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Power Output and Dissipation in Class B Transistor Amplifiers

"CLOSE ENOUGH FOR CLASS AB TOO"

by
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Calculations have been presented[1,2] to show that maximum transistor power dissipation in a class B amplifier occurs when the output stage is delivering about 40 per cent of maximum power output to the load and maximum transistor power dissipation amounts to about 20 per cent of maximum sine-wave power output in class B output stages. These calculations are based on several important assumptions, including that of perfect power-supply regulation. This Note considers the effect of power-supply regulation on the ratio of music power to continuous power, the ability of the amplifier to reproduce program material, and the economics of amplifier construction.

POWER-SUPPLY REGULATION

Regulation curves for typical rectifier power supplies with capacitive input filters show that the drop in dc output voltage E_{dc} is nearly a linear function of the dc output current I_{dc} over the entire useful range of the supply. Fig.1 shows a regulation curve for a typical transformer/rectifier supply with a capacitive input filter. The slope of the curve is equal to the effective value of the internal resistance of the supply. The supply voltage E_S may be related to the no-load supply voltage E_o as follows:

$$E_S = E_o - R_S I_{dc} \qquad (1)$$

where R_S is the internal resistance of the supply. (This equation is discussed further in Appendix A.)

A single-ended power supply in a class B amplifier delivers current on alternate half cycles. The output current I_{dc} is then equal to the peak output current I_{pk} divided by π, and the supply voltage is given by

$$E_S = E_o - R_S (I_{pk}/\pi) \qquad (2)$$

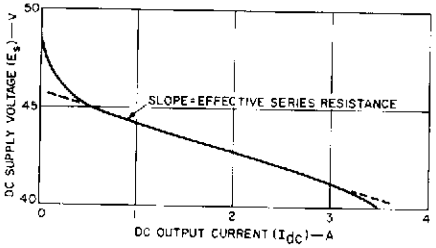

Fig.1 - Typical regulation curve for a transformer/rectifier power supply with a capacitive input filter.

Each half of a balanced split supply delivers the same magnitude of current on alternate half cycles. For the split supply, E_S and E_o in Eq. (2) represent the sum of the voltages of both sides; R_S is the sum of the effective series resistance of both sides.

POWER OUTPUT AND TRANSISTOR POWER DISSIPATION

When the value of E_S derived from Eq. (2) is used as the supply voltage, the maximum transistor dissipation $P_{T(max)}$ may be expressed as follows:

$$P_{T(max)} = E_o{}^2/(8R_S + 4\pi^2 R_L) \qquad (3)$$

where R_L is the resistance of the load.

The maximum unclipped power output for an amplifier with a perfectly regulated supply is often called the music power output,* P.O.(music), and is given by

$$\text{P.O.(music)} = E_o{}^2/8R_L \qquad (4)$$

Maximum average transistor dissipation is related to the music power output by the following expression:

$$\frac{P_{T(max)}}{\text{P.O.(music)}} = \left[\frac{\pi^2}{2} + \frac{R_S}{R_L}\right]^{-1} \qquad (5)$$

The power output at which maximum average transister dissipation occurs, P.O. (max diss), is related to the music power output as follows:

$$\frac{\text{P.O.(max diss)}}{\text{P.O.(music)}} = \left[\frac{\pi^2}{4} + \frac{R_S}{R_L} + \frac{R_S{}^2}{\pi^2 R_L{}^2}\right]^{-1} \qquad (6)$$

The continuous power output at the clipping level, P.O. (clipping), is related to the music power output by the following expression:

$$\frac{\text{P.O.(clipping)}}{\text{P.O.(music)}} = \left[1 + \frac{R_S}{\pi R_L} + \frac{R_S{}^2}{4\pi^2 R_L{}^2}\right]^{-1} \qquad (7)$$

Eqs. (5), (6), and (7) are plotted in Fig.2. Power levels are normalized with respect to the music power output and are plotted as a function of R_S/R_L. These equations are derived in Appendix A.

Fig.2 shows that transistor power dissipation is only a small fraction of the clipping power output for higher ratios of R_S/R_L. For example, a 100-watt amplifier can use transistors and associated heat sinks capable of a maximum dissipation of only about 7 watts each. However, Eqs. (5), (6), and (7) (and consequently the curves of Fig.2) do not reflect high line voltage or the effects of ripple voltage. Calculations of average power dissipation in transistors should also include no-signal bias dissipation, the increase in bias dissipation with increasing ambient and junction temperatures in class AB circuits, storage effects, phase shift, and thermal tracking.[3,4]

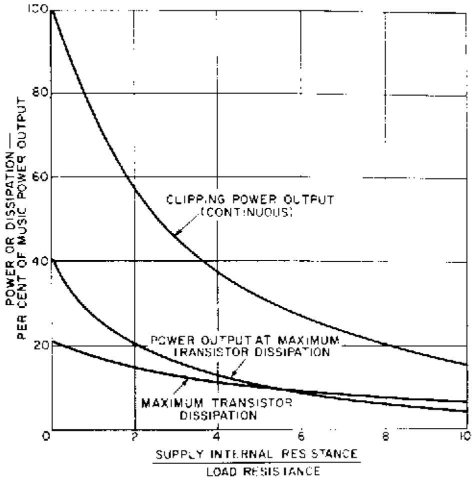

Fig.2 - Power output and dissipation as a function of the ratio of internal supply to load resistance.

Of the above factors, bias dissipation probably contributes the greatest percentage of average worst-case transistor dissipation. The output stage is usually biased "on" slightly (class AB) to reduce crossover distortion.

A Practical Class B Amplifier

Fig.3 shows a class B complementary-symmetry power-amplifier circuit in which bias dissipation is not a problem; it is negligible at all practical temperatures. One side of the amplifier operates at cutoff and the other conducts less than one milliampere. Thermal runaway cannot be initiated in the output-stage transistors at any junction temperature below the maximum transistor rating. Consequently, thermal tracking may also be neglected as long as the sum of the ambient temperature plus the product of the instantaneous dissipation and the junction-to-ambient thermal resistance is below the maximum junction-temperature rating.

Storage effects are also negligible in the amplifier because of the reverse bias provided for the "off" transistor by the "on" transistor in the complementary-

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* Although the EIA standard (RS-234A) refers to the point at which total harmonic distortion is 5 per cent when a regulated supply is used, for the purpose of this discussion the maximum unclipped sine-wave power output is referred to as the music power output. The EIA value is about 10 per cent greater.

symmetry configuration. Fig.3, then, represents a practical example of an amplifier capable of achieving the characteristics shown in Fig.2. The amplifier circuit is discussed in further detail in Appendix B.

Amplifier Economics

Some economic advantages afforded by the class B amplifier using high values of R_S/R_L and correspondingly high ratios of music-power output to transistor dissipation are as follows:

1. Reduced transistor or heat-sink cost. (Because the volt-ampere capacity of the transistor is determined by the music power output, it is not likely that reduced thermal resistance requirements will result in significant reduction in transistor cost. Alternatively, heat-sink requirements may be reduced and a less expensive heat sink used.)
2. Reduced power-supply costs. (Transformer and/or filter-capacitor specifications may be relaxed.)
3. Reduced speaker cost. (Continuous power-handling capability may be relaxed.)

These cost reductions can be passed along to the consumer in the form of more music power per dollar.

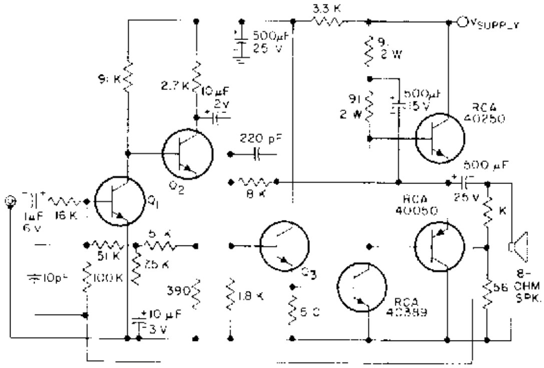

Fig.3 - A practical class B amplifier circuit.

Amplifier Fidelity

The question arises as to how high the ratio of R_S/R_L and the corresponding ratio of music-power output to continuous-power output may go before amplifier fidelity, the capability of the amplifier to reproduce program material, is impaired.

The objective in any high-fidelity amplifier is to provide the listener with a close approximation of the original "live" performance. This goal requires the reproduction of sound-pressure levels approaching those of the concert hall. Although the peak sound-pressure level of the live performance is about 100 dB, the average listener prefers to operate his system at a peak sound-pressure level of about 80 dB.[5] However, the amplifier should also accommodate those who wish to listen at higher-than-average levels, perhaps to peaks of 100 dB.

A sound-pressure level of 100 dB corresponds to a power of about 0.4 acoustical watt for an average room of about 3,000 cubic feet.[5] If speaker efficiencies in the range of one per cent are assumed, a stereophonic amplifier must be capable of delivering about 20 watts per channel. The peak-to-average level for most program material is between 20 and 23 dB. A system capable of providing a continuous level of 77 dB and peaks of 100 dB satisfies the requirements of nearly all listeners. To achieve this output level, the power-supply voltage cannot drop below the voltage required for 100 dB of acoustical power while delivering the average current required for 77 dB. Furthermore, because sustained passages 10 dB above the average may occur, the power-supply voltage cannot drop below the voltage required for 100 dB of acoustic power while delivering 87 dB (87 dB corresponds to about 1 watt per channel). For 8-ohm loads, therefore, neglecting output-circuit losses, the power-supply voltage must not drop below 36 volts while delivering the average current required for 1 watt per channel (0.225 ampere dc).

The power-output capability of the amplifier on peaks, while the amplifier is delivering a total of two watts, does not represent the music-power rating of the amplifier because the power-supply voltage is below its no-signal value by an amount depending on its effective series resistance.

Maximum Effective Series Resistance

There must be a relationship between the maximum effective series resistance R_S of the power supply and the music-power rating of the amplifier if the amplifier is to perform according to the standards described above. R_S may be expressed as a function of music-power output as follows:

$$R_S = \left[\frac{(8R_L)\ \text{P.O.(music)}}{\bar{I}^2}\right]^{1/2} - \frac{E_{S(min)}}{\bar{I}} \qquad (8)$$

where $E_{S(min)}$ is the minimum voltage required for 100 dB of acoustical power output, and $\bar{I}$ is the current required for 87 dB of acoustical power output; $\bar{I}$ does not include idle current. This relationship is discussed further in Appendix C. In practice, $E_{S(min)}$ is increased by peak output-circuit voltage losses.

Eq. (8) is plotted in Fig.4. Each value of R_S represents the absolute maximum value of effective supply resistance corresponding to a music-power value that will allow the amplifier to deliver a minimum of 100 dB of acoustical power output as described above.

Comparison of Fig.4 with Fig.2 shows that very high ratios of music-power output to continuous-power output may be utilized without sacrificing the ability of the amplifier to reproduce program material. This technique provides economic advantages while adhering to a minimum "power margin" for the faithful reproduction of program material, even at high peak listening levels.

The information presented in this Note covers the requirements of nearly all home listening environments and defines the minimum "power margin" for power amplifiers, as well as the minimum performance objectives for nearly all listeners. Component-type amplifier systems, which are sometimes used in conjunction with acoustic suspension speaker systems, may require an increase in the minimum power margin to accommodate reduced efficiencies, especially in the bass region. This increase, however, is probably less than 3 dB.

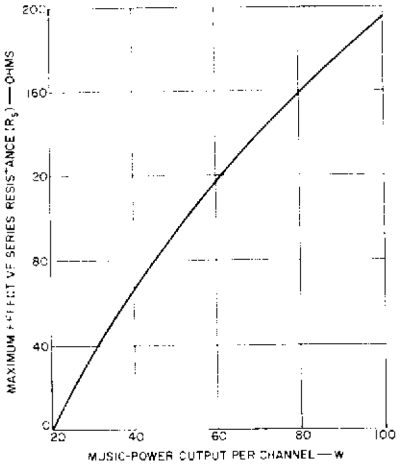

Fig.4 - Maximum effective series resistance as a function of music power.

APPENDIX A

Ideal Power Dissipation (Regulated Supply)

Typical complementary-symmetry circuits are shown in Fig.5. Under no-signal conditions, the capacitor C is charged to a voltage equal to $E_S/2$ at the clipping level. The maximum peak load current $I_{pk(max)}$ is given by

$$I_{pk(max)} = E_S/2R_L \qquad (A1)$$

Because the supply delivers current on alternate half-cycles, the average supply current I_S is given by

$$I_S = I_{pk}/\pi \qquad (A2)$$

The power delivered by the supply P_S can then be expressed as follows:

$$P_S = (I_{pk}E_S)/\pi \qquad (A3)$$

The power delivered to the load, P.O., is given by

$$\text{P.O.} = (I_{pk}^{\ 2}R_L)/2 \qquad (A4)$$

The dissipation P_C for each transistor is equal to half the difference between the supply power delivered P_S and the power dissipated in the load, P.O., as follows:

$$P_C = (P_S - \text{P.O.})/2$$

$$P_C = \frac{I_{pk}E_S}{2\pi} - \frac{I_{pk}^{\ 2}R_L}{4} \qquad (A5)$$

If Eq. (A5) is differentiated and solved for the peak load current I_{pk} at maximum average transistor dissipation, the following expression is obtained:

$$I_{pk} = E_S/(\pi R_L) \qquad (A6)$$

When this value is substituted in Eq. (A5), the ratio of maximum average transistor dissipation P_C(max) to power delivered to the load at full power output P.O.(max) can be expressed as follows:

$$\frac{P_C(\text{max})}{\text{P.O.(max)}} = \frac{2}{\pi^2} \qquad (A7)$$

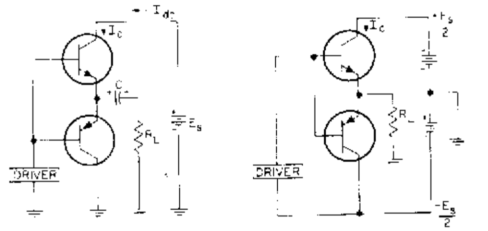

Fig.5 - Typical complementary-symmetry circuits.

Eq. (A7) indicates that maximum transistor dissipation is approximately 20 per cent of full power output. At the point of maximum dissipation, the power output is given by

$$\text{P.O.(max diss)} = \frac{E_S^{\,2}}{2\pi^2 R_L} \qquad \text{(A8)}$$

The ratio of the power output at maximum dissipation P.O. (max diss) to maximum power output P.O, (max) is then given by

$$\frac{\text{P.O.(max diss)}}{\text{P.O.(max)}} = \frac{4}{\pi^2} \qquad \text{(A9)}$$

Non-Regulated Supply

Fig.6 shows a typical regulation curve for a rectifier power supply that has a capacitive input filter. The voltage is a linear function of the average supply current over most of the useful range of the supply. However, a rapid change in slope occurs in the regions of both very small and very large currents. In class B amplifiers, the no-signal supply current normally occurs beyond the low-current knee, and the current required for the amplifier at the clipping level occurs before the high-current knee. The slope between these points is nearly linear and may be used as an approximation of the equivalent series resistance of the supply.

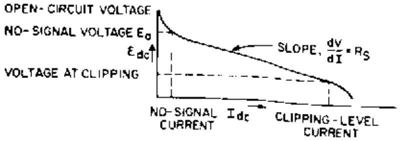

Fig.6 - Typical regulation curve for a rectifier power supply with a capacitive input filter.

Figs.7 and 8 show equivalent circuits for capacitive-input rectifier supplies. In these circuits, I_{dc} is the average supply current, R_S is the equivalent series resistance of the power supply, E_o is the no-signal supply voltage, and E_S is the steady-state supply voltage. The steady-state voltage E_S is related to the no-signal voltage E_o as follows:

$$E_S = E_o - R_S I_{dc} \qquad \text{(A10)}$$

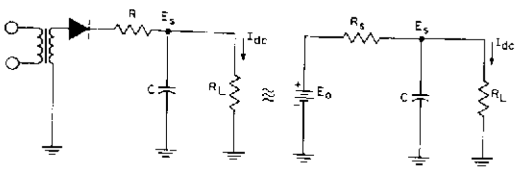

Fig.7 - Equivalent circuits for a single-ended capacitive-input rectifier power supply.

If this value is substituted for the supply voltage E_S in Eq. (A3), Eq. (A5) can be rewritten as follows:

$$P_C = \frac{I_{pk}E_o}{2\pi} - \frac{R_S I_{pk}^{\,2}}{2\pi^2} - \frac{I_{pk}^{\,2}R_L}{4} \qquad \text{(A11)}$$

The partial derivative of this equation with respect to I_{pk} is set equal to zero, tested for a maximum value, and solved for I_{pk}. This value of I_{pk} is then used in Eq. (A11) to determine the maximum transistor dissipation P_C(max), as follows:

$$\frac{\partial P_C}{\partial I_{pk}} = \frac{E_o}{2\pi} - I_{pk}\,\frac{2R_S + \pi^2 R_L}{2\pi^2} \qquad \text{(A12)}$$

$$I_{pk} = \frac{E_o\pi}{2R_S + \pi^2 R_L} \qquad \text{(A13)}$$

$$P_C(\text{max}) = \frac{E_o^{\,2}}{8R_S + 4\pi^2 R_L} \qquad \text{(A14)}$$

Clipping begins at the point where the peak collector current I_{pk} is given by

$$I_{pk} = \frac{E_o\pi}{R_S + 2\pi R_L} \qquad \text{(A15)}$$

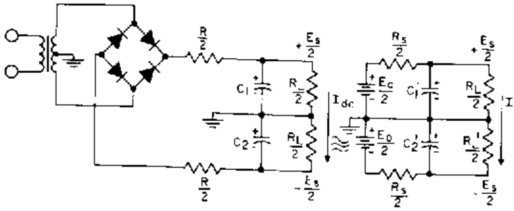

Fig.8 - Equivalent circuits for a split capacitive-input rectifier power supply.

Power output at clipping can then be expressed as follows:

$$\text{P.O.(clipping)} = \frac{E_o^{\,2}\,\pi^2 R_L}{2(R_S + 2\pi R_L)^2} \qquad \text{(A16)}$$

If $R_S = 0$ is substituted in Eq. (A16), the music power may be shown to be equal to $E_o^{\,2}/8R_L$. The ratio of clipping power to music power output is given by

$$\frac{\text{P.O.(clipping)}}{\text{P.O.(music)}} = \left[1 + \frac{R_S}{\pi R_L} + \frac{R_S^{\,2}}{4\pi^2 R_L^{\,2}}\right]^{-1} \qquad \text{(A17)}$$

Maximum transistor dissipation occurs at the peak-current level given in Eq. (A13). The power output at maximum dissipation is given by

$$\text{P.O.(max diss)} = \frac{E_o^{\,2}\pi^2 R_L}{2(2R_S + \pi^2 R_L)^2} \qquad \text{(A18)}$$

The ratio of power output at maximum dissipation to music power can then be expressed as follows:

$$\frac{\text{P.O.(max diss)}}{\text{P.O.(music)}} = \left[\frac{\pi^2}{4} + \frac{R_S}{R_L} + \frac{R_S^{\,2}}{\pi^2 R_L^{\,2}}\right]^{-1} \qquad \text{(A19)}$$

APPENDIX B

Class B Amplifier (Circuit Description)

The amplifier shown in Fig.3 is, for all practical purposes, a true class B amplifier. There are no emitter resistors in the output stage and the bases of the output transistors are tied together. If there were no dc feedback current through the voltage-divider network (i.e., the resistors from the emitters of the output transistors to the base of the pre-driver transistor and then to ground) used to establish the center voltage of the output stage, both output transistors would be cut off or reverse-biased. However, because of the dc feedback the upper transistor in the output stage turns on at a current level determined by the voltage-divider network. In the amplifier of Fig.3, this current is at least one order of magnitude less than the idle current normally used in the output stage to reduce crossover distortion. When the upper transistor is "on", the bottom transistor is reverse-biased by the amount of the forward base-to-emitter voltage of the upper transistor required to supply the dc feedback current. The dissipation in the upper transistor resulting from the dc feedback current is negligible and is reduced further as a result of the inverse proportion that exists between dc feedback current and temperature; dc feedback current decreases with reductions in base-to-emitter voltage in the transistors in the driver and pre-driver stages as transistor temperatures in those stages increase. The fact that the no-signal current in the upper transistor is negligible and the bottom transistor is reverse-biased further demonstrates that the circuit shown in Fig.3 acts as a true class B amplifier.

Some advantages derived from the class B mode of amplifier operation and from the complementary-symmetry amplifier design shown in Fig.3 in particular are as follows:

1. There is no dissipation in the output stage under zero-signal conditions, for the reasons discussed above.
2. Hum and noise at the output are reduced. The bottom half of the output stage is normally reverse-biased or "off" and is not turned on by hum and noise. Only that hum and noise amplified by the top transistor appears at the output.
3. The total harmonic distortion is low as a direct result of the large amounts of feedback necessary to reduce the crossover distortion. An additional gain stage is required by this amplifier because of this feedback. The output-stage bias diode and emitter resistors are no longer necessary with the added gain stage and feedback. The crossover distortion is always larger in class B than in class AB amplifiers; however, the class B amplifier can be designed with an acceptable intermodulation (IM) distortion level. (Crossover distortion appears as IM distortion.)
4. There is no storage effect in the output transistors. This feature is an advantage of all true complementary-symmetry amplifiers: when one of the output transistors turns "on" it automatically reverse-biases the other and thus pulls the stored charge out of the base region of the "off" transistor.
5. A lower power-supply voltage is required as a result of the absence of emitter resistors in the output stage. There are no voltage drops between the power supply and the speaker except those in the transistor; therefore, the power-supply voltage can be reduced by $2(R_E I_p)$, where R_E is emitter resistance and I_{pk} is peak collector current.

In summary, the many advantages of the amplifier circuit of Fig.3 overshadow the presence of a very slight but acceptable crossover distortion. Furthermore, the cost of the extra transistor stage, the pre-driver stage, is partially offset by the elimination of bias diodes and emitter resistors.

APPENDIX C

Maximum Allowable Effective Series Resistance and Music-Power Output

During sustained passages of a high average sound-pressure level of the order of 10 dB above the normal listening level, the power-supply voltage should not collapse below the point at which the amplifier with its speaker system can deliver a peak sound-pressure level of 100 dB.[5] This point corresponds to a stereo power output of 20 watts per channel. The normal sound-pressure level is 77 dB, which corresponds to an amplifier power output of 0.1 watt per channel. The sustained high average sound-pressure level is, then, 87 dB, which corresponds to an amplifier power output of 1.0 watt per channel. Both of these power outputs are based on a speaker efficiency of 1 per cent and a room volume of 3,000 cubic feet.[5] To determine the relationship between maximum allowable effective series resistance, R_S, and music-power output, P.O. (music), only the load resistance R_L or speaker impedance need be known. It was determined above that the dc power-supply voltage $E_S(\text{min})$ must be large enough for the amplifier to deliver 20 watts per channel for a short time when it is delivering an average of 1 watt per channel. Fig.9 shows a power-supply regulation curve. The power-supply voltage at zero signal is E_o; the power-supply voltage is $E_{S(\text{min})}$ when the amplifier is delivering 1 watt per channel or 2 watts total. The zero-signal current I_o and the difference between I_o and the steady-state current drain at a total power output of 2 watts is $\bar{I}$. For this discussion, R_L is 8 ohms.

The rms current I_{rms} in the load resistance R_L at a total output P_{out} of 2 watts is given by

$$I_{RMS} = \sqrt{\frac{P_{out}}{R_L}} = 0.5 \text{ ampere} \qquad \text{(C1)}$$

At this current level the difference $\bar{I}$ between the zero-signal current I_o and the steady-state current drain at a total power output of 2 watts is given by

$$\bar{I} = \frac{I_{RMS}\sqrt{2}}{\pi} = 0.225 \text{ ampere} \qquad \text{(C2)}$$

The power-supply voltage at zero signal, E_o, can be determined from the following equation:

$$E_o = E_{S(\text{min})} + \bar{I}R_S \qquad \text{(C3)}$$

where $E_{S(\text{min})}$ is the power-supply voltage at a total power output of 2 watts and R_S is the maximum allowable effective series resistance.

The music-power output P.O.(music) is

$$\text{P.O.(music)} = \frac{E_o^{\,2}}{8R_L} \qquad \text{(C4)}$$

Combination of Eqs. (C3) and (C4) results in the following relation:

$$\text{P.O.(music)} = \frac{\left[E_{S(\text{min})} + \bar{I}R_S\right]^2}{8R_L} \qquad \text{(C5)}$$

The solution of Eq. (C5) for R_S is as follows:

$$R_S = \frac{\sqrt{8R_L\ \text{P.O.(music)}}}{\bar{I}} - \frac{E_{S(\text{min})}}{\bar{I}} \qquad \text{(C6)}$$

For a load resistance of 8 ohms, R_L is given by

$$R_S = \frac{8}{\bar{I}}\sqrt{\text{P.O.(music)}} - \frac{E_{S(\text{min})}}{\bar{I}} \qquad \text{(C7)}$$

The required $E_{S(\text{min})}$ for a music-power output of 20 watts per channel is

$$\begin{aligned} E_{S(\text{min})} &= \sqrt{20\,(8R_L)} \\ &= 35.8 \text{ volts} \qquad \text{(C8)} \end{aligned}$$

Substitution of $\bar{I}$ and E_S then provides the following expression for R_S:

$$R_S = 35.6\sqrt{\text{P.O.(music)}} - 159 \qquad \text{(C9)}$$

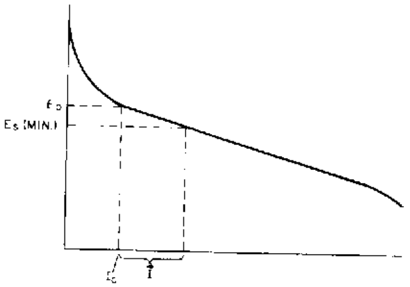

Fig.9 - A power-supply regulation curve.

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