Tricks of the Trade

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The previous ToTT [**1**] marked the 50th anniversary of the start of UK offshore commercial radio broadcasts when, in March 1964, Radio Caroline from the M/V Frederica was the first on the air with a 10 kW Continental Electronics Type CE316C transmitter on 1520 kHz and, subsequently after April 1966, running 20 kW on 1169 kHz from the combined outputs of two such transmitters. This ToTT continues the historical theme into the description of the types of transmitter used by the offshore stations. Unlike units used by the BBC on MF in the UK, which were principally anode modulated by a Class B modulator or a linear amplifier following a choke modulator in the case of the 1930s regional stations, the offshore transmitters were state-of-the-art types though, surprisingly, using techniques first described in the 1930s.

Introduction

The perennial problem with generating AM is to superimpose (modulate) efficiently the audio signal on to the RF carrier. In very early transmitters this was done at relatively low power simply by connecting an audio amplifier valve in parallel with an RF amplifier valve and feeding both stages with a common voltage supply through an inductor ('Heising modulation'). As the applied audio signal caused the audio valve to take more current, it 'starved' the RF amplifier of supply thus reducing its output and *vice versa*. Although very crude, Heising modulation was the only practical method of modulating an RF carrier in the earliest days of AM broadcast in the 1920s.

These simple modulator stages were followed by 'linear' RF amplifiers as the amplitude of the modulated RF signal had to be amplified faithfully to provide listeners with a low-distortion signal at higher power. Unfortunately, simple linear amplifiers using Class A or Class B stages are very inefficient, typically providing overall transmitter efficiencies in the range 20-30%, meaning much wasted electricity and surplus heat. Thus, a 50 kW linear amplifier could produce in excess of 150 kW of heat which had to be removed from the transmitter.

More effective techniques were being developed by the 1930s, including Class B high-level anode modulation, still regarded today as the 'classic' way to generate AM, whilst engineers such as Cheriex and Doherty looked for more efficient ways to produce AM without having to apply high-level modulation to the RF power amplifier. Doherty's solution to the problem, which he patented in 1936, was to design a high-efficiency linear amplifier which could be used to amplify the output of a low-powered transmitter of any type. Although, by default, often referred to as 'Doherty Modulation', this is incorrect as it is not a modulation technique in its own right, but an amplification technique.

Continental Electronics used screen grid modulation (SGM) on transmitters up to 10 kW. For higher-powered transmitters, a screen grid modulator was originally coupled to an external high-power amplifier system, employing the Doherty technique producing a linear (low distortion) signal whilst remaining electrically efficient. In later, high-power models, Continental combined the two systems and applied SGM directly to a Doherty power amplifier to obtain a very efficient (CE317C) transmitter, with simple circuitry and a low valve-count. This article will now explain the principles of SGM and Doherty amplification.

The CE315, CE316 and CE317 transmitters

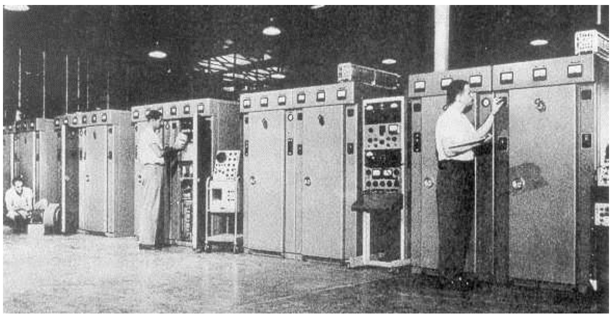

Figure 1. CE315s and CE316s on the production line in the late 1950s from a CE sales brochure

The CE315B and CE316B transmitters (**Figure 1**) were released in the late 1950s and used the newly patented technique of SGM of the output valve to produce an RF output of 5 kW (CE315B) or 10 kW (316B). A separate unit, the CE317B, was simply a linear amplifier using Doherty circuits to raise the power of either of the smaller units to 50 kW. The driver transmitter remained independent (though with some control circuits interlocked) and, at the press of a switch, could be put on the air directly if required. This was advantageous for day/night power changes and for maintenance purposes. The models were updated in the mid-1960s by the CE315C/CE316C which electrically were similar to the earlier versions but in a radically different cabinet layout and by the CE317C (**Figure 2**) which was a complete 50 kW sender and thus dispensed with the need for the earlier separate modulated driver transmitter. These transmitters were available as both medium wave and shortwave variants with very little difference in circuitry and many hundreds, if not thousands, have been built and shipped around the world since the 1960s. The basic design readily extends itself to super high-power operation and Continental has manufactured these up to the 1 MW RF output level (**Figure 3**). The shortwave variant of the CE317C was still being manufactured into the new Millennium and the design has been licenced to other manufacturers over the years.

Figure 2. The CE317C 50 kW screen grid-modulated Doherty transmitter as installed at Orfordness.
Photograph by Andy Matheson G3ZYP

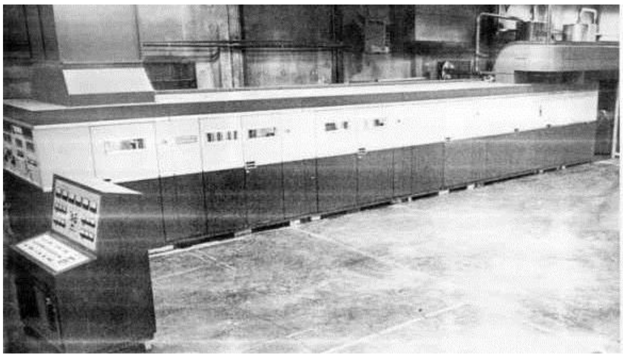

Figure 3. The CE323C transmitter capable of generating 1 MW of AM carrier power. From a CE sales brochure

Screen grid modulation

As SGM is the heart of the Continental design it will be considered first before moving on to Doherty amplifiers. Also known as 'efficiency modulation', SGM involves using two separate grids within a single amplifier valve to carry the two signals to be amplified and modulated together. As the name suggests, the RF drive is applied to the control grid of a suitable valve, whilst the modulation (normally audio) is applied to the screen grid of the same tetrode valve. In theory, the technique could also be used on the suppressor grid of a pentode valve but, in practice, tetrodes are almost always used for this particular RF application.

Although the SGM technique had been used for some time, it was not until the development of high-power tetrodes (the Eimac 4CX series) in the 1950s that manufacturers gave consideration to exploiting the technology. In an ideal world, a 'switch' valve, such as used for RF power generation, is either fully on or fully off, thus wasting little power internally. Although non-linear and resulting in an output wave rich in harmonics (though luckily the tuned output tank circuit cleans up the waveform), such RF power generation is fairly efficient.

To use a 'switch' valve as a modulated amplifier requires that the anode supply voltage be made to vary in sympathy with the audio (*i.e*. anode modulation) or some other means of controlling the output must be adopted. Adding audio to the control grid is ineffective as the output is a squared and distorted version of the grid voltage but modulating the screen grid allows control of the output amplitude. Since the operation of a tetrode valve is such that the screen grid voltage can, in effect, be regarded as a crude 'RF Gain' control, the valve can still be driven hard on its control grid to force it to switch on and off cleanly and waste little power in the switching process, but the point to which it switches on is set by the voltage on the screen grid.

Consider a tetrode with anode supply of, say, 1000 V. If the screen grid voltage is set to 500 V and the control grid driven with RF, the anode voltage is expected to switch cleanly between 1000 V and 500 V. Although little power is lost in the switching part of the cycle, a significant amount of power will be dissipated in the valve when it is switched on, as there would be 500 V drop across the device. If the screen grid voltage were to be modulated, the output appearing on the anode would vary in sympathy with the modulating voltage for a continuous RF drive condition on the control grid. The reader is asked to note that while this account is not strictly technically correct, it does give a readable analogy of the process.

In the above example, in the unmodulated 'carrier' condition, the dissipation of power due to the 500 V dropped from anode to cathode makes the SGM arrangement much less efficient (about 40% efficient) than a typical Class C power amplifier (about 75% efficient). However, as the modulation level is increased (towards either peak positive or peak negative), the valve will tend to operate more in a Class C condition, being either fully on or fully off. Thus as the average modulation level increases so does the efficiency of the transmitter, whereas high levels of anode modulation cause increased losses within the components in a conventional transmitter. These considerations of efficiency are why SGM is often known as efficiency modulation. As radio stations tend not to transmit silent carriers very often, the overall efficiency of screen grid modulation is comparable to that of conventional modulation systems such as anode modulation.

The CE 50 kW 317B transmitter

Figure 4 is a simplified circuit diagram of the 50 kW CE317B transmitter. The driver is, in effect, a 5 kW CE315B transmitter: RF line up to and including the pair of 4CX5000s. As the gain of tetrodes is relatively high, the RF drive requirements are minimal and two stages of amplification after the oscillator are sufficient to drive both the 4CX5000s.

Audio modulation is applied to the screen grids of the 4CX5000s from three 4-65 valves in parallel which function as a simple 'series regulator'. The simplicity of the audio circuit has to be admired; there are no iron-cored modulation transformers required with their attendant compromises on audio quality and initial cost. Since only c. 100 W of audio power is required to modulate the screen grids, the audio stages require no real high power technology or complicated techniques.

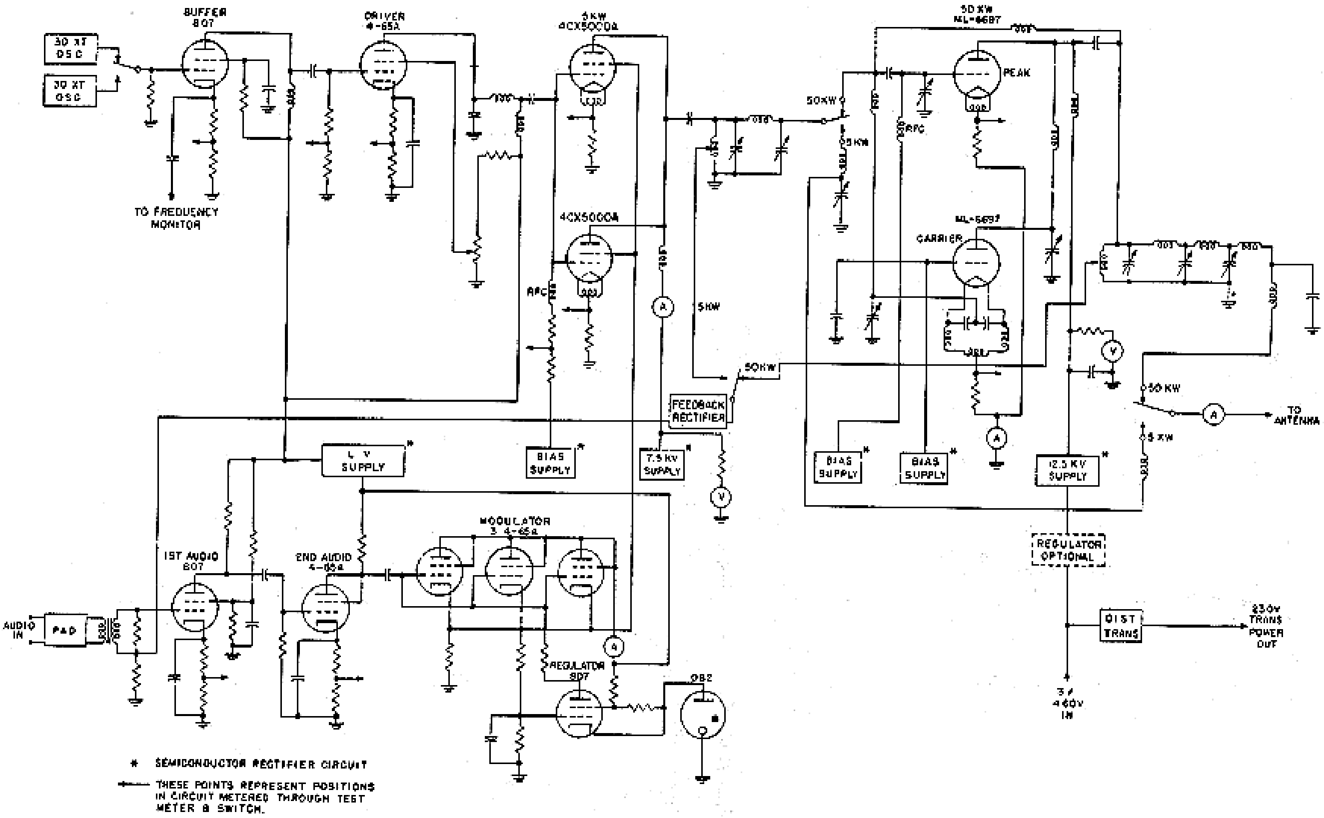

Figure 4. Simplified circuit diagram of the 50 kW CE317B transmitter

The system is also able to cope well with over-modulation and similar transients, carrier regulation is good as there are no large audio amplifiers consuming power from the power supply and the modulator itself incorporates a regulator. Also, the 'efficiency modulation' analogy lends itself to improved 'carrier shift' as the current drawn by the PA stage of an SGM transmitter is much more constant between carrier and peak positive than in a conventional transmitter, the relatively higher current required for the 'resting' carrier being dissipated as heat in the reduced efficiency of the PA. The mechanical design of the CE315/CE316B was such that it could be built within the enclosure space of the larger CE317B thus giving the impression of a single transmitter.

Doherty linear amplification

When William H Doherty first proposed his two-valve 'carrier' and 'peak' high efficiency amplification system in 1936, few engineers took him seriously, such was their reluctance to believe it was possible to build an efficient RF linear amplifier. It was only in the post-war period, with the major expansion of broadcasting around the world combined with the massive leaps in both valve and component technology generated by WWII, that his system was looked at in detail.

Simplistically, there are two amplifier valves, one to be referred to as the 'carrier' valve and the other as the 'peak' valve. During the course of the modulation cycle, both valves operate as Class B linear amplifiers at some points in the cycle and, at others times, in Class C. At the unmodulated carrier condition, the 'carrier' valve is normally biased to operate in Class C and provide *c.* 95% of the output power, and the 'peak' valve to provide *c.* 5%. As the RF drive is increased, the 'carrier' valve saturates and contributes no more voltage swing across the load (but remains in Class C), however, the 'peak' valve is then driven further into conduction (Class B) and thus adds power to the output. As the input is driven below the carrier point, the 'peak' valve is cut off and produces no output, and the 'carrier' valve is changed gently from Class C to Class B status thus producing less output voltage swing as the modulation heads towards peak negative. However, as the modulation of a radio station will always lie between the positive and negative extremes, and for symmetric modulation will always average at carrier level, the Doherty amplifier will always tend to operate in an efficient manner. Thus, on plain carrier, the 'carrier' valve is operating in Class C, at positive peak, the 'carrier' valve is saturated and the 'peak' valve is in Class C, whilst at negative peak, the 'peak' valve is cut off and the carrier valve is barely conducting. However, the above is an over-simplification of the process and the real feature of the Doherty amplifier is how the two valves are driven and then combined into the common load.

The 90° phase shifts and quarter-wave networks

The 'peak' valve is connected 'directly' to the load (*via* the anode tank circuit, output filters, *etc.*) whereas the 'carrier' valve is connected to the same load through a 90° (quarter wave) network. When the carrier valve is operating alone, this combining network has little effect other than to provide an incidental phase-shift. However, without the phase-shift circuit, as the 'peak' valve starts to conduct, the 'apparent' impedance seen at the combining point would start to rise. While the genuine load impedance has not changed and the anode voltage swing is the same, the power to the load remains the same, but now two devices are supplying power. Thus, each valve would be required to supply less power and hence it will 'see' an apparent increase in load impedance. However, with the impedance inverting properties of a quarter wave network taken into account, as the peak valve starts to supply power and the apparent impedance increases, this increase will be reflected through the quarter wave section as a lowering impedance on the carrier valve anode. As the anode voltage swing is the same and the load impedance is effectively decreasing, the effect is for the carrier valve to supply more power to the load than at carrier. When this is added to the power supplied by the peak valve, the power to the actual load also increases. The circuit is so arranged that, at 100% positive modulation, equal power is supplied by both valves. In order for the circuit to work correctly, one last feature needs to be added. As the power delivered by the two valves at the combining point is 90° out of phase, an additional 90° 'phase advance' circuit must be incorporated between the grids of the two valves, such that the outputs appear in phase. Finally, suitable bias must be applied to the control grids of the two valves to ensure that they are driven to the right conditions at carrier level.

The basic Doherty circuit as described above was modified for the CE317B by a patented Continental innovation known as the 'Weldon grounded grid' (Mr James O. Weldon, 1905-1993, was the founder of Continental Electronics) in which the carrier valve was operated in grounded grid configuration, with the drive applied to the cathode (the lower of the two valves in **Figure 4**). This enables further efficiency benefits in that the drive power is passed through to the load circuits and not wasted as heat dissipation in the grid structure as in a conventional grounded cathode amplifier stage. Also, neutralisation of a triode is not required when operating in grounded grid, thus making associated cost savings.

An alternative explanation

A BBC Head Office engineer, Roy Bliss, published a resumé of the Doherty system in an internal BBC Transmission document "BBC Engineering" in July 1980 **[3]** and it is reproduced below. This explains beautifully the system with text and three diagrams and neatly details the system as 'impedance modulation' and introduces the idea of peak envelope power into the explanation.

"When two identical generators supply power to the same load the resistance presented to each generator is twice that offered to either of them when the other is absent. Thus, in **Figure 5**, the value of the load resistance is clearly R, whereas the effective value of load resistance presented to each generator in **Figure 5** is 2R (providing that the generators are identical in amplitude and phase of output and in internal impedance) although the actual common load resistance is still R and this is what generator A will 'see' if the switch is opened. If, however, we connect a quarter wave line between generator A and the load (and change the phase relationship between the two generators to quadrature so that they deliver co-phase voltages to the load) as in **Figure 6**, the load presented to generator A will rise when the switch is opened because of the inverting impedance property of a quarter-wave line.

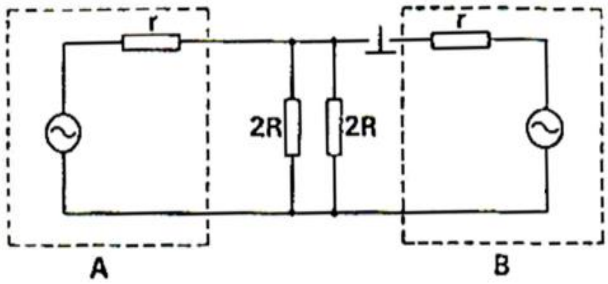

Figure 5. Two RF generators connected to a common load

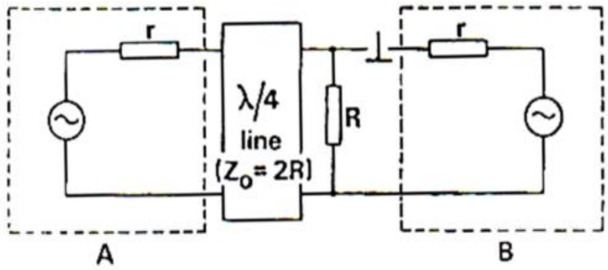

Figure 6. Adding a quarter wave in series with the output of one of the generators

In a practical circuit (**Figure 7**) we might use an actual load of 500 Ω which, with the peaking valve off, would appear to the carrier valve as 2000 Ω because the lumped-constant quarter-wave line has a characteristic impedance of 1000 Ω. Biasing arrangements are such that at carrier level the 'carrier' valve saturates and the 'peaking' valve just begins to conduct. For levels above the carrier, therefore, the 'peaking' valve also supplies power to the load and raises its effective value to 1000 Ω which reduces the value seen by the 'carrier 'valve to the same figure.

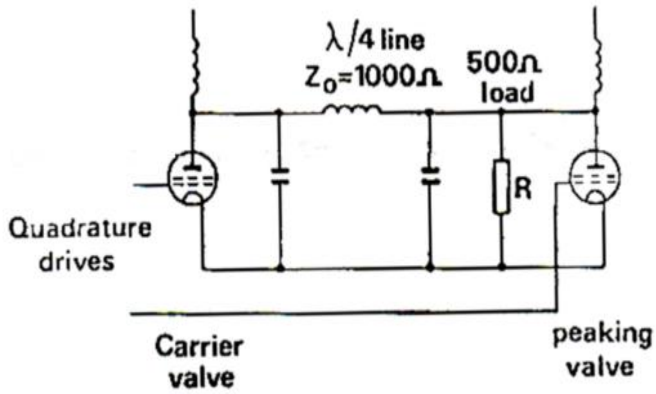

Figure 7. Quadrature feed to the two valves

So, without any increase of voltage the 'carrier' valve can now deliver twice the power and the 'peaking' valve can deliver a like amount. Thus, up to four times the carrier power is available, to supply up to 100% modulation peaks. A 50 kW transmitter gives 200 kW PEP at 100% modulation.

Earlier versions of the Doherty circuit used control grid modulation (as only triodes were available) requiring linear valve operation, Class A through to Class B, but using tetrodes with screen modulation permits Class C operation with greatly improved efficiency."

Conclusion

This article began with details of the offshore stations using the 10 kW CE316B SGM transmitters and it is appropriate to add that others used the CE317C 50 kW unit, including the pair on the ship the M/V Laissez Faire that originally hosted the stations Swingin' Radio England and Britain Radio. Radio Caroline South was upgraded to 50 kW in 1966 with a CE317C. The Dutch offshore station Radio Veronica used a pair of CE316Cs on its second ship the M/V Norderney.

It is interesting to note that the UK FCO/DWS also bought a pair of CE317Cs. These two transmitters were shipped off to Bechuanaland (now Botswana) to broadcast the BBC World Service into Rhodesia after the declaration of UDI by Premier Ian Smith, the first going into service on 30th December 1965 at CARS, the Central Africa Relay Station. Later, one was brought back to the UK and used first to jam Radio Northsea International in the spring of 1970 and then in 1978 as a daytime service release and evaluation transmitter at Orfordness on 648 kHz.

Next time

Even with the CE marque seemingly conquering the market for those who required a 50 kW Doherty transmitter, other manufacturers did go on to make their versions and, in the next ToTT, at least three others will be detailed. Also a start will be made on the story of the arch competitor to the CE317C in the USA.

References

1. D Porter G4OYX. Tricks of the Trade. *Signal* 2014, **32** (July), 31–32.
2. http://www.rossrevenge.co.uk/tx/continental.htm
3. R Bliss. *BBC Engineering* 1980, (July), 13.