RF Frequency Switching Power Supply

T.P. Robbins
Telecom Australia Research Laboratories, Clayton VIC
R.A. Minasian, SMIREE
Department of Electrical Engineering
University of Melbourne, Parkville VIC

Results from a switching power supply operating at 2MHz are presented. The 60W, 48V to 12V DC-DC converter features an efficiency of 83%, short-circuit proof operation and measured radiated interference levels of -45dB below the VDE standard. The dynamic response of the converter for a 40% to 80% load change was 6 sec with a well dampered waveform.

INTRODUCTION

Switching power supplies and regulators have undergone remarkable developments in recent years. Their current widespread use arises from the inherent higher efficiency performance and small size and weight, relative to linear power supplies. However, present switching converter designs have some disadvantages compared with linear supplies in terms of regulation speed of response and interference generation. There has been a steady drive towards increasing the switching frequency of converters so as to improve the dynamic response and contain interference generation, while further reducing size and weight. The majority of converter designs reported operate at frequencies up to several hundred kHz [1,2], although a larger increase in frequency is necessary to make an impact on switch-mode supply performance.

This paper reports on the design and operation of a switching converter operating with a significant increase in frequency over conventional designs. A 2MHz switching frequency with high efficiency performance has been achieved, by using improved switching devices and a high frequency switch-mode topology [3,4], and results for a 60W DC-DC converter are presented.

CONVERTER DESCRIPTION

The circuit topology of the RF converter is shown in figure 1 and is derived from the converter investigated by Gutmann [3]. The class E mode [5] is used for DC to AC inversion. This circuit features a very high operating efficiency by synthesizing a switch transient response with a connected reactive load network that minimizes concurrent switch voltage and current levels during the switching transition. This circuit therefore alleviates switching requirements, allowing the active device switching times to be a significant part of the switching period. The switching waveforms are of sinusoidal form for ease of switching, filtering and EMI control. A power MOSFET is used as the controlled switch and dominant parasitic reactances are incorporated into the circuit operation. The inverter AC output is transformed by an impedance matching network. After rectification with a Schottky diode, the output is filtered to deliver DC power to the load. Due to the high operating switching frequency, only low value energy storage elements are required and miniature low loss capacitors and high frequency inductors are employed in the converter circuit.

Regulation of the output is achieved by narrow-band pulse frequency control of the inverter

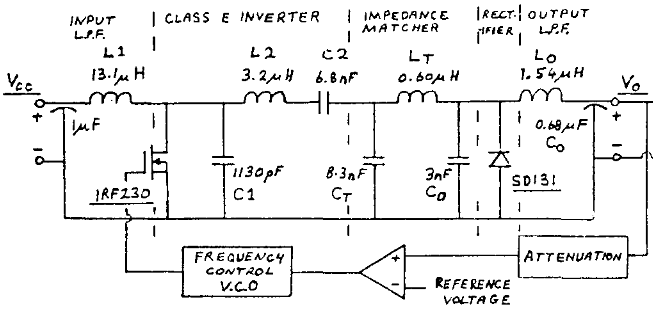

FIGURE 1. Circuit diagram of 60W, 48V-12V RF converter.

switching frequency using a voltage controlled oscillator. Feedback compensation has been implemented to obtain a high unity loop gain bandwidth, which directly results from the increased operating switching frequency.

CONVERTER DESIGN

Design guidelines are now presented for an optimized RF converter [7] with frequency regulation of the output voltage. The nominal operating frequency ($\omega/2\pi$) should be chosen in the region of 1-5 MHz, which will then allow both high efficiency performance and the high frequency advantages of small size, weight and EMI control.

The inverter section is optimized when the load network Q is made small in the range of 2-4. Designing for a low Q reduces the required inductance value of L2 for a given transformer network input impedance R_E, and hence minimizes the significant power loss in the inductor series resistance. The design equations for the inverter are given by,

$$L2 = Q \cdot R_E / \omega \quad (H) \quad (1)$$

$$C1 = \{1 + 0.81\,Q/(Q^2+4)\}/(5.45\,\omega . R_E) \quad (F) \quad (2)$$

$$C2 = \{1 + 1.11/(Q - 1.79)\}/(\omega . Q . R_E) \quad (F) \quad (3)$$

$$R_E = V_c^2 . \eta / (1.73\, V_o . I_o) \quad (\Omega) \quad (4)$$

where V_C = maximum input voltage

V_O = regulated output voltage

I_O = maximum output current

η = efficiency (≈ 0.85)

The input filter inductance affects both the transient response and the input ripple characteristics of the converter, and is given by,

$$L1 = 1.73 \; R_E / \omega_1 \qquad (H) \quad (5)$$

The low-pass input filter corner frequency ω_1 can be set to a value up to 0.5ω to increase the transient response of the converter, however increasing ω_1 involves a trad-off with increasing input ripple current.

The impedance matching transformer section is designed using a three reactance pi network with a low pass filter characteristic and a fractional octave matching bandwidth. The design incorporates the parasitic diode junction capacitance of the following rectifier section. The matching network design equations are,

$$X_{CT} = R_E / N \qquad (6)$$

$$X_{CD} = R_O / \sqrt{(R_O/R_E).(1+N^2)-1} \qquad (7)$$

$$X_{LT} = R_E(N + R_O/X_{CD})/(N^2+1) \qquad (8)$$

$$N > N_{MIN} = \sqrt{(R_E/R_O)-1} \qquad (9)$$

where $R_E > R_O$, $X_C = 1/\omega C$, $X_L = \omega L$ and N is an arbitrary design variable chosen to be about 1.1 N_{MIN}. The design equations are reversed when $R_E < R_O$. Short-circuit proof operation of the converter is achieved by designing $X_{CT} > X_{LT}$.

The low pass output filter is designed to give a critically damped response at full load to optimise the converter's regulation characteristics. Design equations are,

$$L_O = V_O / (2\,\omega_O . I_O) \qquad (H) \quad (10)$$

$$C_O = 4\,L_O / R_O^2 \qquad (F) \quad (11)$$

where $V_O = I_O.R_O$ and the filter corner frequency ω_O is nominally set to $\omega/10$.

State-of-the-art active devices are used in order to achieve high-efficiency performance, and are the power MOSFET switch and the Schottky diode rectifier. The main loss components in the converter have been identified and are in the order of importance - the inductor L2, the rectifier, the switch and the inductor L_T.

Peak stresses on the active devices are:

	Voltage Stress	Current Stress
MOSFET	$4\,V_C$	$\{1+1.86(1-1/2Q_E)\}\,V_O.I_O/\eta.V_C$
DIODE	$\approx 6\,V_O$	$2\,I_O$

The feedback section regulates the converter output voltage by frequency regulation control using a TI type LS 629 IC voltage controlled oscillator. The converter output voltage is compared with a reference voltage and an amplified difference signal is then used to control the VCO. Lag compensation is incorporated into the circuit at the VCO input by introducing a single-pole low-pass filter network.

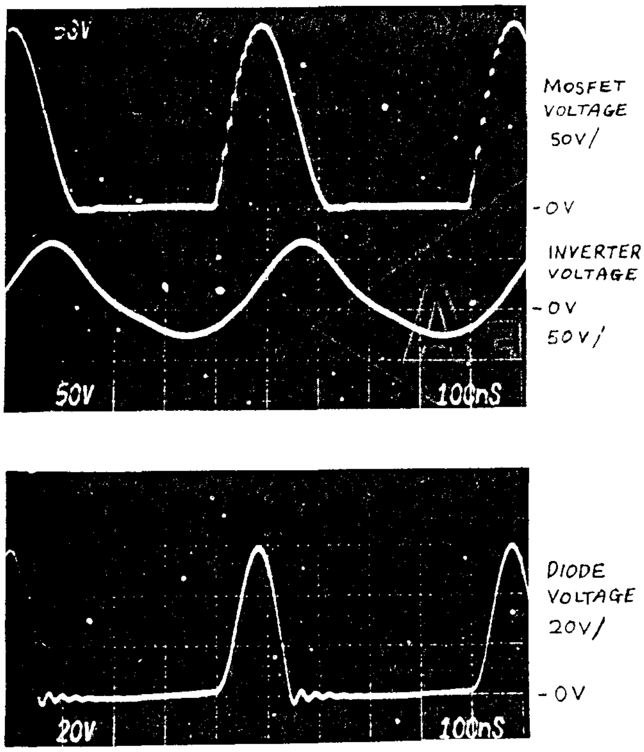

FIGURE 2. RF converter switching waveforms at full load.

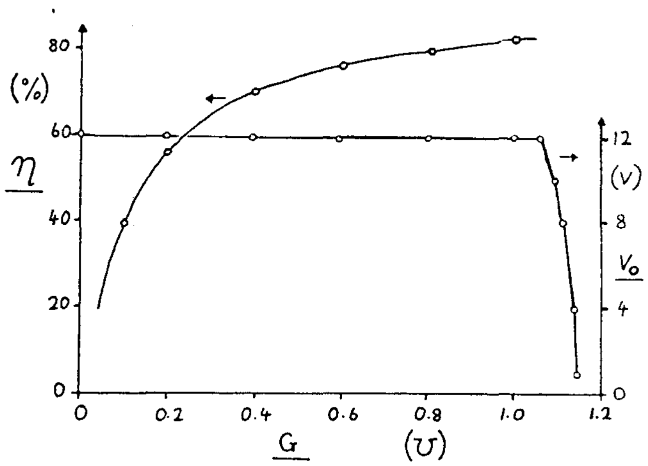

FIGURE 3. Load regulation and efficiency of 60W, 48V-12V RF converter.

RESULTS

Results from an experimental 60W, 48V-12V converter operating at 2 MHz with an overall efficiency of 83% are presented.

The converter circuit was enclosed inside a die cast aluminium box which provided heat sinking and EMI shielding. The RF power circuit inductors L2 and L_T were constructed using air-cores and the filter inductors L1 and L0 were constructed with ferrite-cores to achieve small size and good shielding. The power circuit capacitors used were miniature porcelain dielectric types for values up to 3nF, and silvered-mica types for higher values. The filter capacitors (input and output) used were miniature ceramic feedthrough types to provide good EMI suppression. The converter was constructed with attention to the proper RF practices of minimizing interconnection lead lengths and utilizing the chassis as a low-impedance ground.

The switching waveforms of the RF converter are shown in figure 2, and display the voltage waveforms of the MOSFET, inverter output and diode when operating at full-load. The waveforms show an absence of any severe switching noise, and also show the sinusoidal type waveforms that exhibit relatively low levels of dv/dt allowing enhanced EMI performance at high switching frequencies.

The static load regulation and efficiency characteristics of the RF converter are shown in figure 3 with an input voltage of 48V. Regulation of 0.2% in the output voltage has been achieved over a wide range from no-load to full-load. The output is inherently short-circuit proof and approximates a constant current source during overload. The peak efficiency of 83% (including driver and control circuit constant power consumption of 2.4W) occurs at full load; and the efficiency falls as the load is reduced, though the converter dissipation remains relatively constant over the entire load range.

Lag compensation has been implemented in the feedback control stage to obtain a unity gain bandwidth of 50 kHz. The dynamic response of the converter to a step load change is shown in figure 4. The converter's load is increased in two steps to give a transition in the load current from 0A to 2A at $t=t_1$, and from 2A to 4A at $t=t_2$. The output voltage response shows little ringing, and is consistent with the filter design that achieves a critically damped response at the full load of 5A. The response time of 6µsec for a 40% to 80% load change is significantly faster than previously reported times from any switching supply, and is at least comparable with the best results obtained from linear supplies.

The performance of the converter with regard to the important parameters of radiated and emitted interference has been measured. The use of sinusoidal power waveforms, with essentially natural switch commutation and operation at high frequency alleviates interference generation.

Measured radiated interference levels of the converter are shown in figure 5 and are at least -45dB below the VDE standard for the first few harmonics of the switching frequency. Interference levels at all higher frequencies were below the ambient noise level. The converter input and output voltage waveforms in figure 6 illustrate the low level of conducted interference, showing clean sinusoidal ripple with an absence of switching noise.

The RF converter achieves a low size and weight, improving on the performance of lower frequency switch-mode supplies. The experimental RF converter was constructed in a die cast aluminium box, weighing 494g and having a volume of 604cm³. The enclosure box contributes a significant proportion of the converter's weight (60%), and it is predicted that with suitable design the 60W converter's size and weight would reduce to 450cm³ and 350g respectively.

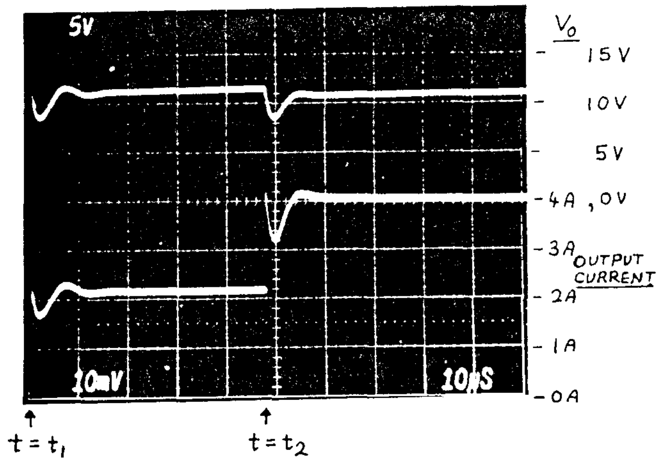

FIGURE 4. Dynamic response of RF converter to two step load changes from 0 to 2A ($t=t_1$) and 2 to 4A($t=t_2$).

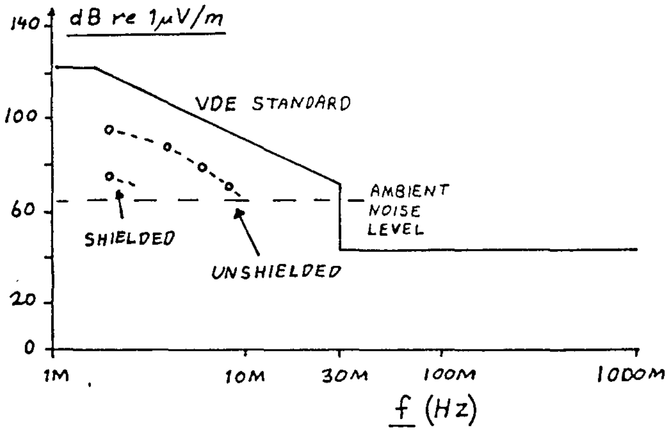

FIGURE 5. Measured radiated interference levels of RF converter compared with VDE limit (measurement distance = 1m).

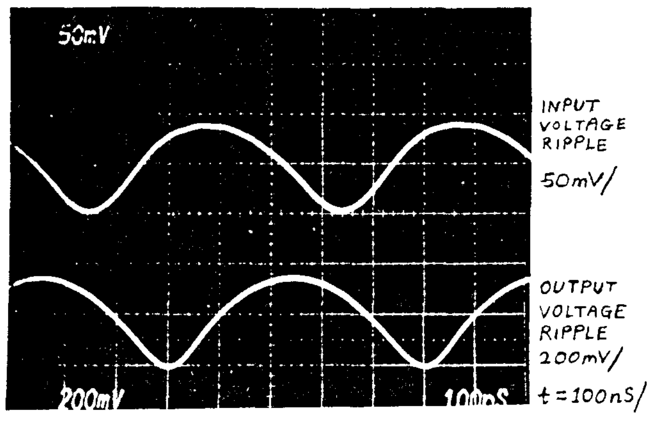

FIGURE 6. RF converter input and output voltage ripple at full load.

Several extensions to the circuit design of the RF converter can be implemented to improve performance and capability, and centre around the utilization of RF power processing techniques. Push-pull class

E inverter operation [6] has been shown to increase the power output capability as well as provide galvanic isolation between input and output. Further increases in the power output capability can be obtained by combining the outputs of several inverter modules using hybrid couplers. The hybrid coupler allows modular construction practices and isolates the failure of any inverter module, thereby increasing power supply reliability due to parallel inverter redundancy.

CONCLUSION

The RF frequency switching power supply combines the advantages of higher efficiency and low size and weight inherent in switch-mode converters, together with the fast regulation speed and low interference generation associated with linear supplies, to achieve an enhanced level of performance in power conditioning applications. Results from a 60W, 48V to 12V converter with an operating frequency of 2MHz and a full load efficiency of 83% have been reported. It is concluded that the RF converter achieves a significant advance in switch-mode power supply performance and technology.

ACKNOWLEDGEMENT

This work was supported by the Australian Telecommunications and Electronics Research Board.

REFERENCES

[1] R.P. Steverns, "High frequency switching regulation techniques", IEEE PES Conference 1978, pp.290-8.

[2] R.L. Steigerwald, "High frequency resonant transistor DC-DC converters", IEEE Trans. Ind. Elec., Vol. IE-31, No. 2, May 1984, pp.181-91.

[3] R.J. Gutmann, "Application of RF circuit design principles to distributed power converters", IEEE Trans. Ind. Elec. and Control Inst., Vol. IECI-27, No. 3, Aug. 1980, pp.156-64.

[4] T. Robbins, R. Minasian and A.Ferguson, "High efficiency DC-DC converter operating at RF frequencies", IREE Conference Digest 1983, pp.631-3.

[5] N.D. Sokal and A.D. Sokal, "Class E, a new class of high-efficiency tuned single ended switching power amplifiers", IEEE J. Solid-State Circuits, Vol. SC-10, No. 3, pp.168-76, June 1975.

[6] T.G. Marshall, "Switched power amplification at low and medium frequencies", M.Eng. thesis, Uni. of Adelaide, 1978.

[7] T.P. Robbins, "RF frequency switching power supply", M.Sc. thesis, Uni. of Melbourne, 1985.