Tricks of the Trade

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It is often the case that, in conducting research for an article, in this case ToTT, it is discovered that others have trodden the same path. Following on from the last few ToTT where the different means of generating AM have been examined, the author (G4OYX) was fortunate to find an article written for the EBU Technical Review in 1995. Here Mr RE Fenn G3RTF formerly of GEC-Marconi Communications had outlined the major technical developments that had taken place from the outset of sound broadcasting. The author was able to contact both Mr Fenn and the EBU and both are only too pleased to permit re-use of the text and the diagrams for Signal **[1]**. It is pertinent to publish Ewan's introduction and then skip to around 1970. For completeness, abridged Class B and Doherty modulation techniques are included and it will be interest to those VMARS members who may have not seen the previous ToTT articles. In addition there is a useful resumé of valve development technology.

The Transmitter by Ewan Fenn

"The Transmitter" **[1]** outlines the major developments which have taken place in sound transmitter equipment and techniques.

Over the years, high-power transmitters have developed into very sophisticated systems. Their progress was initially driven by a thirst for ever-increasing power and audibility. Today, like with many other things, their development is driven by the quest to reduce capital and operating costs.

Improvements in valve technology

The early valves used pure tungsten filaments. These had to be heated to 2,500 K to produce an emission of 7 mA/W and consumed a significant proportion of the transmitter total input power.

A considerable improvement was obtained by Langmuir from a filament which contained 2% of thorium oxide. Even at a reduced temperature of 2,000 K, this device could produce a specific emission of 70–100 mA/W.

The addition of a second grid – the screen grid – brought further advances. As its name suggests, it screened the control grid from the anode, to reduce internal feedback and to ease problems of neutralization. It also increased the amplification factor, thus considerably reducing the driving power required. The earlier grid structures were formed of a cylinder of crossing wires. These wires were spot-welded at each crossing point, such that the wire cage had many irregularities where the wires crossed.

Large modern tetrodes are now made with grids formed from pyrolytic graphite. The grids are made from cylinders of graphite which are 'grown' from gas (methane/ acetylene) in a furnace. The cylinders are then machined and cut away to form a grid structure, either by a laser or by shot-blasting through a mask.

Pyrolytic graphite grids have numerous advantages: there are no joints or overlapping wires, they are strong, and they are less likely to distort when heated. Furthermore, they do not suffer from secondary emission and may be operated at higher temperatures than conventional wire grids.

Cooling of the anodes is now accomplished in several different ways. In small transmitting and receiving valves, the anodes may be cooled by natural convection, by radiation or by forced air blown over the glass envelope. In larger valves, the anode is the outer surface and may be fitted with fins through which air is blown.

On large transmitting valves, water is used exclusively as the coolant. In the early days, the water was pumped over the outer surface of the anode and carried the heat away, with a fairly low rise in the water temperature. This was wasteful, as large water flows were required and the removed heat was of too low a grade for further use.

A better arrangement was to have the anode immersed in a container of water (a boiler) and to allow the water to boil; the heat was removed by the latent heat of evaporation. (170 kW will evaporate one gallon of water each minute at 100°C). The resultant steam rises naturally to the heat exchanger where it is condensed and returns by gravity to the boiler, with the added advantage that no pump is required.

Today's super-power valves also use latent-heat cooling but the steam is condensed inside the anode jacket. The resultant water can exit at up to 100°C and is ideal for heating the building if required by use of a heat exchanger.

We have talked about technological progress in components and will now investigate further improvements in the techniques and equipment design. However, before we proceed, we should look at the signal and the spectrum which is produced by a broadcast transmitter.

Signal characteristics

Double sideband (DSB) modulation comprises a carrier, and a spectrum of side frequencies which is centred about the carrier.

Broadcast transmitters are normally specified by their unmodulated carrier power. The carrier is then amplitude modulated until, at a modulation index of m =1, the carrier is reduced to zero in the trough and increased to twice the carrier voltage at the crest of modulation. The RMS power from a transmitter obeys the familiar expression,

$$P_{RMS} = 1 + \frac{m^2}{2}$$

where P_{RMS} is the RMS power, 1 is the carrier power and m is the modulation index, in the range 0–1.

Therefore, at 100% modulation (*i.e*. when m =1), the RMS power is equal to 1.5 x the carrier power. However, the peak power at 100% modulation is four times the carrier power. Thus, in the case of a fully-modulated 500 kW transmitter, the RMS power is 750 kW and the peak power is 2000 kW (assuming no carrier compression). The final radio frequency amplifier has to handle all these conditions.

Class-B modulation

After the mid-1930s the standard way of modulating a high-power transmitter (up until the mid-1970s) was by means of a class-B push-pull modulator. Its efficiency approached 70% at m=1, but decreased quite dramatically at lower modulation depths. Average modulation levels seldom exceed 30–40%, even with compressed programme modulation.

The side-band energy (*i.e*. the modulation) was supplied by a push-pull class-B audio amplifier (**Figure 1**), which was coupled to the RF amplifier by means of a large modulation transformer. The modulator was required to produce half of the total DC input power to the RF output stage. At high powers, an additional modulation choke (reactor) was used to avoid having to pass a large unbalanced DC component through the transformer secondary winding. The transformer and choke weighed typically more than five tonnes each and could contain several hundred gallons of insulating oil, with its attendant risk of fire.

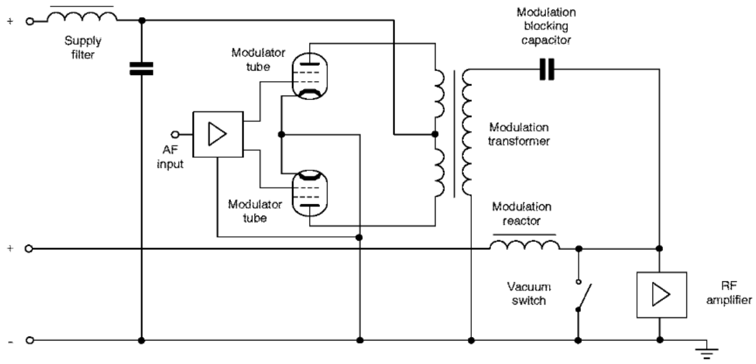

Figure 1. Circuit diagram of a class-B push-pull modulator

Efficiency improvements in class-C amplifiers

In 1958, while working for Marconi, VJ Tyler published a paper describing a means of improving the efficiency of the class-C amplifier. This was achieved by adding harmonic resonators in the anode and the grid circuits of the RF amplifier valve (**Figure 2**).

In practice, these resonators were tuned to the third harmonic frequency and consisted of parallel-tuned circuits in series with the valve electrodes. They presented high impedances at the harmonic frequencies and allowed a third harmonic voltage to be developed at the anode. This had the effect of allowing the valve to operate as an approximate square-wave switch by means of the pulse of grid current that resulted when the grid was driven positive. The Tyler resonator offered only a small reactance at the fundamental frequency which was taken up by the tank circuit.

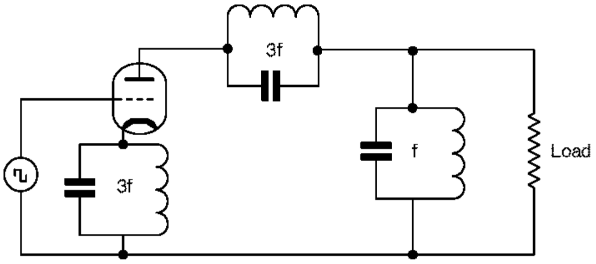

Figure 2. Circuit diagram of the Tyler resonator

At LF and MF, anode efficiencies of 90% were attainable with this system. However, at HF, there were severe difficulties in realising the third harmonic circuits for use at high power. Since the original Tyler patent lapsed, this technique has been adopted, almost universally, by other manufacturers.

Alternative means of generating AM DSB

So far we have only considered the side-band energy that is supplied to the RF amplifier by a separate modulator which varies the instantaneous value of the HT supply. As stated earlier, the requirement of an AM transmitter is to be able to vary the carrier power from its nominal value down to zero in the trough of modulation and up to four times its nominal value at the crest of modulation.

Obviously this has to occur over the bandwidth of the modulating frequencies. If we consider the RF amplifier as a constant-voltage generator that has the ability to vary dynamically the load presented to the valve, we could vary the power dynamically, or produce modulation, without having to vary the HT supply. A novel system to achieve this was devised by WH Doherty in 1936.

Basically it uses two similar power valves. The first produces the carrier power and the negative modulation. The second valve produces part of the additional power which is required for positive modulation and, at the same time, it reduces the load impedance seen by the carrier valve so that it also contributes extra power at positive modulation. In fact at 100% modulation, both the carrier valve and the peaking valve each contribute half of the total power.

This system has been particularly successful when used with modern high-gain tetrodes. The RF drive is applied to the control grids and the audio signals are fed to the screen grids. Transmitters which use Doherty modulation have been built successfully by numerous manufacturers, notably Continental Electronics in the USA who have produced LF and MF transmitters of 2 MW carrier power

The Doherty system offers several advantages. It does not require a modulation transformer or reactor; the RF amplifiers do not have to tolerate the HT voltage being doubled at the crest of modulation and, consequently, they can be operated at higher mean anode voltages. This improved efficiency and output power has been achieved by using HT voltages in the range 15–20 kV.

The Doherty principle can also be used at HF but it suffers from difficulties in maintaining the RF phase relationships, particularly at frequencies above 20 MHz.

Further improvements

The search for improved operating efficiency was accelerated in the early 1970s when energy costs escalated. The advantages gained at lower frequencies by Tyler and Doherty were not easily applied to HF, which still relied mainly on the class-B modulator of that period. A replacement was sought which would improve efficiency, particularly at typical programme modulation levels, and explore further savings in power consumption with controlled carrier operation. This was not dissimilar to the floating-carrier operation of the 1930s which had used a linear series modulator.

At this time, manufacturers in the USA, Germany, the UK and other European countries began to develop Pulse Width Modulation (PWM) systems which use the modulator valve as a switching device rather than operating it over the linear part of the characteristic. These developments eventually led to a PWM system by Harris Gates in the USA and the Pantel system by Telefunken in Germany. A shunt system known as Pulsam was developed by the Marconi Co., followed by a DC-coupled system known as Advanced Pulsam. By using these systems, the modulator efficiency was improved to better than 90%, giving overall HF transmitter efficiencies of between 60 and 70%.

Series-PWM modulation systems

All PWM systems must be designed to take account of the effects of stray capacitance on the switching valve as this results in power loss and also causes distortion of the audio signal in series-PWM systems. Thus, the simplest series-PWM system, with the switching valve connected to the high potential rail and the filter in series with the RF amplifier, is unsuitable for use at high powers. The effects of stray capacitance are too great.

One way of avoiding this is to have the cathode of the modulator valve at earth potential (**Figure 3**), but this arrangement requires the whole RF amplifier and its circuit components to be at elevated potential, which is not very convenient. Also, the switching valve and its associated components must be in close proximity to the RF amplifier, which becomes more difficult at high power due to their physical size.

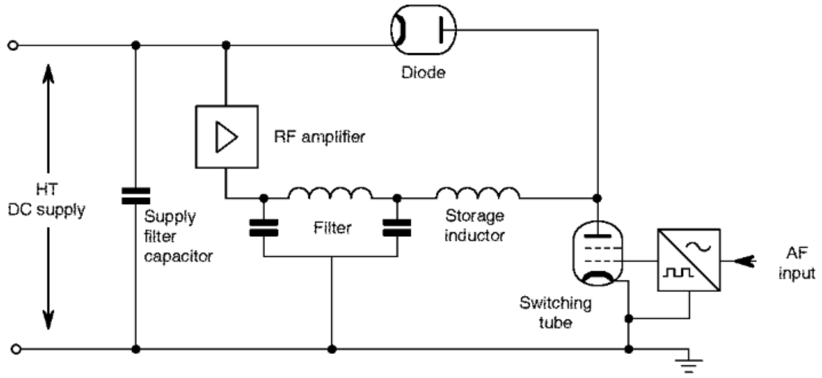

Figure 3. Circuit diagram of a series-PWM system

The Pantel system

The Telefunken Pantel system has the RF amplifier with its cathode at earth potential, which removes any restriction on its use at high powers. In the basic circuit shown in **Figure 4**, the effects of stray capacitance on the switching valve are minimised in a novel arrangement which locates the unwanted effects inside the filter. The diode is necessary to return energy to the filter when the switching valve is turned off. Its connection is straightforward in the simple series system (**Figure 3**) but is more involved in the Pantel arrangement (**Figure 4**), requiring a tightly-coupled winding on the storage inductor.

With any form of series system, the total power to the RF amplifier has to be passed by the modulator. Consequently, its conversion efficiency is of paramount importance to the overall efficiency of the system.

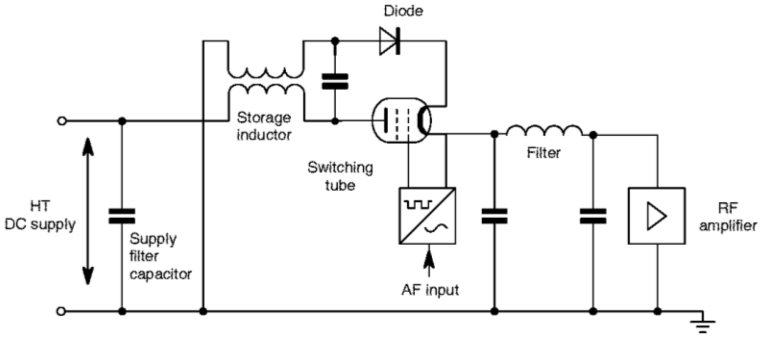

Figure 4. Basic circuit diagram of the Pantel series-PWM system

The Pulsam system

The Pulsam system, produced by The Marconi Co., uses a somewhat different approach in that it still only handles the sideband energy in much the same arrangement as the push-pull class-B modulator. The RF amplifier could be the same as that used with the class-B modulator. It receives its DC input from a dedicated supply *via* a modulation reactor (**Figure 5**) and can be powered independently of the modulator. This has advantages when commissioning or fault finding. The modulator requires a separate supply of just over twice the voltage of the RF supply although it is considerably smaller, having only to contribute the sideband energy.

The audio input is processed to produce a pulse train which is applied to the control grids of the switching valves. The pulse repetition frequency is approximately ten times the maximum required audio frequency and, consequently, is in the range 50–70 kHz. The signal may be applied to the control grid of the lower valve as, in this arrangement; the control grid of the upper valve is automatically pulsed in antiphase. The two valves are connected in series across the HT supply, with their mid-point feeding the storage inductor. In the unmodulated carrier condition, the two valves are driven in antiphase by pulses which are on for 50% of the duty cycle.

By the action of the storage inductor, this sets the mid-point voltage to half the supply voltage. This is approximately equal to the DC voltage which feeds the RF amplifier. The mid-point is then connected to the RF amplifier *via* a DC-blocking capacitor. When modulation is applied, the pulse widths vary with the amplitude of the audio frequency signal. At a modulation index of m=l, the lower valve is almost backed off for a number of switching pulses and the upper valve is almost continually conducting. At the trough of modulation, the valve conditions are reversed.

The Pulsam system offers several advantages:

- The RF stage does not depend on the modulator to be powered.
- The modulator only handles the sideband power so that it uses comparatively small valves.
- The fault energy dumped in the RF valve, under flash arc conditions, is limited by the modulation reactor.

The disadvantages are that two separate power supplies and a modulation reactor are required and the radio frequency HT supply voltage cannot be varied as it can be with a series modulator.

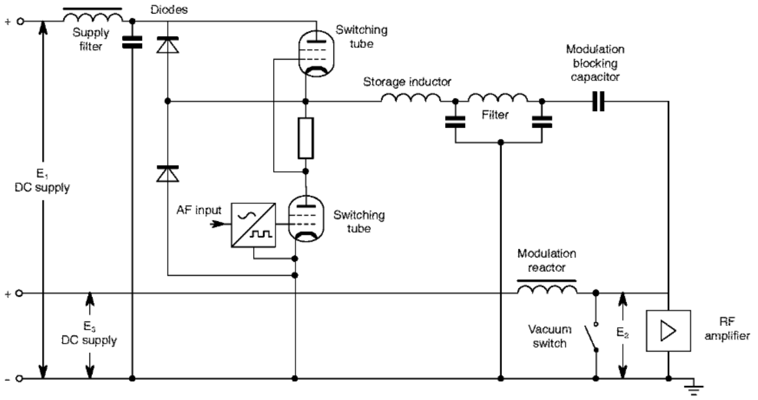

Figure 5. Basic circuit diagram of the Pulsam system

The Advanced Pulsam modulator

The Advanced Pulsam modulator is a variation on the classic series modulator. The valve is mounted on a low-capacity box which houses power FETs. These are used to drive the control grid and the screen grid with constant current feeds and a third electronic switch provides the PWM drive to the control grid. At the carrier, the valve is driven with a mark-to-space ratio of approximately 50:50 and, consequently, the DC potential is half that of the HT supply voltage.

With increased modulation, the on-period becomes longer and the off-period is shorter. Conversely, in the trough of modulation, the duty cycle becomes reversed. The cathode of the valve is at high potential with respect to ground and, therefore, requires a highly-insulated filament transformer. This is constructed on a similar principle to the toroidal transformer on mast lighting to reduce its capacitance to a minimum and has to pass about 10 kW of filament power.

A similar construction is used for the bias and screen transformer. Control signals are fed to the valve and monitoring signals are sent back by means of fibre-optic cables which provide very good electrical isolation and high noise immunity.

The series modulator, with its ability to control the DC voltage to the RF amplifier, opens up the possibility for further energy-saving modes of operation.

Energy-saving modulation systems

There are two standard modes to save energy, both relying on controlled-carrier operation:

Dynamic Amplitude Modulation (DAM by Telefunken)

This method reduces the carrier power at low modulation levels. In the case of a 500 kW transmitter, the carrier power at zero modulation is typically reduced to 180 kW. Up to modulation levels of say 90%, the carrier level is still reduced. However, further increases in the modulation level increase the carrier power up to the point where, at full modulation, it is back to 500 kW.

Depending on the programme material, power savings of 40% are achievable with DAM. The drawback with this system occurs at the fringe of the reception area, or in areas of interference. As the carrier is reduced under low-modulation conditions, the AGC of the receiver increases its gain and reduces the received signal-to-noise ratio which can be most annoying to the listener.

Amplitude Modulation Companding (AMC by the British Broadcasting Corporation)

This system, devised by the BBC, is almost the reverse operation of DAM. Here, under conditions of low modulation, the carrier power is at a maximum and, in fact, may even be enhanced above the normal carrier level. When modulation is applied, the carrier is reduced until, at a level corresponding to 100% modulation, it may be as low as 6 dB down on its original level.

This approach has a beneficial effect at the receiver. At low modulation levels, the large carrier reduces the noise at the receiver. Conversely, when the modulation is high and the carrier is reduced, the noise in the receiver will be swamped by the demodulated signal. Energy savings of up to 50% have been reported when using the AMC system.

Single-sideband broadcasting

Modern HF transmitters are required by the ITU to have the capability for single-sideband (SSB) operation. The carrier suppression must be adjustable over the life of the transmitter, as increasingly more receivers designed for SSB reception become available to the domestic audience. Initially, operation with only 6 dB of carrier reduction is proposed. This will allow a compatible signal to be received with a conventional double-sideband receiver.

As cheaper SSB receivers become commonplace, the carrier level may be reduced further. The purpose of this is to reduce the occupied band-width and to save power.

The conventional way to produce an SSB transmission has been to generate the SSB signal in the drive circuit, and to amplify it to the required power level by means of linear power amplifiers. These, of course, are not very efficient but they are acceptable at powers of only a few tens of kilowatts, as used in communication transmitters.

With broadcast transmitters, the required peak envelope power may be in excess of 1 MW and, obviously, a more efficient solution is required.

A method originally proposed by Kahn is in wide-spread use; it does not require the high-power amplifier to be linear and, consequently, it can use the efficient class-C operation. It also requires a DC-coupled modulator, *i.e*. a series modulator.

The SSB signal is generated in a low-power drive in the normal way. It is then demodulated to retrieve the envelope signal which is fed to the high-power modulator. The SSB signal is then hard limited to remove any amplitude information; the remaining signal, which contains the original phase modulation, is amplified and used to drive the class-C output stage. The amplitude signal and the phase-modulated signal then combine at the anode of the output stage to produce a high- efficiency SSB signal.

Solid-state modulators for HF broadcasting

The efficiency of thermionic-valve modulators had been improved to the point where anode-conversion efficiencies in excess of 90% were commonplace. There was, at this time, little room for improvement as the power dissipated in the filament and the grids was now very significant. The only way forward was with semiconductors.

Insulated-gate bi-polar transistors (IGBTs)

Bi-polar transistors – capable of switching many amperes at comparatively high voltages – had already been developed for motor control. These devices were manufactured with the drive circuitry built into the package, to produce insulated-gate bi-polar transistors. Devices of this type are now available to switch several hundred amperes and are capable of blocking 1000 V or more.

IGBTs are much more suitable than thyristors for switching purposes as they can be turned off quite simply rather than having to be commutated off by reversing the current.

The Pulse Step Modulator system

The Brown Boveri Co. in Switzerland has produced the Pulse Step Modulator (PSM) system which, basically, consists of a quantity of lower-voltage power supplies connected in series. The output of each power supply incorporates an IGBT switch, shunted by a diode. These IGBTs can be switched on individually and instantaneously to provide the optimum voltage requirements at any given instance during transmission of a modulated carrier. The shunt diode allows current to pass through the module if its IGBT is switched off, so that the module offers a low impedance when it is not contributing any voltage to the series chain. The system can be likened to a very large digital to analog (DAC) converter.

At MF, high-power transmitters are now available which use all-solid-state devices. A typical example is the Harris DX series where solid-state power blocks are combined up to the total output power which is required. The digital AM system uses a 12-bit analog to digital converter (ADC), a digital modulation encoder and a power-multiplying DAC which recreates an AM signal from the processed digital information. A typical arrangement, using a 12-bit ADC, utilises the 7 most-significant bits to turn on modules of the same size; the 5 least-significant bits are used to control the binary-weighted amplifiers, thus giving 12-bit resolution.

There is no theoretical limit to the power that can be obtained by combining suitable power blocks – only one of economics. Obviously, to double the power of a transmitter which uses modular construction, it is necessary to double the hardware (unlike in the case of valve transmitters). Modular construction does, however, offer the benefits of graceful failure and the elimination of the replacement costs and the catastrophic inconvenience which occurs when a large valve fails. High efficiency and good audio performance are claimed for this solid-state system.

HF transmitter control systems

In the early days, transmitters were adequately controlled by rheostats, knife switches and a few relays. Today their control systems use the latest microprocessor and computer systems. Not only have the energy costs risen with time, but also the labour costs. Not so many years ago, high-power HF transmitting stations were manned around the clock with both operational and maintenance personnel.

Today, HF transmitters change their frequency completely automatically, with frequency-follow auto-tuning systems. It is only necessary for the exciter frequency to be changed; the transmitter tunes automatically to the new frequency and loads itself to the correct conditions, making due allowance for the antenna VSWR. Equipment is required to change frequency ten or more times daily and accomplishes each change, typically, in less than ten seconds.

On large HF transmitting stations, computers now operate not only the transmitters but the complete system. By means of a matrix of feeder switches, any transmitter can be routed to any antenna, which may well have the ability to be slewed in azimuth and/or elevation. Programme material is also routed to the appropriate transmitter along with the required-frequency-change command. The status of all equipment can be monitored *via* VDU screens and keyboards in the control rooms, with printouts of any irregularities. Some stations are already operating completely unmanned during part of the 24-hour cycle.

At a large HF station, it is most impressive to see ten 500 kW transmitters change frequency simultaneously – without an operator in sight.

Conclusion

The above from Ewan neatly covers the time-line of transmitter developments almost to the present and so on the next ToTT where the engineering of the above methods will be described with examples from the manufacturer’s literature and other sources.

Acknowledgements

1. The author (G4OYX) is grateful to G3RTF and to Roger Miles and Shannon Frame at the European Broadcasting Union, EBU, for permission to reproduce sections and diagrams from the original. They ask that the following link be added: https://tech.ebu.ch/publications/trev_263-fenn and, of course, should VMARS members wish to view the original in its entirety then it is on that link

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