Bootstrap circuit generates high-voltage pulse train

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A circuit can easily be built to generate a high-voltage pulse train from a low-voltage power supply. Such a circuit is used in a recently developed spacecraft instrument to generate a 400-hertz square wave with an amplitude of 4 kilovolts from 20 identical 200-volt stages connected in series. A high-voltage supply is not needed because each stage includes a capacitor that functions as a floating power supply for the next stage. These capacitors are charged in parallel and then connected in series so that the pulse generator does its own dc-to-dc conversion.

The schematic of Fig. 1 is drawn to emphasize the modularity of the circuit. To simplify the explanation, it is assumed that all transistors and diodes are perfect switches, having infinite impedance when turned off and zero voltage-drop when turned on.

Suppose, first, that transistors $Q_{1\text{-}1}$, $Q_{1\text{-}2}$, . . . $Q_{1\text{-}N}$ are all turned off. Then diodes $D_{1\text{-}1}$, $D_{1\text{-}2}$, . . . $D_{1\text{-}N}$ are forward-biased and transistors $Q_{2\text{-}1}$, $Q_{2\text{-}2}$, . . . $Q_{2\text{-}N}$ are driven to saturation. Capacitor $C_{1\text{-}1}$ charges through the path $D_{3\text{-}1}$, $C_{1\text{-}1}$, $D_{2\text{-}1}$, and $Q_{2\text{-}1}$. Concurrently, $C_{1\text{-}2}$ charges through the path $D_{3\text{-}2}$, $C_{1\text{-}2}$, $D_{2\text{-}2}$, and $Q_{2\text{-}2}$. So, in this circuit condition, all of the capacitors charge in parallel, and the potential difference across each capacitor is equal to the supply line voltage of 200 volts:

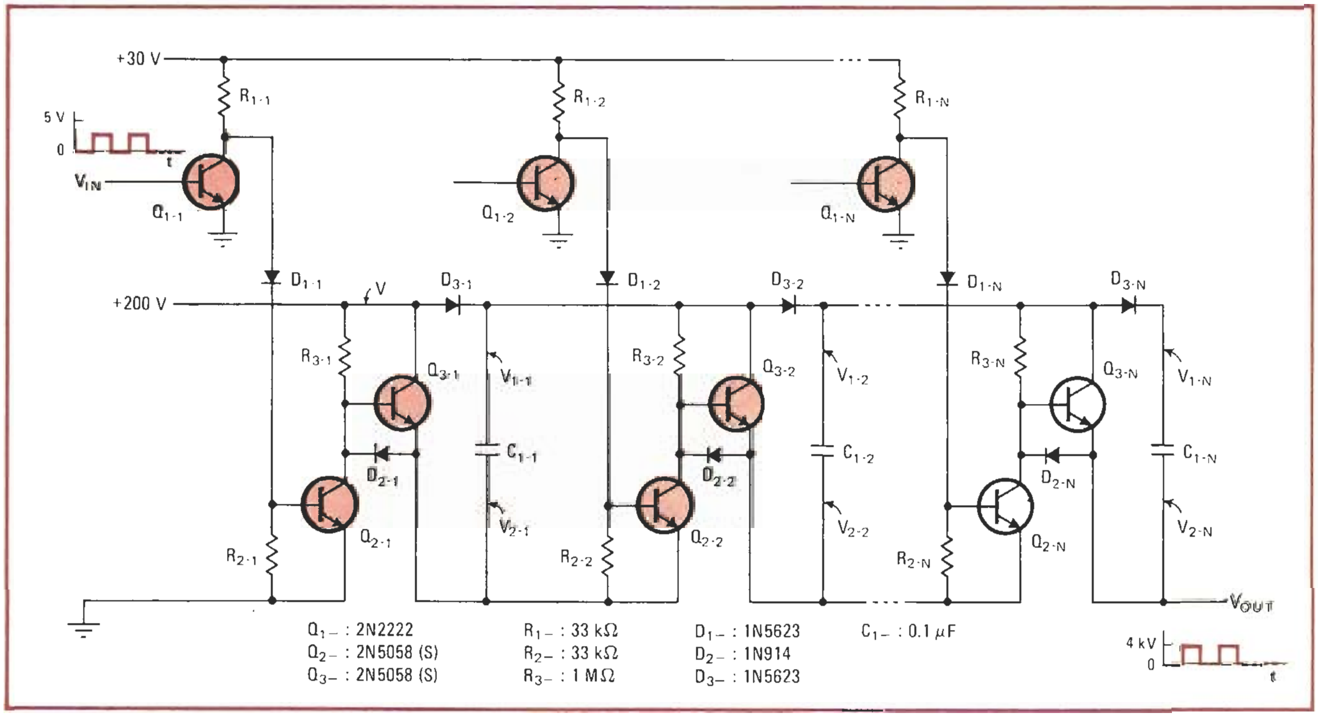
$$V_{1\text{-}N} = V_{1\text{-}2} = V_{1\text{-}1} = V = +200\ v$$
$$V_{out} = V_{2\text{-}N} = V_{2\text{-}2} = V_{2\text{-}1} = 0$$

If, now, $Q_{1\text{-}1}$ is turned on, diode $D_{1\text{-}1}$ no longer conducts, so $Q_{2\text{-}1}$ turns off. Current through resistor $R_{3\text{-}1}$ then causes $Q_{3\text{-}1}$ to turn on, and the emitter potential of $Q_{3\text{-}1}$ approaches its collector potential so that $V_{2\text{-}1} = V = +200$ v. And, because $C_{1\text{-}1}$ was previously charged to the supply voltage, $V_{1\text{-}1} = V_{2\text{-}1} + V = 2V = +400$ v.

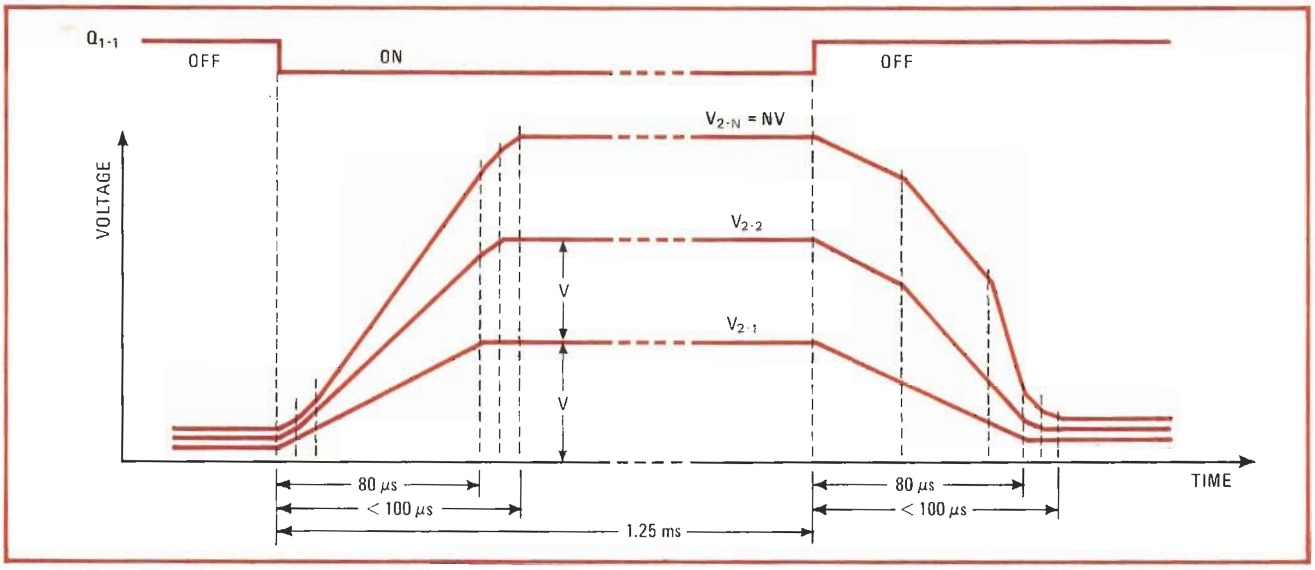
Now, regardless of the state of $Q_{1\text{-}2}$, when $V_{2\text{-}1}$ becomes positive, $D_{1\text{-}2}$ becomes reverse-biased, and therefore $Q_{2\text{-}2}$ turns off. Current through $R_{3\text{-}2}$ then causes $Q_{3\text{-}2}$ to turn on, and the emitter potential of this transistor approaches its collector potential so that:

$$V_{2\text{-}2} = V_{1\text{-}1} = 2V = +400\ v$$
$$V_{1\text{-}2} = V_{2\text{-}2} + V = 3V = +600\ v$$

As illustrated by Fig. 2, this sequence continues along the series of stages, each stage increasing the positive level of the pulse by V volts. The final output voltage is NV volts, where N is the number of stages and V is the



1. Kilovolt generator. Square wave of 4 kV at 400 Hz is produced by circuit with 20 low-voltage stages. Each stage includes a capacitor (C_1) that acts as a floating power supply for the next stage. The capacitors are charged in parallel and then connected in series. If lower output voltage is desired, input can be applied to $Q_{1\text{-}2}$ or $Q_{1\text{-}3}$ or . . . instead of $Q_{1\text{-}1}$. (Actual circuit also includes elements shown in Fig. 3.)



2. Timing. The stages start switching sequentially, as diodes D_{1-1}, D_{1-2}, . . . successively become back-biased, but after all stages are switched, they change voltage levels concurrently. Therefore the rise time is essentially that of a single stage. Similarly, the fall time is essentially independent of the number of stages. The output amplitude is the product of the power-supply voltage and the number of stages.

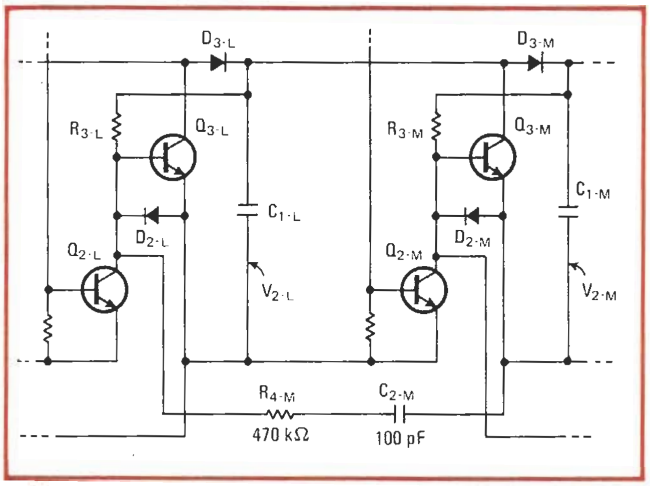
supply voltage. Because the stages switch concurrently, the total pulse rise time is only slightly longer than the rise time of one stage.

Smaller-amplitude pulses can be generated by switching only the last few stages to the "high" state. For example, if Q_{1-1} remains off, but Q_{1-2} is turned on, the first stage will remain in the "low" state with V_{1-1} = V = +200 V but all subsequent stages will switch to the "high" state so that V_{out} = (N − 1)V. If only Q_{1-N} is turned on, the preceding stages will remain in the "low" state and the output pulse amplitude will just be V volts. Generally, then, the output-pulse amplitude can be selected in increments of V up to a maximum of NV.

The positive-going edge of the pulse generated by the circuit of Fig. 1 is quite slow because, in each stage, when Q_2 is turned off, the potential at the base of Q_3 increases exponentially toward a limiting value. Further, the output impedance of the circuit is quite large because the current in R_3 approaches zero in the "high" state and Q_3 never really saturates.

The circuit modification shown in Fig. 3 prevents these problems by the use of positive feedback in and between the stages. R_3 is connected to provide positive feedback within the stage; when Q_2 is turned off and Q_3 starts to conduct, the potential at the top end of R_3 remains V volts above the potential at the emitter of Q_3. Thus, the potential difference across R_3 is sensibly constant, and Q_3 is driven by a constant current supply so that its base potential increases linearly until the base-collector junction is forward-biased. Q_3 then behaves like an inverted switch transistor with a very low offset voltage that is just the difference between the voltage drops of the base-emitter and base-collector diodes.

R_4 and C_2 provide positive feedback from one stage to the immediately preceding stage to speed the switching action. For example, when the stages switch to the "high" state, V_{2-L} increases toward LV while V_{2-M} increases toward MV. The difference between these voltages, MV − LV = (L+1)V − LV = V, causes a transient current through R_{4-M} that drives the base of Q_{3-L} positive more rapidly.



3. Feedback. To achieve 400-Hz operation, the circuit in Fig. 1 is modified as shown here. R_3s provide positive feedback within each stage, and R_4s and C_2s provide positive feedback from each stage to the preceding stages. Without the feedback, rise time is about 1 ms; with feedback, rise and fall times are both less than 0.1 ms.

With these feedback connections, the operating circuit produces a 400-Hz square wave with rise and fall times of about 100 microseconds that are essentially independent of the number of stages switched. The number of stages switched changes only the amplitude of the square wave; this amplitude can be selected in increments of 200 V, up to a maximum of 4,000 V for a 20-stage circuit. The only high-voltage components are the diodes labelled D_1 in Fig. 1. In the spacecraft instrument, series strings of diodes are used as D_1 to provide the necessary isolation for the higher-voltage stages of the pulse generator. □