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Calculating Current Induced by Square-Wave Voltages in Power Electronics Circuits

This application note presents a practical method for calculating current induced by square-wave voltages in power electronics circuits using Fourier harmonic decomposition. It explains how square-wave harmonic content affects inductors, capacitors, MOSFET gate drives, EMI behavior, and MLCC reliability, then outlines how RMS current can be estimated by evaluating circuit impedance across relevant harmonic frequencies and applying bandwidth-limited analysis for practical converter designs.

Scope & Relevance to Power Electronics

Square-wave voltages are widely encountered in power electronics. Converter topologies such as buck, boost, SEPIC, flyback, and resonant converters commonly generate square-wave signals at one or more points in the circuit. Typical sources include:

- MOSFET gate drives
- Switching nodes (SW nodes)
- PWM controller outputs
- Rectifier and clamp waveforms

Square waves differ significantly from sinusoidal and DC signals because they contain substantial high-frequency harmonic content. This harmonic content directly influences:

- RMS and peak current in inductors
- Ripple current in capacitors
- Switching device stress
- EMI generation
- MLCC reliability and temperature rise

This application note outlines a method for calculating current induced by square-wave voltages using harmonic analysis and standard waveform decomposition principles.

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Square Waves in Switching Power Converters

An ideal square wave assumes instantaneous rise and fall times, resulting in infinite harmonic bandwidth. In practical power electronics circuits, square waves have finite rise and fall times, retain significant odd-harmonic content, and are shaped by parasitic inductance and capacitance within the power stage.

Nevertheless, the Fourier harmonic model remains effective for practical analysis. It often provides a conservative estimate, making it useful for worst-case design evaluation.

Fourier Decomposition of Switching Voltages

Any periodic non-sinusoidal waveform can be broken down into a sum of sinusoidal harmonics. For a symmetrical square wave with peak voltage V, that decomposition is:

$$v(t) = \frac{4V}{\pi}\left[sin(\omega t) + \frac{1}{3}sin(3\omega t) + \frac{1}{5}sin(5\omega t) + \cdots\right]$$

Where:

- $\omega = 2\pi f_s^{W}$ (angular switching frequency)
- Only odd harmonics exist in a symmetric square wave
- Harmonic amplitude decreases as 1/n

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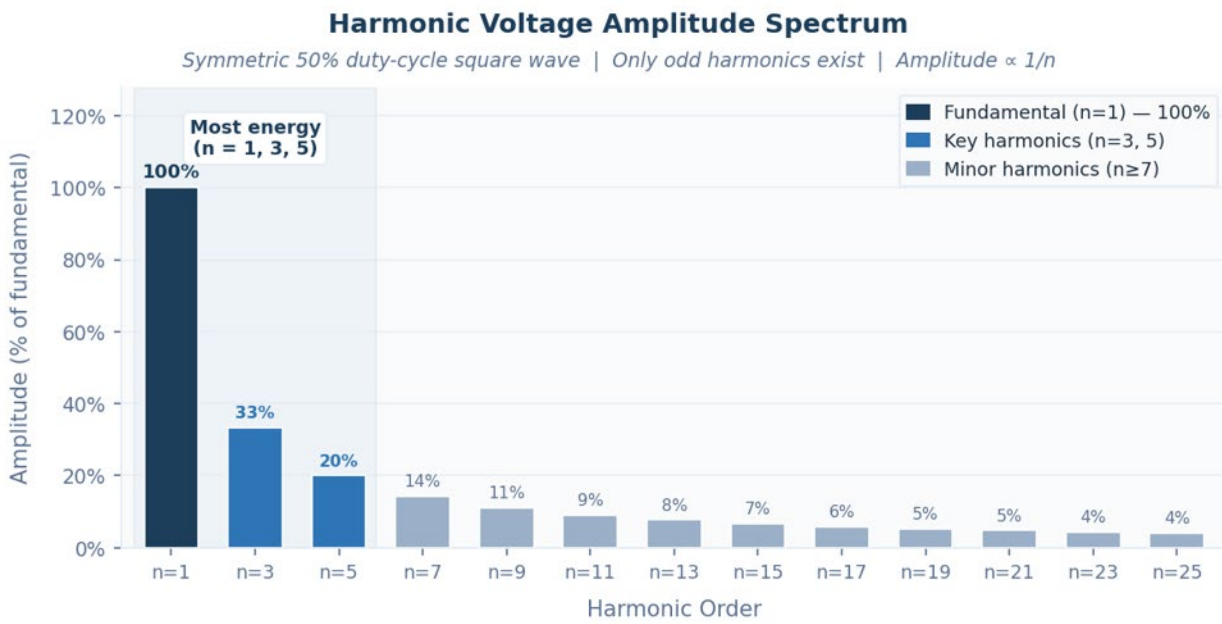

FIGURE 1. Harmonic voltage amplitude spectrum of a symmetric square wave. Amplitude falls as 1/n. Only odd harmonics are present.

This decomposition is particularly useful for analyzing frequency-dependent impedances, such as those associated with inductors and capacitors.

General Method for Calculating Current

Since different circuit elements respond differently at different frequencies, current must be evaluated on a harmonic-by-harmonic basis. The general process is:

1. Decompose the square wave into harmonic voltage components
2. Determine the circuit impedance at each harmonic frequency
3. Calculate the current amplitude for each harmonic
4. Combine currents using RMS summation or time-domain reconstruction

$$I_n = \frac{V_n}{Z(\omega_n)}$$

This approach directly applies mixed-frequency circuit analysis principles.

Common Power Electronics Cases

Inductor Current from a Switching Node Square Wave

For an inductor, the impedance increases linearly with frequency:

$$Z_L(\omega_n) = j\omega_n L$$

Substituting this expression into the general formula yields the harmonic current:

$$I_n = \frac{4V}{\pi(2k-1)} \cdot \frac{1}{\omega_n L}$$

Higher harmonics contribute progressively less current because the inductor impedance grows with frequency. The inductor naturally attenuates square-wave harmonics. Even so, the total RMS current can still exceed what a simple DC analysis would predict.

Design Note: *Inductor copper loss is dominated by low-order harmonics. EMI is dominated by the high-order harmonics that make it through.*

Capacitor Ripple Current from Square-Wave Voltage

For a capacitor, impedance drops as frequency increases:

$$Z_C(\omega_n) = \frac{1}{j\omega_n C}$$

The harmonic current therefore scales with frequency:

$$I_n = V_n \cdot \omega_n C$$

Capacitor ripple current increases with harmonic order, allowing high-order harmonics to dominate total RMS current. As a result, square-wave excitation can be especially challenging for MLCCs, DC-link capacitors, and snubber or clamp capacitors.

Design Note: *Even when the average voltage across a capacitor is low, the fast voltage edges at switching transitions can dominate the capacitor's stress.*

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MOSFET Gate Drive Current

Gate drivers apply a square-wave voltage to what is essentially a capacitive load. The gate current is:

$$I_{gate}(t) = C_{iss} \cdot \frac{dV}{dt}$$

Gate current is driven primarily by high-frequency components. Fast edges dramatically increase peak current demand on the driver. Driver power losses also scale with switching frequency and edge rate.

RMS Current Calculation in Practice

Computing an infinite number of harmonics is not practical. Power electronics engineers typically bound the analysis by limiting the harmonic count to the bandwidth defined by the rise time. The practical RMS current estimate is:

$$I_{RMS} \approx \sqrt{\sum_{n=1}^{N} {I_n}^2}$$

Where N is set by the system bandwidth. Parasitic elements naturally limit contributions from very high-order harmonics, so the sum converges quickly for inductive loads. SPICE FFT simulation is commonly used to validate this estimate.

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Design Implications for Power Electronics

The table below summarizes the square-wave risk for common power electronics components and the standard design response:

Component	Square-Wave Risk	Design Action
Inductors	Elevated RMS current	Size copper for harmonic current, not just DC
MLCCs	High ripple current	Use parallel MLCCs and apply derating
MOSFETs	Switching device stress	Control edge rate to limit peak current
Gate Drivers	Peak current demand	Verify drive strength for the target edge rate
EMI Filter	Harmonic excitation	Tune cutoff frequency below key harmonics

Harmonic Content: Percentage of RMS Current by Harmonic

For an ideal symmetric square wave with 50% duty cycle, the harmonic amplitudes follow the classic odd-harmonic Fourier series where amplitude is proportional to 1/n. The distribution of current by harmonic order depends heavily on the load impedance.

Two load cases are most useful in power electronics:

- Resistive path (R): I_n proportional to 1/n, same scaling as voltage harmonics
- Inductive path (L): $Z_l = j\omega L$, so I_n proportional to $1/n^2$

Harmonic (n)	% RMS (R)	Cumulative % (R)	% RMS (L)	Cumulative % (L)
1	81.057%	81.057%	98.553%	98.553%
3	9.006%	90.063%	1.217%	99.770%
5	3.242%	93.306%	0.158%	99.928%
7	1.654%	94.960%	0.041%	99.969%
9	1.001%	95.960%	0.015%	99.984%
11	0.670%	96.630%	0.007%	99.991%
13	0.480%	97.110%	0.003%	99.994%
15	0.360%	97.470%	0.002%	99.996%
17	0.280%	97.751%	0.001%	99.997%
19	0.225%	97.975%	0.001%	99.998%
21	0.184%	98.159%	0.001%	99.998%
23	0.153%	98.312%	0.000%	99.999%
25	0.130%	98.442%	0.000%	99.999%
>25	**1.558%**	**100.000%**	**0.001%**	**100.000%**

The inductive case converges rapidly because inductor impedance increases with n, causing current to decrease as $1/n^2$. The RMS contribution therefore scales as $1/n^4$, with the fundamental contributing more than 98.5% of the total RMS current.

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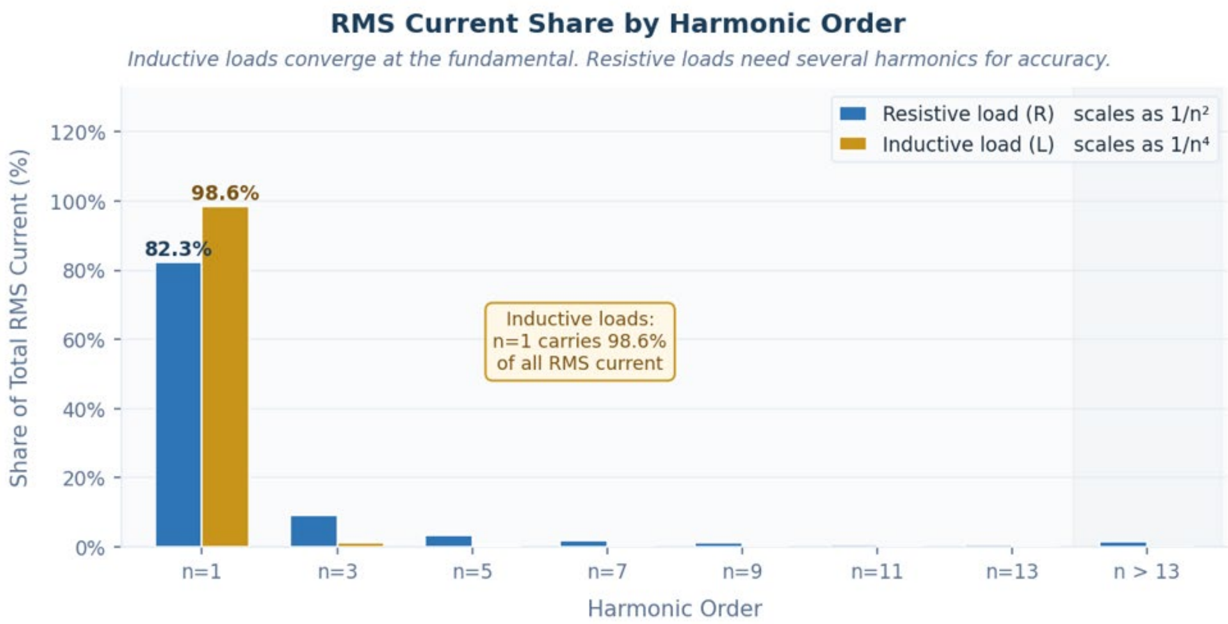

FIGURE 2. Percentage of total RMS current contributed by each harmonic. The inductive load (gold) is overwhelmingly dominated by the fundamental. The resistive load (blue) converges much more slowly.

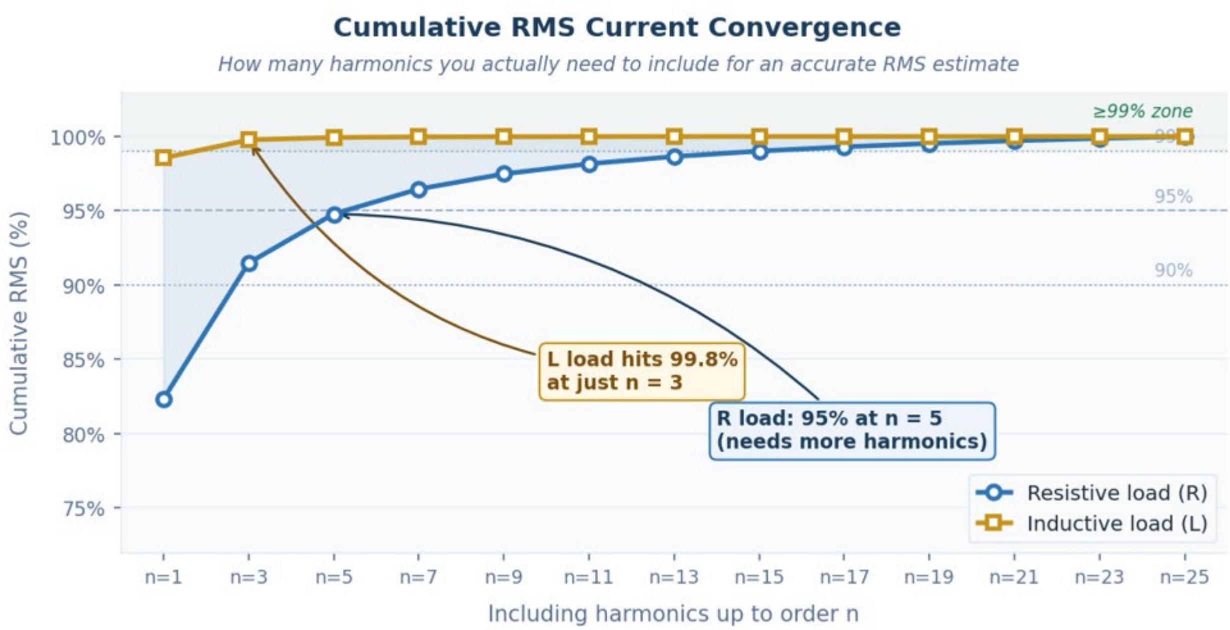

FIGURE 3. Cumulative RMS current convergence. An inductive load reaches 99.8% of total RMS at just the 3rd harmonic. A resistive load requires harmonics through the 13th to cross 97%.

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Practical Note on Capacitor Ripple Current

For capacitor ripple current driven by a switching node, the analysis is inverted. Capacitive impedance decreases with frequency to the SRF point, so high-frequency harmonics drive more current rather than less. In an ideal model, high-order harmonics can dominate the RMS current.

In practical converters, extreme high-frequency content is constrained by the rise and fall times of the switching waveform, as well as parasitic inductance and layout effects. Accurate capacitor ripple-current estimation should therefore account for edge rate or an effective bandwidth cutoff.

Summary

Square-wave voltages are fundamental to power electronics operation and cannot be accurately analyzed using only DC or single-frequency sinusoidal methods. Harmonic decomposition provides a rigorous and practical framework for calculating the currents produced in inductors, capacitors, and switching devices.

- Inductors naturally attenuate square-wave harmonics. The fundamental dominates RMS current in inductive paths.
- Capacitors do the opposite. Higher harmonics drive more current through capacitive paths.
- Gate drivers deal with capacitive loads and are stressed by fast switching edges.
- RMS current should be estimated using Fourier analysis truncated at the system bandwidth, then validated with SPICE.

Component selection for inductors, MLCCs, and MOSFETs needs to account for harmonic content, not just DC or average values.

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