A Low-Power High-Efficiency DC to DC Converter

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Recent component and design advances have enabled the operation
of relatively large electronic systems at power levels of fractions of
a watt.[1]   To date, the majority of such low power systems have been
designed for use in the space environment. They often require a
number of well-regulated supply voltages to insure satisfactory operation.
Since these voltages are generally not available from the main space -
craft power supply, a DC to DC converter and regulator is usually employed.
Typical currently available converter-regulator designs have an efficiency
of 70 to 75 percent at the 1 watt level and 80 to 90 percent at the 10 watt
level. These designs usually develop maximum efficiency for only a limited
range of output power close to the maximum level. Thus, particularly
in applications where wide variations in required power level are anticipated,
many of the advantages of low power circuitry are negated by converter-
regulator inefficiencies. This paper presents a design technique for
converter-regulators which overcomes some of the limitations inherent
in many previous types.

The essential elements of typical currently available high efficiency
DC to DC converter-regulators are shown in the block diagram of Figure 1.
Multiple output voltages are obtained by rectifying the outputs from a
conventional DC to AC converter, consisting of a solid state chopper and a
transformer with multiple outputs. Feedback from one or more of the

output voltages is applied to a pre-regulator which controls the input voltage to the DC to AC converter in order to maintain the desired output voltages.

A majority of the losses in a converter of this type, particularly when operating at a fraction of maximum output power, arise in the DC to AC converter section, since the operating frequency of this element is essentially independent of the power level. Thus, as output power is reduced, core losses dissipate an increasingly larger fraction of the total input power.

In any application where the input voltage is not extremely well regulated, pre-regulation is accomplished with a switch driving a resonant charging network since the inefficiencies inherent in a dissipative regulator operating over a wide dynamic range are intolerable. Two methods for effecting resonant regulation are shown in Figure 2. The first method requires that E_{in} be more positive than E_{out}. When the switch is closed current increases in the inductor, charging the output capacitor and storing magnetic energy in the inductor. When the switch opens the diode shorts due to inductor voltage flyback, permitting transfer of the energy stored in the inductor to the capacitor. In the second configuration, current also increases in the inductor when the switch is closed. The energy stored in the inductor is transferred to the output capacitor through the diode when the switch is opened. Both of these methods provide theoretically lossless conversion from one voltage level to another, since the cycle ends when inductor current, and thus the energy stored in the inductor, is zero. In either case, control of E_{out} is achieved by varying switch duty cycle.

Examination of the second method of accomplishing resonant regulation indicates that it should be possible to replace the single inductor shown with

a tapped inductor and include additional diodes and capicitors. If the various output taps are tightly coupled, multiple output voltages can be obtained which are related by the turns ratios of the various taps. It is also possible to store magnetic energy in the primary magnetizing induc- tance of a transformer with multiple secondary windings, as shown in Figure 3. Assuming zero leakage inductances for the transformer, the various output voltages are simply related by the relative turns ratios among the multiple secondary windings. Since energy is placed on the output capacitors during flyback, the output voltages can be controlled independently from the input voltage. Thus the basic method permits both regulation and conversion to multiple output voltages in a single stage. If the switch drive is arranged so that a constant energy is transferred from the input to the output on each cycle of operation, the output voltage can be regulated by varying the frequency of operation of the switch. In this case, conversion losses are directly related to the power being transferred, permitting a design with efficiency which is essentially independent of operating power level.

The first prototype of a power supply utilizing this principle employed a blocking oscillator as the energy transfer element.[2] This design had the advantage of extreme simplicity (only two transistors were used) but the maximum efficiency obtained was only 70 percent at the 200 mw level. The inefficiency resulted primarily from rather poor control of the switch transistor in the blocking oscillator configuration.

A detailed block diagram for a more recently tested version is shown in Figure 4. One of the seven output voltages is compared with a zener reference, and the error signal applied to a voltage to frequency converter. This v to f converter has extremely sharp characteristics; with the 12 volt output approximately 50 mv below the reference, the frequency output is a maximum (30 KC for the experimental model) while a 50 mv high voltage

cuts off the v to f converter. Since the reference network and the static power requirements of the v to f converter must be supplied continuously and thus represent a power overhead, these circuits are designed for extremely low power operation, with a combined dissipation of approximately 250 μw. Output pulses from the v to f converter trigger a one-shot multivibrator which drives the switch transistor. Since the static power requirements of the one-shot must be supplied continuously, a monostable version of the basic four transistor complementary switching circuit [3] is used which results in a static dissipation of approximately 50 μw. Output pulse width of the one-shot is inversely related to the input supply voltage in order to keep the energy transferred from input to output per cycle constant. Thus the frequency of operation is linearly related to the power being delivered to the load.

The experimental converter described above delivers a maximum power of one watt. Total dissipation with no load connected to the converter is approximately 0.5 mw. When the converter is loaded with equal value resistors connected between the +12, +6, and -9 volt outputs and ground, an incremental efficiency in excess of 84 percent is obtained. The efficiency for any operating power level can be obtained from the empirical relationship

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{\text{Power Out}}{(1.19)\ \text{Power Out} + 5 \times 10^{-4}}$$

where all powers are expressed in watts. Thus, for example, an efficiency exceeding 80 percent is obtained at a 10 mw output power level.

The converter functions adequately with no measurable change in efficiency for input voltage variations from 10 to 30 volts. The +12

volt output is the best regulated since feedback is obtained from this
output. Regulation of the +12 volt output is within ± 2 percent for all
combinations of output power and input voltage tested over the temperature
range of $-60^{\circ}C$ to $+110^{\circ}C$. Regulation of the other outputs is somewhat
poorer due primarily to transformer leakage inductance. However, if
the ratios of currents supplied from the various output voltages are
maintained constant within a factor of 2:1, regulation to within ± 10 percent
is obtained from the 3 volt outputs, with regulation for all other outputs
to within ± 5 percent.

Approximately half of the converter incremental losses are attributable
to the forward drops of the output diodes. Thus it seems that a further
increase in efficiency can be obtained by using synchronous rectification.
Additionally, careful redesign of the reference network, v to f converter
and one-shot should reduce the power overhead to 0. 2 mw or less.

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CAPTIONS

Figure 1 - Conventional DC to DC converter and regulator.

Figure 2 - Two methods for resonant regulation.

Figure 3 - Method for achieving regulation and conversion to multiple

voltages in a single stage.

Figure 4 - Block diagram of experimental 1 watt converter-regulator.
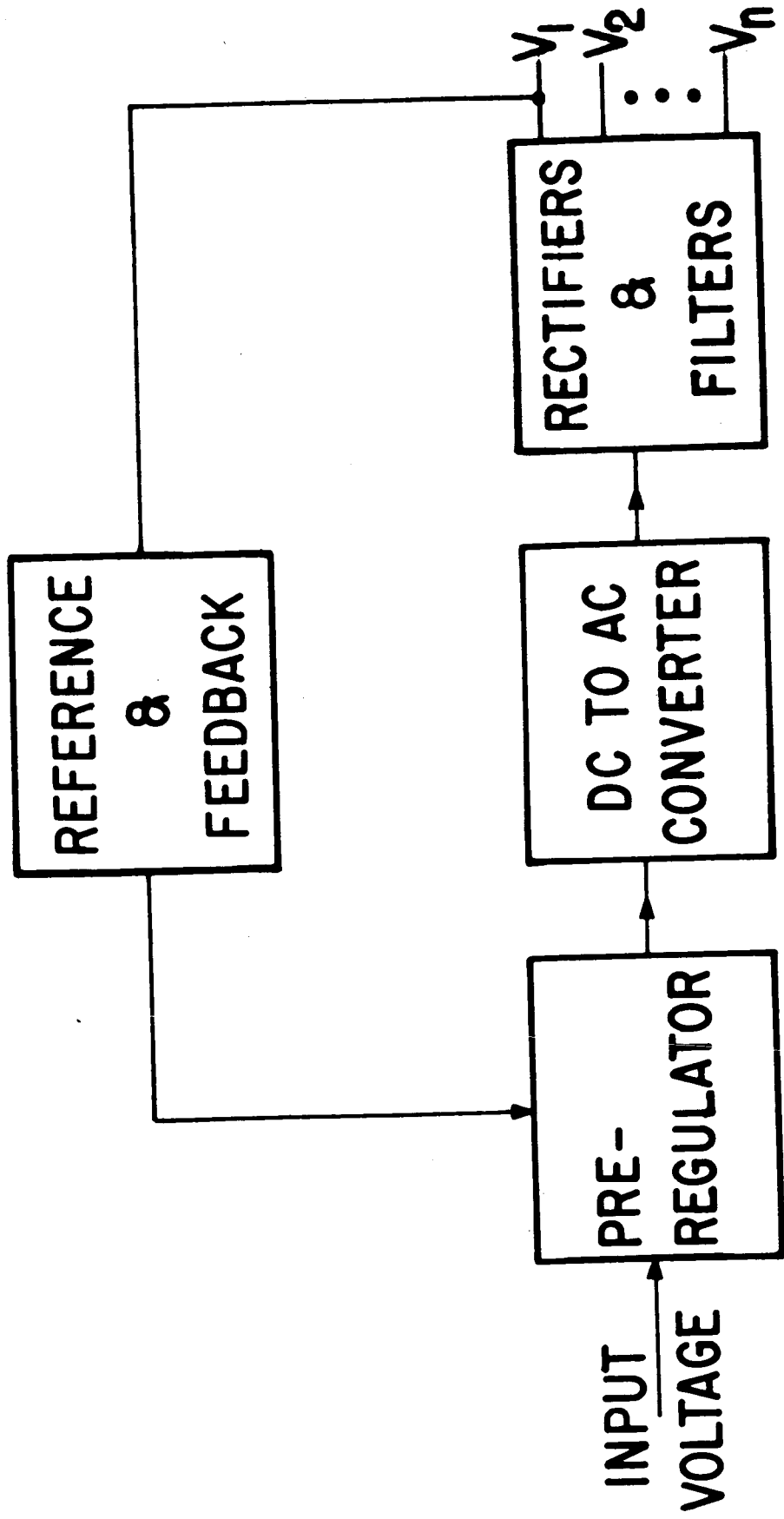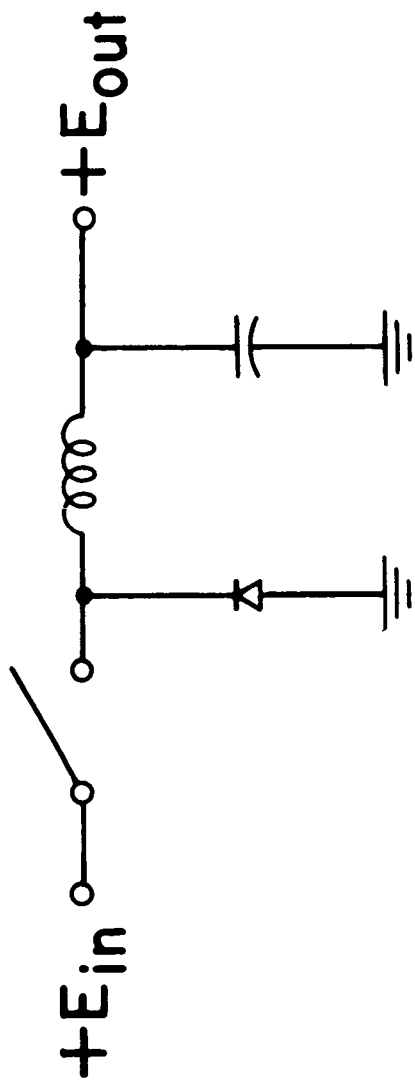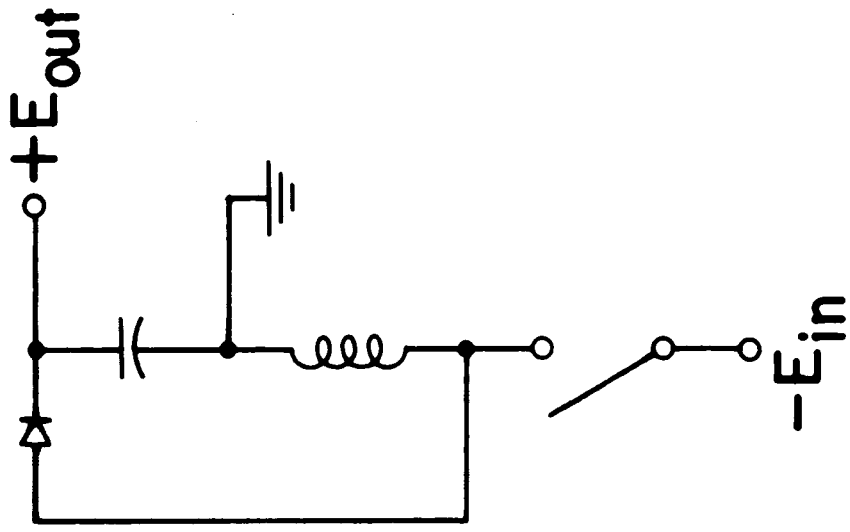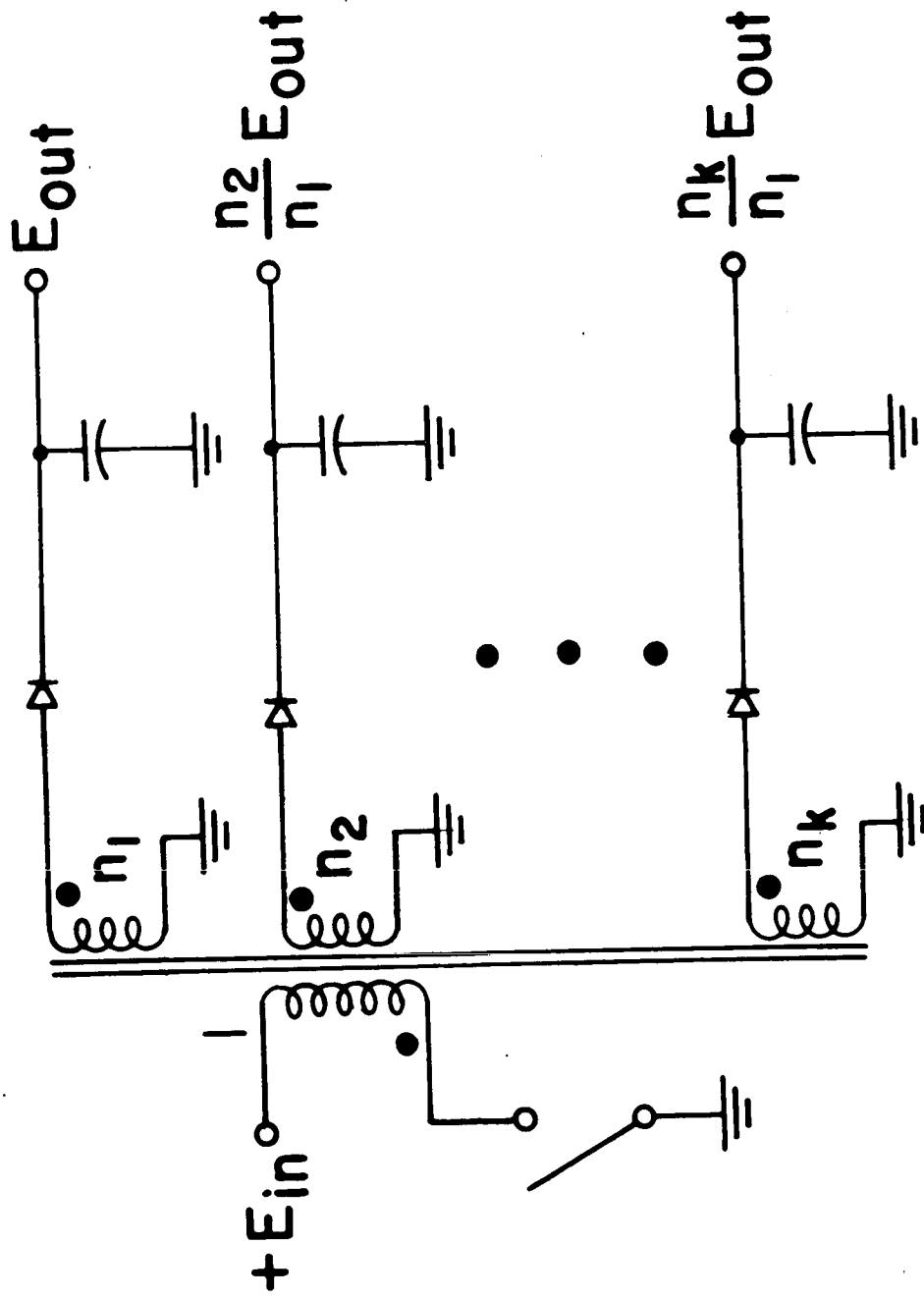
INPUT
VOLTAGE

PRE-
REGULATOR

DC TO AC
CONVERTER

RECTIFIERS
&
FILTERS

V_1

V_2

V_n

REFERENCE
&
FEEDBACK

FIG. 1

$+E_{out}$

$+E_{in}$

$+E_{out}$

$-E_{in}$

FIG. 2

FIG. 3

FIG. 4

V TO F CONVERTER

REFERENCE

ONE-SHOT MULTIVIBRATOR

SWITCH

TRANSFORMER, DIODES, FILTERS

V_{in}

OUTPUT VOLTAGES

+12
+9
+6
+3

−3
−6
−9