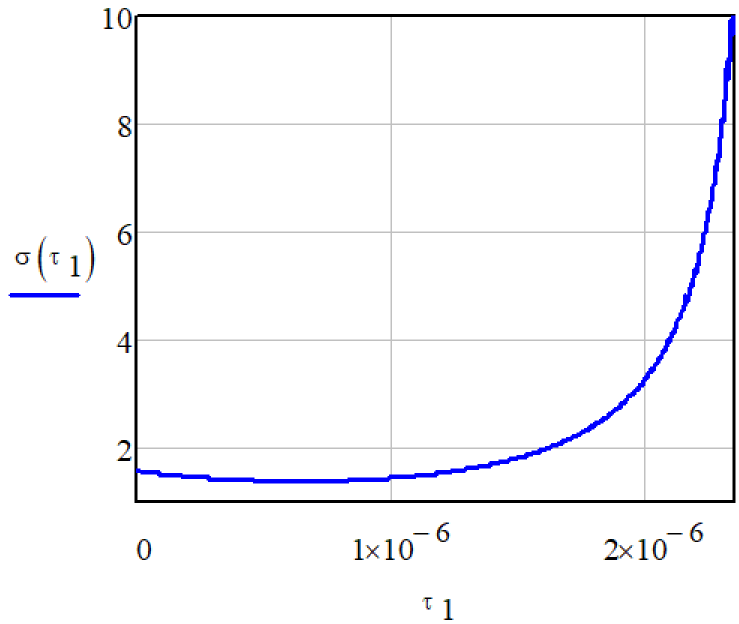


Fig. 3. The power utilization ratio compares power delivery in resonant and non-resonant modes of operation for a range of displacement values. The advantage of the non-resonant mode is maximized at higher values of displacement.

The pulse utilization ratio shows the extent to which a rectangular current pulse is more efficient than a sine wave current pulse (resonant converter) when transferring power. So when choosing a power supply topology, it's recommended that designers thoroughly consider the advantages of the phase-shift ZVT converters over the LLC and other resonant configurations in order to determine which topology best suits your application.

Reference

"Zero-Voltage-Switched, Full-Bridge, Phase-Shifted DC-DC Converter With Improved Light/No-Load Operation," U.S. Patent 6,909,617 B1, June 21, 2005.

About The Author

Gregory Mirsky is a design engineer working in Deer Park, Ill. He currently performs design verification on various projects, designs and implements new methods of electronic circuit analysis, and runs workshops on MathCAD 15 usage for circuit design and verification. He obtained a Ph.D. degree in physics and mathematics from the Moscow State Pedagogical University, Russia. During his graduate work, Gregory designed hardware for the high-resolution spectrometer for research of highly compensated semiconductors and high-temperature superconductors. He also holds an MS degree from the Baltic State Technical University, St. Petersburg, Russia where he majored in missile and aircraft electronic systems.

Gregory holds numerous patents and publications in technical and scientific magazines in Great Britain, Russia and the United States. Outside of work, Gregory's hobby is traveling, which is associated with his wife's business as a tour operator, and he publishes movies and pictures about his travels online.