TRANSMITTERS FOR ANALOG TELEVISION

Significant advances continue to be made in television (TV) transmitter technology. New technology has been introduced to provide high-quality TV signal transmission while improving reliability, reducing maintenance, and lowering overall cost of ownership. These new technologies include solid-state, high-power amplifiers and improvements in UHF tube transmitters. The FCC continues its policy of technical deregulation which allows more flexibility in transmitter design and system operation. This article discusses the relevant technology and provides the information needed to understand the operation, design criteria, and some of the future developments of TV transmitters. Although this information is presented from the viewpoint of equipment used in the United States, the principles apply to analog TV broadcasting worldwide. Specific details and numerical constants may differ in other systems, but the fundamental principles are the same.

TV transmitters are composed of two essential components, the exciter and the RF power amplifier (PA). The exciter provides the signal processing functions to convert a baseband TV signal into a modulated RF signal on the assigned channel. These functions include baseband signal processing, modulation, precorrection, equalization, upconversion, band limiting, and amplification to a relatively low power RF signal. Although different methods are used for different types of signals, all functions must be performed whether or not the baseband signal is video or audio. Because the output of the exciter is a modulated RF signal, most commercially available exciters are considered low-power transmitters.

The basic block diagram of a television transmitter that provides separate amplification of visual and aural signals is shown in Fig. 1. The visual portion of the exciter receives a video baseband signal, processes it, and converts it to a fully modulated vestigial sideband signal. Because intermediate frequency (IF) modulation is used in all modern TV transmitters, most of the signal processing occurs in the video and IF stages. In similarly, the aural portion of the exciter receives the audio baseband signal, processes it, and converts it to a frequency-modulated signal. The exciter includes all blocks through the upconverter.

For transparent transmission of video, it is important to optimize the incoming signal which is done in the video processing section of the exciter. The following are the main functions of the exciter video processing circuitry:

- assurance of proper sync to video ratio
- removal of common mode signals
- provision for overall video level control
- dc restoration
- prevention of overmodulation
- frequency response correction

In nearly all IF modulated transmitters, the visual modulator is a broadband, balanced, diode mixer. It is configured for maximum rejection of the local oscillator signal and biased to provide excellent linearity, low noise, and capability to achieve carrier cutoff. The video signal is dc offset to provide the proper modulation level. Peak of sync corresponds to maximum IF envelope output and white corresponds to minimum IF output. The output signal of the modulator is a double-sideband AM signal that has a modulation depth of 12.5%. A surface acoustic wave (SAW) filter removes the lower sideband and produces vestigial sideband (VSB) modulation. This filter also band-limits the upper sideband to within 4.75 MHz of the visual carrier.

In its most basic form, the aural exciter consists of an audio processor, a frequency-modulated IF oscillator, and upconverter. To ensure that the transmitter is not the limiting factor in monaural and stereo audio reproduction, the transmitter must add as little distortion as possible to the incoming signal. Baseband audio of the BTSC Multichannel Television Sound (MTS) system may include monophonic or stereo, a second audio program (SAP), and professional channels. These signals may include frequency components out to 105 kHz. To achieve good stereo separation and minimum cross talk between the stereo and the SAP channels, it is necessary to achieve good phase linearity, low distortion, and reduced amplitude ripples and roll-off over the stereo passband. Errors in phase linearity and amplitude response within the audio circuitry contribute to stereo separation degradation. As a general rule, amplitude roll-off should be less than 0.1 dB, and departure from phase linearity should be less than 1° for quality stereo.

Transmitters employing IF modulation generate visual IF, aural IF, and master oscillator signals for translating visual and aural IF to the final carrier frequencies. These signals are implemented with either digital synthesizers or crystal oscillators. An advantage of the synthesizer is that only one crystal is needed at a single standard frequency for all TV channels. Synthesized sources should be tested for spurious

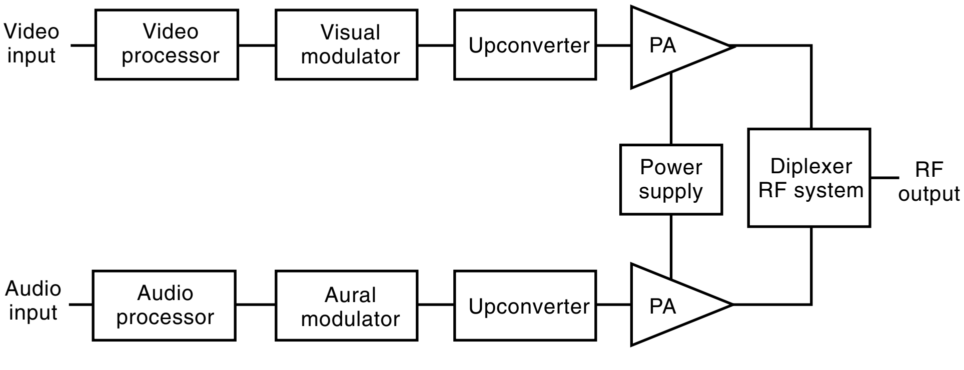

Figure 1. Block diagram of a basic television transmitter.

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frequencies which may appear as FM noise. The crystal oscillator usually involves simpler circuitry.

The PA provides the "muscle" to amplify the modulated RF signal to the desired level for transmission. The type of power amplifier technology used to perform this function is key. Both solid-state and tube devices are available in commercial equipment. For VHF channels, solid state devices predominate. For UHF, both solid-state and tube devices are used. TV transmitters are unique in that no other application requires such high levels of linear RF power generation while operating virtually uninterruptedly. This has led to the development of specialized techniques to assure highly efficient and reliable operation. The need for high efficiency has led to the near universal use of partially saturated Class AB final power amplifiers. This, in turn, has resulted in the development of precorrection and equalization techniques to compensate for residual nonlinearity inherent in this class of operation. To achieve the levels of reliability required, redundant system architectures that minimize single points of failure are used.

Traditionally, TV transmitters have used separate RF amplifier chains for the visual and aural signal paths. This is generally the most cost-effective approach for high-power, solid-state transmitters for both VHF and UHF. Many broadcast engineers believe separate amplification provides the highest quality transmitted video. With the introduction of inductive output tubes (IOT) as final high-power UHF amplifiers, it has become popular to combine the visual and aural signals in the exciter and amplify them together in the stages that follow.

For visual signals in separate amplification and combined aural and visual signals in common amplification, it is important that the power amplifier have a linear transfer characteristic in amplitude and phase and flat, symmetrical frequency response and minimum group delay variation across the modulation passband. For visual only signals, the required bandwidth is 4.5 MHz. For common amplification and digital signals 6 MHz is required.

Even though linear Class AB amplifiers are used, some residual nonlinearity remains. With combined amplification, the visual, color subcarrier and aural signals are mixed to produce in-band as well as the out-of-band intermodulation (IMD) and cross-modulation products. The out-of-band products sufficiently removed from the channel of operation may be eliminated by a high-level filter. However, in-band products can be reduced to acceptable levels only by making the transmitter sufficiently linear. This requires highly effective precorrection circuits in the IF and/or RF signal paths. For example, the IMD within ±920 kHz of the visual carrier can be precorrected by low level IF circuitry.

For optimum stereo performance a nonlinear Class C amplifier with flat response and group delay across the modulation passband may be used. Because frequency modulation and demodulation is a nonlinear process there is not a one-to-one correspondence between RF amplitude and phase response and baseband stereo separation and cross talk. Generally, a 3 dB bandwidth of 1.5 MHz provides excellent stereo and SAP performance.

Other key functions in the PA, common to all amplifier technologies, include cooling and ac-to-dc power conversion. Proper cooling of the power amplifier, whether solid-state or tube, is important for safe operation and high reliability. For example, it is generally acknowledged that the service life of a transistor doubles approximately for every 10°C reduction in junction temperature. Power amplifier cooling may employee either liquids or air. Distributed air cooling systems using more than one fan offer good redundancy for solid-state amplifiers. Motor and fan technology has matured to the point where a single, large, direct drive fan is as reliable as many smaller fans. Because many RF power amplifiers modules may be employed in a solid-state transmitter, a large volume of air is needed to cool the heat sinks adequately. Low-pressure fans or blowers may be used if heat-sink fin density is not high. This aids in reducing audible noise. The heat is distributed over a large volume of air, and the temperature rise is relatively low.

Cooling of most tube amplifiers requires large volumes of liquid. For example, cooling a 60 kW IOT, typically used for high-power UHF applications, requires about 25 gallons per minute of liquid for the collector under maximum ambient temperature conditions. The body of the tube is also liquid cooled. A 50:50 water/glycol solution is typically used in cold climates without any special water purification. Input and output cavities are air cooled. Lower power IOTs may be air cooled. Air cooling is also used to cool other transmitter components, such as the intermediate power amplifier (IPA).

Power supply design is critical to the performance and reliability of television transmitter power amplifiers, whether solid-state or tube. Because FET and bipolar devices are low-voltage devices, the power supplies which serve solid-state transmitters must provide low voltage and high current. High reliability connections must be guaranteed in the dc distribution. Because the available power output from any amplifier varies with the square of the dc voltage applied, it is desirable that the supply remain very tightly controlled over incoming ac line variation. The amplifier current also changes with modulation, thus requiring video frequency currents from the power supply. The supply must provide excellent regulation from no load (white picture) to full load (peak sync output) and a low source impedance for all video frequencies. The efficiency of the power supply is important because dissipated power results in heat and unnecessarily high utility costs. Any voltage or current transients or voltage sags at the ac input should be suppressed before reaching any solid-state device.

Television transmitters that employ separate amplification and use a common antenna and transmission line for visual and aural require a high level diplexer to combine the visual and aural signals before transmission. Other components required in the output RF system include harmonic filters and a color notch filter. If multiple transmitters or PA cabinets are combined, power combiners and RF switching devices are also required.

KEY PERFORMANCE FACTORS AND OPERATIONAL CONSIDERATIONS

The key performance factors for the visual portion of a television transmitter include power output, linearity, efficiency, and reliability. These factors are also important for the aural section except that linearity in separate amplification aural amplifiers is not needed.

The geographical separation and effective radiated power (ERP) of television stations are carefully specified by the FCC to assure reliable service within the coverage area and to avoid interference between stations operating on the same frequency, that is cochannel interference. The visual transmitter power output (TPO) is determined from the ERP by using the antenna gain (1) g and the transmission line efficiency η. Stated mathematically,

$$\mathrm{TPO} = \frac{\mathrm{ERP}}{g\eta}$$

ERP is given in kilowatts (kW) of power at the peak of the synchronizing (sync) pulse so that the TPO is also in kW at the peak of sync. Table 1 relates TPO and ERP for typical low-band VHF, high-band VHF, and UHF stations using the maximum allowable ERP for each band.

The transmission line efficiency varies depending on tower height and the type and size of line selected. The minimum line size is determined by the TPO and desired line efficiency.

Aural power may range from 5 to 20% of the visual peak sync value. Most stations transmit aural at 10% although some UHF stations using common amplification reduce the aural power to as low as 5% to reduce IMD products.

Calibration of transmitter power is vitally important. ERP is specified by the FCC. Thus maintaining TPO within tolerance assures that the ERP is in accordance with the allocation. If the power output is not accurately known, the amplifier dissipation and efficiency are equally unknown, and power amplifier device life may be shortened. In addition, linearity precorrection circuits must be set up at a known, stable power level to assure that system linearity is maintained. Calibration of power level is best done by using a calorimeter, especially for higher power transmitters. In a calorimeter, the temperature rise of a known volume of water caused by the heat generated in a water-cooled load is used to determine the average power output. For the visual transmitter, this measurement is done with modulation at blanking level, or 75% of peak sync. The measured average power is converted to peak sync power by multiplying by the peak to average ratio (1.68). The formula for the power calculation is

$$P_o = (1.68)(0.264)(T_o - T_i)R_f$$

where T_o is the temperature of the water exiting the load in degrees Celsius, T_i is the temperature of the water entering the load, and R_f is the flow rate in gallons per minute. The numeric factor 0.264 is the specific heat of water.

Table 1. Typical Transmitter Power Output for VHF and UHF

Band	ERP, kW	Antenna Gain	Line Efficiency, %	TPO, kW
Low VHF	100	6	85	19.6
High VHF	316	12	80	32.9
UHF	5000	30	76	219.3

For aural output, the measurement technique may be similar. However, because the peak and average power for a frequency-modulated signal are the same, the peak to average factor is unity. Alternatively, the aural power may be set by observing the relative levels of the visual and aural signals on a spectrum analyzer. This is especially useful for measurements made after the signals are combined, as in common amplification.

Accurately calibrated couplers and low-level power meters located at the output of the transmitter RF system are also widely used for power measurement. Because the coupling factor is known, the reading of the power meter may be calibrated to the actual power output.

Efficiency

Because of environmental concerns and the high cost of electricity, TV transmitters must operate efficiently. Although efficient power conversion is important at VHF, it is unusually important for UHF transmitters because the transmitted power is almost always much higher and consequently much more expensive to generate. When considering the efficiency of TV transmitters, several factors must be understood. To determine total power consumed, the ac to RF conversion efficiency is the parameter of interest. For systems with unity power factor, determining the ac input power is relatively straightforward. For power factors less than unity, the relative phase of the ac fundamental voltage and current must be determined. In addition, in systems generating significant line harmonics, the relative level of these harmonics must be known (2). Power factor is expressed either as displacement power factor or total power factor. Displacement power factor (DPF) is the cosine of the phase between the voltage and current at the fundamental frequency:

$$\mathrm{DPF} = \cos(\phi_v - \phi_i)$$

The displacement power factor is equal to the total power factor only for undistorted sinusoidal voltage and current waveforms.

Total power factor is the ratio of total ac power input P_i to the apparent power VI.

$$\mathrm{PF} = \frac{P_i}{VI}$$

Determining input power is simplified by considering only the dc to RF conversion process. In this case it is necessary to determine only the voltage and current provided by the power supply to the final amplifying devices. Although this is a useful tool for evaluating power amplifier performance, it has the disadvantage of ignoring the power consumed elsewhere in the transmitter, such as power supplies for drive stages, cooling systems, filament power, magnet power, and control system power. If these items are to be included in the efficiency calculation, they must be determined separately.

Determining output power for efficiency calculation is equally complex. As we have seen, transmitters are rated in terms of peak sync visual power. Exclusive use of this number neglects the aural output. Some amplifier technologies exhibit apparent efficiencies greater than 100% if visual peak power is used as the measure of output power. This has given rise to the use of a figure of merit (FOM) defined as

$$\mathrm{FOM} = \frac{P_\mathrm{o}}{P_\mathrm{dc}}$$

where P_o is the visual peak sync output power and P_dc is the dc input power at 50% average picture level (APL). This definition is valid for transmitters using separate amplification. For common amplification, the aural input and output power must be added to the denominator and numerator, respectively. Typical values of the figure of merit for several tube amplifiers operating in separate amplification are shown in Table 2 (3).

The dc input power for a typical visual only power amplifier is given by

$$P_\mathrm{i} = V_\mathrm{b}(I_\mathrm{s}\mathrm{DF}_\mathrm{s} + I_\mathrm{v}\mathrm{DF}_\mathrm{v}]$$

where V_b is the beam voltage, I_s, is the beam current at peak sync, DF_S is the duty factor of the sync pulse (0.08), I_v is the beam current during video, and DF_v is the duty factor of the video (0.92). For a 60 kW pulsed klystron, typical values are V_b = 24 kV, I_s = 5.5 A, and I_v = 3.7 A, so that

$$P_\mathrm{i} = 24[(5.5 \times .08) + (3.7 \times .92)] = 92.2\,\mathrm{kW}$$

and

$$\mathrm{FOM} = \frac{60}{92.2} = 0.65$$

Other important efficiency factors to consider include the power lost in the RF system and antenna transmission line. These losses can be considerable and represent added cost of operation after the full cost of generating the transmitter output power has been spent. Thus it is extremely important to minimize these losses. If losses are to be minimized, the largest coaxial transmission line or waveguide should be used consistent with avoiding higher order modes and within the wind-load capability of the transmission tower. At UHF, the choice is usually between $6\frac{1}{8}$ inch or $8\frac{3}{16}$ inch coaxial line or rectangular or circular waveguide. The larger the coaxial line, the lower the loss. However, at the higher UHF channels, $8\frac{3}{16}$ inch line supports an evanescent waveguide mode. Rectangular and circular waveguides provide lower loss but are larger in cross section than coaxial lines. The larger the physical size of the line, the higher the wind load. Because of its cross-section, circular waveguide, offers lower wind load than rectangular. Thus many factors must be considered when selecting transmission line type and size. The larger size coaxial lines and waveguides are more expensive to purchase and install. However, this is a one-time cost that should be carefully weighed against the long-term reduction in transmitter plant efficiency resulting from the use of a line with excessive loss.

Table 2. Figures of Merit for Commonly Used Tube Amplifiers

Amplifier Device	Figure of Merit
Tetrode	0.9-1.0
Integral cavity klystron	0.65-0.75
External cavity klystron	0.65-0.75
Klystrode or IOT	1.1-1.3
Depressed collector klystron	1.2-1.3

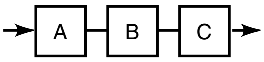

Figure 2. Subsystems in series.

Reliability

Many stations operate continuously unattended, making reliability a key requirement. There are many factors which affect the reliability of a TV transmitter. Overall design philosophy, device technology, module design, control architecture, power supplies, cooling, and cabinet design are critical areas, all of which must be considered. Consider a transmitter design which uses subsystems in series with no system redundancy. If one device fails, the entire transmitter fails, that is, each subsystem represents a critical point in the event of failure. This is illustrated in Fig. 2 which shows a system of three subsystems in series with no redundancy. This might represent a tube-type transmitter with a single exciter and IPA. If each device (a, b, c) has a reliability or probability of functioning until time t, the reliability of the system $R_\mathrm{s}(t)$ is given by the product of each subsystem reliability:

$$R_\mathrm{s}(t) = R_\mathrm{a}R_\mathrm{b}R_\mathrm{c}$$

If three identical subsystems are operated in parallel, as in Fig. 3, and only one is required for on-air operation, there are no single points that may cause system failure. This represents a parallel arrangement of identical PAs, each with their own IPA. In this case, the overall system reliability is given by

$$R_\mathrm{s}(t) = R_\mathrm{a} + R_\mathrm{b} + R_\mathrm{c} - R_\mathrm{a}R_\mathrm{b} - R_\mathrm{a}R_\mathrm{c} - R_\mathrm{b}R_\mathrm{c} + R_\mathrm{a}R_\mathrm{b}R_\mathrm{c}$$

To illustrate, assume that each subsystem has a reliability of 0.5. In the series case, the system reliability is only 0.125. In the parallel case, the reliability is 0.875, an improvement by eight times.

The reliability is related to failure rate λ as follows:

$$R(t) = e^{-\lambda t}$$

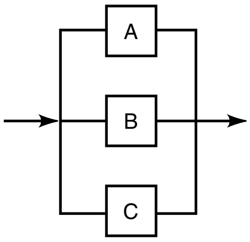

Figure 3. Subsystems in parallel.

The mean time between failures (MTBF) is the reciprocal of the failure rate:

$$\text{MTBF} = \frac{1}{\lambda}$$

On-air availability is related to reliability but perhaps even more important. On-air availability is the percentage of time the transmitter is available for service, defined by the following equation:

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR} + \text{MPMT})} \times 100\%$$

where MTTR is the mean time to repair and MPMT is the mean preventative maintenance time. All quantities are stated in hours (or other consistent time units).

There is little point in designing a transmitter that has high a MTBF figure if because of poor design and mechanical packaging, it takes an inordinate length of time to make repairs, or if the transmitter has to be shut down frequently for routine preventative maintenance.

Many stations have very short sign-off windows or operate 24 h a day. This often results in a less than optimum maintenance schedule which can lead to premature failure or out of tolerance operation. One way to reduce the amount of off-air maintenance time is by making provisions for on-air maintenance or to have redundant transmitters. This significantly reduces the MPMT.

Several design factors should be considered for optimum on-air availability. These include high reliability of the fundamental circuits and provision for fast, easy access to all subassemblies. A subassembly, which can be readily removed, can be repaired by station personnel or returned to the manufacturer for exchange. Another factor contributing to availability is the maximum use of common parts and subassemblies. If fewer items are needed, it is more economical for the station to maintain a full inventory of spares. If spares are on hand, the repair time may be much shorter.

Linearity

This parameter refers to the degree with which the transmitter output signal is directly proportional to the input. Common terms used to quantify the degree of transmitter nonlinearity include low frequency or luminance nonlinearity, differential gain and AM to AM conversion. Output phase may also be a function of input level. The deviation from linear phase is often quantified as incidental carrier phase modulation (ICPM), differential phase, and AM to PM conversion. These deviations from linearity are called nonlinear distortions, that is distortions to the transmitted signal introduced by nonlinear components in the transmission path. A nonlinear component is any device whose complex output voltage is not directly proportional to input voltage. Power amplifiers operating near compression and intermediate power amplifiers (IPAs) are major contributors to nonlinear amplitude distortion. This process creates the frequency spectra of the lower sideband, usually called lower sideband reinsertion. Filters are commonly used to reduce sideband spectral components, but these introduce phase distortions.

Differential gain is nonlinear chroma gain as a function of luminance level. A change in the picture color saturation results from differential gain. Differential phase is nonlinear chroma phase as a function of luminance level. A change in picture hue results from differential phase. Low frequency or luminance nonlinearity is the change in luminance gain as a function of picture brightness level.

Precorrection is a technique to compensate for nonlinear distortion. The objective of precorrection is to provide a complementary transfer function that when operating on the nonlinear transfer function of the power amplifier, minimizes total system nonlinear distortion. Precorrection may be introduced in the baseband, IF or RF sections of the system and may be manually or adaptively adjusted.

IF linearity precorrection provides the correction for nonlinear distortions in the intermediate frequency (IF) sections of the exciter. There are important advantages to correcting at IF. Because most distortions are caused in the high power RF amplifiers after vestigial sideband (VSB) filter, a precorrector placed after the VSB filter can most accurately precorrect the modulated signal. Intermodulation products are caused by the nonlinear transfer function of the IPA and PA. As the power output increases toward saturation, amplitude compression and phase lag occurs. The nonlinear transfer function gives rise to mixing products which occur at sum and difference frequencies around the visual carrier. Precorrection spectra generated at IF after the VSB filter produce energy components which can cancel intermodulation products generated in the amplifier stages. This is particularly important for pulsed klystron or common amplification transmitters.

An example of a basic gain expansion circuit used for precorrection is shown in Fig. 4. The signal is normally attenuated a fixed amount by using a resistive L-pad, $R1$ and $R2$. The diodes, D1 and D2, are normally reverse biased by equal but opposite dc voltages. Reducing the dc voltage permits the diodes to conduct on the signal peaks, inserting additional resistance in parallel with the series arm of the L-pad attenuator, thereby decreasing the attenuation. Varying the resistance in series with the diodes provides variable gain expansion.

Incidental-Carrier Phase Modulation

Nonlinear phase distortions in high power amplifiers produce incidental-carrier phase modulation (ICPM) or spectral com-

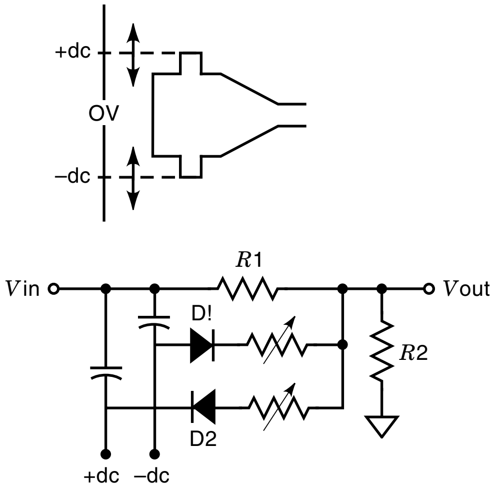

Figure 4. Basic gain expansion circuit.

ponents in quadrature with the modulated signal. Fast video amplitude changes, such as a step or pulse, cause larger incidental-phase spectral components than slow changes. Receivers make this condition worse by attenuating the lower sidebands below 0.75 MHz. The receiver responds to the extra sidebands created by the phase modulation as if they were amplitude-modulated single sidebands, producing spikes. The faster the rise time of the signal, the more high frequency energy is present, resulting in edge distortions in the picture.

The picture impairment due to ICPM is similar to simultaneous group delay and differential-phase errors in that edges are less sharp and the color hue changes with brightness. On a waveform monitor, overshoots are visible on trailing edges and as rounding of leading edges. These overshoots vary in severity depending on how far into saturation the power amplifier is driven.

Audio impairment is produced by ICPM in receivers employing intercarrier conversion. Intercarrier receivers use an AM or synchronous detector to produce a 4.5 MHz aural IF from the composite video IF. Any phase modulation on the visual carrier is transferred to the aural carrier. For monoaural baseband audio, the effect of increasing amplitude versus frequency of ICPM is nullified to some degree by receiver deemphasis. With multichannel sound, however, there is no deemphasis applied to the baseband stereo signal, and the distortion is more pronounced at the stereo subchannel and pilot frequencies. Audio companding is employed to counteract the effects of ICPM and other noise sources on the stereo subchannel. Although the audio companding process reduces some of the effects of ICPM, precorrection is essential for delivering clear, low-noise audio to intercarrier receivers.

There is no defined level of ICPM for a given stereo performance level because the signal-to-buzz ratio is highly dependent on the picture spectral components. Refer to the EIA Recommended Practices (4) for recommendations on ICPM limits.

ICPM precorrectors are grouped into two types: those using a phase modulator and those inserting a fixed phase directly on the signal. The phase modulator uses video to modulate the IF or a master oscillator with a phase characteristic opposite that of the nonlinear amplifier. A phase modulator can also operate directly on the IF signal using a video signal to set the amount of modulation. A block diagram of a master oscillator phase modulator is shown in Fig. 5.

ICPM precorrectors operating directly on the IF signal are implemented in several ways. Direct precorrection at IF is similar in concept to baseband differential phase precorrection. In both cases, the visual signal is split into two-phase quadrature paths, as shown in Fig. 6. In the IF corrector, the full video bandwidth is processed, whereas in the video precorrector only the chroma signal is affected. One method of implementation is to modify the quadrature signal gain function with level-dependent diode expansion or compression circuits. This can be done by the same techniques as in the linearity corrector.

The vector diagram shown in Fig. 7 illustrates the operating principles of the ICPM and linearity correctors. The input signal is represented by the vector on the left. Because of nonlinear distortions in the transmitter, the output signal is shifted in phase and compressed, producing the resultant distorted signal. To produce the correct output signal, it is necessary first to expand the in-phase signal and introduce an equal and opposite quadrature signal. When the resultant signal is amplified, the output signal is restored to the undistorted TV signal.

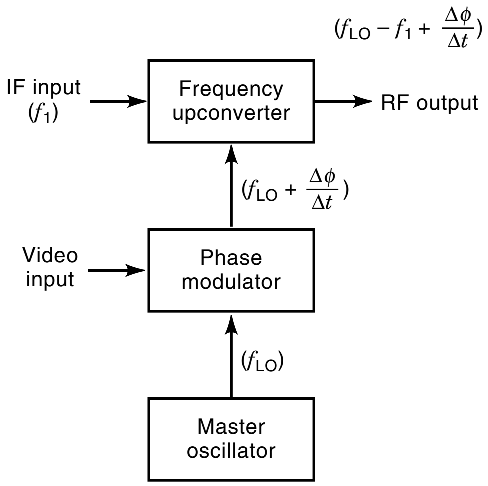

Figure 5. Block diagram of master oscillator phase modulator.

Linear Distortions

These are distortions to the transmitted signal that are not level-dependent. Unlike nonlinear distortions, linear distortions can be introduced by linear (as well as nonlinear) components in the transmission path. These components include any device with a nonconstant frequency response, such as matching networks, cavities, filters, diplexers, and other tuned circuits. Variations in both amplitude and phase are produced, that is, variations in both in-band amplitude response and group delay produce linear distortions.

Group or envelope delay (GD) is the nonuniform delay of different frequencies over the signal bandwidth, that is, the first derivative of phase with respect to frequency:

$$\mathrm{GD} = \frac{d\phi}{d\omega}$$

Group delay is caused by nonlinear phase as a function of frequency inherent in RF amplifiers, filters, combiners, and other devices. In general, the closer the amplitude roll-off is

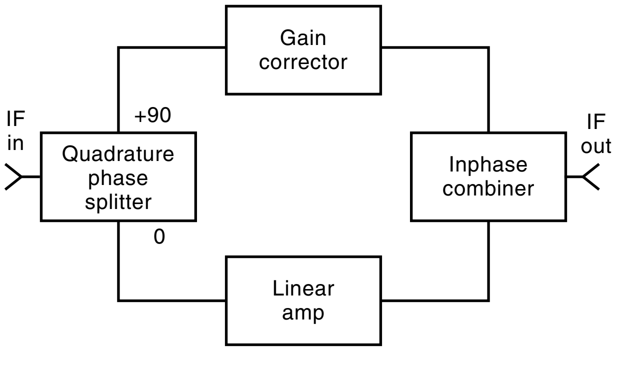

Figure 6. Direct ICPM corrector.

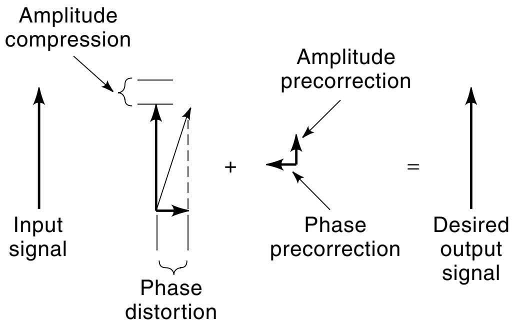

Figure 7. Vector representation of precorrection.

to the passband of a tuned circuit, the higher the group-delay distortion.

Equalization is the technique used to compensate for linear distortions. The objective is to provide a complementary transfer function that when operating on the frequency response function, minimizes linear distortion. Equalization may be introduced in the baseband, IF, or RF sections of the system and may be manually or adaptively adjusted.

Group-delay equalization of the aural transmitter introduces group-delay equalization in the IF section of the aural modulator, effectively correcting the group delay in the diplexer. The result is improved TV stereo separation. The notch diplexer is a passive device, but it can introduce significant linear distortions that degrade stereo separation because the FM stereo signal is most sensitive to the notch diplexer group delay and amplitude response over the occupied bandwidth of the FM signal. The group delay and amplitude response of a single-cavity diplexer optimized for minimum aural reject power is shown in Fig. 8. The bandpass is somewhat narrow, and the group delay is steep. Fortunately, the response curves have a high degree of symmetry which makes equalization possible. Equalization of the FM bandpass allows using a lower cost, single-cavity notch diplexer. A stagger-tuned, dual-cavity, notch diplexer might be used to provide more bandwidth. However, a dual-cavity, notch diplexer introduces more group delay in the visual path and is more expensive than a single-cavity diplexer.

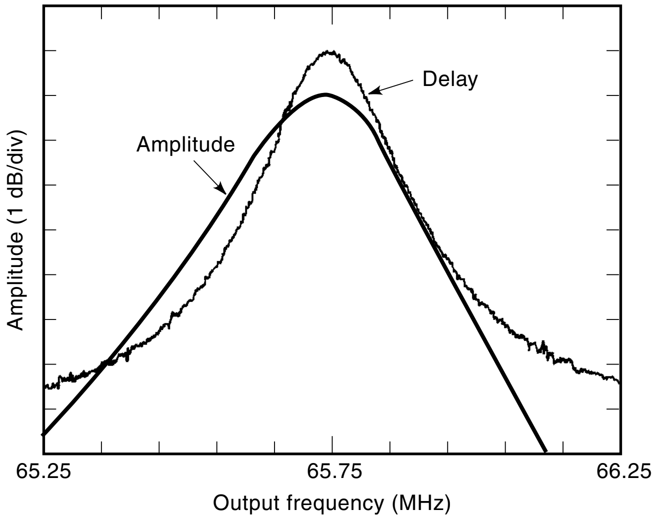

Figure 8. Single-cavity notch diplexer amplitude response and group delay.

Transmitter Control Systems

The transmitter control system provides the interface to the user. It provides control, monitoring, and protection for the transmitter. Essential control features include transmitter on and off, output power raise and lower, remote or local control selection, and automatic gain or level control. Other automatic control features, such as VSWR foldback, are desirable. VSWR foldback reduces forward power when reflected power is high, such as in antenna icing, and restores RF power to normal when the reflected power returns to normal.

Easy to read status indicators are essential for quick fault diagnosis. Typical status conditions displayed include exciter fault, VSWR fault, VSWR foldback status, power supply fault, controller fault, loss of cooling air, door open, fail-safe interlock open, ac phase loss, RF power module fault, visual drive fault, aural drive fault, and external interlock open.

If individual RF amplifier modules and power supplies are self-protecting, the system control and monitoring functions are relatively simple and straightforward. A most effective approach is to distribute the control system throughout the transmitter, as shown in Fig. 9. In the distributed control system, the failure of any individual controller component does not affect the operation of the others. For example, failure of any single cabinet controller would not affect the operation of the other cabinet controllers or the main controller. Failure of the main controller would not cause an off-air condition if the cabinet controllers operate independently of the main controller. Failure of monitoring and metering should not cause an off-air condition. It is also important that the controller have back-up memory to restore the transmitter operating condition after ac power failure.

TRENDS IN TV TRANSMITTER DESIGN

Television broadcasting is a mature technology. In the near half century since the adoption of the color standard there has been steady progress in transmission technology. The prospect is for improvements to continue. Many of these will

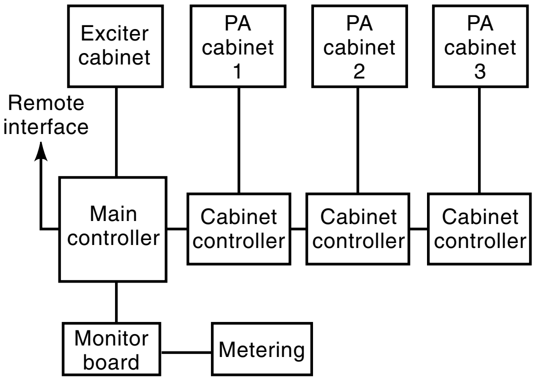

Figure 9. Distributed control and monitoring.

occur simply because TV transmitters involve such a wide range of electronics technology. Others will be driven by the implementation of digital television (8). It may be expected that the analog transmission will benefit from many of the improvements created by the digital revolution. Improvements that reduce the cost of ownership, improve the human to transmitter interface, and simplify operation and maintenance are the areas in which the most progress can be expected. These will include steady improvements in high-power, solid-state devices and high-power UHF tubes, advances in digital signal processing and in microprocessor-based controls, and improved displays for monitoring functions. The pervasive use of digital technology will allow more and more functions that have traditionally been defined by the hardware design to be part of software.

SOLID-STATE DEVELOPMENTS

Technological advances in bipolar and field effect transistors (FET) have made the development of solid-state, high-power, linear amplifier modules for TV applications both practical and cost effective. By combining RF modules, it is practical to create transmitters at any power range up to 75 kW. This is especially true for the VHF bands and is becoming increasingly true for UHF. The trend in solid-state technology is to devices that produce higher power at higher frequencies and lower cost. As costs are reduced, the feasibility of higher power transmitters at UHF is enhanced. Solid-state power amplifiers are operated in class AB for the best tradeoff of efficiency, linearity, reliability, and cost. Driver stages usually contain class A amplifiers.

There are several advantages to high-power, solid-state technology. Solid-state transmitters maintain their performance over extended periods of time because of the absence of tuning controls and degradation of filament emissions. No warm-up time is required. Solid-state transmitters produce full rated power within seconds of activation. Solid-state transmitters most often are air cooled. This has the advantage of eliminating any chance of coolant spills and concern for cooling system freeze up in cold climates. There have been some attempts to develop liquid-cooled solid-state transmitters. The advantages of liquid cooling include somewhat quieter operation and improved cooling efficiency. Safety is also enhanced in solid-state systems. Operating voltages are usually 65 V or lower compared to tens of kilovolts for tube amplifiers. There is no need for crowbars to protect solid-state devices in the event of a short circuit. However, protection against lightning and static-induced transients is required. Maintenance is also eased. Solid-state transmitters employ modular architectures in which a large number of RF and power supplies modules operate in parallel. Failure of any one of these units has only a minor effect on TPO. Thus immediate corrective action is not as critical as in tube transmitters in which there may be only a single output tube. Simple diagnostic displays make the identification of the failed unit easy. Hot pluggable designs and a minimum of spare modules make it possible to remove and replace the failed unit while the transmitter remains on-air. Repair of the failed unit may be done off-line.

Both bipolar and field effect transistors (FET) are used today as RF amplification devices. Vertical metal oxide silicon field effect transistors (MOSFET) are the devices of choice for VHF transmitters. Both bipolar transistors and MOSFETs have been available for UHF. However, UHF vertical MOSFETs are not as linear and therefore not as cost effective as bipolar devices. Recently, laterally diffused metal oxide silicon field effect transistors (LDMOS) have developed cost-effective linear power for UHF. This has enabled producing cost-effective, solid-state transmitters for UHF. Although both bipolar transistors and FETs have merit, FETs have some advantages over bipolar devices. FETs have an amplification factor higher than bipolar transistors, reducing the number of driver stages required. The fewer the drive stages, the lower the manufacturing cost, and the better the linearity because there are fewer parts contributing to cost and nonlinearity. The higher power supply voltage required by FETs reduces the current rating required for the power supply. Power supply cost is driven by current rating. Simple bias circuitry for FETs minimizes parts count and amplifier production cost.

New developments in high-power, solid-state devices are ahead. Silicon carbide (SiC) materials make it possible to produce a variety of devices. In addition to blue light-emitting diodes (LEDs) and switching transistors, linear high-power UHF transistors are under development (6). These transistors promise to operate at voltages and temperatures higher than ordinary silicon devices, thereby increasing available power output, system efficiency, and cooling effectiveness while lowering transmitter system cost.

TRANSMITTER TUBES

Because higher transmitter power is needed, power consumption and efficiency are of utmost importance for UHF transmitters. Although solid-state transmitters offer many advantages to the broadcaster, many UHF stations find that the most cost-effective transmitter design is based on tube technology. Many of the advantages of solid-state transmitters may be adapted to tube-based designs. For the highest power multiple output tubes, each with its own drive chain, provide a minimum level of redundancy and the benefits of a soft-fail architecture. The high beam voltage required by tubes minimizes power supply cost. Liquid cooling for high-power tubes results in low acoustic noise within the transmitter plant. Some of the lower power and more efficient tubes are air-cooled. High-power tube designers have shown great ingenuity in improving operating efficiency and bandwidth, so that tubes remain a viable alternative for UHF transmitters (7).

A variety of tube technologies are available to address UHF requirements. These technologies include tetrodes, klystrons, multiple-stage depressed collector klystrons (MSDC) and inductive output tubes (IOT). Some are most suited for lower power transmitter designs, and others are more appropriate for the highest power requirements. Work has been recently reported on a constant efficiency amplifier (CEA) that promises dramatic improvements in UHF transmitter efficiency. This tube combines the design of the IOT and the MSDC to achieve near constant and high efficiency independent of drive level.

TETRODES

Tetrodes are a generic category of four-element tubes suitable for the linear amplification of RF signals (5). The anode and screen grid are cooled with distilled water. Typical peak sync power ratings are up to 30 kW, although a “dual tetrode” design boasts a 60 kW rating. Tetrodes are biased for Class AB operation and therefore, are more efficient than the Class A klystron. The tetrode beam voltage is much lower than that of the klystron or inductive output tube. Tetrodes exhibit excellent linearity. The tradeoff for performance in these areas is power gain lower than most other amplifiers. The gain of a tetrode is only about 15 dB. Tetrode filament currents are high to minimize cathode current modulation of the cathode temperature. “Black heat” is used to reduce the time to on-air. This feature provides a lower than normal filament voltage and current to keep the filament warm when the transmitter is off-air. This reduces the thermal stress on the filament when going quickly to full power.

UHF power tetrodes combine visual and aural amplification. Ten percent aural power is the norm, and tubes are rated according to peak sync power with the aural carrier. For example, a typical UHF tetrode may be rated at 30 kW peak sync. With 10% aural power, the peak envelope power (PEP) is 52 kW.

KLYSTRONS

For a discussion of klystrons, refer to the article on this subject. See also Ref. 3.

INDUCTIVE OUTPUT TUBES (IOT)

The IOT combines features of a tetrode and a klystron. The electron beam is constrained similarly to that of a klystron by using electromagnets. The mode of operation of the IOT is similar to that of a tetrode. However, there are significant differences because of differing geometry. An IOT, shown schematically in Fig. 10, is composed of an electron gun very similar to a klystron, a control grid, an input cavity, accelerating anode, drift tube, output cavity, and collector. The electrodes are arranged linearly unlike the concentric configuration of a tetrode. An IOT is physically smaller than a klystron. The electron beam is formed at the cathode. It is density-modulated by the input signal applied to the control grid via a resonant cavity and then accelerated through the anode aperture. The grid is biased negatively near cutoff. The first part of the tube may be thought of as a triode with a perforated anode through which the electron beam is guided by electric and magnetic fields. The beam is bunched at the radio frequency and is accelerated by the high anode potential. In its bunched form, the beam drifts through a field-free region (the anode extension cylinder, which is an electrostatic shield). Then the beam interacts with the RF field at the drift-tube gap in the output cavity. Power is extracted from the beam in the output cavity in the same manner as a klystron. The spent beam is dissipated in the collector which is separate from the output RF interaction circuit. The grid may intercept some electrons causing a small amount of grid current. This increases markedly if the tube is overdriven.

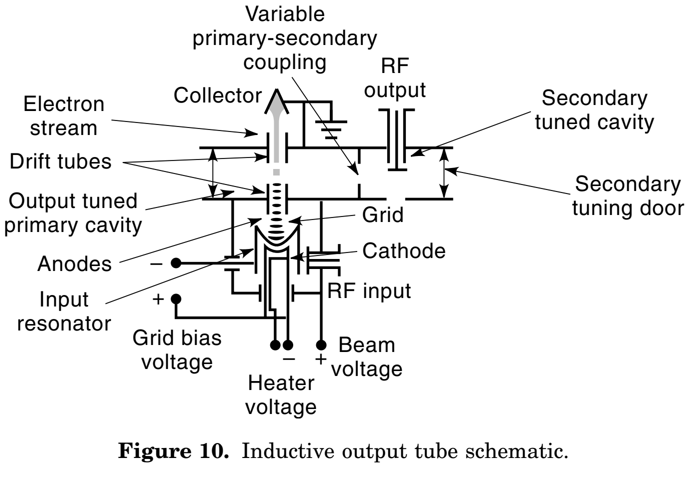

Figure 10. Inductive output tube schematic.

The fundamental benefit of the IOT is that it operates as a Class AB amplifier, resulting in high efficiency. Thus the beam current I_b, is proportional to the RF drive signal, V_g and follows the modulation envelope according to the three halves law:

$$I_{\mathrm{b}} = K(\mu V_{\mathrm{g}} + V_{\mathrm{a}})^{3/2}$$

where μ is the amplification factor. The perveance K is proportional to the cathode area and inversely proportional to the square of the grid-to-cathode spacing. The drive voltage is not normally high enough to make the instantaneous grid voltage positive.

In aural service, the IOT is tuned the same as for visual service. A single tube covers cover the entire UHF operating band, although two slightly different input cavities are required. Power gain in either visual or aural service is about 21 dB. Thus, drive power is about 500 W for the visual and 50 W for the aural, assuming 10% nominal aural power.

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