POWER-SUPPLY RIPPLE AFFECTS POWER AMPLIFIERS

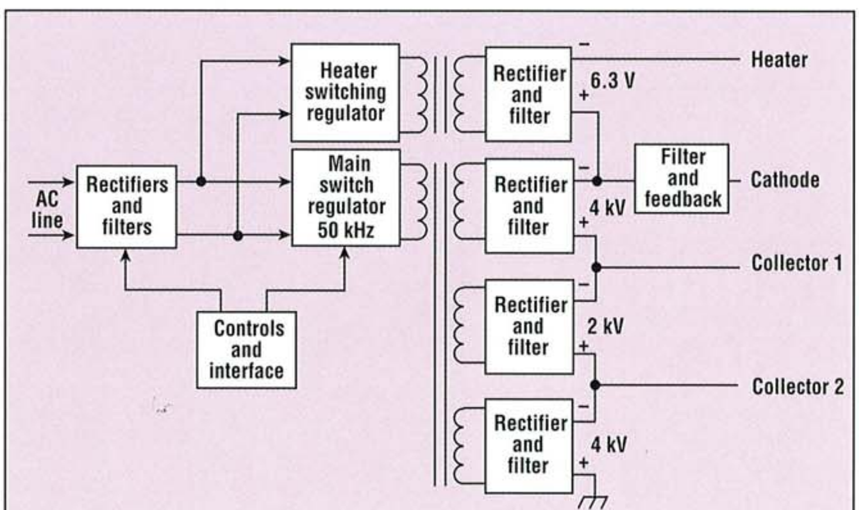
Understanding the causes of power-supply ripple voltage can enhance the performance of high-power RF amplifiers.

POWER supplies are often taken for granted by RF engineers. While most RF engineers would like to assume that a DC power supply provides pure DC output voltage, such an assumption can be damaging. In reality, the "composition" of a DC power supply's output voltage can seriously affect the performance of the high-power amplifier that it drives.

The DC voltage produced by most commercial power supplies also contains many unwanted signals that contribute to amplitude modulation (AM) of the DC voltage. Power-supply engineers refer to this DC output-voltage AM as ripple voltage. When applied to a microwave amplifier, such ripple voltage results in adverse effects on the amplifier's output signals, including unwanted AM, phase modulation (PM), and frequency modulation (FM).

By analyzing the causes of this ripple voltage, it is possible to predict the location in the RF spectrum where these unwanted sidebands will occur. This is important because the RF specifications are often frequency dependent. Sources of undesired power-supply ripple include the AC-line frequency of 60 Hz and its harmonics at 120 Hz, 180 Hz, and so on; the AC-line frequency of 400 Hz with harmonics at 800 and 1200 Hz; regulator switching frequencies from 10 to 500 kHz and their harmonics; the high-frequency ringing of switching devices from 1 to 100 MHz; and resonances in the output filter section from 1 to 30 MHz.

All power supplies contain one or more of these unwanted signal sources, while most contain several. A typical power supply for a microwave tube, such as a traveling-wave tube (TWT), operates from a rectified and filtered AC line (Fig. 1). This unregulated DC voltage is then switched at a 50-kHz rate into a step-up transformer. The transformer outputs are then rectified and filtered to provide the final DC outputs to the TWT. Regulation is accomplished by controlling the duty cycle of the 50-kHz switch. In this design, AM (ripple) of the DC outputs is expected to occur at the AC-line harmonics of 60, 120, 180, and 240 Hz (generally the 120-Hz second-harmonic component is the largest) and at the switching harmonics of 50, 100, and 150 kHz (the 100-kHz second-harmonic component is usually the largest). Low-level modulation may also be present in the 10-to-20-MHz range due to the natural resonance of the high-voltage output filter.



1. This block diagram shows the functional segments of a typical power supply for a traveling-wave-tube (TWT) amplifier.

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Table 1: AM sensitivity and power-supply ripple limits for –40 dBc

Element	α_m (dB/V)	Power-supply ripple (V RMS)
Cathode	0.02	6.0
Collector 1	0.002	60
Collector 2	0.001	120
Heater	0.05	2.4
Focus electrode	0.05	2.5

These unwanted AM, PM, and FM components produce coherent, repetitive sidebands on the microwave output. These sidebands are offset from the microwave carrier by an amount that is equal to the frequency of the corresponding ripple voltage signal on the power-supply output. There are two sidebands for each ripple frequency: one above and one below the carrier frequency. For example, a 40-kHz power-supply ripple voltage produces unwanted sidebands at $f_o = \pm 40$ kHz. RF engineers often call these unwanted sidebands "residual" sidebands, referring to unwanted outputs remaining after incoherent signals are removed.

From AM modulation theory for a single sideband, residual AM can be predicted from:

$$Residual\ AM = m/2 \quad (1)$$

where:

m = the modulation index, δV/V,

V = the RF peak voltage, and

Residual AM = the AM sideband ratio with respect to the carrier frequency.

The TWT AM modulation sensitivity, α_m, is presented by TWT vendors as a ratio of the change in output power, P (in dB/V), so that:

$$10\ log[(P + \delta P)/P] = \alpha_m \times \delta v_{pk} \quad (2)$$

where:

δv_{pk} = the power-supply ripple voltage.

In terms of the RF voltage:

$$20\ log[(V + \delta V)/V] = \alpha_m \times \delta v_{pk} \quad (3a)$$

By rewriting this through antilogarithms:

$$[(V + \delta V)/V] = 10^{\alpha \times \delta v_{pk}/20} \quad (3b)$$

$$\delta V/V = 10^{\alpha \times \delta v_{pk}/20} - 1 = m \quad (3c)$$

and making substitutions to rewrite the expression in terms of residual AM:

$$Residual\ AM = \left(10^{\alpha \times \delta v_{pk}/20} - 1\right)/2$$

it is now possible to show Eq. 2 in decibels:

$$Residual\ AM = 20\ log\left(10^{\alpha \times \delta v_{rms}/14.14} - 1\right) - 6\ dBc$$

These relationships help power-supply engineers predict what the power-supply ripple voltage will be under certain conditions. By rearranging Eq. 3, it is possible to solve for $\alpha_m \times \delta v_{rms}$, which contains the ripple voltage, v_{rms}, and is independent of amplifier sensitivity:

$$\alpha_m \times \delta v_{rms} = 14.14\ log\{1 + antilog[(Residual\ AM_{dBc} + 6)/20]\} \quad (4)$$

Similarly, it is possible to solve for the residual PM. For a single PM sideband:

$$Residual\ PM = \delta\Phi^R{}_{peak}/2 = \delta\Phi^\circ{}_{rms}/81.05$$

where:

$$\delta\Phi^\circ{}_{rms} = \alpha_p \times \delta v_{rms}$$

Therefore:

$$Residual\ PM = \alpha_p \times \delta v_{rms}/81.05$$

where:

Φ = the RF-output phase relative to the input RF phase,

α_p = the phase pushing factor (in deg./V),

δv_{rms} = the power-supply RMS ripple voltage, and

Residual PM = the PM sideband ratio with respect to the carrier.

Expressed in decibels, residual PM becomes:

$$Residual\ PM = 20\ log\,\alpha_p + 20\ log\,\delta v_{rms} - 38.2\ dBc \quad (5)$$

Solving this equation for the quantity $\alpha_p \times \delta v_{rms}$ provides the useful result:

$$\alpha_p \times \delta v_{rms} = antilog[(Residual\ PM_{dBc} + 38.2) \times 20] \quad (6)$$

Residual FM is directly related to residual PM by the expression:

$$\delta f = \delta\Phi^R \times f_{mod}$$

where:

δf = the peak frequency deviation (in Hz), and

f_{mod} = the frequency of the modulation:

Table 2: PM sensitivity and power-supply ripple limits for –30 dBc

Element	α_p (deg./V)	Power-supply ripple (V RMS)
Cathode	2.0	1.25
Collector 1	0.5	5.0
Collector 2	0.02	125
Heater	0.2	12.5
Focus electrode	4.0	0.625

Table 3: Test data on the dB-3304B TWTA							
Ripple frequency (Hz)	Cathode voltage (V)	Collector 1 voltage (V)	Collector 2 voltage (V)	Heater voltage	Focus electrode	Residual AM data (dBc)	Residual FM data (dBc)
1200	0.58	—	—	—	—	-59.0	NA
73,000	0.40	0.79	0.63	NA	nil	-61.5	-45.0
130,000	—	—	—	6.3	—	-50.0	-51.0

$$\delta f = \alpha_p \times \delta v_{rms} \times f_{mod} \times 40.52 \quad (7a)$$

which is expressed in decibels as:

$$Residual\ FM = 20\ log\, \alpha_p \times \delta v_{rms} + 20\ log\, f_{mod} - 38.2\ dBc \quad (7b)$$

Equations 4 and 6 can be expressed graphically as a function of the quantity $\alpha \times \delta v_{rms}$ (Fig. 2). These formulas are accurate for sideband levels below –20 dBc and approximately have a 2-percent error at –10-dBc levels.

Often, the design specifications that guide a power-supply engineer are significantly tighter than necessary. The following is a technique for objectively determining power-supply ripple specifications:

1. Determine the RF requirements. This is fairly straightforward and generally falls out of the RF system requirements. Often this is governed by an international specification (such as IESS-308, for international Intelsat QPSK/FDMA requirements) or a customer-generated system specification. Requirements should be broken down into categories that can easily be evaluated, such as residual AM sidebands, residual PM sidebands, and residual FM. Note that FM and PM are really the same (FM = PM × F_{mod}), and usually one or the other is sufficient to specify performance.

2. Select the microwave amplifying device (i.e., a particular solid-state amplifier, TWT, or klystron device).

3. Obtain the sensitivity factors for the various voltage elements of the microwave device. Generally, the worst-case performance will occur in the small-signal or linear operating region, as well as at the highest microwave frequency in the operating band. It is important to know the operating conditions that relate to the vendor sensitivity factors.

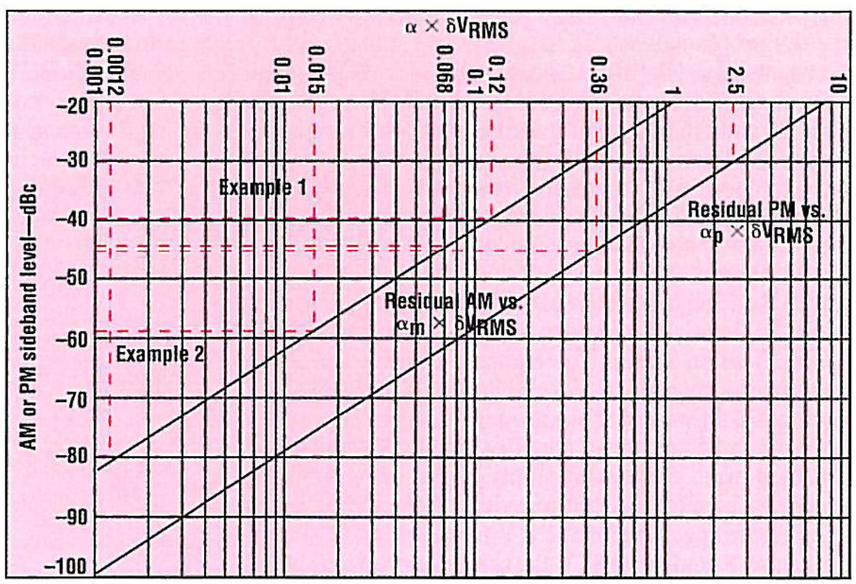
Table 4: AM sensitivity and power-supply ripple limits					
		δv_{rms} (V)			
Element	α_m (dB/V)	< 10 kHz	40 kHz	80 kHz	> 500 kHz
Cathode	0.007	9.7	2.14	1.07	0.171
Collector 1	0.0005	136	30	15	2.4
Collector 2	0.0005	136	30	15	2.4

4. Use these factors to convert the RF specification limits to power-supply ripple voltage limits.

5. Consider the effects that power-supply ripple has on each amplifier tube element as well as on the total RF amplifier performance.

6. Analyze and set the final power-supply ripple specifications.

The effects of power-supply ripple voltage on actual power-amplifier performance can be illustrated with two examples. The first example is based on model dB-3304B, a 200-W TWT amplifier designed for use from 7 to 18 GHz. The amplifier, which is manufactured by dB Control (Fremont, CA), is suitable for various airborne electronic-countermeasures (ECM) applications that do not require tight specifications (Fig. 3). For this amplifier system, the following RF specifications are assumed: residual AM of –40 dBc, residual PM of –30 dBc, and residual FM that is not specified. With these specifica-



2. These values were calculated by means of substitutions into Eqs. 4 and 6. They apply to the two amplifier power-supply examples.

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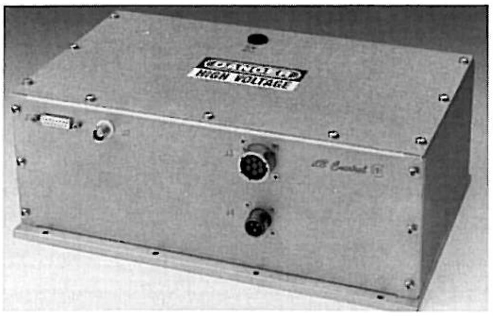
tions, the amplifier could be either a 10-W or a 10-kW device. Since the specifications are expressed in dB below the carrier, the actual power level is irrelevant.



3. This rugged power supply is typical of those used with TWT amplifiers for airborne applications.

The microwave tube used in this amplifier is an MTI-5170A TWT from Teledyne Electronics Technology (Mountain View, CA). The TWT's sensitivity specifications have been tabulated for both AM and PM (Tables 1 and 2). Five different TWT elements are considered in this analysis: two collectors, a cathode, a heater, and a focus electrode. A curve of $\alpha_m \times \delta v_{rms}$ (which is based on Eq. 4) shows that, for a residual AM specification of –40 dBc, $\alpha_m \times \delta v_{rms} = 0.12$. When the different values of α_m are substituted into Eq. 4 for each tube element, it is possible to determine the power-supply ripple voltages that would generate a –40-dBc sideband level.

When analyzing PM effects from a curve of $\alpha_p \times \delta v_{rms}$ (which is based on Eq. 6), a residual PM specification of –30 dBc results from a $\alpha_m \times \delta v_{rms}$ value of 2.5. By substituting different values of α_p into Eq. 6 for each tube element, it is possible to determine the power-supply ripple that will generate a PM sideband level of –30 dBc.

If the power-supply ripple frequencies are similar on all power-supply outputs, their effects will be additive (on a vector basis) in the microwave device, according to the relative phases of the ripple voltages. Because there are five potential additive sources of PM, this complicates the problem.

Fortunately, the situation can be simplified. The TWT's focus electrode runs at less than 50 V when the tube is turned on. Setting the focus electrode to a specification of 0.20-percent ripple (a relatively-easy specification to achieve) will virtually eliminate it as a source of residual sidebands. The TWT's heater operates from 6.3 V, well below the 12.5-V limit, and at a different frequency from the other supplies, so it does not need to be considered. By focusing on the other three voltages, a solution can be found. This is done by combining the AM and PM specification limits. The tightest requirements are 1.25 V for the cathode, 5 V for collector 1, and 120 V for collector 2. All three of these are high-voltage supplies.

Since the collector power supplies handle the bulk of the DC tube power, the power-supply ripple for these tube elements is the most difficult to reduce. A good choice is to set the ripple specifications to 3 V for collector 1, to 10 V for collector 2, and to 0.125 V for the cathode. This should reduce the effects of the cathode's and collector 2's supply ripple to a negligible level, as well as make the dominant effect due to collector 1's supply ripple.

Table 5: PM sensitivity and power-supply ripple limits

Element	α_p (deg./V)	δv_{rms} (V)	
		AC line	All others
Cathode	1.2	1.5	0.3
Collector 1	0.003	600	120
Collector 2	0.003	600	120

At this point, power-supply engineers should seriously consider giving up their oscilloscope. While the oscilloscope will always be a primary tool for the power-supply engineer, a low-frequency spectrum analyzer is more effective for measuring power-supply ripple. The analyzer will accurately measure and separate the power-supply ripple elements into the Fourier components necessary to verify power-supply performance. Also, it measures RMS voltage, which fits directly into Eqs. 4 and 6. The oscilloscope cannot do either of these.

In the first example, the amplifier operates from three-phase, 400-Hz AC power, while its switching regulator operates at 37 kHz (Table 3). The specification choices made for the cathode and collectors are entirely different than suggested, although both sets of choices are effective and the first set would likely be less costly to implement. Note that there is a sizable margin above the specification requirements.

The heater in this unit operates directly from a 6.3-V RMS 130-kHz AC source. Calculations from the TWT specifications indicate –31.6-dBc AM and –36-dBc PM sidebands at 130 kHz. Measurements show –50-dBc AM and –51-dBc PM sidebands. The differences can be attributed to the filtering effect of the heater's thermal time constant, since the TWT's specifications apply to a change in DC voltage.

A second example involves model dB-4300, a 350-W Ku-band transmitter also manufactured by dB Control. It has much tighter performance specifications than the unit in the first example. It is designed to operate fully exposed to the environment, attached to the antenna in a hub-mount configuration. It operates from a 230-V, 60-cycle power supply and has an approximate switching frequen-

Table 6: Combined power-supply ripple limits

Element	δv_{rms} (V)			
	< 10 kHz	40 kHz	80 kHz	> 500 kHz
Cathode	0.3	0.3	0.3	0.171
Collector 1	120	30	15	2.4
Collector 2	120	30	15	2.4

Table 7: Final power-supply ripple specifications

Element	δv_{rms} (V) < 10 kHz	40 kHz	80 kHz	> 500 kHz
Cathode	0.15	0.15	0.15	0.08
Collector 1	10	10	5.0	1.0
Collector 2	10	10	5.0	1.0

cy of 40 kHz.

The RF specifications for this system include residual AM of –45 dBc below 10 kHz, a value of –20 (1 + $\log f_{kHz}$ dBc from 10 to 500 kHz, and –80 dBc above 500 kHz. In addition, the residual PM of –33 dBc is specified for the AC-line frequency and –39 dBc total (added on a power basis) for all other frequencies.

The microwave tube used in this amplifier is a VTU 6395M5 TWT from CPI (formerly the Traveling Wave Tube Products Division of Varian). Unlike the device in the first example, there is no focus electrode to consider in this TWT.

In this example, several power-supply ripple frequencies are significant. These are the second harmonic of the line frequency, the power-supply switching frequency and its second harmonic, and the heater frequency if it is driven from a different frequency than the main switch.

Regarding PM specifications, it is safest to allow a 5-dB margin for these three sources of ripple (or 6-dB margin for four ripple sources). It is also safe to assume that an additional 3-dB margin for the remaining ripple sources should ensure that, when all ripple sources are added together, the –39-dBc specification will be met. This results in a specification of –39 dBc – 8 (or 9) dB = –47 (or –48) dBc. In this example, –47 dBc is used for the PM limit.

For a residual AM specification of –45 dBc, $\alpha_m \times \delta v_{rms} = 0.068$ (from Fig. 2). At 40 kHz, the specification is –58 dBc and $\alpha_m \times \delta v_{rms} = 0.015$. At 80 kHz, the specification is –64 dBc and $\alpha_m \times \delta v_{rms} = 0.0075$. Above 500 kHz, the specification is –80 dBc and $\alpha_m \times \delta v_{rms} = 0.0012$. As in the first example, by substituting the values of α_m for each tube element into Eq. 4, it is possible to determine the power-supply ripple voltage that would generate the specified AM sideband level (Table 4).

For a residual PM specification of –33 dBc at the AC-line frequency, $\alpha_p \times \delta v_{rms} = 1.8$ (from Fig. 2). For a residual PM specification of –47 dBc, $\alpha_p \times \delta v_{rms} = 0.36$. By substituting the different values of α_p for each tube element into Eq. 6, it is possible to determine the power-supply-ripple voltage that would generate PM sideband levels of –33 dBc and –47 dBc (Table 5).

The tube's heater operates from a DC supply. For this tube component, a regulation and ripple specification of 0.5 percent should be adequate for AM and PM specifications down to –90 dBc (Table 6). The final power-supply ripple specifications must change with frequency. It is also necessary to account for the possible additive effects of ripple from the cathode, collector 1, and collector 2 power supplies. Since the >500-kHz requirement dominates the other requirements, it is set first (Table 7). Actual test results show the validity of these predicted values (Table 8).

In both examples, the performance levels of the power supplies exceed the requirements. While some margins are desired in microwave power-amplifier designs, a customer is usually unwilling to pay for such excess. Also, most tube vendors have margins built into their AM and PM sensitivity specifications. Accordingly, an optimum power-supply design might have somewhat higher power-supply ripple and still meet the performance specifications, while being less costly to build.

Logarithmic worksheet masters for calculating power-supply ripple are available upon request from the author. Readers can also generate their own worksheets by using the following intersection points for the residual AM versus $\alpha_m \times \delta v_{rms}$ curve: residual AM values of –21.0, –41.7, –61.8, and –81.8 dBc correspond to $\alpha_m \times \delta v_{rms}$ values of 1.0, 0.1, 0.01, and 0.001, respectively. Similarly, worksheets for residual PM versus $\alpha_p \times \delta v_{rms}$ can be generated with residual PM values of –18.2, –38.2, –58.2, –78.2, and –98.2 dBc corresponding to $\alpha_p \times \delta v_{rms}$ values of 10, 1.0, 0.1, 0.01, and 0.001. ••

Table 8: Test data on the dB-7350-KuH

Ripple frequency (Hz)	Cathode voltage (V RMS)	Collector 1 voltage (V RMS)	Collector 2 voltage (V RMS)	Residual AM data (dBc)	Residual PM data (dBc)
60	0.03	0.38	0.47	–67.0	–58.7
120	0.056	1.32	1.26	–77.5	–61.4
40,000	0.018	0.30	0.40	–73.0	–71.0
80,000	0.05	0.18	1.12	–70.4	–63.5
> 500,000	0.011	0.033	0.45	–89.5	–72.0
Sum of all others					–57.8