

A novel approach to switching regulator design

Simultaneous use of feedback and feedforward for low ripple regulators

by D. M. Divan and V. V. Ghate

The design principle proposed here uses feedback and feedforward simultaneously to allow switching regulators to operate with a very low ripple. Unlike other designs, it requires no compromises in switching frequency, the bulk of filter components, transient response, circuit complexity or efficiency. The example circuit discussed in the text is a 7.6V, 5A, 25kHz switching regulator which is shown to have an output ripple of only 2 to 4mV r.m.s.

SWITCHING REGULATORS, whether of the self-oscillating type or the constant-frequency, pulse-width modulated type, have certain limitations. The high frequency ripple required for regulator operation can be of the order of 50 to 100mV for a d.c. level of 5 volts, and attempts to improve this figure normally require a compromise. The compromise may involve an increased switching frequency or a poor transient response, or both. The best switching regulators available today still have to make do with a 20mV ripple and a settling time that could be of the order of 50ms^{1,2,3}.

Other regulator problems faced by designers, especially those working with free running switching regulators, are stability, behaviour under light loading, variations of switching frequency with load and supply, the dependence of the output ripple on the filter, hysteresis, and the possibility of the regulator malfunctioning with certain types of reactive loads².

This article describes a new approach to regulator design that allows the designer to retain the advantages of the switching regulator without the accompanying disadvantages.

Principle of operation

The method which is to be described here uses feedback and feedforward simultaneously. A similar configuration was first used by P. J. Walker, in what he called a "current dumping amplifier", to get over distortion and thermal runaway problems in class B audio amplifiers⁴.

The principle can best be understood by considering the block schematic shown in Fig. 1. Consider the non-linear element N to be an arbitrary non-linear function. It can be shown that, if the voltage obtained at the output is to be

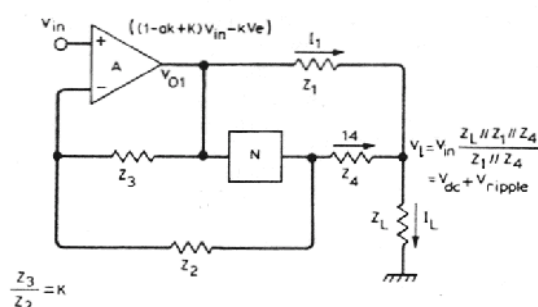
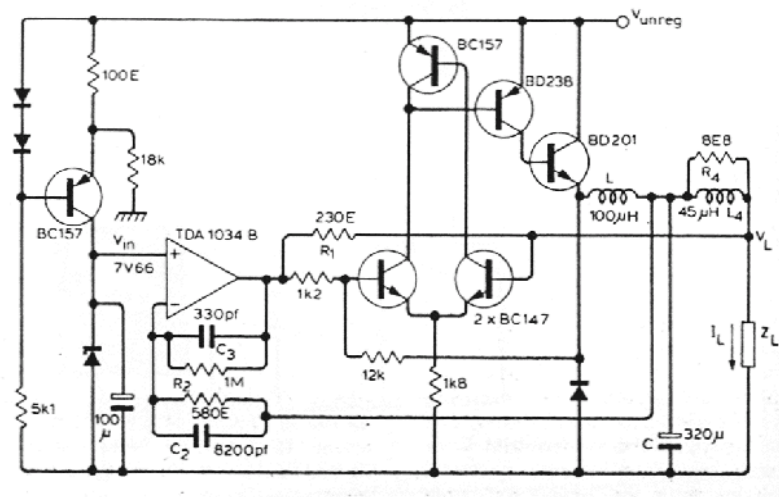
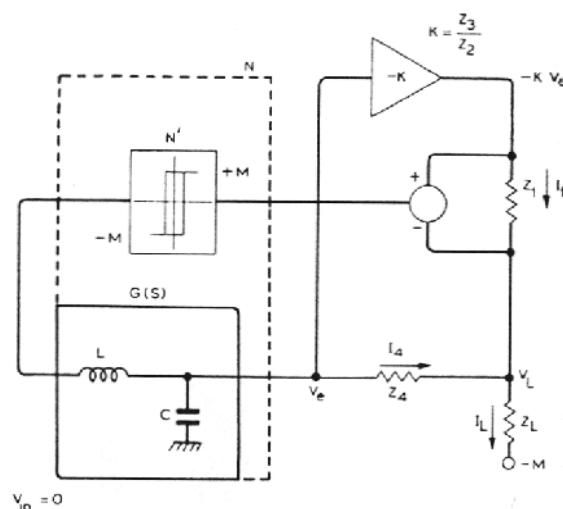


Fig. 1. Block diagram of a basic circuit showing how the use of both feedback and feedforward can result in error cancellation.

Fig. 2. (a) Block diagram of a switching regulator which incorporates feedback and feedforward. (b) Actual circuit diagram of switching regulator.



independent of $N(V_{01})$, the following condition has to be satisfied.

$$(Z_1 Z_2)/(Z_3 Z_4) = 1 \quad (1)$$

Mathematically, the equations indicate that the output is independent of the non-linearity, but it is not easy to get a physical feel of the circuit's operation, or to understand how the principle can be applied to improve the switching regulator design. The voltage $N(V_{01})$ can be said to consist of two parts, one part linearly dependent on V_{in} , aV_{in} , and the other, an error voltage V_e , independent of V_{in} . For the voltage V_{in} , the operational amplifier acts like a non-inverting amplifier and it can be derived that the output voltage is:

$$V_L = V_{in} \cdot \frac{Z_4 // Z_1 // Z_4}{Z_1 // Z_4} \quad (2)$$

where $//$ means "in parallel with".

This conforms to the expression calculated for the entire circuit. Considering V_e as an independent voltage source, the operational amplifier output will be $-(Z_3/Z_2)V_e$. The output voltage will be independent of V_e only when Equation 1 is satisfied. This way of looking at the circuit's operation, though not mathematically rigorous, allows the designer to get a feel of how the circuit operates, and to distinguish between the feedforward and the feedback mechanisms in the system.

The next step is the application of the principle to switching regulator design. A switching regulator is obtained if the non-linear block N is considered to be a switch having hysteresis followed by a low pass filter $G(s)$, as indicated in Fig. 2(a). The actual circuit is shown in Fig. 2(b).

Current flowing through Z_1 generates the voltage required to overcome the hysteresis of the comparator. As the capacitor C charges up, the operational-amplifier output voltage starts falling, eventually causing the current through Z_1 to change direction. This, in turn, makes the comparator switch again. The process is therefore self-sustaining. If the bridge, consisting of the elements Z_1 , Z_2 , Z_3 and Z_4 , is balanced, the output will be free of any ripple. In fact, the ripple voltage at the filter output is analogous to the error voltage V_e in the above problem, and it is cancelled by feedforward.

The concept of using feedback and feedforward together, though well known, has not previously been applied to the design of switching regulators. The method is attractive because a number of operations are performed by a single gain element. The operational amplifier provides feedback for precise regulation, feedforward for ripple cancellation, and ripple amplification. By amplifying the ripple the need for a very sensitive comparator is alleviated. The equations given above also hold for a real operational amplifier with a finite gain bandwidth product, albeit with

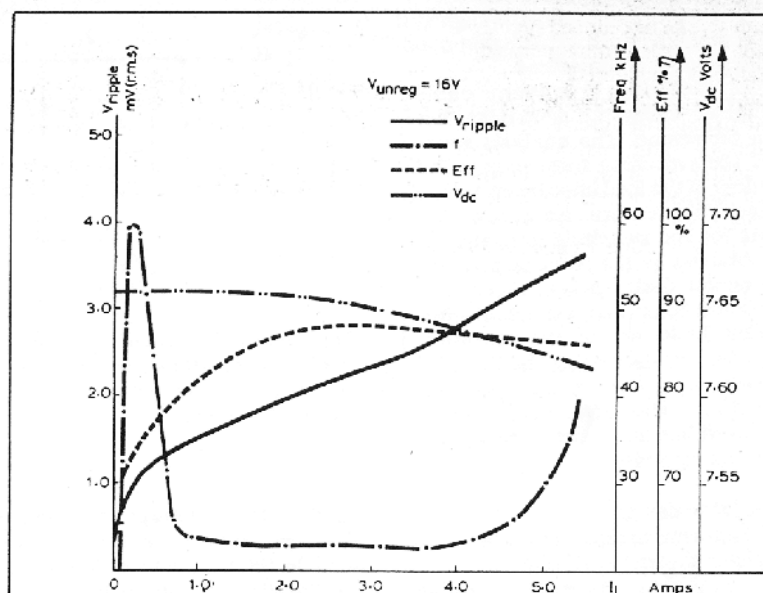


Fig. 3. Regulator characteristics for variations in load current when an unregulated input voltage of 16V is applied.

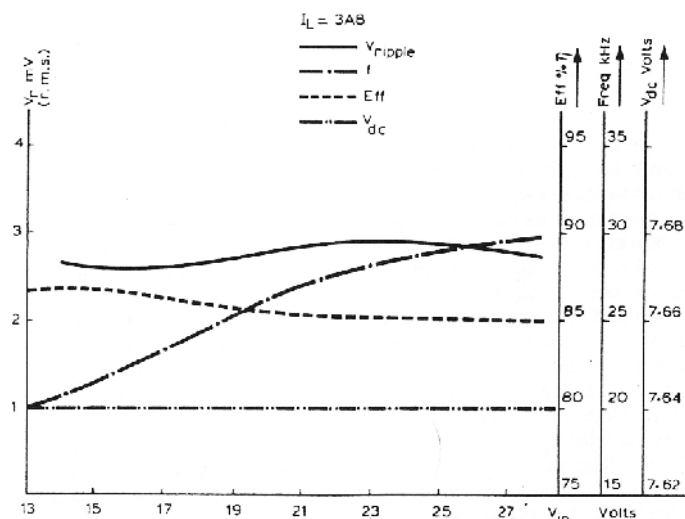


Fig. 4. Regulator characteristics, plotted against unregulated input voltage, for a load current of 3.8A.

minor modifications. Although the derivations are left for the interested reader, a simplified, nevertheless accurate, stability analysis of the system, using the describing function technique, yields an operating limit cycle which gives the switching frequency and the magnitude of the ripple that is to be cancelled. A knowledge of both of these parameters is of prime importance to the designer.

Design procedure

The output impedance of the power supply can be shown to be equal to Z_1 in parallel with Z_4 . Consequently, to obtain good regulation, either Z_1 or Z_4 have to be inductors, so that the d.c. resistance of the branch is zero. Since most of the output current flows through Z_4 , making it the inductor helps to minimise power losses. A resis-

tor is used for Z_1 because the current flowing through it activates the comparator. It also allows the regulator to behave like a linear regulator for load currents which are insufficient to activate the comparator. Finally, to balance Equation 1, a resistor is chosen for Z_2 and a capacitor is chosen for Z_3 .

To obtain low output impedance, and to avoid (Z_3/Z_2) having a low value at higher frequencies, a resistance is added in parallel with L_4 and a capacitor is added in parallel with R_2 . The bridge balance condition is therefore maintained for all frequencies if the following equation is satisfied:

$$\frac{R_1 R_2 / (1 + sC_2 R_2)}{(1/sC_3) (sL_4 R_4 / (sL_4 + R_4))} = 1 \quad (3)$$

$$\text{which requires that } R_2 C_3 = L_4 / R_1 \quad (4)$$

$$\text{and that } L_4 / R_4 = R_2 C_2 \quad (5)$$

Capacitor C_3 can be reduced slightly if a real amplifier with a finite gain bandwidth product is considered.

The switching frequency can be calculated using the describing function technique. The analysis reveals that the switching frequency is independent of the load impedance, which is a desirable feature. An approximate value for the switching frequency can be obtained by the procedure given in the sample design below. However, an important constraint is the short-circuit current limitation of the operational amplifier. By decreasing the maximum current demand from the operational amplifier, the efficiency can be improved but this is detrimental to the transient response.

Regulator design

The following design steps refer to the regulator shown in Fig. 2(b):

For high frequencies, K is chosen as 25.

That is, in the limit ω approaches infinity:

$$(Z_3/Z_2) = C_2/C_3 = 25 \quad (6)$$

where $\omega = 2\pi f$

and from Equations 4, 5 and 6:

$$R_2 C_3 = L_4/R_1 = R_2 C_2/25 = L_4/25 R_4 \quad (7)$$

The operational amplifier has an output current capability of 40mA and a maximum voltage swing of 5V pk-to-pk is to be allowed at its output. To allow a correction current of 10mA, R_1 should be 230 Ω , and to allow the same amount of correction current to flow through Z_4 , L_4 is fixed at 45 μ H, corresponding to an operating frequency of 25kHz. Assuming a value of 330pF for C_3 , the values of R_2 , C_2 and R_4 must be 580 Ω , 8200pF and 8.8 Ω respectively.

While calculating the exact values of the filter components L and C , it is necessary to consider the load on the filter due to L_4 . A complete analysis can only be made using the describing function technique. The relationship between the operating frequency f , L and C can be determined very approximately by considering that, at the frequency of operation, a 16V pk-to-pk square wave is attenuated to a 200mV pk-to-pk triangular wave by a low pass filter having an inductor ($L + L_4$) and a capacitor C with its equivalent series resistance. A 320 μ F capacitor was used with an equivalent series resistance of 0.12 Ω and an inductor (L) of 100 μ H.

Performance data

Performance curves for the regulator indicated in Fig. 2(b) are given in Figs 3 and 4. Fig. 3 gives curves for efficiency, output ripple, regulation and switching frequency as functions of the output current and Fig. 4 shows how the same parameters vary for different input voltages.

Referring to the design described, the equations for calculating the frequency of operation are valid only when the

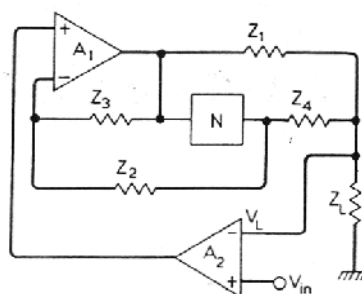


Fig. 5. Block diagram of circuit giving improved regulation performance. Amplifier A_2 should have a larger time constant than A_1 .

ripple current through the inductor L does not decay to zero. For very light loading the equations do not hold and the regulator tends to behave like a linear regulator and operates at very low switching frequencies. The switching frequency is highest at the point beyond which the regulator stops acting in the linear mode. For load currents higher than 600mA, the frequency of operation remains more or less constant until the inductor L starts saturating.

The efficiency of the regulator compares favourably with other switching regulators^{1,2}. Also, the load regulation is seen to be within 0.6% and the line regulation is better than 0.15% for a 100% change in the input voltage.

For any input or load condition the output ripple is seen to be within 4mV r.m.s. and spikes on the output are within 40mV pk-to-pk. Better ripple performance can be obtained by improving the bridge balance, minimising stray capacitances and improving ground layout. On a breadboard prototype made by the authors, these factors significantly affected the performance of the regulator. The ripple at the switching regulator output is reduced by 26dB by the feedforward mechanism.

By following the schematic in Fig. 5¹, the regulation performance of the regulator can be further improved.

Conclusions

It has been seen that the performance of a self-oscillating switching regulator can be improved by the simultaneous application of feedback and feedforward. This principle can be applied to a constant frequency, pulse-width modulated switching-mode supply without any conceptual changes.

By combining feedback and feedforward, it is possible to design a switching regulator with the following characteristics:

- Extremely low output ripple — despite the use of a low switching frequency and small filter components.
- High efficiency — resulting from a low switching frequency.



Deepakraj M. Divan received his B. Tech. degree in Electrical Engineering from the Indian Institute of Technology, Kanpur, India in 1975. He worked for two years for Messrs. Philips India Ltd as a development engineer with their electro-acoustic development laboratory where he worked primarily on the design and development of audio system components. Presently, he is working in the field of power electronics towards an M.Sc. in Electrical Engineering at the University of Calgary, Calgary, Canada.

- A reasonably constant switching frequency over a large operating range.
- Very good regulation.
- Ripple amplification — enabling the use of an extremely insensitive comparator.

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