Design, Implementation and Analysis of a New Topology of a Boost DC-DC Voltage Converter

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***Abstract*—** *This paper reports the design, implementation and analysis of a step-up DC-DC voltage converter in which capacitors are used as energy-storage elements. A number of characteristics of this converter such as its output voltage, load power and efficiency are observed with the variations in the frequency of the driving-circuit's oscillator, base-emitter voltage of the power transistors and the source voltage. It is shown that, in optimal conditions, the converter's output voltage is twice its input voltage. The analysis shows that the calculated values of the output voltage match reasonably well with the experimentally measured values. This kind of converter is easy to fabricate, and can be used in power modules located inside portable systems where smaller size and lower weight are crucial considerations.*

I. INTRODUCTION

DC-DC voltage converters are used in a wide range of applications in electronics. Among a large number of commercially-available varieties of these converters, the step-down and the step-up are the basic converter topologies [1-3]. A step-down DC-DC converter will have a lower average output voltage compared to its input DC voltage whereas a step-up converter will give higher average output voltage than its input DC voltage. A conventional step-up DC converter, also known as boost regulator, contains an inductor as an energy-storage element. In these converters – boost regulators - the average value of the output or load voltage (V_L) is always greater than the input or supply voltage (V_S) and may be several times of the input voltage depending upon the duty cycle of the switching converter. Recent years have seen a phenomenal growth in lap-top computers and portable personal communication systems such as mobile telephones and pagers. The process of miniaturisation for the power modules located inside these portable systems is in progress. The size and weight of a DC-DC converter is important for portable systems [4-6]. Therefore the technology that might help to achieve this miniaturisation, at high-frequency operation, of the energy-storage elements – inductors and capacitors – is urgently needed. One way to solve this problem could be the use of capacitors as the only energy-storage elements in step-up DC converters. When compared with inductors generally capacitors are more light, have smaller sizes and technologically easier to fabricate. We have successfully designed and implemented a step-up DC-DC converter in which the inductor is eliminated, and rather capacitors are used as the energy-storage elements. This paper describes the characteristics and properties of this boost DC converter.

II. EXPERIMENTAL SET-UP

The circuit diagram of the step-up converter is shown in Fig. 1. The converter consists of two capacitors - C_1 and C_2 - as energy-storage elements; two power bipolar junction transistors (BJTs) - T_1 and T_2 – operated as switches and two diodes - D_1 and D_2. The diode D_1 prevents the discharging of C_2 through the voltage supply and C_2 whereas D_2 prevents the discharging of C_1 through T_2, when it is conducting, and C_1. The power transistors T_1 and T_2 are driven by an oscillator through a three-winding transformer, T_r, shown in Fig. 1(b). The transformer's secondaries are connected to the base and the emitter terminals of T_1 and T_2 in such a way that V_{B1E1} – the voltage at the base of T_1 with respect to its emitter – is 180° out of phase with V_{B2E2} – the voltage at the base of T_2 w.r.t. its respective emitter.

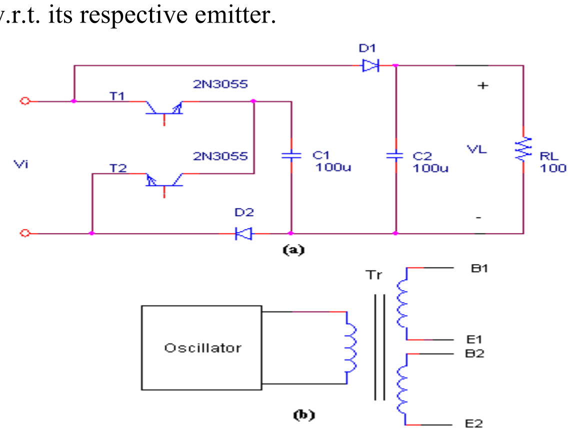


Fig. 1. (a) A step-up DC-DC converter and (b) transformer driven circuit.

III. ANALYSIS OF THE CIRCUIT

Fig. 2 shows the equivalent circuit diagrams of the DC-DC converter for three modes of operation when: the switches T_1 and T_2 are 'OFF' (Fig. 2-a); the switch T_1 is 'ON' and T_2 is 'OFF' (Fig. 2-b), and the switch T_1 is 'OFF' and T_2 is 'ON' (Fig. 2-c). When the switches T_1 and T_2 are 'OFF' (Fig. 2-a), the capacitor C_2 is charged up to the input or supply voltage – V_S - and the output or load voltage – V_L - becomes equal to the input DC voltage. When T_1 is 'ON' and T_2 is 'OFF' (Fig. 2-b), the capacitor C_1 is also charged up to V_S. When T_1 is 'OFF' and T_2 is 'ON', the capacitor C_1 is connected in series with the input DC voltage V_i and the capacitor C_2 is charged up to $2V_S$. During next cycle when T_1 is 'ON' and T_2 is 'OFF', the diode D_1 is reverse biased and thus isolates the load from the supply side: C_2 is discharged through the load while at the same time C_1 is again being charged to the input DC voltage. So the output voltage depends upon the switching frequency; the frequency with which the

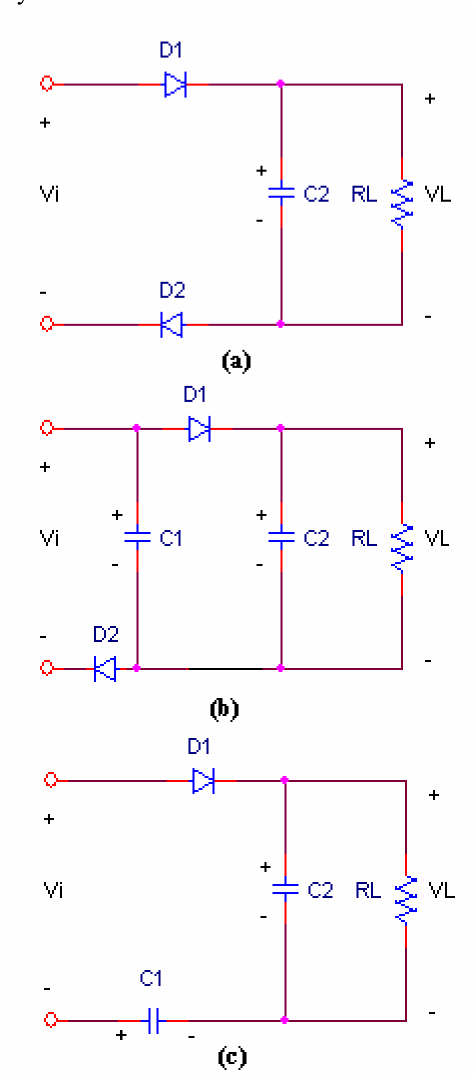


Fig. 2. Equivalent circuits of the DC-DC converter for three modes of operation.

switches T_1 and T_2 are operated. In this analysis we have neglected the conducting voltage drops in D_1, D_2, T_1 and T_2. So this DC-DC converter is a step-up converter where the maximum value of the output voltage is twice of the supply or input voltage, i.e. this converter is in fact a voltage doubler.

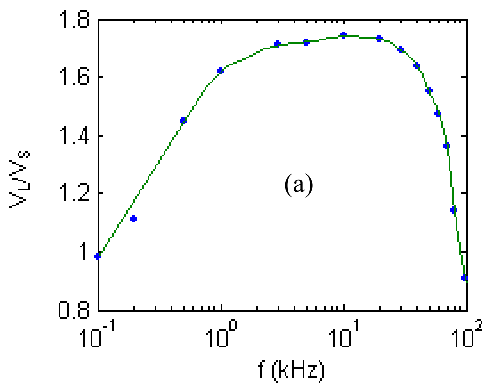
The power transistors T_1 and T_2 are switched in such a way that only one of them can be in 'ON' state at a given time: both of them are never 'ON' simultaneously. In fact both will be in 'OFF' position for a short time interval, known as the blanking time, around the instant when the oscillator's sinusoidal voltage is passing through its zero value. The blanking time may be neglected if we consider the switches to be ideal ones which can be turned 'on' and 'off' in zero time.

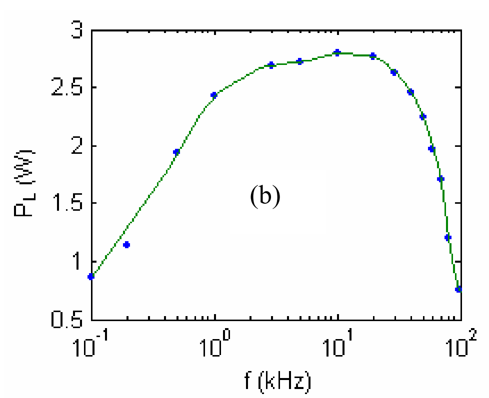
In these experiments the sinusoidal-wave oscillator (with open-circuit output voltage of 8 V, RMS value) was used to drive the switches T_1 and T_2. The secondary windings of the transformer – T_r – were connected to the base-emitter of T_1 and T_2 with opposite polarity such that there was 180^o phase displacement between the base-to-emitter voltages of T_1 and T_2. All three modes of operation (Fig. 2) were observed for low-power test experiments. The power transistors - 2N 3055 series - used as switches have the following maximum ratings: V_{CE} = 70 V; V_{EB} = 7 V; I_C = 15 A; I_B = 7 A, and the collector power dissipation, P_C = 115 W.

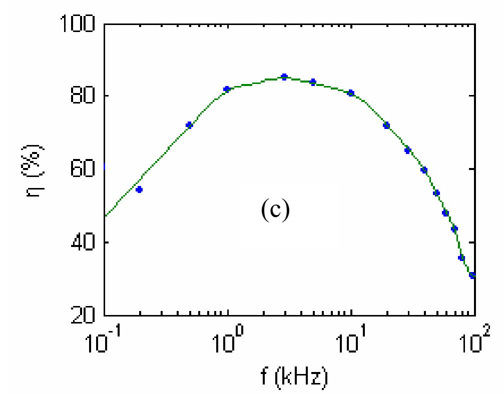
IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 shows the plots of output to input voltage ratio (V_L/V_S), average value of load power (P_L), efficiency (η) – ratio of the average output power to the input power - and the transistors' base current (I_B) as functions of the frequency of the oscillator. The base-emitter voltage was kept constant at 1.2 V in these experiments. It is observed that the maximum values of V_L/V_s, P_L and η occur in the frequency ranges of (3-20) kHz, (5-20) kHz and (1-10) kHz respectively. The output voltage and output power should increase with the increase in frequency as C_2 then would have lower time to discharge through the load until we reach a point beyond which the capacitors C_1 and C_2 would not be fully charged in such short charging times and due to the internal resistances present in the circuit. The maximum efficiency occurs in the lower frequency range because with the increase in frequency the average value of the input power increases due to the increase in average input current [lower ripple in input current corresponding to higher switching frequency]. The base current, I_B, decreases monotonously with an increase in the frequency in the range of (0.2-98) kHz. This is expected as an increase in the frequency of the oscillator should result in a linear increase of the inductive reactance of the oscillator and thereby decreasing the base current.

The plots of the output to input voltage ratio (V_L/V_s), average value of the output power (P_L), efficiency (η) and base current (I_B), as a function of the magnitude of base-emitter voltage (V_{BE}), are shown in Fig. 4. In these experiments the frequency of the oscillator and the input DC voltage were kept constant; at 3 kHz and 10 V respectively. It was observed that I_B was increasing monotonously with an increase in the values of V_B, in the range of (0.5-1.3) V. The values of V_L/V_S and P_L increased initially with an increase in V_B and then saturated, while the behavior of η showed a maximum value (86-87 %) in the interval of V_B = 0.7-1.2 V. Increase in the base current should increase the corresponding collector current for a power switch and thus the corresponding capacitor would be charged to higher voltage values, but at the same time higher 'ON' [collector] current would be associated with a higher conducting voltage across the switch and thereby reducing the voltage value to which the capacitor would have charged otherwise.







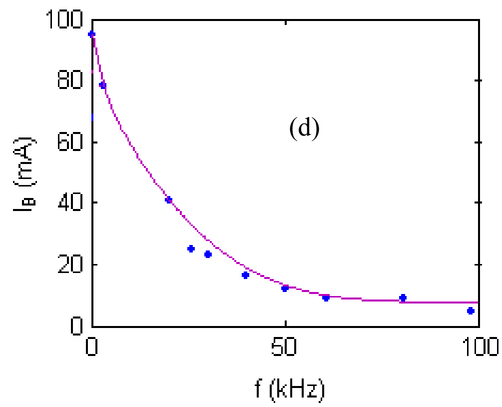
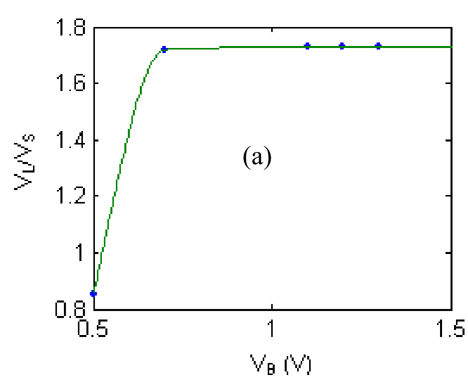


Fig. 3. (a) Dependences of gain, V_L/V_S, (b) DC power in load, P_L, (c) efficiency, η and (d) transistor's base current, I_B, as a function of switching frequency.

Fig. 5 shows the relationships of V_L/V_S, P_L and η with V_S, the input or supply voltage. In this case the base-emitter voltage and the switching frequency were kept constant at 1 V and 3 kHz respectively. It was observed that all investigated parameters increased with an increase in the input voltage, V_S. If the input voltage is large compared with the conducting voltage drops in the switches, we should expect an increase in our investigated parameters.



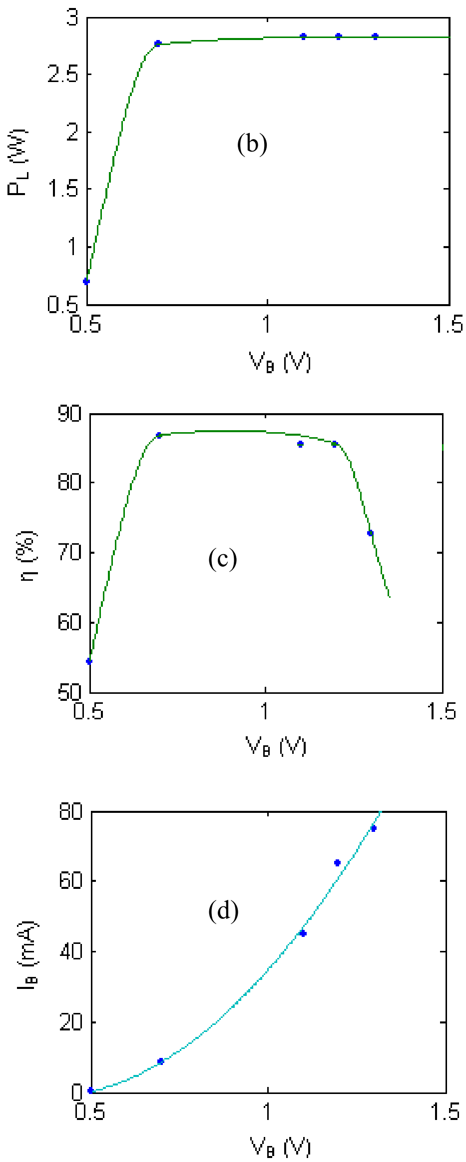
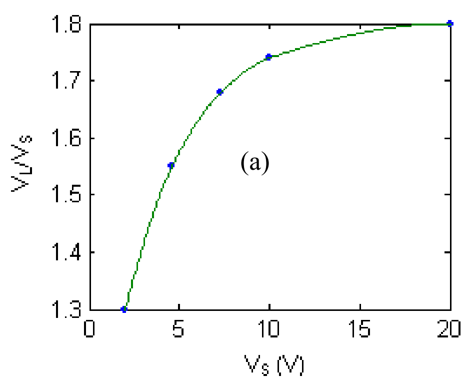


Fig. 4. (a) Dependences of gain, V_L/V_S, (b) DC power in load, P_L, (c) efficiency, η, and (d) base current, I_B, as a function of base-emitter voltage (V_{BE}).



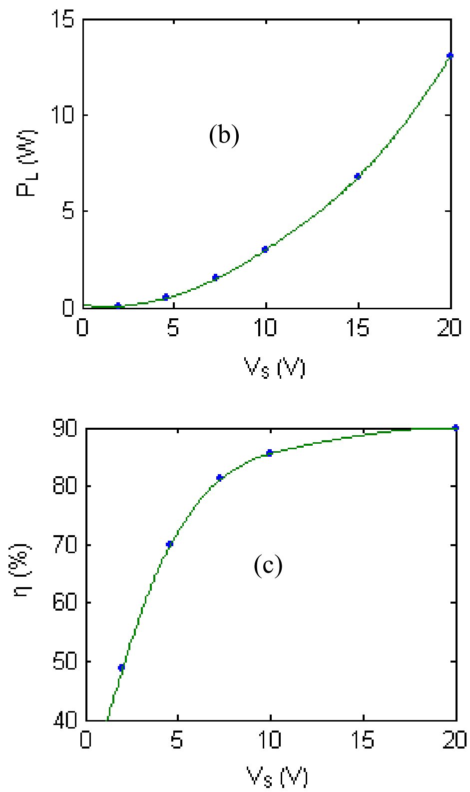


Fig. 5. (a) Relationship of voltage gain, V_L/V_S, (b) DC power in load, P_L, and (c) efficiency, η, as a function of supply voltage (V_S).

The output voltage and the ratio of the ripple voltage [in output] to the average output voltage - V_R/V_L - are plotted as a function of the switching frequency in Fig. 6. In these experiments the input voltage and the base-emitter voltage were fixed at 10 V and 1 V respectively. It was observed that V_R/V_L decreased with an increase in the switching frequency and passed through its minimum value around 30 kHz. The V_L was maximum in the frequency range of (3-30) kHz. Fig. 7 shows the waveform of the ripple voltage with the peak-to-peak value of 0.2 V, and time period of 0.2 ms corresponding to the switching frequency of 5 kHz, input voltage of 10 V and the base-emitter voltage of 1 V: the output voltage was 18 V. It was observed that the ripple-voltage waveform reflected the charging-discharging process of the capacitor (C_2): its frequency was equal to the oscillator's frequency.

The average value of the load voltage can be calculated by the following expression [7]:

$$V_{L,av} = \frac{1}{T}\int_{t_1}^{t_1+T} v_L(t)\,dt \tag{1}$$

where $v_L(t)$ is the instantaneous load voltage, T is the time period of the oscillator's switching signal and t_1 is an arbitrary time chosen [the integration is to be performed over one cycle].

In Fig. 2 it has been shown that the operation of the circuit is based upon the charging and discharging of capacitors. The voltage across a charging and discharging capacitor is given by [7]:

$$v_{charg}(t) = V_{mc}\left(1 - e^{-\frac{t}{rC_1}}\right) \quad (2)$$

$$v_{disch}(t) = V_{md}\, e^{-\frac{t}{RC_2}} \quad (3)$$

where V_{mc} is the maximum value of the charged capacitor, r is the charging resistance and C_1 is the charging capacitance of the circuit [the capacitor voltage is assumed to be zero at the beginning of the charging process]; V_{md} is the initial value of the discharging capacitor, R is the discharging resistance and C_2 is the discharging capacitance.

Assuming that $V_{mc} = V_{md} = V_m$, and r to be the internal resistance of the power supply, the conducting transistor and diodes and R as the load resistance (R_L) we can write:

$$V_m = 2\frac{V_S R_L}{R_L + r} \quad (4)$$

Now the instantaneous load voltage can be written as:

$$v_L(t) = \begin{cases} V_m & for\ t = 0, \\ V_m e^{-\frac{t}{R_L C_2}} & for\ 0 \le t \le T/2, \\ V_m\left[e^{-\frac{T}{2R_L C_2}} + \left(1 - e^{-\frac{t-\frac{T}{2}}{rC_2}}\right)\left(1 - e^{-\frac{T}{2R_L C_2}}\right)\right] & for\ \ T/2 \le t \le T \end{cases} \quad (5)$$

Substitution of (5) in (1) and then solving for the average value of the load voltage, using well-known mathematical approaches [8], results in:

$$V_{L,av} = \frac{2V_S R_L}{R_L + r}\left[\left((1 - e^{\frac{-T}{2R_L C_2}})\right)\frac{R_L C_2}{T} + 0.5 - \left((1 - e^{\frac{-T}{2rC_2}})\right)\mathrm{x}\left((1 - \mathrm{e}^{\frac{-\mathrm{T}}{2R_L C_2}})\right)\frac{rC_2}{T}\right] \quad (6)$$

Assuming r = 10 Ω and T = 0.333 ms [for 3 kHz frequency], and using the circuit parameters as V_S = 10 V, R_L = 100 Ω, C_2 = 100 μF we can calculate the instantaneous and average values of the load voltage from (5) and (6) respectively. The average load voltage turns out to be 18 V: the calculated average voltage and the ripples in the load voltage [$v_L(t) - V_L(t)$], in fact, match very well with the experimentally measured data shown in Fig. 6 and Fig. 7. The instantaneous values of the load voltage for the 3 kHz oscillator' switching signal is shown in Fig. 8.

This DC-DC converter may be optimized for a given load power and is easy to fabricate, in principle, by IC technology as well. The converter would be suitable for especially low power applications in power modules located inside portable systems.

V. CONCLUSION

A new topology of a step-up [or boost] DC-DC converter has been designed, experimentally tested and then theoretically analysed. This topology eliminates the use of inductor in conventional step-up DC-DC converters, and uses only capacitors as the energy-storage elements. A number of characteristics of this converter such as the output voltage, load power and the efficiency were determined against (a) the frequency of driving oscillator, (b) base-emitter voltage of switches, and (c) the source voltage. The ripples in the output voltage were also observed, and the variation in the ratio of ripple voltage to the average output voltage was observed against the switching frequency. For the given values of capacitors and load impedance the optimal values of the switching frequency, base-emitter voltage and the source voltage were determined which would result in the optimal values of output voltage, load power and the efficiency. It was found that, in optimal conditions, the output voltage was twice the value of the source voltage. The calculated values of the output voltage has been shown to match reasonably well with the measured values.

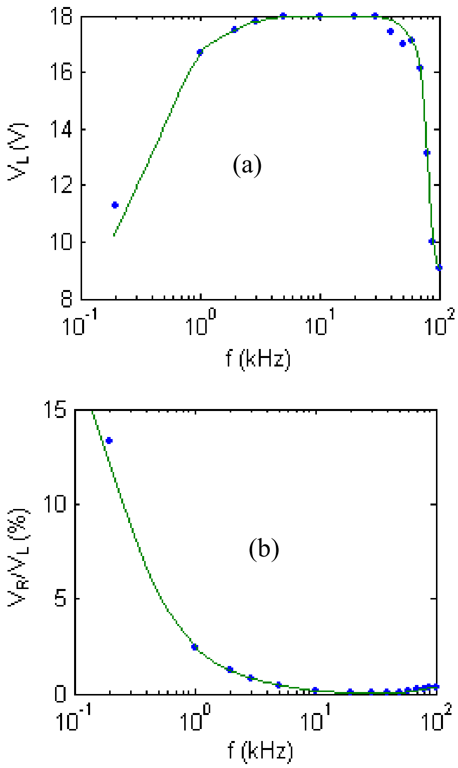


Fig. 6. (a) Dependences of output voltage, V_L, and (b) the ratio of ripple to the output voltage, V_R/V_L, on the switching frequency.

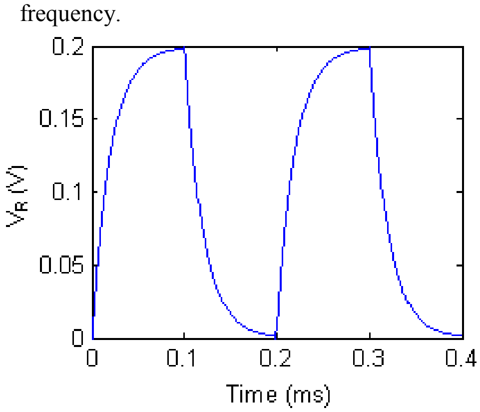


Fig. 7. Ripples' waveforms in output.

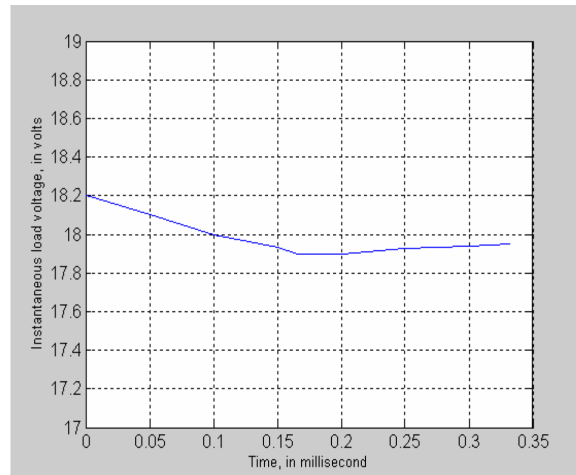


Fig. 8. The instantaneous load voltage as a function of time, for the oscillator frequency of 3 kHz.

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