Fundamental Considerations for Very High Frequency Power Conversion

Richard Redl

ELFI S.A.

Electronic Feasibility Investigations

Montévaux 14

CH-1726 Farvagny-le-Petit

Switzerland

Tel.: +41 26 411 0026

Fax: +41 26 411 0027

E-mail: rredl@sunrise.ch

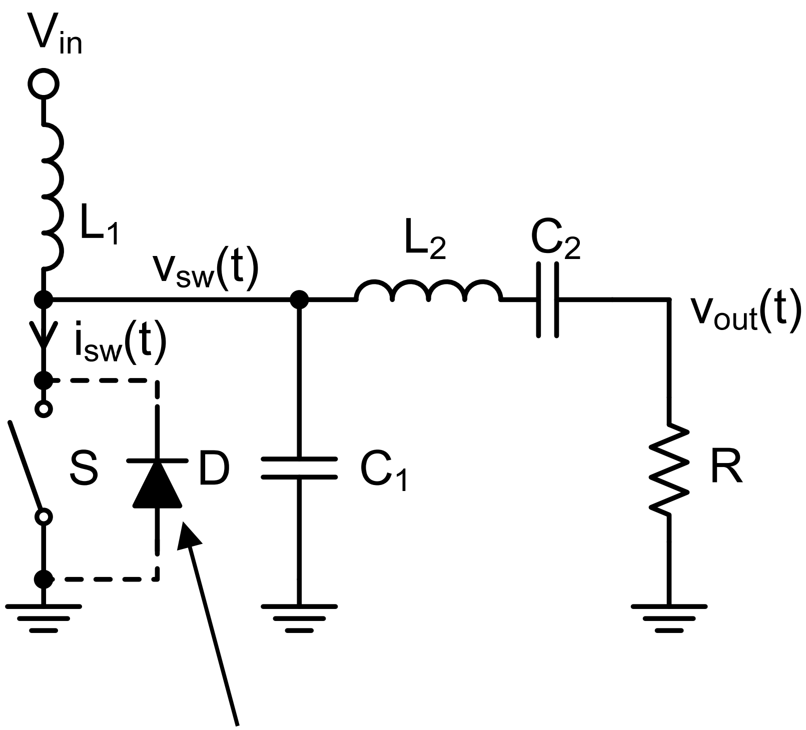
Outline

- **Class E dc-dc converter overview**
  - **Class E amplifier**
  - **Class E dc-dc converter—history and circuit variations**
  - **Control/regulation approaches**
  - **Gate drivers**
- **Component load/stress factors**
  - **Converter comparisons based on CSFs**
- **Alternative HF/VHF dc-dc converter solutions**
  - **Multiphase evenly interleaved hard-switching converters operating with critical conduction**
  - **ZVS noninverting buck-boost**
  - **Unregulated isolated converters [Class $(DE)^2$, "sine amplitude"]**
- **Conclusions**

VHF Power Conversion – Why and How?

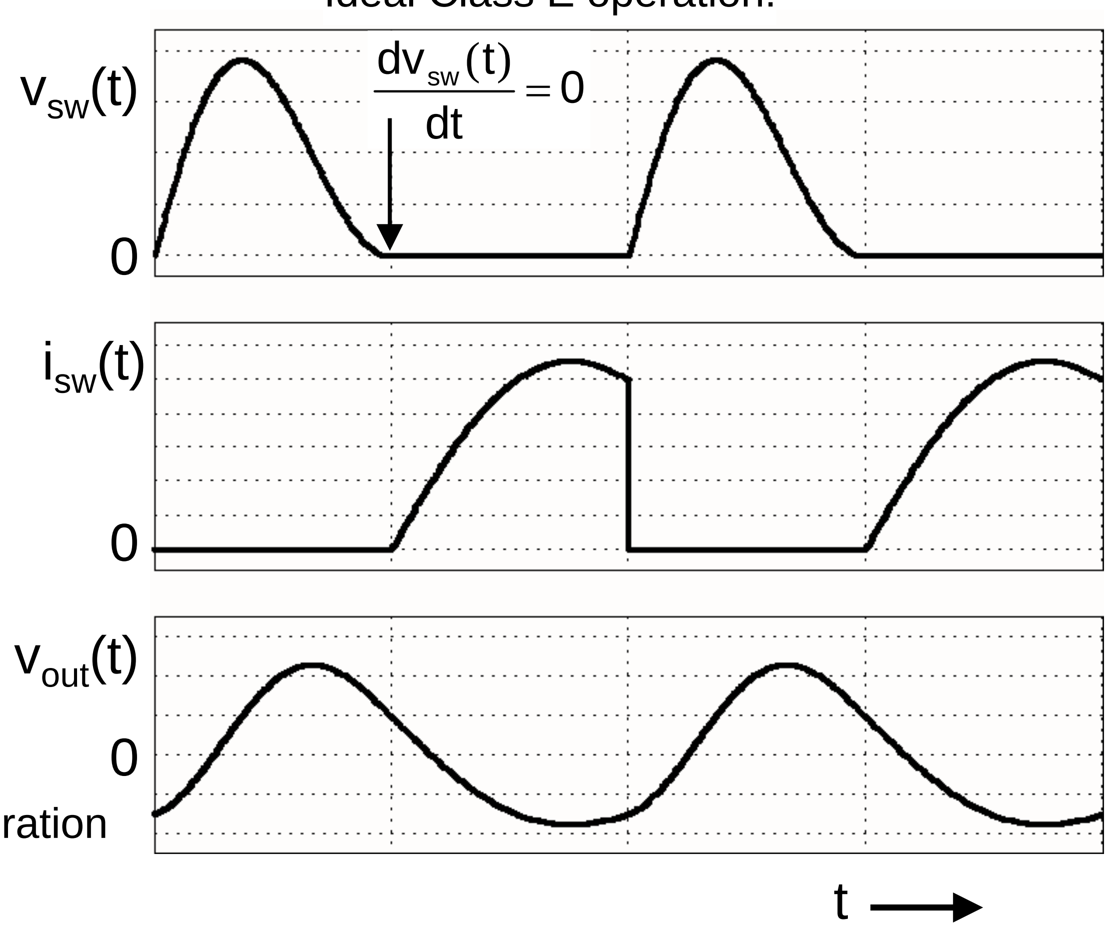
- **Definition of VHF**
  - **Nominally: Frequency between 30 and 300 MHz**
  - **For power supply engineers (and for this discussion): Frequency above 10 MHz**
- **Expected benefits of VHF power conversion**
  - **Drastically reduced filter size → increased power density, possibility of realizing the converter on chip**
  - **Increased loop-gain bandwidth → faster correction of perturbations, faster programmability**
  - **Improved load transient**
    - **Rate of rise of current injected to the output might match the rate of rise of load current (e.g., in μP applications) → reduced volume/cost of output capacitor**
- **Standard approach**
  - **ZVS resonant converter, typically Class E based**
    - **Single, ground-referenced switch**
    - **Switch output capacitance and optional parallel capacitance: Losslessly discharged by external network before turn-on → no turn-on loss; reduced turn-off loss due to snubbing action of the same capacitances**
    - **Reduced sensitivity of the efficiency to speed of drive signal**

Class E Amplifier/Inverter



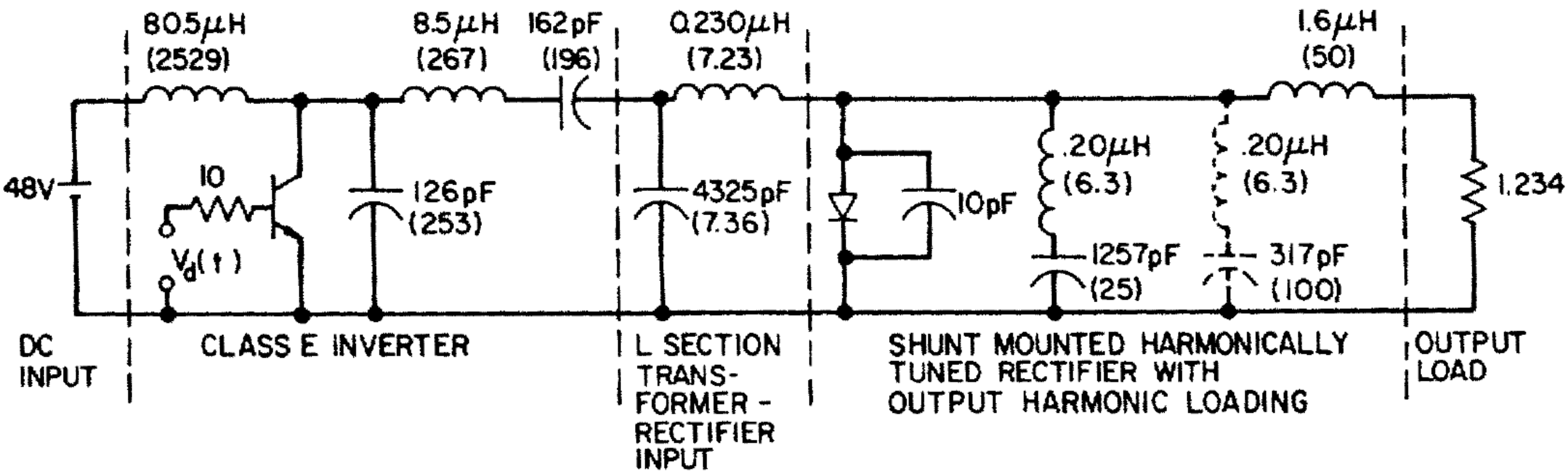
Note: Diode not needed with ideal Class E operation

Ideal Class E operation:



N. O. Sokal and A. D. Sokal, "Class E - A new class of high-efficiency tuned single-ended switching power amplifiers," IEEE Journal of Solid-State Circuits, vol. SC-10, no. 3, pp. 168-176, June 1975.

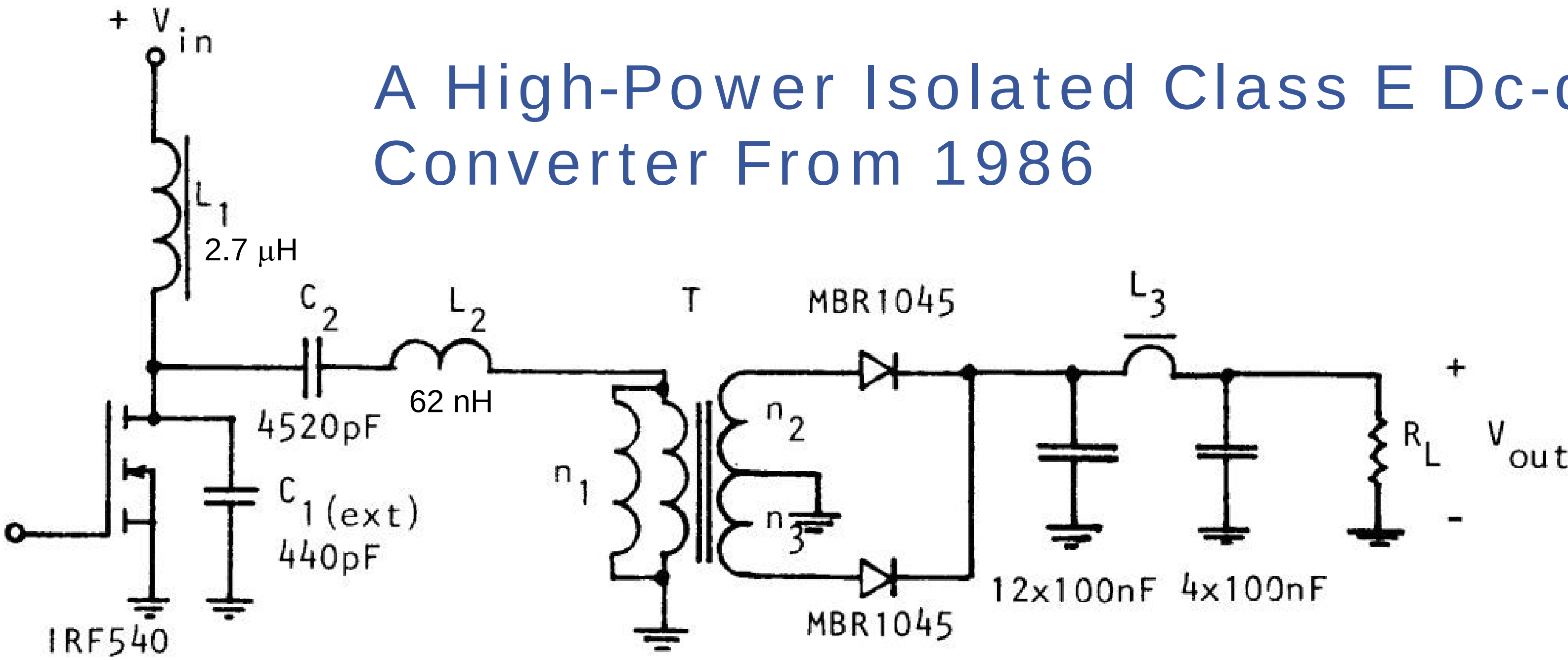
First Proposed Class E Dc-dc Converter (From 1980)



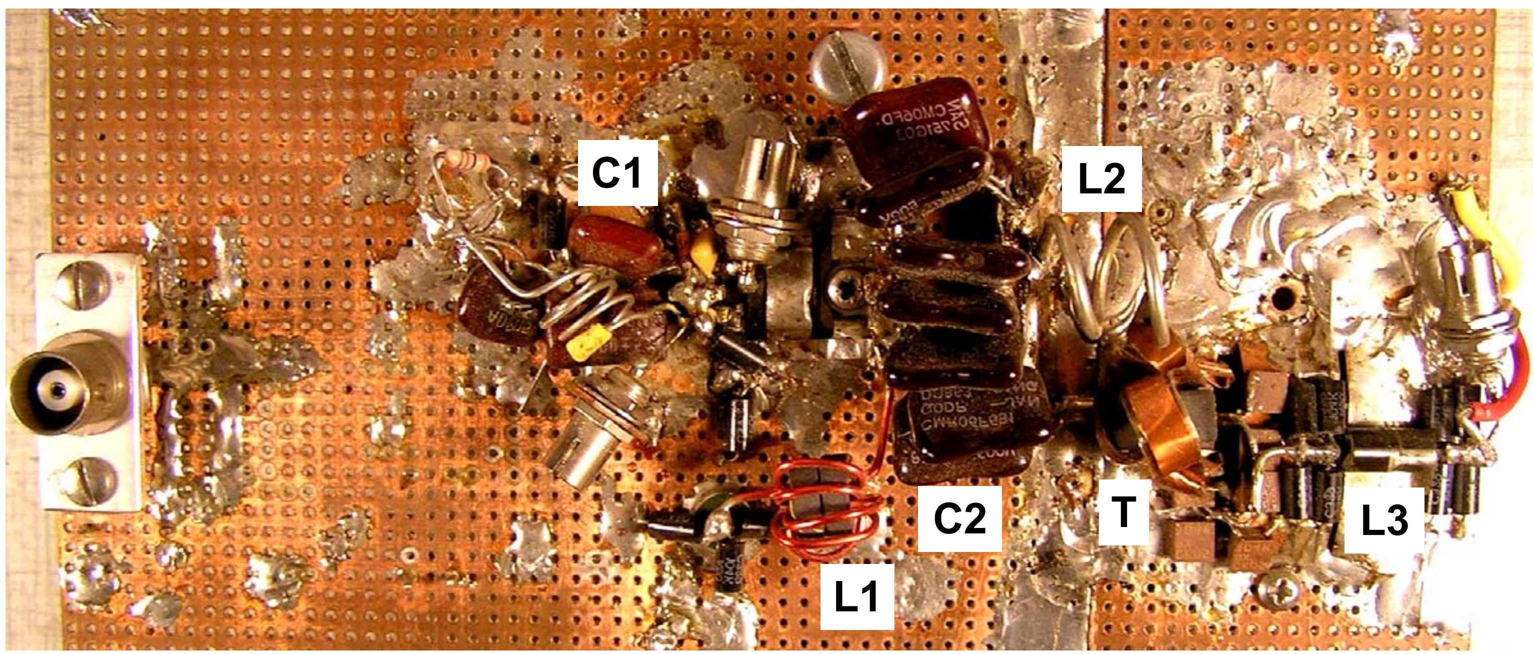
Designed for 5 MHz, 48 V to 5 V, 25 W; actual experiment with a commercially available Class E demonstrator: 10 MHz, 25 V to 5 V, 5 W; efficiency: app. 68%

R. Gutmann, "Application of RF circuit design principles to distributed power converters," IEEE Trans. Ind. Electron. Contr. Instrum., vol. IECI-27, no. 3, pp. 156-164, Aug. 1980.

A High-Power Isolated Class E Dc-dc Converter From 1986

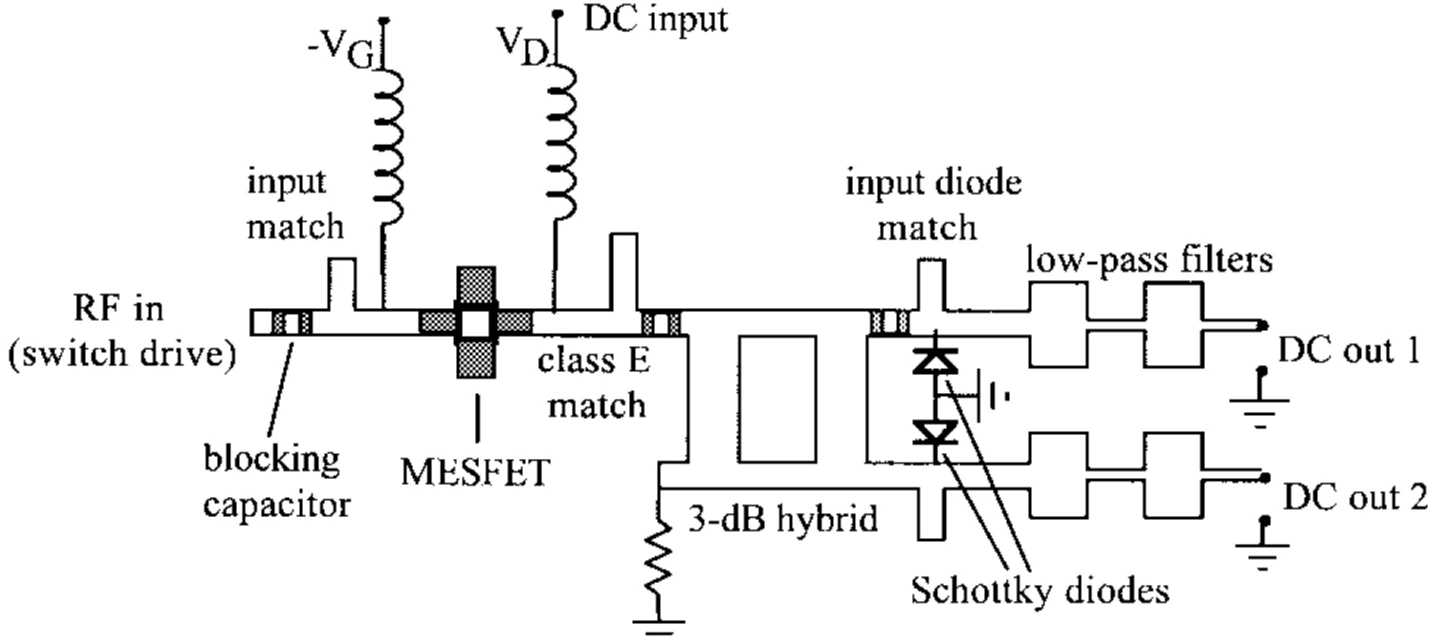


14 MHz, 20 V to 20 V, 100 W, efficiency: app. 87%



R. Redl and N. O. Sokal, "A 14-MHz 100-Watt Class E resonant converter: Principles, design considerations and measured performance," Proc. Power Electronics Show and Conference, San Jose, CA, Oct. 1986, vol. 1, pp. 68-77.

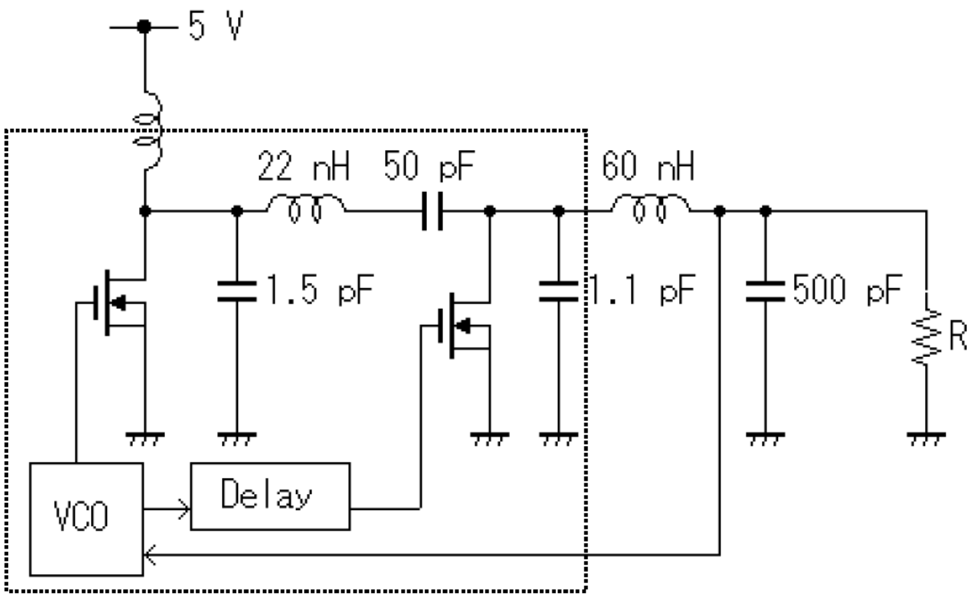
A Microwave Class E Dc-dc Converter From 1999

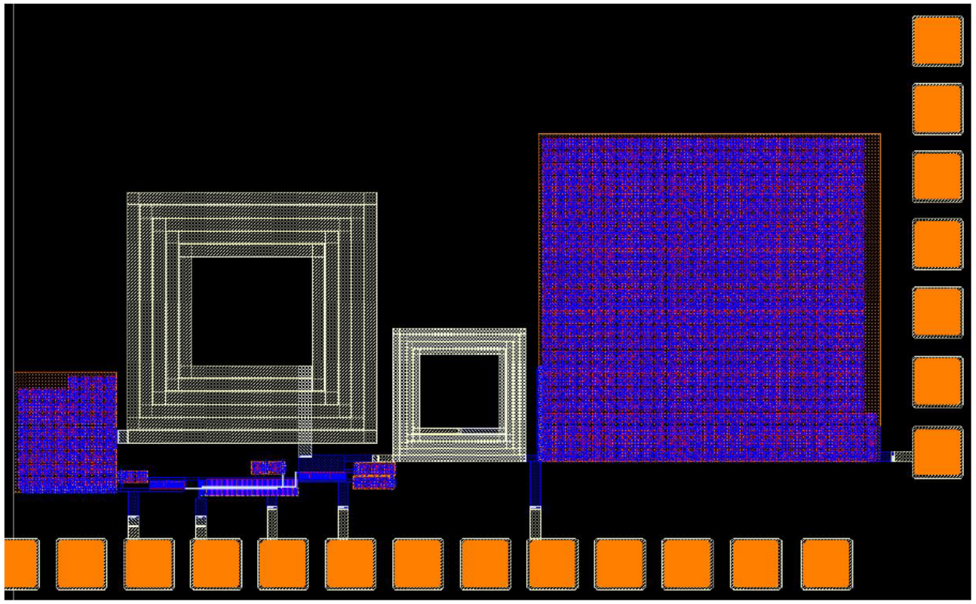


4.5 GHz, 3 V to 2.15 V, 120 mW, efficiency: app. 64%, dimensions: 140 x 70 x 0.508 mm

S. Djukić, D. Maksimović, and Z. Popović, "A planar 4.5-GHz dc-dc power converter," IEEE Trans. Microwave Theory and Techniques, vol. 47, no. 8, August 1999, pp. 1457-1460.

An On-Chip Class E Dc-dc Converter From 2003

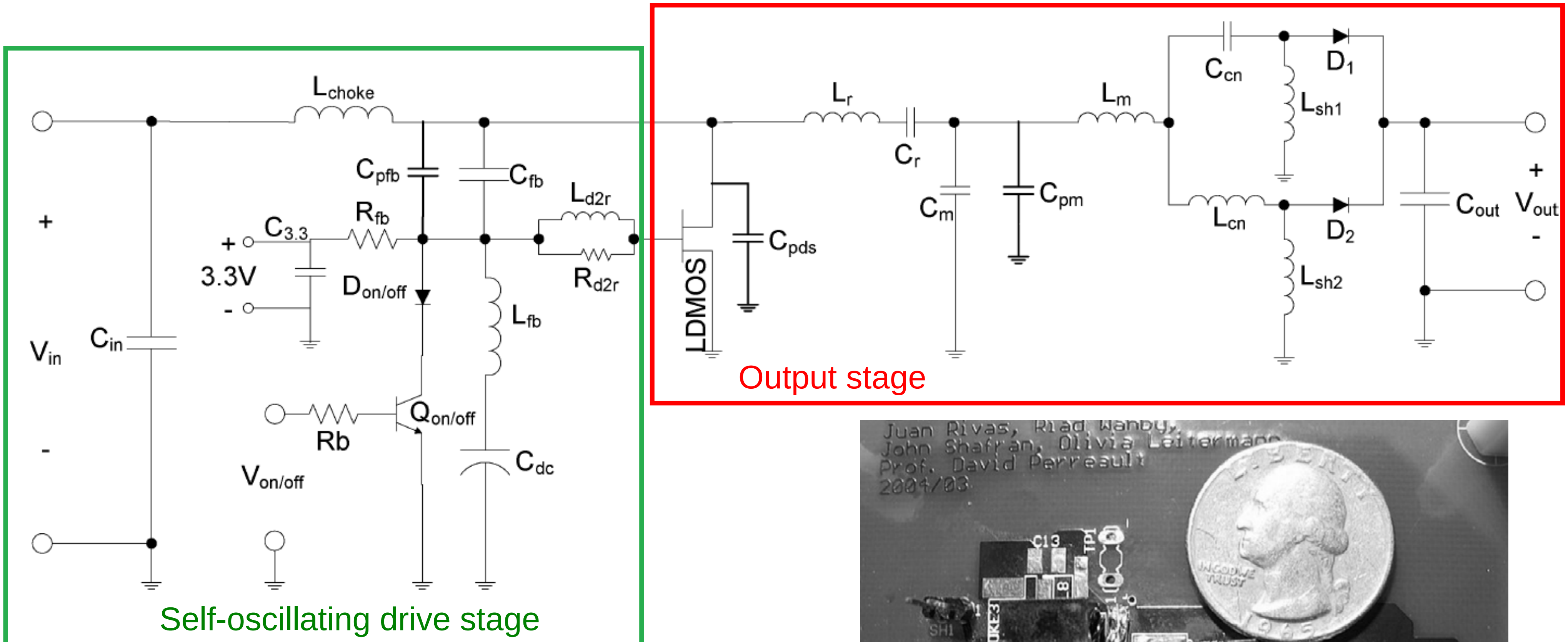


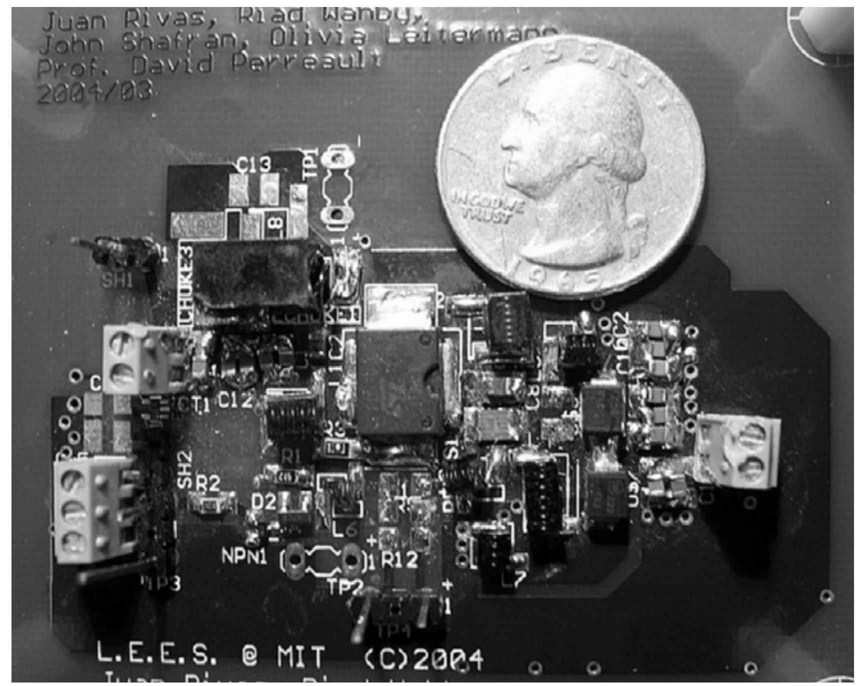


800 MHz, 5 V to 4.5 V, 200 mW, efficiency: app. 72%, dimensions: 0.96 x 1.6 mm

T. Suetsugu and M. K. Kazimierczuk, “Feasibility study of on-chip Class E dc-dc converter,” IEEE International Symposium on Circuits and Systems, Bangkok, Thailand, May 25-28, 2003, vol. III, pp. 443-446.

A 100 MHz Class E Converter From 2004

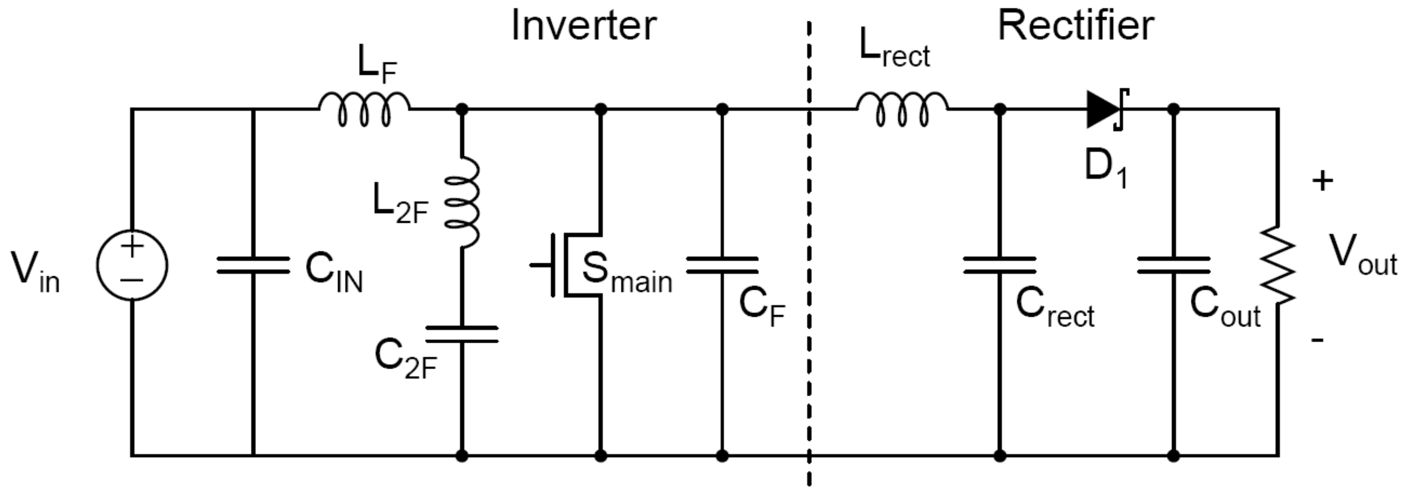




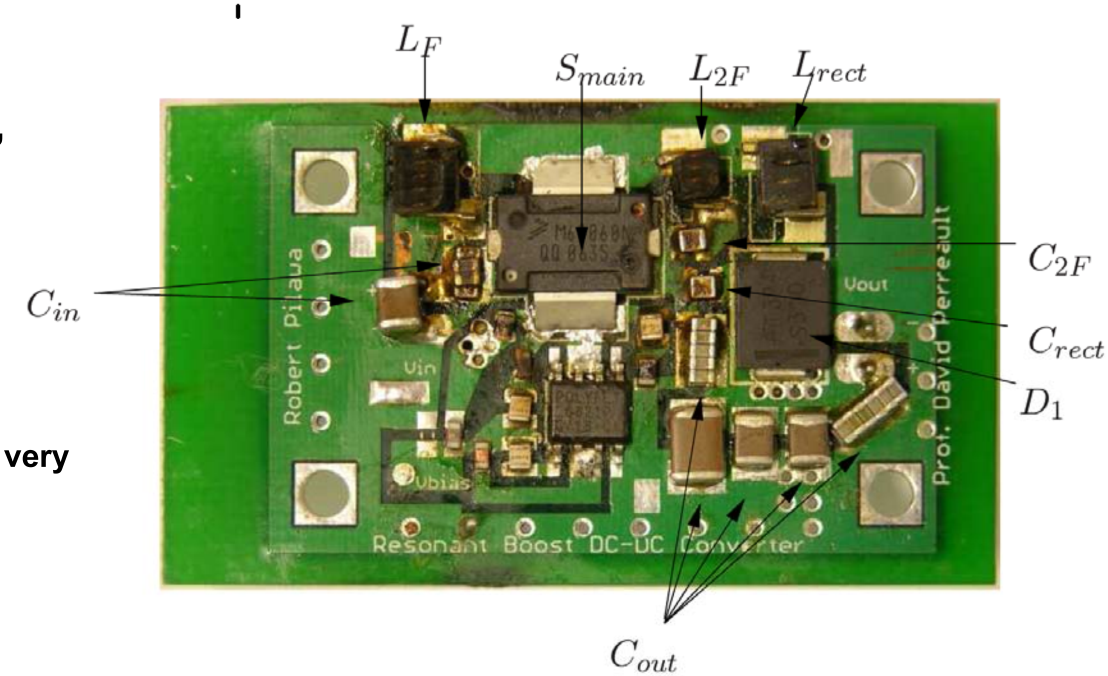
100 MHz, 16 V to 5.1 V, 6 W, efficiency: app. 78%

J. M. Rivas, J. Shafran, R. S. Wahby, and D. J. Perreault, "New architectures for radio-frequency dc/dc power conversion," IEEE Tans. Power Electronics, vol. 21, no. 2, March 2006, pp. 380-393 (originally presented at PESC 2004).

A Class E Derivative: Resonant Boost Converter (Φ_2 Inverter Combined With Resonant Rectifier) From 2007



110 MHz, 14.4V nominal to 33 V nominal, 23 W, efficiency: app. 87%



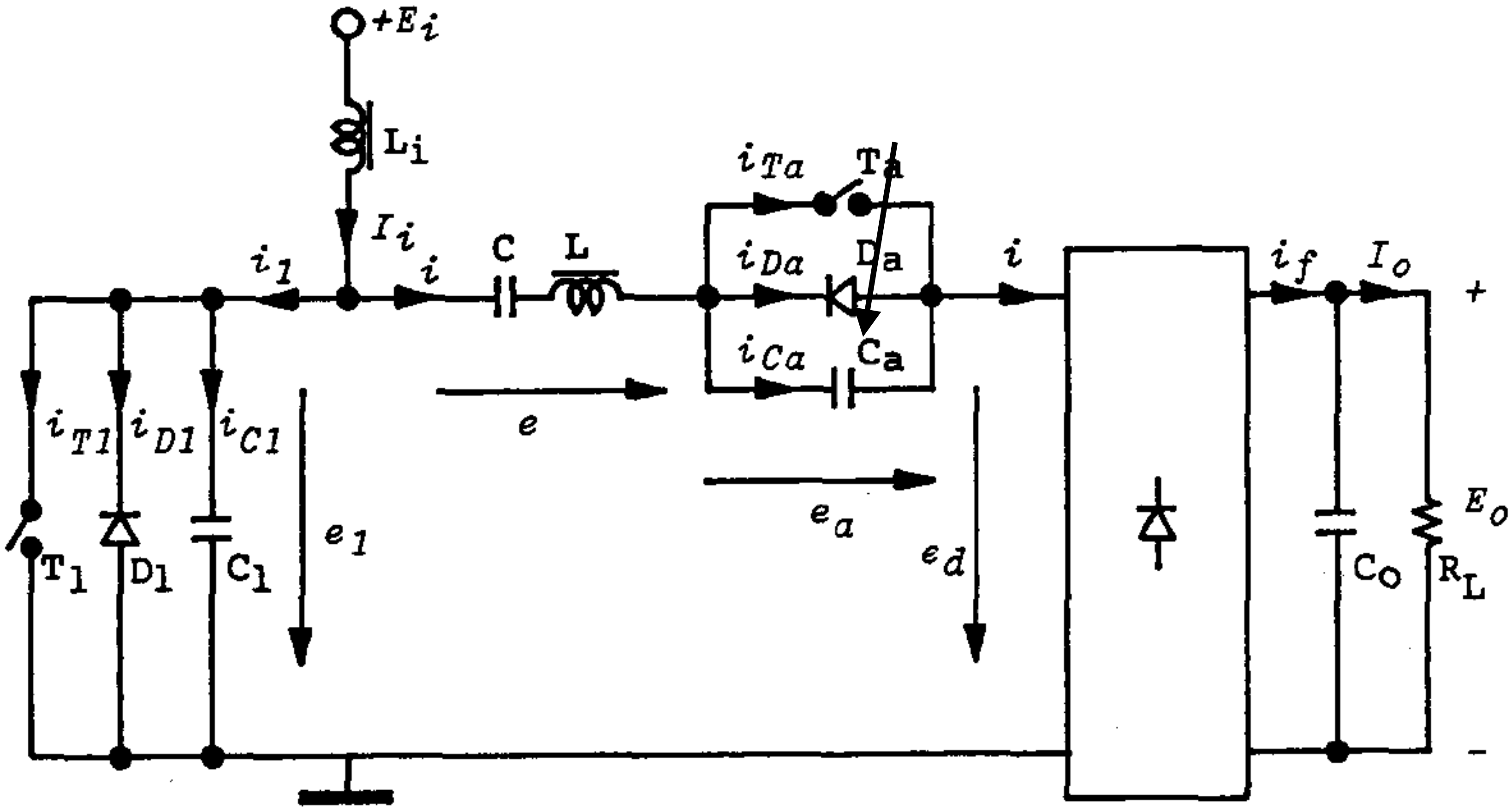
R. C. N. Pilawa-Podgurski, “Design and evaluation of a very high frequency dc/dc power converter,” Thesis, MIT, February 2007.

Control/Regulation Techniques for the Class E Dc-dc Converter

- **Frequency modulation**
  - **Increasing frequency reduces the output voltage.**
  - **Range depends on the Q of the series resonator L_2C_2; can exceed 2:1.**
  - **Reactive preload required for maintaining regulation at no load**
- **On-off control[1]**
  - **Simple on-off control (single-phase)**
  - **Vernier regulated cell architecture (on-off controlled cells plus low-power regulating cell)**
  - **Time-modulation-regulated architectures (multiphase; hysteretic, PWM, etc. modulation strategies)**
  - **Power DAC (on-off control using non-uniform sized cells, e.g. with 2^N weighting)**
- **Fixed-frequency control with auxiliary switch (see next)**
- **Discrete control (see 2nd next)**

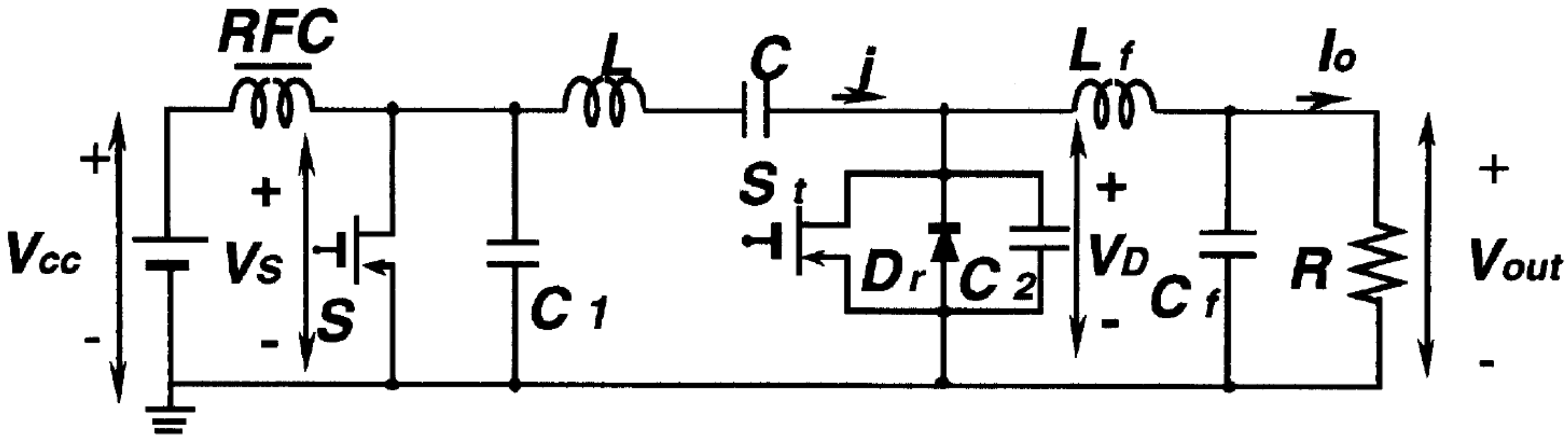
[1]J. M. Rivas, J. Shafran, R. S. Wahby, and D. J. Perreault, "New architectures for radio-frequency dc/dc power conversion," IEEE Tans. Power Electronics, vol. 21, no. 2, March 2006, pp. 380-393 (originally presented at PESC 2004).

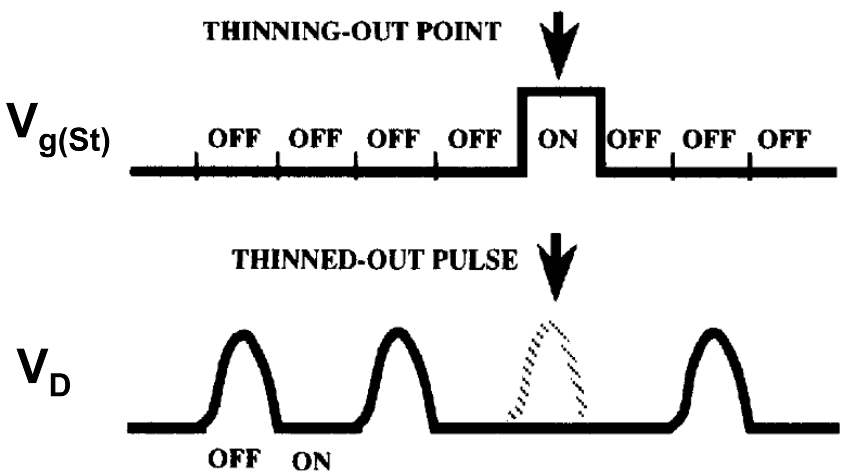
Fixed-Frequency Control With Auxiliary Switch

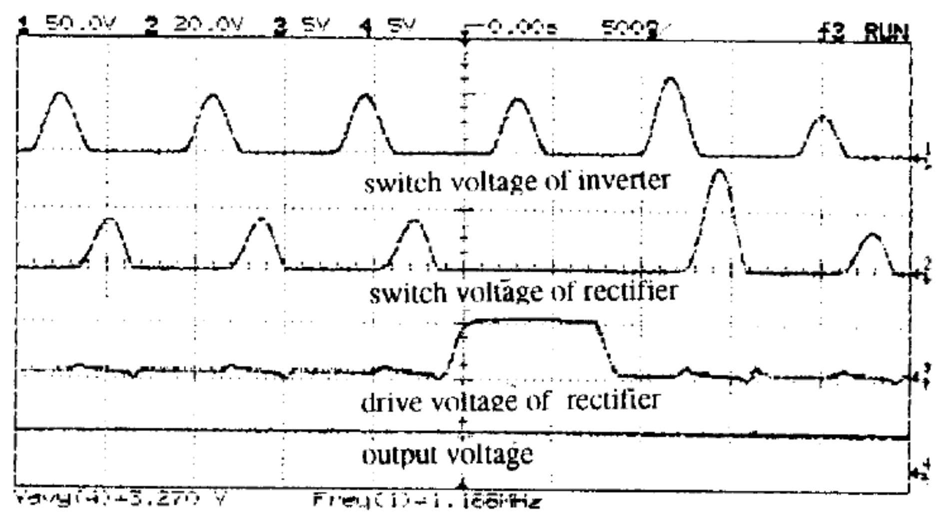


W-J Gu, K. Harada, "A circuit model for the class E resonant DC-DC converter regulated at a fixed switching frequency," IEEE Trans. Power Electronics, vol. 7, no. 1, Jan 1992, pages 99-110.

Discrete Control of the Class E Dc-dc Converter







M. Fujii et al, "Resonant dc/dc converter with Class E inverter and Class E rectifier using thinned-out method", Proc. APEC '95, pp. 510-515.

Gate Drivers

- **Main issue: Power loss**
  - **Minimum drive power of a size-optimized MOSFET[1]** →
  - **Gate drive power of an advanced trench MOSFET at 30 MHz is about 5% of the output power.**
- **Standard (brute-force) gate driver**
  - **Lossy charge and discharge of gate capacitance**
- **Low-loss/resonant gate drivers[2]**
- **RF power amplifier as driver**
- **Self-oscillating gate drivers**
  - **Power stage is an oscillator[3]**
  - **Separate oscillator as driver[4]**

$$P_{drive(min)} = I_{rms} V_G \sqrt{\frac{f}{f_B}}$$

where

$$f_B = \frac{1}{R_{ds(on)} C_{in}}$$

and

$$R_{ds(on)} = \frac{V_G}{I_{rms}} \sqrt{\frac{f}{f_B}}$$

[1]J. Baliga, "Advanced power semiconductor devices for high frequency applications," HFPC – May 1989 Proceedings, pp. 24-31.

[2]Y. Chen, "Resonant gate drive techniques for power MOSFETs," Thesis, VPI & SU, May 2000.

[3]J. M. Rivas, J. Shafran, R. S. Wahby, and D. J. Perreault, "New architectures for radio-frequency dc/dc power conversion," IEEE Tans. Power Electronics, vol. 21, no. 2, March 2006, pp. 380-393 (originally presented at PESC 2004).

[4]J. M. Rivas, D. Jackson, O. Leitermann, A. D. Sagneri, Y. Han, and D. J. Perreault, "Design considerations for radio frequency dc-dc converters," PESC 2006 Record, pp. 2287–2297.

Component Load Factor

- **CLF (a measure of component utilization)**
  - $$CLF = \frac{V^* I^*}{P_{out}}$$ **where V* and I* are defined for each component**
  - $$CLF_{FET} = \frac{V_{peak} I_{rms}}{P_{out}}$$ **for a MOSFET transistor**
  - $$CLF_{filter\ inductor} = \frac{|V| I_{dc}}{P_{out}}$$ **for a filter inductor**
  - $$CLF_{filter/bypass capacitor} = \frac{V_{dc} I_{rms}}{P_{out}}$$ **for a filter/bypass capacitor**
- **Total CLF (i.e., CLF for one type of components in a converter)**

$$CLF_{total} = \sum_{i=1}^{n} CLF_i$$

- **Not well suited for evaluating resonant converters.**

B. Carsten, "Converter component load factors; a performance limitation of various topologies," PCI '88, Munich, Germany

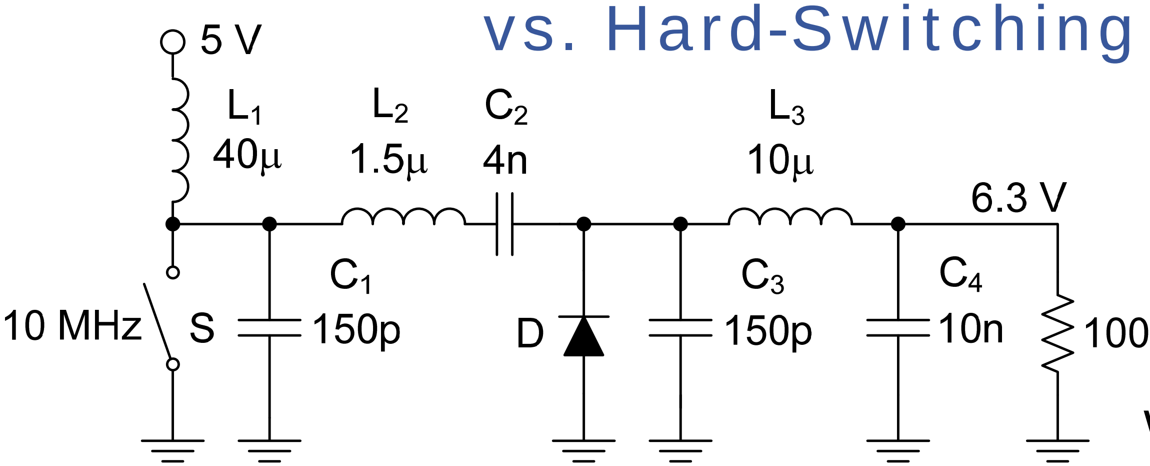
Component Stress Factor

- **CSF improves on the concept of CLF by considering the power dissipated in a component. CSF also takes into account the voltage dependences of $R_{DS(ON)}$ and the losses in the winding resistance or capacitor ESR. Furthermore it includes a weighting factor W that represents the relative size of the component.**
- $$CSF = \frac{V_{peak}^2 I_{rms}^2}{P_{out}^2} \frac{\sum_{i=1}^{n} W_i}{W}$$ **same general expression for semiconductors, windings and capacitors**

- **SCSF: CSF for semiconductors**
- **WCSF: CSF for windings**
- **CCSF: CSF for capacitors**

E. H. Wittenbreder, Jr., "High efficiency power supply design," Professional Education Seminar, APEC 2006, Dallas, TX

First Comparison—Class E Dc-dc Converter[1] vs. Hard-Switching Boost Converter



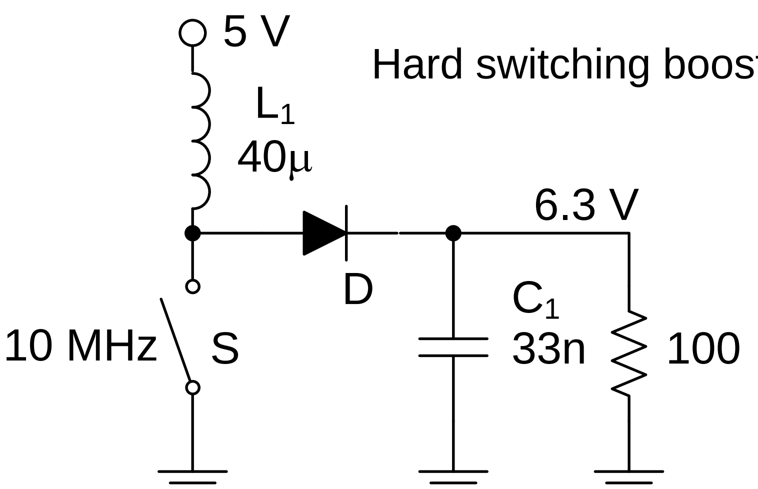
Class E dc-dc converter

$$SCSF_{total} = 23.6_S + 26.8_D = 50.4$$

$$WCSF_{total} = 5.28_{L1} + 30.1_{L2} + 5.05_{L3} = 40.4$$

$$CCSF_{total} = 8.96_{C1} + 0.30_{C2} + 21.3_{C3} + 0.03_{C4} = 30.6$$

Hard switching boost converter



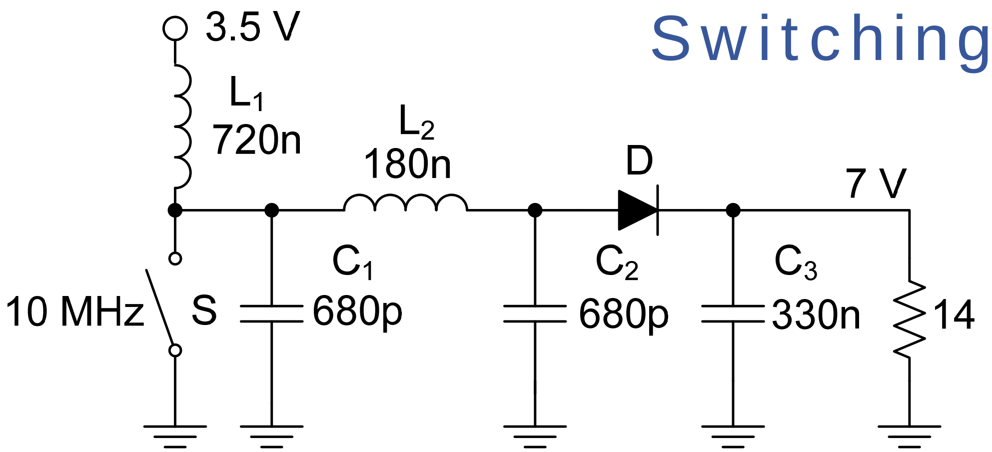
$$SCSF_{total} = 0.346_S + 1.293_D = 1.64$$

$$WCSF_{L1} = 1.01$$

$$CCSF_{C1} = 0.28$$

[1] **Scaled version of a converter discussed in "Feasibility study of on-chip Class E dc-dc converter," IEEE International Symposium on Circuits and Systems, 2003, by T. Suetsugu and M. K. Kazimierczuk**

Second Comparison—Class E Based Resonant Boost Converter vs. Hard-Switching Boost Converter



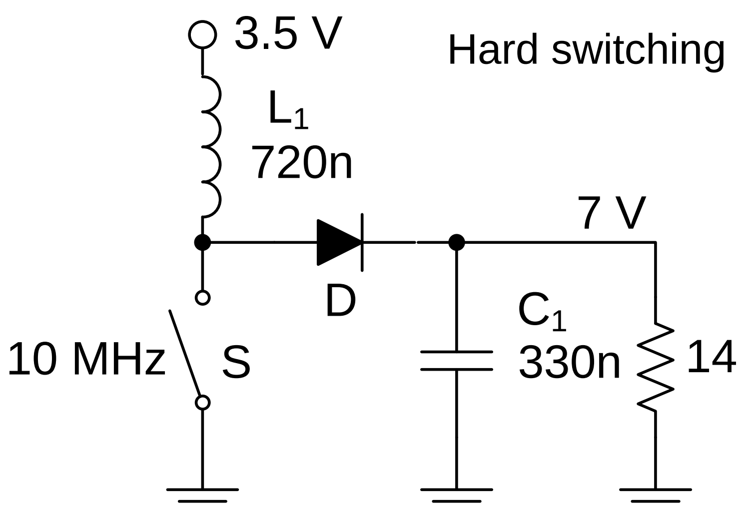
Class E based resonant boost converter[1]

$$SCSF_{total} = 10.5_S + 9.2_D = 19.7$$

$$WCSF_{total} = 12.9_{L1} + 20.8_{L2} = 33.7$$

$$CCSF_{total} = 3.72_{C1} + 0.46_{C2} + 1.42_{C3} = 5.60$$

Hard switching boost converter



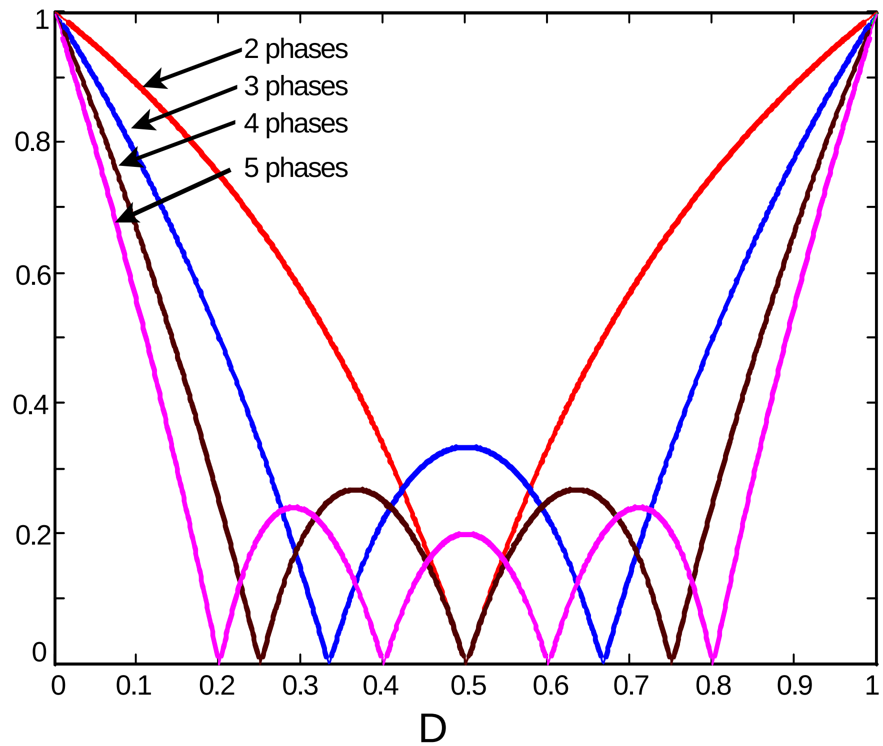
$$SCSF_{total} = 2.71_S + 2.04_D = 4.75$$

$$WCSF_{L1} = 1.01$$

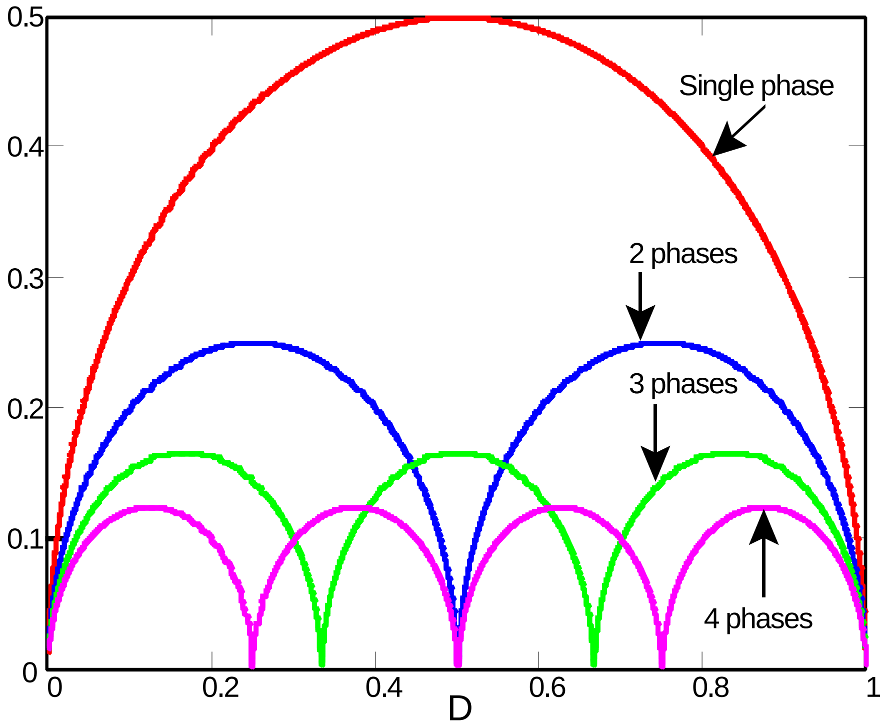
$$CCSF_{C1} = 1.02$$

[1]Scaled version of a converter discussed in "Transistor selection and design of a VHF dc-dc power converter," IEEE Trans. Power Electronics, vol. 23, no. 1, January 2008, pp. 27-37, by J. R. Warren, III, K. A. Rosowski, and D. J. Perreault

Normalized Output and Input Ripple Currents of the Evenly Interleaved Multiphase Buck Converters vs. the Duty Ratio

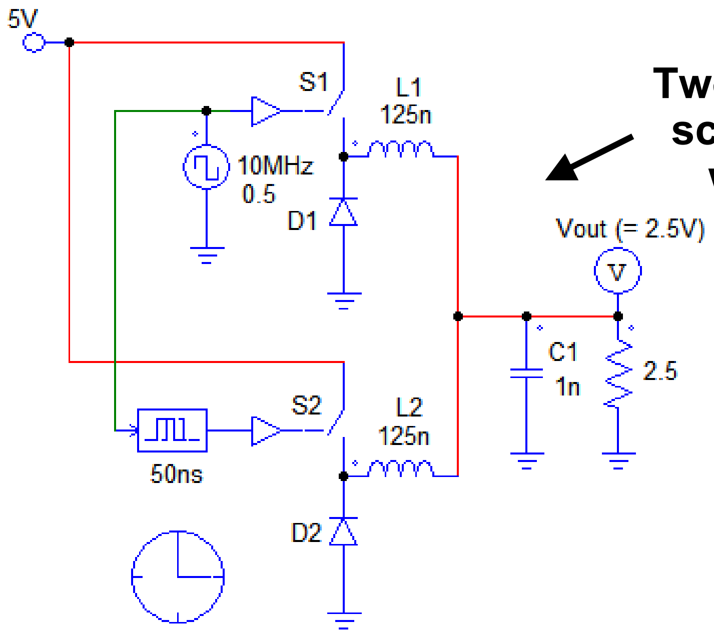


Normalized output ripple current

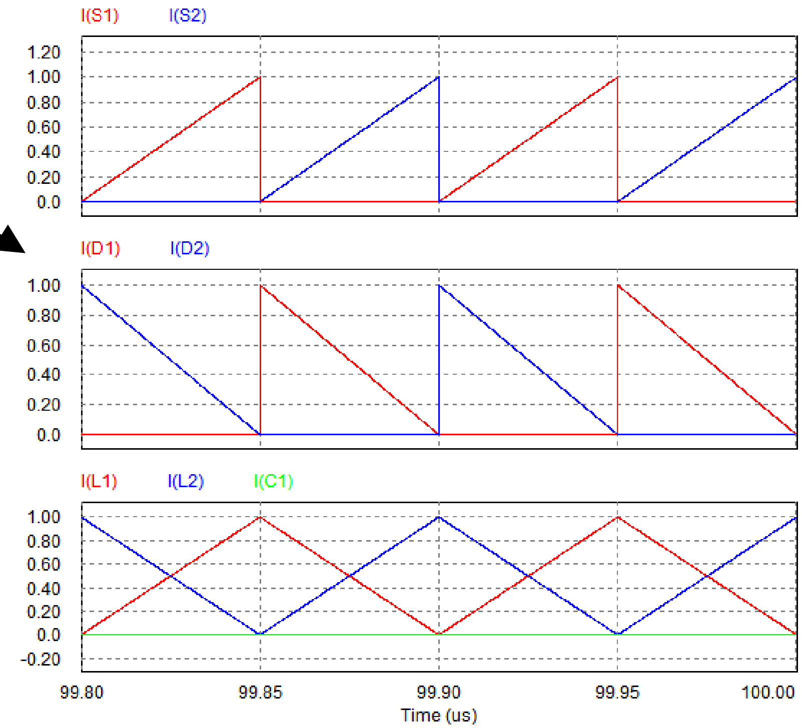


Normalized input ripple current

CSFs of the Two-Phase Interleaved Buck and Boost Converters Operating at 50% Duty Ratio With Critical Conduction



Two-phase buck schematic and waveforms



CSFs of the two-phase buck converter:

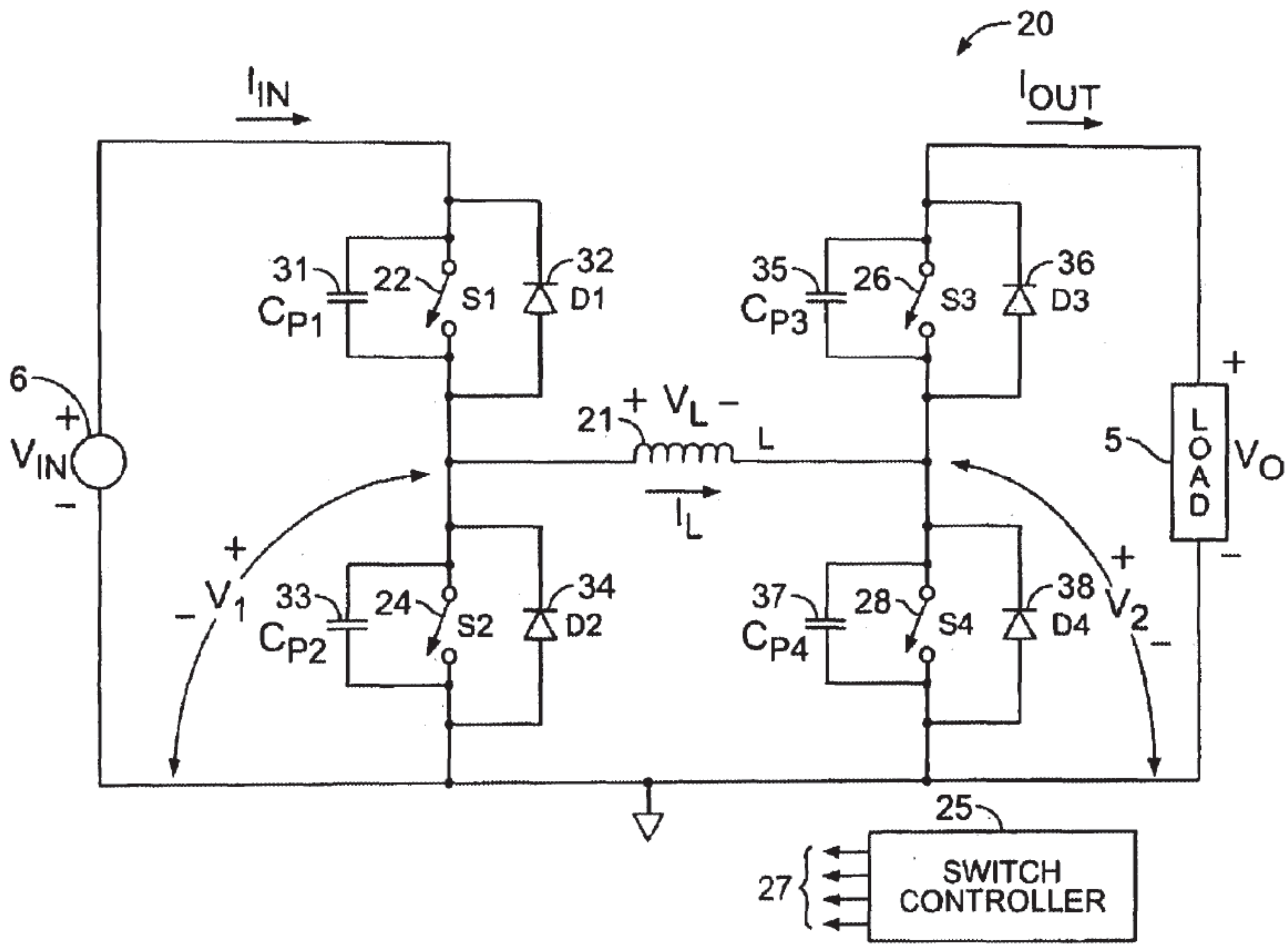
$$SCSF_{total} = 4\frac{5^2 \cdot 0.409^2}{2.5^2} = 2.67 \qquad WCSF_{total} = 2\frac{2.5^2 \cdot 0.578^2}{2.5^2} = 0.667 \qquad CCSF_{C1} = 0$$

CSFs of the two-phase boost converter:

$$SCSF_{total} = 2.67 \qquad WCSF_{total} = 0.667 \qquad CCSF_{C1} = \frac{5^2 \cdot 0.29^2}{2.5^2} = 0.337$$

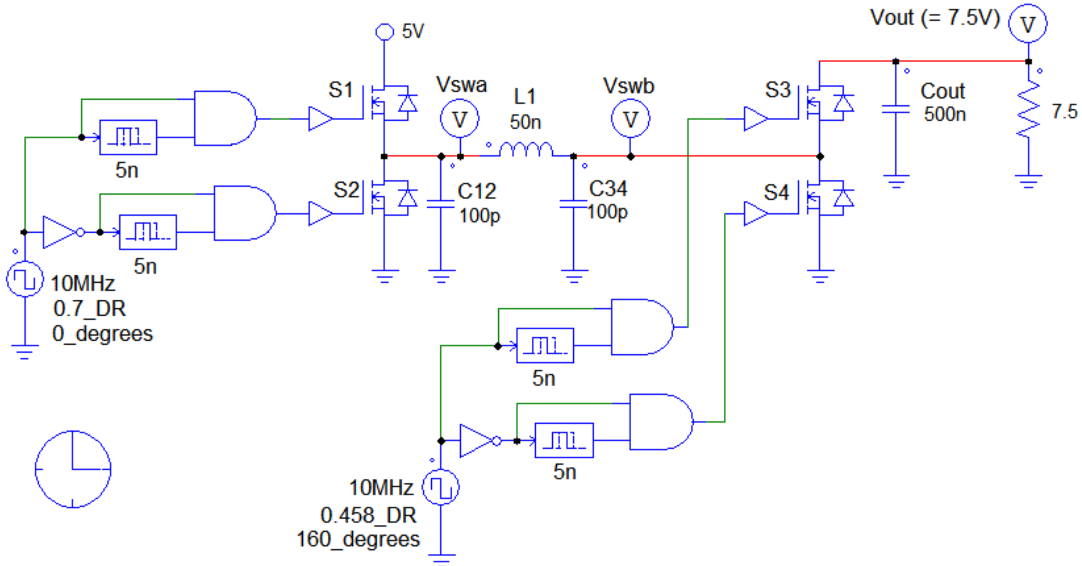
Both are attractive choices for integration with operating frequencies in the 5 to 15 MHz range. The concept can be extended to more than two phases.

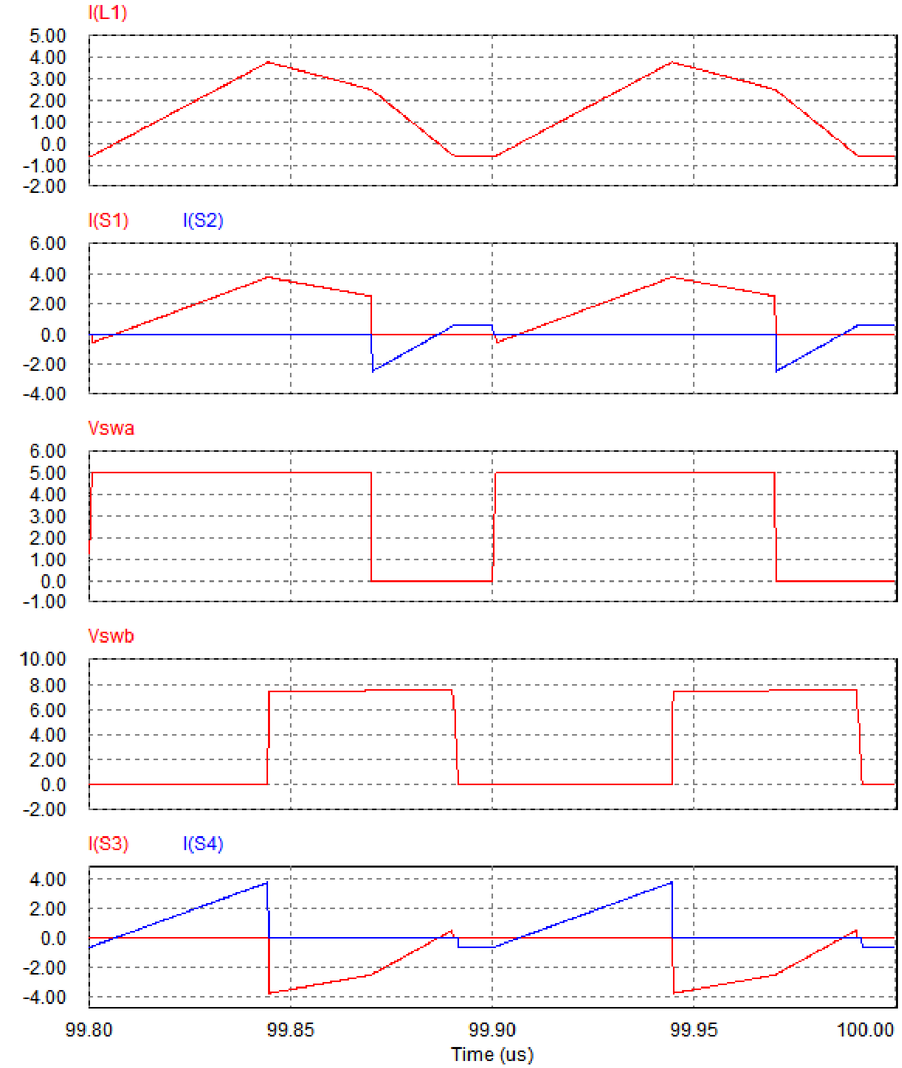
ZVS Noninverting Buck-Boost Converter



P. Vinciarelli, "Buck-boost dc-dc switching power conversion," U.S. Patent 6,788,033

Typical Waveforms and CSFs in Boost Mode





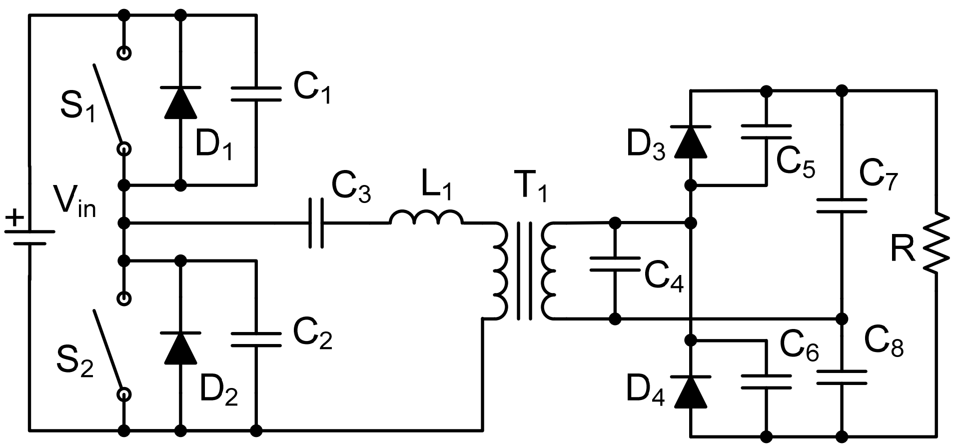
$$SCSF_{total} = 1.94_{S1} + 0.17_{S2} + 2.89_{S3} + 1.85_{S4} = 6.85$$

$$WCSF_{L1} = 4.77$$

$$CCSF_{total} = 0.007_{C12} + 0.033_{C34} + 1.90_{Cout} = 1.94$$

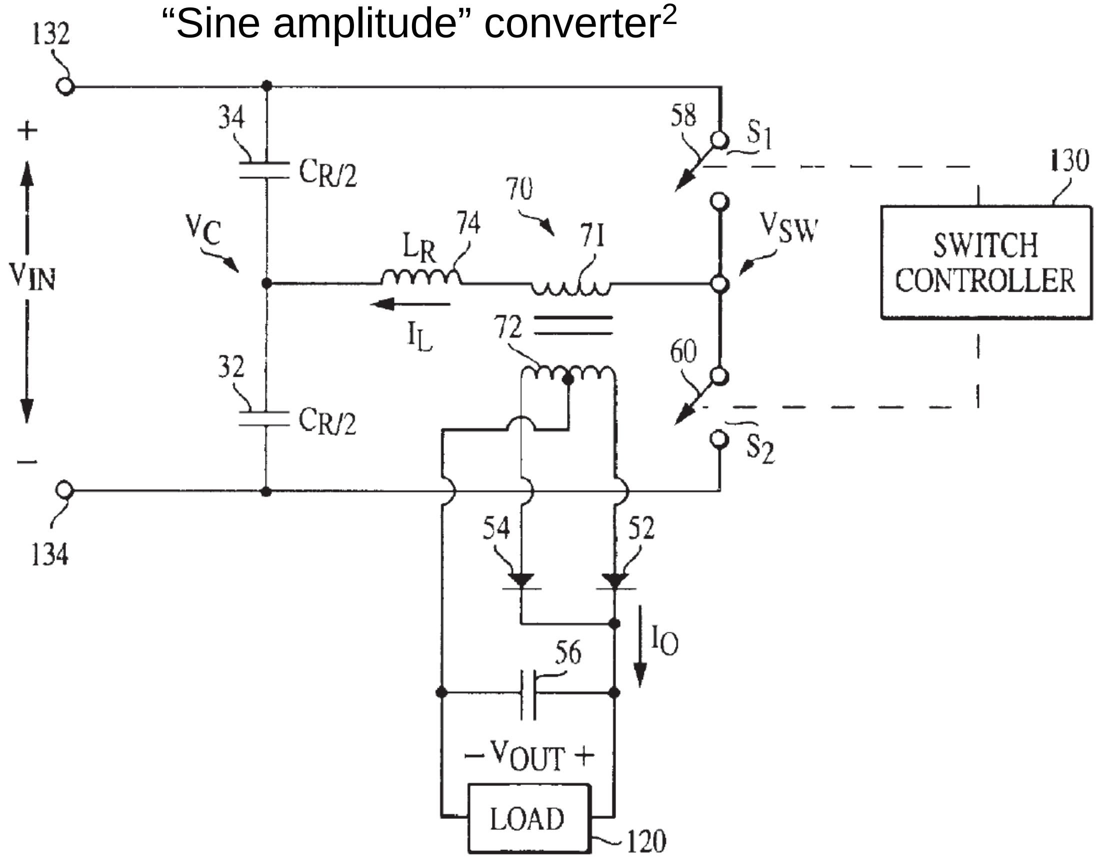
For CSF not as good as the standard boost but significantly better than the resonant boost and far better than the Class E dc-dc converter. Full ZVS operation, flexible, easy to control.

Unregulated Isolated Converters to Consider for VHF Operation



Class (DE)^2 converter[1]

“Sine amplitude” converter[2]



With L_R and C_R resonating at f_{sw} and with D = 50% the switch currents are half sine-waves. The magnetizing current of the transformer provides ZVS.

$$SCSF_{total} = 9.90$$

$$WCSF_{L_R} = 19.8$$

$$CCSF_{C_R} = 15.1$$

[1]D. C. Hamill, “Class DE inverters and rectifiers for dc-dc conversion,” PESC ’96 Record, pp. 854-860.

[2]P. Vinciarelli, “Factorized power architecture with point of load sine amplitude converters,” U.S. Patent 6,930,893

Conclusions

- **Very high frequency power converters require resonant ZVS operation (although not always[1]) and tend to suffer from:**
  - **Poor full load efficiency due to high drive power, high residual switching losses and excessive CSFs**
  - **Even poorer light load efficiency because of the additional increase in the ratio of circulating current to load current and/or the loss of ZVS**
  - **Poor controllability**
  - **A complex circuit structure that is not well suited for on-chip implementation**
- **For high-density and on-chip power converter applications alternative lower-frequency solutions should be sought instead, e.g.:**
  - **Multiphase converters operating near the ripple-current notches and with critical conduction (for minimum-size inductors and also for reduced switching losses)**
  - **Novel ZVS converters with improved controllability, e.g. the ZVS non-inverting buck-boost**
  - **Unregulated optimally resonant converters, e.g., Class (DE)[2] or "sine amplitude"**

[1]G. Schrom et al, "A 480-MHz, multi-phase interleaved buck dc-dc converter with hysteretic control," PESC 2004 Record, pp. 4702-4707.