STEPPING OUT

Ian Hegglun's new voltage multiplier promises higher efficiency and simpler implementations.

Cockroft-Walton voltage multipliers or charge-pumps can eliminate inductors in some power converters such as negative rail generators and voltage doublers. Higher conversion steps are possible by cascading doubler stages. But losses increase rapidly with higher ratios making high ratio multipliers less practical than inductor based converters.

A recent multiplier arrangement improves efficiency[1]. To demonstrate this a 12V to ±50V dual rail 300W converter is presented. The Mosmarx multiplier[2] is another technique that achieves high efficiencies, but it is limited in voltage by mosfet voltage ratings. The new arrangement is not limited and can produce hundreds of kilovolts.

Recent improvements in low-impedance electrolytics, mosfet drivers, mosfets and lower cost schottky diodes make voltage multipliers attractive for a wider range of power converter applications. Adding the improved multiplier gives higher efficiency, power density, i.e. W/kg, and specific power, W/cm^3, with values similar to inductor based dc-to-dc converters at similar frequencies. Also, the problem of efficient voltage regulation with multipliers appears to be overcome in the demonstration circuit.

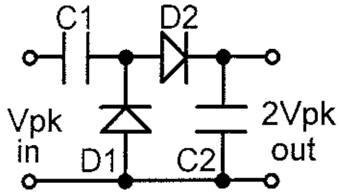

Fig. 1. The Cockroft-Walton doubler is the simplest voltage multiplier.

Conventional half-wave multipliers

The simplest multiplier, the Cockroft-Walton voltage doubler, is shown in **Fig. 1**. Output voltage reaches twice the peak input voltage, but when loaded the output voltage falls by two diode volt drops plus an ac ripple component. This is because of current flow in the capacitors.

Figure 2a is a simple voltage doubler based on a popular mosfet half-bridge driver. Negative rail generator **Fig. 2b** is similar to the doubler circuit but it sits on the 0V rail with diodes and capacitors reversed. These circuits can be very efficient with low on resistance mosfets, schottky diodes and low impedance electrolytics. Mosfet driver ics greatly simplify the circuitry.

Higher multiples are made from cascading

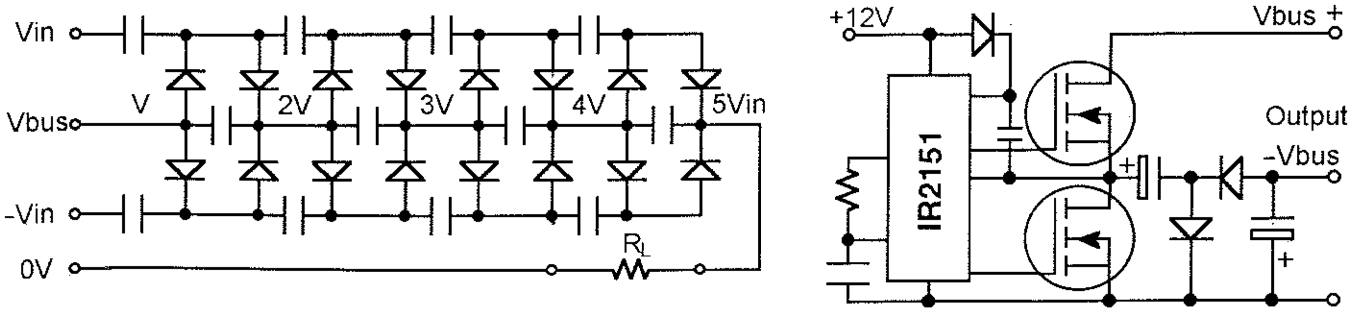

Fig. 2. a) Simple voltage doubler based on a popular mosfet half-bridge driver. Negative rail generator b) is similar to the doubler circuit but it sits on the 0V rail with diodes and capacitors reversed. b) is a negative rail generator

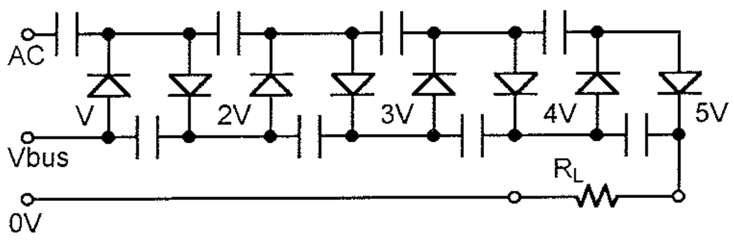

Fig. 3. Higher multiples of the input voltage are obtained by cascading several doubler sections.

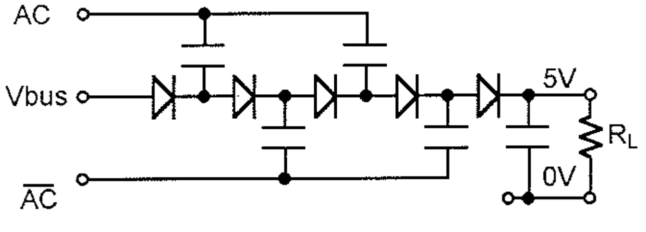

Fig. 4. Improved half-wave pentupler. Compared to Fig. 3, this multiplier needs three fewer diodes and two fewer capacitors.

several doubler sections as shown in **Fig. 3**. Voltages indicated are those for a multiplier that sits on the dc bus. This enables a dc-to-dc pentupler to be made with only four stages instead of five, increasing efficiency and reducing cost.

Note the difference in output when a multiplier is fed from an ac source such as from a transformer as in Fig. 1, rather than a pulsed dc waveform as in Fig. 2. With an ac source, input capacitor C_1 charges to the peak input voltage on the negative half cycle. When the input reverses, $2V_{pk}$ is presented to C_2 ultimately charging it to $2V_{pk}$. But in Fig. 2b, a pulsed dc waveform is fed to C_1. When the low-side mosfet Tr_2 conducts the input capacitor C_1 is charged to V_{bus} via D_1 and when the high side mosfet Tr_1 conducts C_2 is charged ultimately to V_{bus}, not $2V_{bus}$ as might be expected from Fig. 1.

This can be explained by looking at the Fourier series for a pulsed dc waveform. A dc component of $0.5V_{bus}$ is present which is blocked by C_1. The remaining ac component, a square-wave with a peak value of $0.5V_{bus}$, is doubled giving V_{bus} across C_2 and $2V_{bus}$ at the output to 0V.

As a rule, the peak-to-peak input voltage determines the output voltage of each stage and each additional stage adds another component of peak-peak input voltage.

Improved half-wave multiplier

Fig. 4 shows Ian Hickman's improved half-wave multiplier[1]. Compared to Fig. 3, only five diodes are needed rather than eight for a pentupler that sits on the dc bus, and only five capacitors are required rather than seven. However, two drivers are required to generate the complementary squarewave drive but this can be done relatively simply these days with ics.

Full-wave multipliers

A full-wave pentupler is shown in **Fig. 5**. This circuit is effectively two half-wave multipliers in parallel. Hence the output current can be doubled for the same output ripple and efficiency.

Apart from the complications of the extra diodes, capacitors and a differential drive either from a full-bridge converter or a transformer, these complications are partly offset by the double pulse frequency in the dc capacitors. As in conventional full wave rectifiers, the value of the filter capacitor can be half that of half-wave for a given ripple content. Also, as I discovered, the dc capacitors can be eliminated when the input is fed with a square wave.

Improved full-wave multiplier

When Fig. 5 is fed with a squarewave such as from a full H bridge, the dc capacitors can be removed without upsetting operation since the output duty cycle is close to 100%.

With the capacitors removed there is a current path through the junction of the four diodes in **Fig. 6a**. These current paths are independent so the junctions can be broken. Since there are now two diodes in series in each path, the circuit can be simplified to **Fig. 6b**. Although I have not done an exhaustive literature search, this full-wave circuit appears to be new.

Safety hazard
The high voltage multiplier described here is potentially lethal. Do not attempt to build or use it unless you fully understand the dangers of extremely high-voltages and follow the safety warnings given in this text.

Fewer diodes means lower cost – especially in low voltage converters when using schottky diodes. Reducing diode numbers also improves efficiency; in low voltage converters diode losses tend to predominate. Eliminating the dc capacitors also reduces cost and improves efficiency because there are fewer charge transfers. In Fig. 6 for example, there are four charge transfers. This includes one from the supply reservoir capacitor, compared to eight charge transfers for a conventional full-wave pentupler. Comparing diodes, there are five diode volt drops compared to eight.

In general, there are $2n$ diodes where n is the multiplication factor and where V_{bus} is used to reduce the number of stages by one. Note that there are two diodes more than the number of capacitors; the last two diodes can be seen as termination diodes. Adding an extra two diodes at any point can tap-off different voltage steps if required.

All these improvements are achieved with the same voltage and current ratings of both diodes and capacitors and without compromising output power. Compared to the simpler half-wave multiplier the only extra components, apart from the two extra diodes, is the extra half bridge, which is relatively simple these days.

Capacitor losses

The law of charge conservation can be used to show that capacitor losses are independent of how much or little resistance is in the circuit when two capacitors are connected together. Energy loss when transferring charge from C_1 initially at V_1 to C_2 initially at V_2 is,

$$\Delta E = \frac{1}{2}\left[\frac{C_1 \times C_2}{C_1 + C_2}\right]\left[V_1 - V_2\right]^2$$

Even if diode losses could be eliminated, the efficiency of a charge pump multiplier is limited by the sum of the squares of the individual capacitor ripple voltages. Capacitors for power converters are costly so it is important to choose capacitors carefully.

Choosing capacitor values

To minimise the cost of capacitors you need to know how much output ripple is acceptable

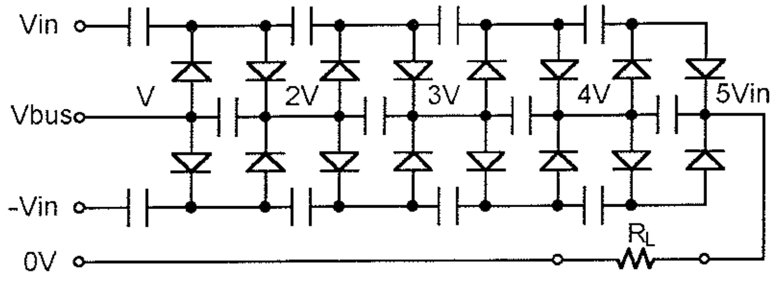

Fig. 5. Conventional full-wave pentupler. This circuit is effectively two half-wave multipliers in parallel.

and the output current. Electrolytic capacitors are useful up to several hundred volts and work best in the 3-30kHz range. Electrolytics are usually chosen for their ripple rating rather than for minimum capacitance because they have high losses. Typical D figures are 0.1 to 0.2 compared to non-electrolytics with 0.001 to 0.01, where D, and tan δ, is the dissipation factor.

I have used various types of electrolytics in multipliers. Standard electrolytics can be used but they are more bulky and require a lower frequency for minimum impedance and hence maximum efficiency. The XYB series miniature low impedance 105°C electrolytics from Rubycon are used in my recent designs. The RS catalogue provides useful ripple current data.

I have found the continuous ripple current rating of 105°C capacitors can be more than doubled for an ambient temperature not exceeding 50°C. The Philips electrolytic capacitor data book gives useful information on temperature over-rating.

In the absence of suitable data, run a test to measure the temperature rise at maximum current. From this the highest safe ambient temperature can be found. For example, a temperature rise of 45°C means 105°C capacitors can operate up to an ambient temperature of 60°C, so a 50°C ambient temperature will be safe.

Bipolar types that are non-electrolytic are chosen on the basis of output voltage ripple; for 5% peak-peak output ripple the final capacitors reactance should be a hundredth of the load resistance[3]. Given an operating frequency and reactance, the value of the final capacitor in the multiplier chain can be calculated.

Grading capacitor values in proportion to current helps to minimise charge transfer losses. For Figs 3 and 5, capacitors closer to the input carry more current than the final stages, increasing linearly along the chain starting from the load. For example, if I_L is the average current flowing through the load in Fig. 3 then the input capacitor carries $4I_L$.

12V-to-100V 300W converter

Fig. 7 shows a 13.8V to ±50V 300W dc-dc converter. It demonstrates that output power of several hundred watts are relatively easy to achieve. An efficiency of over 90% can be maintained from a few watts up 300W – even with a multiplication ratio of eight times If load current must be returned to 0V, this reduces to 150W and ±4 times. Peak efficiency was 95–96% for loads from 0.2A to 1A.

Comparing this multiplier to that in Fig. 6b, shows that the capacitors are arranged slightly differently; they are common to the input rather than in a string. This improves efficiency of electrolytic based multipliers, where higher voltage electrolytics generally have lower losses (D) per microfarad. Note that the capacitor voltages increase toward the output in this arrangement. Also, capacitor currents are similar so each capacitor needs to be rated for the output current. For the values shown the highest capacitor case temperature rise was 30°C with 2.2A load.

The W/kg power density and W/cm^3 specific power compare favourably to inductor based converters. For example, an *ETD34* ferrite core measures about 50cm^3 and weighs 50gm. At 200W the power density and specific power are 400W/100gm and 4W/cm^3 respectively. For this multiplier (capacitors, diodes and pcb) the values are similar at 300W/100gm and 6W/cm^3. If schottky diodes are not used to maximise efficiency, the cost per watt for this converter is better than inductive converters. These comparisons are valid for non-isolated step-up converters with ratios of up to ±5 or so – ten or so for a floating load.

Although Fig. 7 includes voltage regulation, it is easily removed if not required. By adding C_1 and R_1, IC_1 can run in self-oscillating mode. If you only require a single output, then simply remove one of the multipliers. Also, given higher voltage mosfets, diodes (not forgetting D_1 and D_2) and capacitors, the bus voltage can be as high as 500V.

With no regulator circuitry, the operating frequency is preset with R_1 for maximum efficiency. This can be found by making R_1 variable. Best efficiency is seen as a peak in the output voltage (or input current) as the frequency is raised and for the values shown it is 12kHz.

There is little change in efficiency until 35kHz, but at 100kHz and full load the output power falls by 15% and efficiency falls from 91% to 88% . The reduction in efficiency and power can be attributed mainly to the *IR2151*'s 1μs dead time. Setting the operating frequency too high reduces efficiency at light loads because of the increased gate drive losses. Too low a frequency requires larger and more expensive capacitors.

The unregulated version gives 90% efficiency down to 2W. This is possible because the frequency is only 12kHz, resulting in only 4mA supply current for the ics plus 10mA from the supply bus. The regulated version is less efficient at light loads because it operates up 100kHz when lightly loaded.

This converter was intended to feed a standard 100W amplifier for operation from a nominal 12V supply. For this application it is desirable to keep the frequency above 20kHz to prevent audible interference and preferably above 40kHz to prevent intermodulation products being heard at low audio levels.

To drive a 100W amplifier, the peak current required into 8W is 5A and the minimum voltage to the amplifier should be 45V. The converter in Fig. 7 is rated for 2.5A average and can deliver 5A peak without large reservoir capacitors ($C_{6,7}$).

By delivering the peak current directly rather than from say two 10,000μF reservoir capacitors, for 30Hz low frequency roll-off, the converter is more compact. If reservoir capacitors are added it is possible to run two 100W amplifiers on music signals, but amplifier clipping needs to be avoided.

The right-hand *IR2151* is slaved from the oscillator of IC_1 via R_1 to the comparators of the *555* type internal oscillator. Propagation delay through the comparators is insignificant compared to the 1μs dead time delay for the mosfets. Using two *IR2151* drivers was a lower cost option than full H-bridge drivers advertised at the time. This circuit does not require a separate oscillator for the unregulated option. Resistor R_2 is added as a precaution in the event of IC_2's under-voltage shutdown being enabled before IC_1.

Regulating the output

It is difficult to regulate the output voltage of a multiplier by the usual means, such as pulse width modulation. Attempting to reduce the frequency to increase capacitive reactance also increases losses in proportion to voltage

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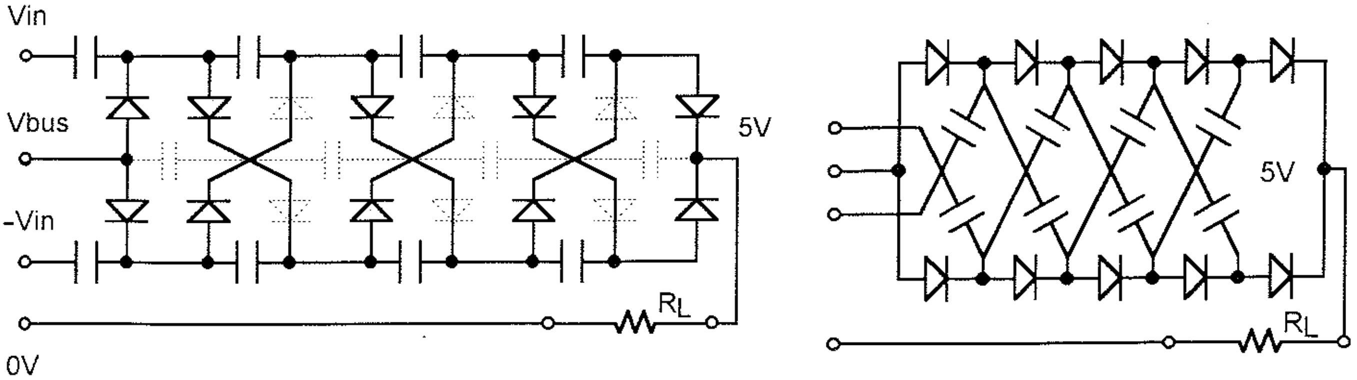

Fig. 6a. Improved full-wave pentupler. Compare with Fig. 5. Dotted components can be removed. b) is the improved pentupler redrawn.

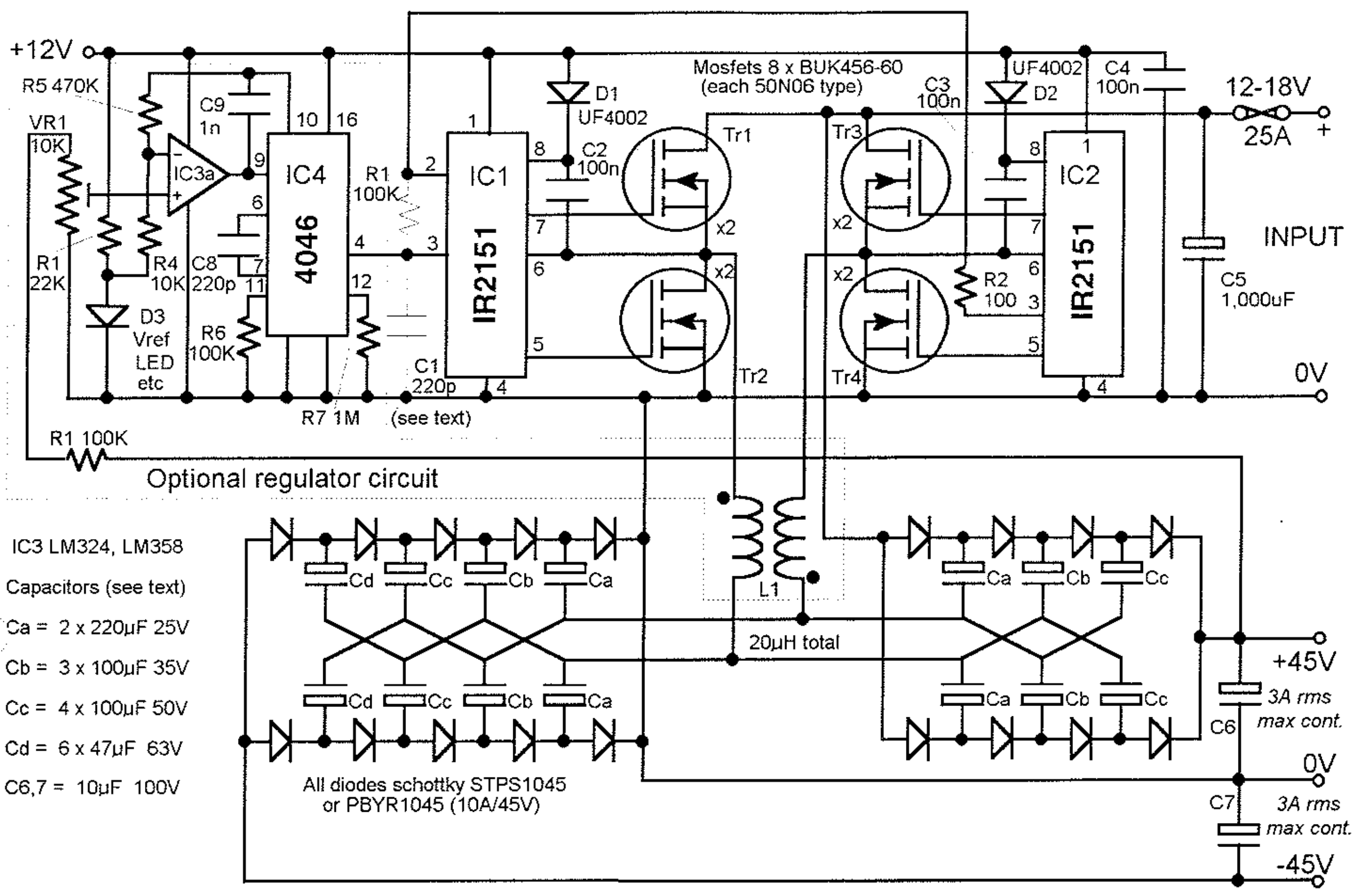

Fig. 7. 300W voltage multiplier featuring over 90% efficiency. It can be used to supply a standard 100W split rail amplifier using a 12V source.

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dropped. Both methods give the same losses; the same as adding series resistance or a series regulator, which is inefficient with large voltage drops.

I concluded that the only way to efficiently vary the output voltage over a wide range is to use an a inductor, either a separate switching regulator, or as part of the multiplier. The latter method was chosen, where a series inductor is inserted between the dc-to-dc converter and the multiplier.

This method of efficient regulation is possible, but only over a limited current range down to about 10 or 20% of full load. This is because frequency is increased to reduce the output current. In turn, this increases gate drive losses at light loads which pulls efficiency down. This places a practical limit on the upper frequency of around 200kHz.

The inductor value is chosen so only a small fraction of the output voltage, around 1V or 2%, is lost at full load where frequency is at its lowest. A relatively small air-cored coil is sufficient, similar to two Zobel inductors but bifilar wound It should consist of dual seven-turn coils of 1.3mm wire on a 20mm former. Note the connection polarities.

Efficiency at half full voltage, i.e. a quarter of full power, is around 90%. The other methods mentioned above are 50% efficient. If independent regulation of the plus and minus rails is required then two single mosfet H bridges are needed. A separate regulator circuit including a level shifted feedback signal is needed, via an opto-coupler for example.

If regulation down to no load is required, a low drop-out linear pre-regulator can regulate from the point where the main regulator loses regulation. In this way dissipation in the series regulator will be at most $^1/_{25}$th of full output power. In **Fig. 8a**, both low-side mosfets $Tr_{2,4}$ can be used as regulators by controlling their on resistance at low loads. However, output capacitances C_6 and C_7 need to be 22µF or more to ensure linear regulation rather than burst or on-off regulation. Burst regulation can generate annoying interference in the audio range for some applications.

Figure 8b can be used where the fm regulator and inductor are omitted. A 2.2kΩ resistor is placed in the emitter of the feedback transistor to ensure linear operation. Output capacitors C_6 and C_7 should be at least 10µF.

These additions prevent the multipliers capacitors and/or diodes from being destroyed if the input voltage rises too high. The ratings of the diodes and capacitors can be rated closer to levels for normal output which reduces size and cost.

A *4046* voltage-controlled oscillator is used with an op-amp for closed loop voltage regulation. The full load (minimum) frequency is set with R_7 and the light load (maximum) frequency is set with R_6 to 100kHz in my circuit. With the improved full-wave multiplier, voltage regulation and response time is very good since only a minimal value of output capacitance is required to remove ripple due to dead-time in the H bridge – about 10% of the multipliers capacitance. Again, 10µF is sufficient. However, if the output capacitance is too large, the feedback loop may become unstable and require lag-lead compensation around IC_{3a}. Capacitor C_9 speeds up the oscillator's voltage follower and provides some overall loop phase advance.

Transient response time for a multiplier is related to the number of stages. Output increases from 0V at start up in an exponential way. The time constant was noted to be equal to *n* times the oscillators period. Here, *n* here is the number of multiplier stages. For example, four stages with an input frequency of 20kHz has a time constant of 200µs, which can be represented by a pole at 796Hz.

A multiplier for high voltage

The combination of a multiplier and transformer allows extremely high voltage dc to be generated – far higher than a transformer with a simple rectifier can achieve due to the limitation of secondary winding capacitance. The multiplier in **Fig. 9** has been used to generate 160kV from 12V using two pentuplers parallel fed similar to Fig. 7. Feeding two multipliers in this way reduces the number of charge transfers and the size of capacitors.

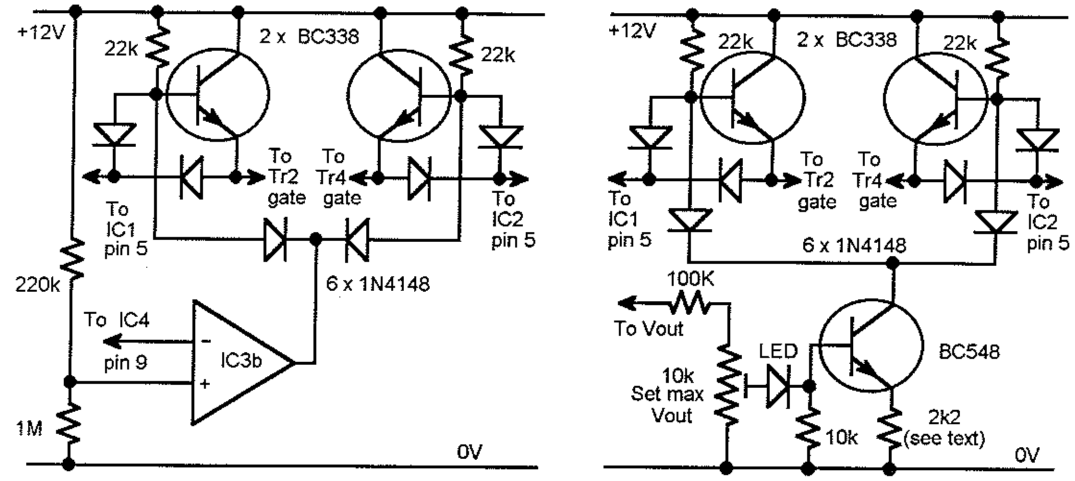

Fig. 8a) Add on circuit for Fig. 7 controls on resistance of the low side mosfets for over-voltage protection of capacitors and diodes. In b), also an add on for Fig. 7, the inductor regulator is not used.

Since the secondary is isolated, any one of the three output terminals can be earthed. This gives the option of either a positive supply, a minus supply, or a split supply. The secondary of a television line transformer provides 16kV peak with five turns on the primary using a an ht lead that can withstand 80kV. Alternatively 2mm thick SCL tubing from Raychem Corporation can be applied to normal wire.

Secondary resonance at around 30kHz is used to advantage to lift the secondary voltage from $3kV_{pk-pk}$ to 16kV. Varying the frequency from above, or below, resonance can be used for voltage control. A string of *BYV96E* 1.5A/1kV avalanche rated diodes – all 384 of them – were used to prevent over-voltage destroying diodes and capacitors by acting like zener diodes. Although the circuit in Fig. 4 can reduce the diode count to 192, the full-wave version provides a low ripple dc output without the very high voltage output capacitor in Fig. 4.

Note that the resistors in the output prevent high peak currents from damaging the diodes if the terminals flash over or are shorted. For those of you wanting to design a high voltage converter and experiment with the effects of high voltage dc, Reference 4 is a good starter. Take care with this converter – high peak currents can be delivered from the capacitors and discharge capacitors after use. When the centre rail is not earthed, the transformer core must be isolated to withstand 80kV to ground.

A provisional patent on the improved full-wave multiplier, regulator and high voltage generator has been filed[5]. Intellectual property enquiries should be directed through Intellpro, GPO Box 1339, Brisbane 4001, Australia, Fax +61 7 3221 4762. Experimenters are free to use these circuits for non-commercial purposes. ■

References

1. Ian Hickman, Multiplier Lowers Impedance, *EDN*, 6 June 1991, p 173.
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3. Ralph E. Tarter, Solid State Power Conversion Handbook, Wiley 1993, pp 244-251.
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5. Australian Patent Application No. PN9832 filed 15/5/96.

Fig. 9. This 160kV multiplier, made up from two pentuplers in parallel, outputs up to 100W. Compared with conventional designs, it is more efficient and uses fewer components