TRANSMITTERS FOR AMPLITUDE MODULATION BROADCASTING

Public broadcasting began at the start of the second decade of the twentieth century using amplitude modulation of a radio frequency carrier signal. The system of modulation chosen for transmission depended heavily on the practical and economic mass production of receiver technology and then current knowledge of signal modulation and transmission. The evidence is clear that amplitude detection was the only known practical method of signal demodulation when the ideas of radio communication and radio broadcasting were formulated in the late 1800s and early 1900s. Some of the earliest technical writings (1) on radio communications show that a general mathematical knowledge of angular modulation, that is, frequency and phase modulation (FM and PM), did not exist until the mid 1920s. Frequency and phase modulation and the necessary receiver technology were not proven practical until long after amplitude modulation had become the early de facto standard of radio technology.

By the 1930s when some commercial and military communications operations were planning a major switch from the relatively simple but inefficient AM system in favor of a single-sideband-suppressed carrier (2) for both long distance

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wire and wireless services, the broadcast industry was already committed to continuing conventional AM because of the need for continued receiver compatibility and the proven mass production economy of such receivers. The AM band remained dominant for global domestic broadcasting through the golden years of radio in the 1930s, 40s, and 50s until VHF-FM broadcasting, with its advantages of improved low noise and hi-fidelity monophonic and later stereophonic music quality transmission, became the dominant local (15–50 miles) radio broadcast medium in the United States and many other developed nations starting in the 1960s. Because of its superior long-range propagation characteristics over VHF-FM, the medium-wave AM band remains the dominant regional radio medium (30–100 miles during daylight hours and up to 1000 miles or more at night).

In the early 1980s, stereo transmission (3) on the AM band became a practical reality. This mode of transmission has become known as AM-stereo. Some AM broadcasters saw AM-stereo as a necessary means to compete with FM-stereo which continues to gain increased public acceptance for many types of programming formats. At this writing, AM-stereo has not proven itself an economic marketing success for either the AM broadcasters or the manufacturers of consumer receivers.

Soon after the emergence of medium-wave AM as a dominant local and regional transmission medium in the 1920s and 1930s, "shortwave" (SW) AM broadcasting began to cover distances longer than were possible on the medium-wave bands. Shortwave was used in North America for coast-to-coast broadcasts and for "cross-border" broadcasting to other countries, for political, economic, religious, and cultural purposes. At certain times of the day and on certain frequency bands, SW transmission via multiple reflections from the ionospheric layers surrounding the earth reaches 5000 miles or more. Historically and still today, the shortwave bands are used in North America primarily by hobbyists or international shortwave enthusiasts. In most parts of the world outside North America, however, shortwave transmission is still a popular medium for international news and information. The medium-wave (MW) AM band is approximately 535–1700 kHz and the international shortwave bands in the 2–30 MHz range are established by international treaties and organizations, such as the International Telecommunications Union in Geneva, Switzerland. In Europe, long-wave (LW) AM bands (153–279 kHz) are still popular and are used for long distance ground-wave regional coverage. Whether long-wave, medium-wave, or shortwave, the systems and methods of achieving amplitude modulation and demodulation of a carrier wave signal are similar.

Table 1. Worldwide AM Bands (Some Local and Regional Exceptions)

Long-Wave

Europe, Africa, Near and Middle East, East Asia and Pacific 153 to 279 kHz with 9 kHz carrier channel spacing.

Medium-Wave

Europe, Africa, Near and Middle East, East Asia and Pacific 531 to 1620 kHz with 9 kHz carrier channel spacing.

North, South, and Central America 525 to 1710 kHz with 10 kHz carrier channel spacing

International ShortWave:
(Including 1992 WARC Allocations)

Meter Band	*Frequency Band*	*Frequency Range*[a]
120	2	2300– 2495 kHz
90	3	3200– 3400 kHz
75	4	3900– 4000 kHz
60	5	4750– 5060 kHz
49	6	5900– 6200 kHz
41	7	7100– 7350 kHz
31	9	9400– 9990 kHz
25	11	11600–12100 kHz
22	13	13570–13870 kHz
19	15	15100–15800 kHz
16	17	17480–17900 kHz
15	19	18900–19020 kHz
13	21	21450–21750 kHz
11	26	25600–26100 kHz

[a]Carrier channel spacing − 5 kHz

AMPLITUDE MODULATION THEORY

The linear amplitude undulations which are characterized by speech and music are impressed onto the amplitude of the radio carrier-wave signal through a mathematical process known as "modulation." The radio carrier-wave signal onto which the analog amplitude variations are to be impressed is expressed as:

$$e(t) = A * E_c * \cos(w_c t) \tag{1}$$

where

$e(t)$ = instantaneous amplitude of carrier wave as a function of time (t);
A = a factor of amplitude modulation of the carrier wave;
w_c = angular frequency of carrier wave (radians/s);
E_c = peak amplitude of carrier wave.

If A is a constant, the peak amplitude of the carrier wave is therefore constant, and no amplitude modulation exists. Periodic amplitude modulation of the carrier wave exists if the magnitude of A is caused to vary with respect to time, for instance, as a sinusoidal wave:

$$A = 1 + (E_m/E_c)\cos(w_m t) \tag{2}$$

where E_m/E_c is the ratio of modulation amplitude to carrier amplitude and w_m is the angular frequency of the modulating wave, leading to

$$e(t) = E_c[(1 + (E_m/E_c)\cos(w_m t)]\cos(w_c t) \tag{3}$$

This is the well-known basic equation for periodic amplitude modulation, and, when all multiplications and a simple trigonometric identity are performed, the result is given by

$$e(t) = E_c\cos(w_c t) + (M/2)\cos(w_c t + w_m t) + (M/2)\cos(w_c t - w_m t) \tag{4}$$

where M = the amplitude modulation factor E_m/E_c.

High-quality musical reproductions include frequency components as high as 15 kHz or higher and therefore the required theoretical bandwidth of the basic double-sideband, full-carrier, AM (DSB-FC-AM) signal capable of reproducing high-quality music is at least 30 kHz. However, carrier spacing on the medium-wave band is 10 kHz in Region 2 (North and South America) and 9 kHz in most of the rest of the world. This narrow spacing of carriers effectively limits the useful interference-free channel bandwidth to considerably less than 30 kHz. With a carrier spacing of 10 kHz, the theoretical limit for interference-free channel bandwidth is 10 kHz, equivalent to a 5 kHz audio bandwidth. Adjacent and next-adjacent channel interference on the AM band can be severe because of very good nighttime propagation characteristics on the AM band. To avoid or minimize this otherwise unavoidable channel interference, receiver manufacturers severely limit the bandwidth of consumer AM receivers, often to as little as 6 kHz, equivalent to a 3 kHz audio bandwidth.

Carrier spacing on international shortwave bands is 5 kHz, further limiting the theoretical adjacent channel interference-free audio bandwidth to 2.5 kHz. The very nature of shortwave transmission, where international cooperation is mostly voluntary among broadcasting organizations, creates wide possibilities of co-channel, adjacent channel, and even next-adjacent channel interference. The global popularity of shortwave, therefore, is not caused by its audio fidelity characteristics, but rather to the information it provides listeners in distant and/or remote locations.

BASIC SYSTEMS OF AMPLITUDE MODULATION

Heising "Constant-Current," High-Level Anode Modulation

The first practical method for generating amplitude modulated signal was Heising constant-current modulation, first described by its inventor Raymond A. Heising (4) of Bell Telephone Laboratories. It is a method of applying audio modulation to the anode supply voltage of a class C radio frequency (RF) amplifier. The Heising modulator was used at least as early as 1920 and was sometimes used to modulate a low-power RF amplifier or master oscillator stage which was followed by several linear amplifier stages until the desired final power level was attained. In some cases the Heising modulator was used to modulate the final RF amplifier stage of a high-power radio transmitter. The Heising shunt modulator operated in the class A mode and, therefore, had low operating efficiency. The modulated Classic C amplifier typically has 80% anode efficiency, but the total system anode efficiency is reduced to approximately 38% because of the Class A efficiency of the Heising modulator. Further, despite its reliable simplicity and good audio fidelity characteristics, the basic Heising modulator, because of its Class A mode of operation and sharing the same dc anode voltage supply as the modulated RF stage, was capable of only approximately 90% peak modulation of the carrier. The Heising constant-current modulation system also had another significant deficiency in that it required a large and, at broadcast power levels, expensive audio modulation reactor. For this reason, engineers preferred the Class B RF linear amplifier described below to achieve the required high carrier and peak modulation power levels.

Class B RF Linear Amplification

The Class B RF linear amplifier, while somewhat lower in operating efficiency than the Heising modulator system, did not require the large and expensive audio modulation reactor required by the Heising system. Amplitude modulation was achieved at low power levels, often by a Heising or similar system described previously, and then amplified to the desired power level by several cascaded "linear" amplifier stages. The linear amplifiers were Class B amplifiers which had to supply the peak envelope power of the AM signal within the "linear" range of amplification. The efficiency at the positive crest of modulation approaches 71% but the efficiency at the unmodulated carrier level, which is exactly one-half the amplitude of the peak modulation crest is therefore approximately one-half the peak efficiency, or 35%. The Class B linear amplifier system for generating high power AM signals was popular for about two decades 1925–1945.

Because of the high cost of electric power and the high power required for AM transmission, engineers have consistently sought more efficient systems of amplitude modulation.

Push-Pull, Class B, High-Level Anode Modulation

Until pulse-width modulation became practical, the most popular method of "high-level" audio modulation of the anode circuit of a class C RF power amplifier was by a high power push-pull class B audio amplifier. This type of modulator was first used to improve the operating efficiency and to increase the output power of AM broadcast transmitters. Class B push-pull audio amplification was first used to improve distortion and output power of telephone transmission amplifiers. The invention was soon recognized by broadcast engineers and applied to high-level anode modulation. With the final RF power amplifier operating at approximately 80% anode efficiency and the class B audio modulator total static current approximately one-twentieth that of an equivalent Heising modulator, total anode efficiencies at carrier level rose to approximately 72% compared with 37% for the Heising system and 35% for conventional linear amplification. Like the original Heising modulator system, a large audio transformer/reactor system is required to couple the required audio power to the RF amplifier anode. The Class B amplifier efficiency is approximately 71% and the static modulator power is less than one-twentieth the Class A static power of the Heising constant-current system. Hence, the total RF/Modulator anode efficiency at carrier level is approximately 76%, and the RF/Modulator anode efficiency at 100% tone modulation is also approximately 76% therefore representing a significant improvement in efficiency over either the Heising constant-current system or the Class B RF linear amplifier system.

Two significant disadvantages exist for high level anode modulation:

1. Large and expensive audio transformers and/or reactors are required.
2. High positive peak modulating anode voltages, relative to carrier anode voltages, are required on the anodes of the final RF amplifier tubes accelerating failure of final tubes and other components.

Chireix "Outphasing" Modulation

Outphasing modulation was originally described in the literature by its inventor Henry Chireix (5) in 1935. It is a unique and ingenious method for obtaining the AM signal by using counterphase modulation and vector addition of two separate radio frequency signals. It was marketed for many years by RCA under the trade name "Ampliphase". Two RF signals are derived from a common excitation source and are split into two separate channels. Each channel is shifted in phase, one positive and the other negative. Then the two channels are each phase-modulated in opposing polarity. The two channels are independently amplified and then recombined in a vector additive network thus producing the desired amplitude modulation. The main advantage, as with all systems previously discussed, is in operating efficiency. The two independent channels contain only phase-modulated RF signals and therefore each can be amplified to the desired power levels in high efficiency Class C or D amplifiers. The actual modulation process takes place at low level, in the phase modulators, and at high level, in a passive output network combiner.

There are two major disadvantages of this system of modulation. First, the efficiency of the output power amplifiers is not quite as high as the simple description above implies, because at all instantaneous levels of modulation except one, the anode circuits must work into a slightly reactive load. Secondly, output carrier power setting is sensitive to tuning of any stage in the RF chain.

Doherty High-Efficiency Linear Amplifier

The Doherty high-efficiency linear amplifier (6) was first described in the technical literature in 1936 by its inventor, W. H. Doherty. So contrary were the terms "linear" and "high efficiency" in the context of amplitude modulated waves that many engineers in broadcasting were reluctant to accept the concept as workable, similar to the reaction Armstrong received when he proposed that frequency modulation (FM) was indeed a practical mode of radio transmission. Nevertheless, the Doherty high-efficiency linear amplification system was soon proven to work by 1938 and has been used at power levels up to 500 kW carrier power (7) in both the original and in the patented Weldon (8) modified form in many installations throughout the world on the medium-wave and international shortwave broadcast bands, and the long-wave broadcast band in Europe. Its implementation resulted from true inventive genius, using one or more known basic scientific principles to create a totally new and necessary product. As with conventional linear amplifiers, the AM signal is generated at low levels and applied to the input of the final amplifier stage. The Doherty system employs two output amplifier stages, one defined as the carrier amplifier and the second as the peak amplifier.

The outputs of the two stages are combined in phase at the anode of the peak amplifier tube. At carrier level, the carrier tube is operated as a nearly saturated Class B amplifier and thus delivers almost all of the carrier power at Class B efficiencies, that is, approximately 70% anode efficiency. The peak tube at carrier condition is biased and driven just above cutoff, and therefore supplies a small amount (approx. 2 to 6%) of carrier power. The anodes of the two tubes are connected together through a 90° impedance-inverting RF network. As the modulated signal increases in the positive direction to both peak and carrier tubes, the current supplied to the output load by the peak tube increases. The saturated voltage drop at the anode of the carrier tube remains constant over the entire positive modulation half-cycle, thus also causing the current at the output of the interanode 90° network to be constant during the positive modulation half-cycle. The rising current from the peak tube anode raises the impedance presented to the interanode network. Because the current from the network is constant, the net effect is an increase in output power from the carrier tube, that is, I^2R_1 increases because R_1 increases. At the 100% positive modulation crest, both tubes are producing exactly twice carrier power to the load, satisfying the requirement that peak envelope power (PEP) = $4 \times P_{\text{carrier}}$. During the negative half-cycle of modulation, the peak tube is slowly cutoff, and the carrier tube behaves as a normal linear amplifier, allowing the envelope power output to drop linearly to zero at the 100% negative modulation trough. The anode efficiency of the Doherty high-efficiency linear amplifier at carrier level is more than twice the efficiency of conventional AM class B linear amplifiers.

The Doherty linear amplifier also has two other important advantages for high-power broadcast transmitters. First, and most important, the peak anode voltage at either tube is only about one-half that required for an equivalent carrier power, high-level anode modulated transmitter, thus allowing reliability and usable tube life to increase significantly. Secondly, no large modulation transformer or special filtering components are used in the final amplifier stages. The main problems of the Doherty linear amplifier are nonlinear distortion and an increase in the complexity of tuning. The major sources of nonlinear distortion are the nonlinearity of the carrier tube at or near the 100% negative modulation crest and the nonlinearity of the peak tube at or near carrier level, when it is just beginning to conduct. Both sources of distortion are effectively reduced by moderate amounts of overall envelope negative feedback.

Pulse-Width, High-Level, Anode Modulation

Pulse-width modulation (PWM) of the dc anode voltage of a class C RF amplifier was first used in commercial high-power broadcast transmitters in Europe in the early 1960s. It was the first commercially successful attempt to significantly improve upon the efficiency of the popular high-level class B modulation system by applying and improving basic PWM concepts described decades earlier by Raymond A. Heising (9). Pulse-width modulation has become a preferred method of high-level anode modulation for both vacuum tube and solid-state modulator designs because of its high operating efficiency. Special low-capacitance isolation transformers are used to supply modulator filament and auxiliary power to minimize capacitive switching losses of the "floating" modulator cathode.

The power lost per modulator switching cycle is given by

$$P_{\text{modsw}} = (CV^2/2) + P_{\text{td}} \tag{5}$$

where C is the shunt modulator filament transformer plus stray capacitance to ground and V is the pulse switching voltage to ground at the cathode of the tube. P_{td} is the saturated tube and diode losses during the respective on and off conduction states.

Besides causing switching losses, the high stray capacitance to ground also causes major modulator distortion (10) at high negative modulation indices. The deleterious effects of modulator high stray cathode and floating deck capacitance have all but disappeared in modern solid-state, pulse-step/pulse-width modulator designs.

High-Efficiency Screen/Impedance Modulation

In 1938, Terman and Woodyard (11) described a modification to the basic Doherty high-efficiency linear amplification system previously discussed. In the new system the grid bias level of two tubes operating in class C is varied at the audio modulation rate thus creating a higher efficiency system of amplitude modulation rather than amplification while still using the impedance-inverting properties of the interanode network described by Doherty. The Terman–Woodyard system of modulation, however, was not used in commercially successful high-power transmitter designs.

High-efficiency screen/impedance modulation (12) is similar to the Terman–Woodyard modulation system except that the audio modulating signal is applied to the screen grids of two tetrode vacuum tubes operating as class C carrier and peak amplifiers. Invented by J. B. Sainton in 1965, the screen/impedance modulation system significantly improves the Terman–Woodyard scheme because RF excitation voltages and audio modulating voltages are isolated from each other thereby eliminating a troublesome source of tuning vs modulation interaction. The peak and carrier tubes are biased and driven in quadrature as Class C amplifiers by the continuous-wave RF drive source. At carrier level, the screen voltage of the carrier tube is adjusted so that the carrier tube is near anode saturation and delivers approximately 96% of the carrier power, and the screen voltage of the peak tube is adjusted so that the peak tube is just into conduction and supplies the remaining approximately 4% of carrier power. The combined anode efficiency at carrier level is better than 77% as shown in Eq. (6):

$$n_{\rm at} = 1/(p_{\rm c}/n_{ac}) + (p_{\rm p}/n_{\rm ap}) \tag{6}$$

In this example, $n_{\rm at} = 1/(0.96/0.81) + (0.04/0.405) = 0.7788$

where $p_{\rm c}$ = percent carrier power supplied by carrier tube (as a decimal); $p_{\rm p}$ = percent carrier power supplied by peak tube (as a decimal); $n_{\rm ac}$ = carrier tube anode efficiency at carrier level (as a decimal); $n_{\rm ap}$ = peak tube anode efficiency at carrier level (as a decimal); and $n_{\rm at}$ = total anode efficiency at carrier level (as a decimal).

The modulation of the RF carrier wave occurs when the screen voltage of the peak tube begins to rise during the positive modulation half-cycle, thus causing the peak tube to supply more RF current to the output load. This increased current into the output network heightens the resistance seen by the interanode network and, because of the impedance-inverting characteristic of the 90° interanode network, proportionally decreases the load impedance presented to the carrier tube anode. The carrier tube resonant anode voltage drop is fully saturated over the entire positive modulation half-cycle and is therefore effectively a constant voltage source. The power output of the carrier tube thus increases during the positive modulation half-cycle because of the modulated decreasing impedance at its anode, until both peak and carrier tubes deliver twice carrier power at the 100% positive modulation crest. During the negative modulation half-cycle, the peak tube is held out of conduction while the carrier tube output voltage decreases linearly to zero output at the 100% negative modulation trough. The advantages of screen/impedance modulation are the same as mentioned for the Doherty linear amplifier except that screen/impedance modulation has higher efficiency at all depths of modulation and is more tolerant of misadjustment of RF amplifier tuning. Screen/impedance modulation has been successfully used in medium-wave transmitters throughout the world at the two megawatt carrier power level and up to 250 kW in automatically tuned transmitters for international shortwave broadcasting.

Solid-State, Pulse-Step/Pulse-Width Modulator

In the early 1980s, solid-state devices with the speed, power, and current capability required for high-power RF amplifier modulation became readily available. However, transistors at that time did not, and may never, have the voltage ratings necessary to provide the tens of kilovolts required by vacuum tube anode modulation. The obvious solution to this dilemma is to place transistor devices in series until the required voltages are achieved. In the early 1980s high-power transistor devices rated at 500 to 1000 working volts became cost effective, making it practical to achieve the required typical peak modulator output voltages of 30,000 V with only 30–60 transistor stages in series. Fully solid-state modulators were built which provide the required analog output voltage with pulse-width or pulse-code modulated steps, each step approximately 500 to 1000 V. By width or code modulating the steps, a smooth or quasi-analog output is achieved which closely approximates the analog modulation output required for low distortion modulation of the RF carrier. Solid-state (transistor) switching modulator efficiencies up to 96% have been achieved for RF power amplifiers to 1000 kW and more, compared with approximately 90% efficiency for pulse-width vacuum tube modulators. Use of solid-state modulator circuitry has resulted in high-power, medium-wave and shortwave transmitters with only one expensive vacuum tube and overall efficiencies of 75% or better.

All Solid-State Broadcast Transmitters

Developments in the application of solid-state technology to high-power medium- and shortwave AM broadcast transmitters has been prolific since about 1984. Early concerns about the reliability of solid-state circuitry in high-power environments are rapidly vanishing at the new designs and products are proving themselves worthy in the harsh environment of high-power transient disturbances caused by gas arcs in associated vacuum tube circuitry and lightning strikes on antennas, power lines, and buildings. Products currently available on the commercial transmitter market offer solid-state modulators for high-level anode modulation of a vacuum tube final RF amplifier up to 1000 kW on medium-wave and 500 kW for shortwave transmitters. Other products are available utilizing fully solid-state designs up to 1000 kW for medium-wave transmitters. The vacuum tube power amplifier still has a future for many years as a practical and economical source of radio frequency power generation for shortwave applications. The new all solid-state AM designs for medium-wave applications are achieving great commercial success because of their higher operating efficiencies, reliability, size, weight, and superior modulation characteristics compared with competitive vacuum tube designs. Similarly, products and designs employing solid-state technology in modulator circuitry for high-level anode modulation of power grid vacuum tubes are also enjoying great commercial success worldwide.

SOLID STATE EQUIPMENT AND CIRCUITRY

Solid-state designs of AM broadcast transmitters currently available on the commercial market fall basically into three categories; (1) Solid-state modulator circuitry supplies the audio modulating power for high-level anode modulation of a power grid vacuum tube RF power amplifier. (2) Solid-state high level collector modulation of solid-state RF power amplifiers. (3) At least one unique product and design is commercially available in which the amplitude modulation process is achieved by pseudodigital pulse-code modulation taking place directly in the RF power amplifier stages.

The main advantage of solid-state circuitry in high-power AM broadcast transmitters is operating efficiency. It is still yet to be determined if the reliability of solid-state designs is distinctly advantageous over power grid vacuum tube circuitry, but the efficiency advantages are clear and proven. The efficiency of a single power grid vacuum tube pulse-width modulator, including filament, control grid, and screen grid power losses, is approximately 90% maximum for a 50 kW transmitter. Pulse-step/width- modulator losses for a solid-state modulator at the same power level are approximately 95%. When solid-state circuitry is also employed in the RF amplifier circuitry, the efficiency advantages are even greater. The typical maximum anode efficiency of a power grid vacuum tube Class C RF power amplifier is 84% neglecting output network circuit losses. This efficiency is improved to approximately 90% by anode voltage waveshaping techniques such as third and fifth harmonic traps in the output anode network. Therefore, the all-tube, pulse-width modulated transmitter overall modulator/RFPA anode efficiency is 0.9×0.9, or approximately 81%. Transmitter designs employing solid-state circuitry in the RF power amplifiers typically use Class D RF power amplifier circuitry which achieve approximately 95% RF collector efficiency at medium-wave frequencies. Therefore, an all solid-state, pulse-width, modulated transmitter can have overall collector efficiency of 0.95×0.95 or approximately 90%, 9% greater than the all-tube transmitter. With energy costs at record high levels in all of the world and constantly rising, the efficiency of high energy consuming products, such as broadcast transmitters, continues to be of prime and ever increasing importance.

Pulse-Step Modulators

Solid-state circuitry is employed in the form of several low voltage step supplies connected in series to achieve the high voltages necessary to supply power to the RF stages of a high-power AM transmitter. The number of "steps" employed range from approximately 28 to 64, depending on the equipment manufacturer. In several popular designs, each "step" is width-modulated to achieve the necessary total linearity required for broadcast transmitter modulation linearity characteristics. Each "step" represents approximately 1000 V in modulator output, yielding a total modulator output capability of approximately 28,000 V at the 100% positive modulation crest. The solid-state devices used to control the approximately 1000 volt steps are high-voltage, high-current transistors.

To achieve high overall transmitter efficiency, design engineers concentrate on the solid-state modulator circuitry and also on techniques to maximize the anode efficiency of the power grid vacuum tube final RF power amplifier and associated circuitry. Medium-wave transmitter designs by several manufacturers using pulse-step modulation employ similar technologies with the addition of anode waveshaping circuitry, which result in anode efficiencies exceeding approximately 92%. Overall shortwave transmitter efficiency has been measured at greater than 76% on some international shortwave bands, and overall efficiency of some medium-wave transmitter types has been measured at greater than 77%.

TRANSMITTER CIRCUITRY

Detailed transmitter circuit design is as varied as the individual designers. There is, however, some basic circuitry common to all transmitter types and models which is briefly discussed in this section.

Carrier Frequency Generator/Exciter

The stable frequency source for all transmitters manufactured since about 1930 has been the quartz crystal oscillator. The quartz crystals used in older model transmitters were large cuts of natural quartz, vacuum sealed in glass envelopes, similar to small-power vacuum tube envelopes, and occasionally mounted in temperature controlled ovens to obtain the required FCC carrier frequency stability. It is more common in modern designs to enclose the quartz crystals in small hermetically sealed metal cans made popular and proven reliable by the military and commercial communications equipment industry, with or without special temperature controlled circuitry. Modern quartz crystal manufacturing technology and proven solid-state crystal oscillator designs allow these types of small metal-sealed units to adequately maintain and even greatly exceed the FCC's current requirement of ± 10 Hz carrier frequency tolerance. The stability of quartz oscillator circuits is normally adequate over the full lifetime of the equipment. Should frequency adjustment ever be required to bring a unit back within the FCC limits, mechanically stable adjustment components, usually a glass or ceramic piston type of capacitor, are provided for use by a qualified station engineer using certifiably calibrated frequency measuring equipment. (Ref: FCC Rules and Regulations Volume III, October 1982, Part 73.1540 and 73.1545). Exciters for all proposed AM-Stereo systems provide the carrier frequency excitation for the transmitter and the stereo generating circuitry. Because of manufacturing advantages, some manufacturers of AM-Stereo exciters generate the desired carrier signal with frequency synthesizer techniques. This method of generating the basic carrier frequency is generally equal to or better than the discrete quartz oscillator method for frequency tolerance but produces higher phase-modulation noise if improperly designed or adjusted.

RF Power Amplifier

Many modern AM broadcast transmitters use power grid vacuum tube final RF amplifiers which employ Class C amplification. Some employ designs using third and fifth harmonic trap circuitry yielding quasi-class D operation for improved efficiency. All solid-state transmitters currently available in North America use Class D RF final power amplification.

High-power amplifiers that produce 0.25 to 50 kW of carrier power are common for AM broadcast transmitters in North America. Carrier power levels up to one megawatt and higher are common in other parts of the world for medium-wave broadcasting, and 500 kW carrier power has, in recent years, become the standard maximum transmitter power on the international shortwave bands. Transmitters delivering these high power levels are designed for high operating efficiency because of the very high cost of electric power in most countries. Although solid-state circuitry became viable and popular in the early 1990s for most high-power, medium-wave transmitters, the most common amplifier that meets the demands of high output power and high efficiency and the amplifier of choice in all modern high-power shortwave transmitter designs is the vacuum tube class C amplifier. Solid-state amplifiers up to approximately 5 kW are becoming more common as driver stages for final vacuum tube amplifiers and for the final power amplifier modules in medium-wave transmitters. As stated previously, the major concerns for both manufacturers and users of modern AM broadcast transmitters are operating reliability and efficiency, hence, operating cost. To achieve high overall operating efficiency, the stages which consume the most power, the final modulator and/or the final RF power amplifier, are designed today for the highest possible operating efficiency.

Some manufacturers increase anode efficiency beyond the limits for typical Class C amplifies with a circuit employing a third harmonic resonator between the output anode connection and the fundamental resonant circuit. This squares up the anode voltage waveform (e_p) thus causing the integral of the $e_p \times i_p$ product, or anode dissipation, resulting in lower anode dissipation for a given RF power output. An amplifier employing the third harmonic anode trap is commonly referred to as class C-D, suggesting an efficiency rating somewhere between conventional class C operation (nominal 120° conduction angle) and true class D operation with rectangular anode or collector (in the case of solid-state designs) voltage waveforms. Anode efficiencies are increased typically to values of 90% for transmitters up to approximately 10 kW carrier power and approximately 85% for transmitters higher than 10 kW carrier power by using the third harmonic trap technique.

RF Output Networks

The purpose of the RF output network is to match the impedance of the load, that is, the common-point impedance of one or more antenna-matching and combining networks, to the impedance required by the final RF power amplifier tube(s) or transistor(s) to produce the desired carrier and sideband power. The output network circuit is also designed to provide the attenuation characteristics necessary to meet requirements for spurious and harmonic output. The shape of the impedance vs frequency curve should be symmetrical (13) about the resistive axis of the Smith chart and should yield the lowest practical VSWR values at the highest expected fundamental sideband frequencies. More severe mismatch and impedance dissymmetry require more complex sideband mismatch corrective networking.

Transmitter Control and Monitoring

AM broadcast transmitter control circuitry is normally very basic and uncomplicated. It is common to find the task of transmitter control performed by discrete digital IC logic circuitry in modern designs that used to be accomplished with simple relay control logic. Some manufacturers are incorporating microprocessor technology in their latest equipment designs to replace discrete digital logic circuitry. The aim of manufacturers is normally to provide the operating engineers and technicians with the most basic, reliable, and easy to maintain and troubleshoot transmitter possible. Experience has shown that well-designed relay control logic, discrete digital IC logic, and microprocessor-based logic are all about equal in terms of reliability and ability to perform the required basic transmitter control functions. Future microprocessor-based transmitter control logic offers the promise of providing self- and remote-assisted diagnostics of transmitter problems and remote interrogation of transmitter operating parameters. Microprocessor-based logic offers the added promise of altering the basic characteristics of a transmitter control system through software control, allowing the basic transmitter design to be more easily "customized" to individual users' operating requirements. Because of the high voltage and high current faults that can exist in any high power transmitter component, extra care must be taken by designers and manufacturers of high-power AM broadcast transmitters to prevent the potential destructive energy in these faults from affecting the performance and operation of the relatively delicate solid-state control logic circuity. High-speed vacuum contactors and solid-state regulator/controllers are used in many modern designs to control the high voltages and currents encountered in all levels of high-power AM transmitters, which previously had been controlled by slower though equally reliable air-magnetic contactors and relays.

Remote control systems are commercially available that allow remote control of almost any transmitter, old or new. These remote control systems, like the basic transmitter control system, use relay, discrete digital IC, microprocessor-based logic circuitry, or combinations of these, depending on the manufacturer of the remote control equipment and the complexity of the remote control functions desired. Many transmitter equipment manufacturers provide limited built-in remote control functions and circuitry.

High-Voltage Power Supplies

High-voltage power supplies in AM broadcast transmitters must be designed to provide minimum acceptable performance in two basic areas: power supply ripple, which affects transmitter hum and noise output, and dynamic regulation, which affects low-frequency modulation transient response. It is typical for transmitters of 5 kW carrier power and lower to operate from single phase ac power sources, usually 240 V in North America. Transmitters with carrier power ratings of 10 kW operate with single-phase or three-phase power source, depending upon the manufacturer of the transmitter. Transmitters with carrier power ratings of greater than 10 kW operate only from a three-phase power source, usually 480 V for power levels up to 100 kW and 4160 or 11,000 V in North America for higher carrier power levels. Three-phase power has the advantage of being easier to filter and usually provides better dynamic regulation of critical modulator voltages than single-phase supplies. Single-phase power is more readily available which is the only reason it is used at the lower transmitter power levels, because initial installation cost would be disproportionately increased were three-phase power required. Single-phase rectifier power supply systems generally require L/C filtering to provide the necessary low ripple output for low transmitter hum and noise specifications. L/C filtering also creates, however, power supply resonances in the audible to subaudible ranges of modulating frequencies and therefore is a source of poor dynamic power supply regulation when the modulator circuitry of the transmitter is excited by vowel sounds or musical percussion sounds. It has been common since about 1970 for higher power transmitters to use special high-voltage supply transformers to generate a six-phase ac supply from the basic three-phase power source. The six-phase supply, when full wave rectified, yields a 12 pulse rectified *dc* waveform with lower ripple content and a higher ripple frequency than conventional three-phase full wave rectification. As a result, the output of the rectifier can be sufficiently filtered with no additional filter inductors, thus improving low audio modulating frequency dynamic power supply regulation and hence, low-frequency transient distortion.

Table 2. Modern AM Transmitter Performance Characteristics

Parameter	Typical Transmitter Performance
Carrier power output	1 kW to 2 MW
Audio Frequency response	50–10,000 Hz, ± 1 dB
Modulation capability	+125/−100%, 50–10,000 Hz
Total harmonic distortion	<2%, 50–10,000 Hz at < than 95% modulation
Intermodulation distortion	<2%, any two tones greater than 50 Hz separation, 50–10,000 Hz
Hum and Noise	Approx. 65 dB relative to 100% modulated carrier
Carrier harmonic output	Less than 80 dB relative to carrier level
Efficiency	Greater than 70%; some as high as 87%
Reliability	Difficult to quantify. Some manufacturers claim as high as 99.95% for medium-wave transmitters. (Mean time before failure (MTBF) = 2000 hours) (Mean time to repair (MTTR) = 1 h)

TRANSMITTER MODULATION PERFORMANCE

At one time broadcast studio and transmitter performance set the standard for audio fidelity in the home entertainment world, but low cost consumer electronics, driven largely by transistorized consumer electronic equipment, has far surpassed most capabilities of even the highest quality AM broadcast transmitter. Nevertheless, modern AM broadcast transmitters today have the highest standards achievable in very high power radio transmission equipment. Since the late 1940s, transmitter modulation performance characteristics reached a plateau that has not been significantly improved upon in modern designs. Modern broadcast transmitter designs have concentrated mostly on improvements in operating cost, that is, operating power consumption and reliability. Table 2 shows typical modern AM transmitter performance characteristics.

IMPORTANT AM-STEREO TRANSMITTER CHARACTERISTICS

Incidental Phase Modulation

All of the proposed AM-Stereo systems utilize a form of phase modulation for encoding the stereo signal onto the carrier of the AM signal. It is for this simple reason that the most important transmitter characteristic affecting AM-Stereo operation is incidental phase modulation (IPM). Excessive IPM affects stereo separation, single-channel distortion, and the occupied bandwidth of a stereo transmission. The most significant of the three is single-channel distortion.

There are many potential sources of IPM but the most common source is incorrect amplifier neutralization of a final modulated RF amplifier or of a lower power driver stage. The solution is, of course, to perform better neutralization of the offending amplifier stages. Since the inception of AM-Stereo broadcasting, manufacturers of the transmitters have paid more attention to the problems of IPM and in most cases have reduced levels of IPM in current production model transmitters to acceptable levels for AM-Stereo operation.

Phase Noise

Residual phase-modulated noise is not normally detected by a standard AM broadcast receiver employing envelope detection, whereas stereophonic AM receivers are sensitive to PM noise. PM to AM conversion occurs on the medium-wave band over multi-ionospheric “hops” (nighttime skywave propagation) which are then detected by receivers employing standard envelope detection. Very early transmitters sometimes produced more residual phase-noise sidebands than those produced by the desired program amplitude modulation.

Significant phase-modulated noise in modern transmitters is virtually nonexistent because of the use of high-quality quartz crystal oscillator and synthesizer circuitry. Phase-noise modulation of 0.6° (0.01 rad) average is fully acceptable for monophonic AM broadcasting. Phase-noise modulation of approximately 0.2° (0.0032 rad) average is usually considered acceptable for AM stereophonic broadcasting.

Stereophonic Phase/Gain Equalization

Standard production exciters for AM-Stereo systems incorporate built-in circuitry designed to approximately match the phase and gain characteristics of the normal monophonic transmitter transmission path to the transmission path for the encoded stereo signal. Transmitters which have excessive in-band nonlinear phase characteristics sometimes require special “out-boarded” phase/gain equalization networks to achieve optimum stereo performance.

INTERNATIONAL SHORTWAVE BROADCAST TRANSMITTERS

International shortwave broadcasting in the United States and North American began at about the same time as medium-wave broadcasting, about 1920, but did not grow substantially until pre-World War II propaganda activities by the influential nations. Until this growth in the mid 1930s, shortwave broadcasting was done primarily by amateur and special industry groups using the higher frequency bands for experimentation and hobbies. Almost immediately after the invasion of Pearl Harbor, accelerated shortwave broadcast activity in the United States began by the Office of War Information (OWI) which later assumed the wartime responsibility of the then inexperienced Voice of America (VOA) in June of 1942. Later, in mid1943 the Armed Forces Radio Service began shortwave relay broadcasts to France and other parts of Europe from bases in England. After WWII, the Voice of America resumed control of its wartime expanded facilities and, together with virtually all nations, began continuous operations of native and foreign language broadcasts for information exchange and general information. Other private interest in shortwave broadcasting also began to expand after the war, primarily from various religious and politically based organizations seeking to advance their cause or provide information and service not otherwise available from government operations. Commercial shortwave broadcasting in the United States has generally not been profitable primarily because of the limited audiences in North America, given the popularity of AM, FM, and TV broadcasting. The quality of signal in shortwave listening is inferior to the three other more popular modes of broadcasting, because of the long distances covered and atmosphere-generated fading and noise. Therefore, shortwave broadcasting in North America attracts a different kind of listener, one who is more dedicated to the “hobby” of shortwave listening and therefore more willing to tolerate the disturbance associated with shortwave listening. Shortwave listening in the world outside North America is very popular and necessary among large segments of the population as a source of news, sociopolitical or religious viewpoints, and some entertainment.

Shortwave Transmitters

Shortwave broadcast transmitters are similar in many respects to medium-wave transmitters and very different in others. The similarities are in methods of modulation, control, and monitoring. The differences, generally, are that shortwave transmitters have higher power, are more complex in tuning, and more difficult to operate and maintain than medium wave “standard” broadcast transmitters. Although there are numerous exceptions, the general rule, written or unwritten, is that the minimum usable carrier power level is 50 kW and the maximum economical carrier power level from a single transmitter is 250 to 500 kW.

It is not unusual for a shortwave transmitter to operate on five to ten separate frequencies every broadcast day. Modern broadcasting schedules of the prestigious broadcasting organizations are very tight, thus necessitating built-in automatic frequency-changing circuitry which allows the transmitter to tune to several programmed frequencies in approximately 10 to 30 s with minimum or no operator intervention. The trend in shortwave transmitter operation is toward unattended or minimally attended sites, with program and frequency changes done by remote and/or computer control.

Single-Sideband Operation on the International Shortwave Bands

Since about 1964, the International Telecommunication Union (ITU) and its radio broadcasting special committee, the International Radio Consultative Committee (CCIR) have encouraged the adoption of a form of single-sideband (SSB) as the standard modulation system for international shortwave broadcasting. This recommendation has been prompted by the ever increasing congestion in the shortwave broadcast bands, the competitive increases in transmitter power levels, which contributes to the congestion, and the realization of the increased efficiency of the SSB mode of transmission. A World Administrative Radio Conference Committee, meeting in Geneva in January and February of 1984, adopted a specific, detailed 20 year plan for conversion to SSB on the international shortwave broadcast bands. The committee report addressed necessary changes in both transmitter and receiver technologies, thus creating the beginning and emphasizing the importance of the changes which can double the available channel space and improve reception quality in the current international broadcast bands.

In 1997, it is felt by many experts worldwide that the transition to SSB on the world’s AM bands will be superseded by the transition to full digital modulation.

AUDIO PROCESSING AND PREEMPHASIS

Audio processing technology progressed significantly in the decade of the 1980s. Manufacturing and research companies developed sophisticated circuitry to further enhance the state of the art in speech and program audio processing toward the goal of producing maximum perceived loudness and quality by the listening public. It is not the intention here to discuss in detail the various processing schemes and advantages that each may offer. However, it is important that the entire transmission system parameters are addressed so that the total system in broadcasting includes certain parameters of the listeners equipment, the radio receiver.

An important achievement in the decade of the 1980s was that the transmitter and audio processor equipment manufacturers, broadcasters, and receiver manufacturers came together in a forum group called the National Radio Systems Committee (NRSC) (3), jointly sponsored by the National Association of Broadcasters (NAB) and the Electronic Industries Association (EIA). Out of this forum came the definition and formal recognition of certain system inconsistencies that were detrimental to the growth of AM broadcasting. As a result of the committee’s work, new and very important standards involving the transmission and receiving ends of the system for AM broadcasting were developed.

The major system inconsistency that exists in AM broadcasting had been known for some time by many individuals in the industry. The offending system parameter is called the transmitter/receiver interface. Because of the nature of nighttime skywave propagation on the standard medium-wave AM band, and the adjacent and sometimes next-adjacent and even not too uncommon next-next adjacent channel interference created by such propagation, receiver manufacturers, for many years, had severely restricted the intermediate frequency (I.F.) and audio bandwidth of the receivers it produced for the AM bands. In some cases the bandwidth restriction was severe, -20 to -30 dB receiver frequency response at 5 kHz was not unusual. Yet, the broadcasters continued to broadcast wideband audio out to at least 10 and often 15 kHz to provide the public with the highest quality signal possible. The committee addressed the transmitter/receiver interface mismatch and produced a recommended standard of restricted transmitted bandwidth to 10 kHz which would encourage receiver manufacturers to widen the I.F. and audio frequency response of the receivers correspondingly. The solution was the only correct one that could be made in light of the present usage and congestion in all of the world's AM bands. The standard that the committee proposed was voluntary only and required the voluntary compliance of a majority of North American broadcasters and manufacturers of AM receiver products for the North American market. This voluntary compliance was enthusiastically instituted by more than 1000 private AM broadcasters in the United States and Canada, prompting the FCC to make the NRSC standard a requirement by all U.S. AM broadcast stations. The FCC requirement took effect on June 30, 1990. Part of the standard generated by the committee involves the recommendation of an AM preemphasis curve to be used in the audio processing equipment at the transmitter end of the link. The proposed preemphasis curve is called a "Modified 75 μs AM Preemphasis Curve and exhibits approximately a 1 dB boost at 1 kHz and approximately a 10 dB boost at 10 kHz, but followed or accompanied by a single-pole low-pass filter with a break frequency of 8.7 kHz to reduce the peak boost at high frequencies. The proposed matching deemphasis curve in the receiver is achieved in the I.F. or audio stages of the receiver, or a suitable combination of the two.

The recommendation by the NRSC and following supportive action by the FCC is at least an important first step in achieving maximum system bandwidth on the North American AM broadcast band. The issue and subject of high audio frequency preemphasis is not without some controversy. Some broadcast engineers believe that the standard is good in concept but does not go far enough, and think that the high frequency boost should be limited somewhat lower than 10 kHz to further reduce or possibly eliminate adjacent channel interference. The European Broadcasting Union (EBU) in conjunction with the CCIR in Geneva, Switzerland recommends moderate high-frequency preemphasis to 4.5 kHz (European AM channels are spaced at 9 kHz intervals), followed by a sharp cutoff low-pass filter at frequencies above 4.5 kHz. An identical standard of 4.5 kHz maximum sideband width is also recommended by the CCIR for shortwave broadcasting where the channel spacing is 5 kHz.

The NRSC also generated a second standard pertaining to measurement of actual occupied bandwidth of a licensed AM broadcast station. The FCC has ordered that all U.S. AM broadcast stations comply with this second new standard.

Digital Broadcasting on the AM Bands

In 1997, serious discussion, consideration, and experimentation by several proponents is taking place regarding the future digitization of part or all of the medium-wave and shortwave AM bands. The goal by all the proponents is to achieve higher transmission quality to the listener in approximately the same spectral bandwidth currently required by analog amplitude modulation.

The transmitters used to transmit whichever system or systems of digital modulation that prevail will be similar to one or perhaps combinations of the types of transmitters described in this section.

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