The Development of Sound-Programme Limiters in the BBC

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Summary: Over-modulation of transmitters produces distortion; under-modulation reduces the service areas. Manual control of audio signal level has been supplemented since the late thirties by automatic limiters to prevent over-modulation. This article describes the development in the BBC of devices of this type from the time of their introduction up to the present.

1 Introduction

Overloading of electronic equipment by audio signals of excessive level produces non-linearity of the transfer characteristic and consequent impairment of the quality of the reproduced programme. When the equipment concerned is a transmitter the overloading can also lead to the radiation of additional components outside the specified channel bandwidth (possibly causing interference to other services) or may even cause automatic switching off ('tripping') of the transmitter to prevent damage. For a variety of reasons, therefore, significant overloading of audio-signal equipment is to be avoided.

In the BBC, sound signals are normally controlled manually at source. For programme material of wide dynamic range (such as orchestral music) it is not feasible to preserve the full range in the transmitted signal without spoiling sustained quiet passages with obtrusive noise. It is therefore usual to make manual adjustments of the level during the course of such programmes, very loud passages being anticipated by gradual reductions of gain and very quiet passages preceded by gradual increases. Though the signals are nominally controlled to a specified maximum level the human operator cannot react with sufficient speed to avoid occasional overloading on unexpected programme peaks.

Two obvious ways of avoiding accidental overloading are either to use signal levels which are sufficiently low to involve negligible risk of reaching the overload point, or, looking at the subject from the other direction, to use equipment which is capable of handling signal levels substantially above the nominal maximum. The former solution inevitably means a degradation of the overall signal-to-noise ratio. The latter solution is generally adopted for low-level signal equipment but is not practicable for an AM transmitter, for example; here the power handling capability can be increased only by raising the carrier power — a very costly solution even if it were allowable under the relevant planning agreements.

It is thus evident that there is a need for some form of automatic protection, particularly to prevent over-modulation of transmitters, and quick-acting limiters have been developed which recognise the presence of peaks above the acceptable limit and reduce the gain by an appropriate amount. It should be noted that a limiter in this context is very different from an instantaneous peak clipper; such a device simply removes the peaks of an input waveform which is too large, producing waveform distortion which, as a general rule, is likely to be objectionably audible. Limiters have been used at transmitter sites since the early nineteen-forties, and in recent years they have also been used at the sending terminals of pulse code modulation (PCM) links to permit realisation of the full potential of the digital systems.

In some circumstances reduction of the dynamic range by automatic means is desirable for technical or aesthetic reasons. This can be done by limiters in two ways. Either the input to the limiter is raised above the nominal level so that the limiting action is deliberately invoked for a significant proportion of the time, or the limiter can be modified to give an input/output characteristic with a finite slope less than unity rather than the normal limiter performance with unity slope up to the limiting level and nominally zero slope above it (section 3.2).

2 Early Overload-Protection Practice

In the BBC, signals are, in general, monitored and regulated in level at the studio. In the early days of radio the control of level was based on signal measurement using various metering arrangements, including, for example, a 'slide-back' voltmeter set so that programme at the correct level gave an indication on signal crests only occasionally. Later, in the late nineteen-thirties, the BBC peak-programme meter (PPM)[1] — a pseudo-peak reading instrument — was introduced and provided a better indication of the relevant peak value of the programme signal.

Throughout the early period of broadcasting, continuous monitoring was also carried out at the transmitter. The transmitter engineer was not normally expected to exercise any control, but he could make adjustments when necessary to avoid, say, repeated overloading or a prolonged period of excessively low modulation. To reduce the risk of false 'corrections' he was warned in advance of any passage of programme to be deliberately kept at low level for artistic reasons.

Experienced and skilled operators would be able to predict changes in programme level to a considerable extent but could not be expected to avoid occasional over-modulation and consequent audible distortion. It was thus inevitable, even with the most skilled and conscientious human control, that listeners suffered occasional distortion due to overloading and some also suffered degradation of the service due to low transmitter modulation. The development of an automatic level control device to replace the human operator at the transmitter was thus obviously desirable.

3 Basic Principles of Quick-Acting Limiters

3.1 General

As a means of avoiding over-modulation, manual control falls short of the ideal mainly because of the long reaction time of the human operator. With advancing technology it became possible to develop automatic protection devices which could react to signals of excessive level much more rapidly, and which would allow the gain to rise gradually when the level of the incoming signal had fallen, thus minimising audible interference with the programme.

Figure 1a is a block diagram of one form of simple quick-acting limiter. The circuit consists of two paths; a programme path and a control path or control 'chain'. The programme path is essentially a variable-gain element whose gain depends on the bias applied to a control input. In operation this bias is derived from the limiter output signal by means of the control chain, acting in the following manner. The output signal is first rectified — full-wave, to ensure that account is taken of the greater peak, of either polarity, of an asymmetrical waveform — then applied to a limiting threshold circuit. This circuit yields no output as long as the signal is below the desired limiting level, but, for higher signals, the crests of the rectified waveform are passed, generally through an amplifier, to a peak-detecting and smoothing circuit. The voltage developed across the smoothing circuit is applied to the control input of the variable-gain element in such a sense that gain is reduced until the control loop is in equilibrium. Peak detection is adopted at the smoothing stage to ensure that the limiter control is related to the crests of the signal waveform, since it is, of course, overloading and waveform distortion on these crests that leads to audible impairment.

The limiter arrangement indicated in figure 1a, known as an output-, or servo-, controlled type, was used in early BBC limiters. The output-controlled configuration is a negative feedback device: it is therefore impossible for it to produce a literally constant output level for a range of input levels though this condition can be closely approached in practice. On the other hand, the use of negative feedback carries with it the advantage that the exact shape of the control characteristics of the variable-gain device is unimportant. The alternative input-controlled configuration can, in principle, compensate completely for input level variations, but demands a precisely-specified control characteristic.

3.2 Static characteristics

Figure 2a shows the gain of a typical output-controlled limiter under steady-state conditions, plotted as a function of input level. Gain is constant for input signals up to the limiting threshold and then decreases by approximately one decibel for each decibel of further increase of input level. The same information is presented in a different form in figure 2b which shows output level plotted as a function of input level; this illustrates more clearly that the limiter output level stays substantially constant as the input level is raised above the limiting threshold. In practice an increase of input level of, say, 20dB beyond the limiting threshold might cause the output level to rise by some ½dB to 1dB.

It must be emphasised that the curve of figure 2b does not imply steady-state waveform distortion (as it would if it related instantaneous input and output voltages) but simply indicates a particular law relating gain and steady-state input level.

3.3 Dynamic characteristics

The dynamic characteristics of a limiter depend on the peak-detection and smoothing circuit, the gain/bias law of the variable-gain stage, and, in the case of the gain-reducing (or 'attack') period, on the gain in the control chain.

Figure 1b shows a typical peak-detection and smoothing circuit for a simple limiter. During the attack period, capacitor C is charged through resistor R_1 (R_2 is normally much larger than R_1) until the bias applied to the variable-

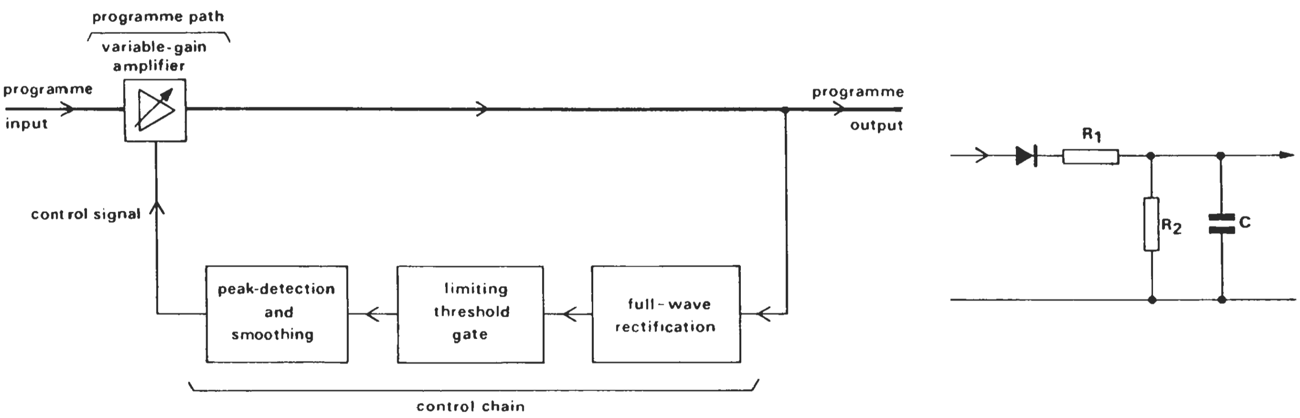

Fig. 1 Simple output-controlled limiter. a. Block schematic. b. Peak-detection and smoothing circuit.

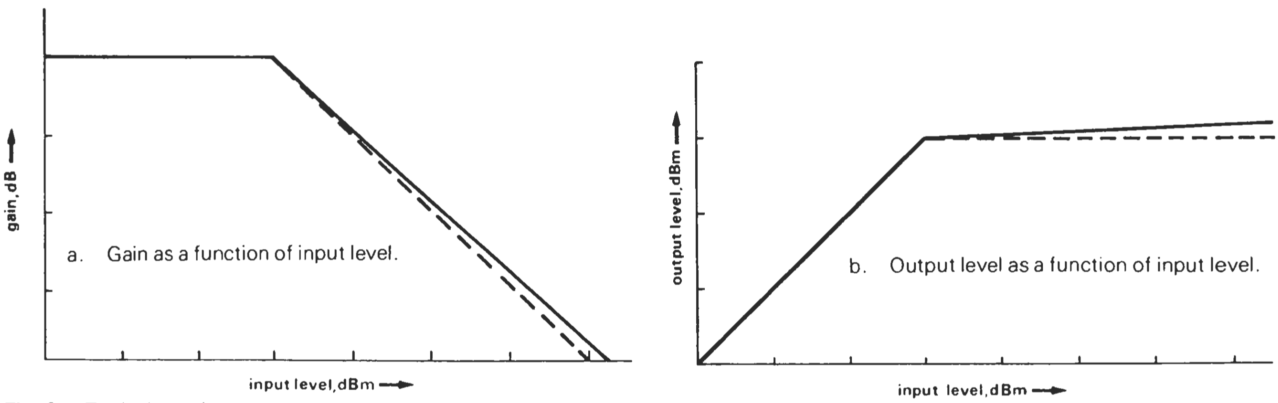

Fig. 2 Typical steady-state characteristics of simple limiter.

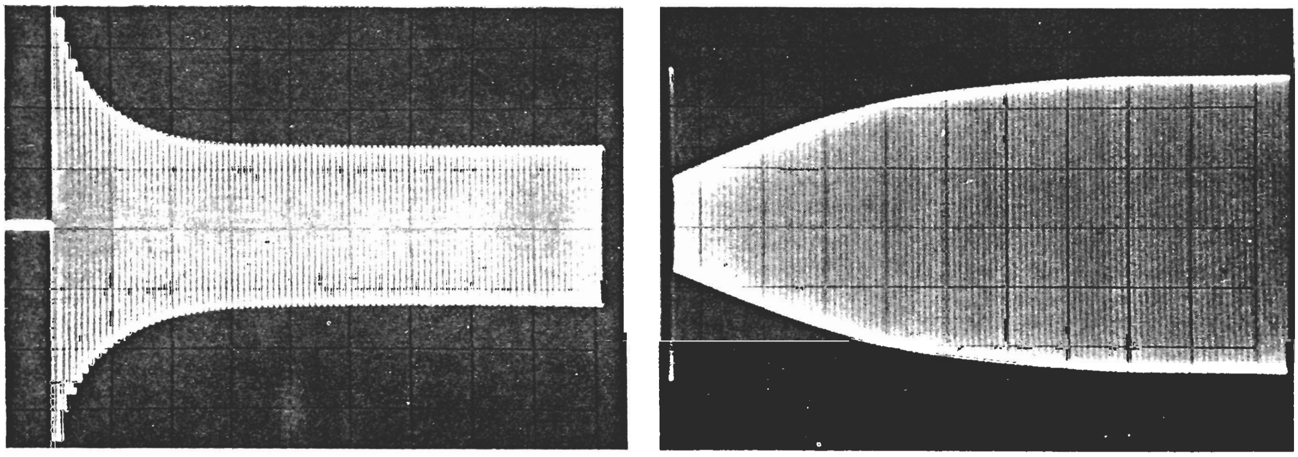

Fig. 3 Typical dynamic characteristics of simple limiter.*

a. Envelope of output signal during 'attack' period: time scale, 2 ms/major division.

b. Envelope of output signal during recovery period: time scale, 200 ms/major division.

gain stage is sufficient to restore the circuit to equilibrium, the process commonly taking a few milliseconds. Until equilibrium is reached the gain in the limiter is higher than its ultimate steady-state value for the signal applied, so there is a transient overshoot at the limiter output. Figure 3a shows the output signal from a typical output-controlled limiter when a steady signal, well above the input limiting level, is suddenly applied at its input. Equipment further along the programme chain can be overloaded during the transient overshoot period, but before the introduction of wide-band loudspeakers, impairment due to such overloading was unlikely to be obtrusive.

When the output level falls below the limiting value, capacitor C discharges through resistor R_2, the bias on the variable-gain stage falls to zero, and the limiter gain returns to its normal maximum value. This 'recovery' period may be arranged to take anything from a hundred milliseconds or so, to several seconds, depending on the requirements. Figure 3b shows a typical envelope of the signal at the output of a limiter when a large input signal, above the limiting

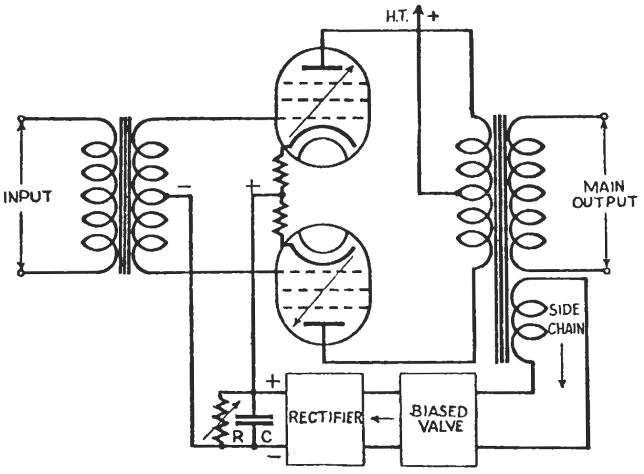

Fig. 4 Simplified circuit diagram of early limiter (from BBC Engineering Division Training Manual, 1942)

threshold, is suddenly reduced to a steady level below that threshold.

Advances in technology have more recently made possible complex attack and recovery characteristics. Delay networks have been used to eliminate the momentary overshoot during the attack period, and the recovery characteristics have been made level- and time-dependent so that the limiting action is still less obtrusive.

4 Valve Limiters

4.1 The first BBC valve limiters

By the thirties the 'variable-mu' valve had been developed in which the grid structure is so arranged that the i_a/v_g characteristic is gently curved, so that valve gain is related to grid bias. The variable-mu valve thus lent itself readily to application as a variable-gain device, the heart of any automatic level control equipment, and was used by the communications engineers of the day in the development of audio limiters. The curved gain/bias characteristic implies a measure of waveform distortion, but the performance was adequate provided the signal level applied was small.

A BBC patent application [2] by Mayo in 1938 describes the principles of a sound-programme limiter using variable-mu valves. The design was developed and went into service in about 1940 as the LIM 2*. Figure 4 shows a schematic diagram of the limiter circuit reproduced from the BBC Engineering Division Training Manual, 1942. This diagram is obviously much simplified and the arrangement used in the LIM 2 was essentially that indicated in figure 1a. It is interesting to note that two variable-mu valves were employed, connected in push-pull. The control bias was applied to the valves in parallel and the push-pull arrangement allowed the control bias voltages, amplified by the two valves, to be cancelled in the anode circuits and thus, ideally, excluded from the limiter output. In practice two valves rarely had sufficiently similar characteristics, so a pre-set control was included to allow an adjustment of the balance. It was set for minimum 'plop' at the output when a voltage step was introduced in the control chain.

The attack characteristic of the LIM 2 was of the general form shown in figure 3a, with an effective attack time of a few milliseconds. The recovery characteristic was of the general form shown in figure 3b, the time constant being set by a switch to give any one of five values of effective recovery time in the range from about 100ms to many seconds. For reasons more fully discussed in Section 5.2.4 any single value of recovery time can be no more than a compromise; the performance was improved by a subsequent modification introducing a form of double-time-constant circuit. An input-level control was provided to allow a set amount of programme compression to be introduced if required. The control range was in excess of 20dB and the total harmonic distortion, measured at 1kHz, was less than 0.25% over this range. Valves in the 'British 4-pin and 7-pin' series were used in the LIM 2 which occupied about 23cm (9") on a 56cm (22") bay. The normal output limiting level was −15dBm.

By the early fifties some of the parts used in the LIM 2 were becoming obsolete and the design was therefore revised using currently-available components.

4.2 Introduction of miniature valves

No fundamental changes in design concept were introduced in the replacement, the LIM 5, though there were changes of detail. The use of small components including 'miniature' valves resulted in a reduction in overall size; the bay space occupied by a given number of limiters was approximately halved.

An output amplifier was added to raise the nominal limiting level to the operationally more convenient value of +8dBm, but the limiting characteristics were substantially unchanged.

4.3 A limiter for FM radio

The system specification for the VHF/FM radio service introduced in this country in the mid-fifties included a 50μs high frequency pre-emphasis of the sound signals applied to the transmitter. Thus a conventional limiter, like the LIM 5, operating on the studio output signals, could not protect the transmitter from over-deviation by high-frequency components raised in level by the subsequent high-frequency emphasis. FM transmitters could be protected from over-deviation by a LIM 5 limiter provided it operated on pre-emphasised sound signals, but the output signal would then have to be de-emphasised for monitoring purposes. A modified limiter, the LIM 6, was therefore developed to fit the operational requirements of the time more closely. Here provision was made to include the appropriate pre-emphasis characteristic in the control chain so that the limiting threshold fell with increasing frequency. Thus the output signal was such that when pre-emphasis was applied at the transmitter, the enhanced high-frequency components were not so large as to over-deviate the carrier.

*The code LIM 1 was allocated to an earlier development version which was not used in service.

LIM 6 limiters were used for the experimental stereophonic FM transmissions in the early sixties, using the pilottone system, in which the peak transmitter deviation is determined by the greater of the left- and right-hand audio signals at any time. Transmitter overload protection can thus be conveniently provided by separate limiters in the two channels. For reasons more fully discussed in section 5.4, limiters used in this way must be interconnected and must have carefully matched characteristics. In the case of the LIM 6 arrangement, adequate matching was achieved by careful selection of the pairs of variable-mu valves used. This was a tedious procedure, fortunately made unnecessary by developments in semiconductor technology exploited in the later transistor limiters used for stereophony.

5 Transistor Limiters

5.1 First generation

The first production limiter designed in the BBC to make use of semiconductors went into service in 1964. Known as the AM6/3 it was engineered to meet the same requirements as the LIM 5 and the LIM 6, but with the increased reliability and other advantages that the adoption of transistor circuits offered.

The limiter was feedback controlled, the output being full-wave rectified and threshold-gated to the control terminals of the variable-gain stage. In the AM6/3 the variable-gain element takes the form of a two-stage transistor amplifier shown in schematic form in figure 5.

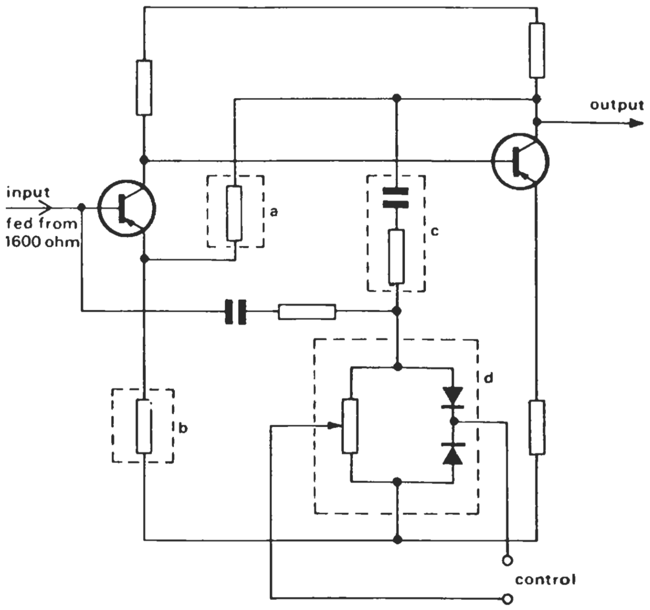

Fig. 5 AM6/3 variable-gain amplifier.

Negative feedback is applied from the output of this amplifier to the emitter of the input stage via the resistors *a* and *b*. Positive feedback which partially offsets the negative feedback is applied to the base of the input stage via the network *c* and *d*. When the limiter is active the control current reduces the dynamic impedance of the diodes in *d* and thereby reduces the positive feedback, allowing the negative feedback to reduce the gain. This circuit can only function when fed from a non-zero source impedance because a source impedance of zero would prevent the application of any positive feedback, regardless of the dynamic impedance of the diodes. To put it another way, the source impedance from which the amplifier is fed can be regarded as part of *d*.

The operation of the circuit can also be considered by regarding *a, b, c,* and *d* as a bridge. The output of the amplifier is connected between the junction of *a* and *c* and the junction of *b* and *d,* while the input to the amplifer is taken from the opposite corners of the bridge. Provided the amplifer has a high intrinsic gain, the bridge will be kept approximately in balance and the signal voltage across the diodes will be almost constant when limiting is taking place. The arm *d* is itself arranged as a bridge so that control voltages are well isolated from the programme chain.

The sensitivity of the control loop is such that under steady-state conditions the output is maintained constant to within 0.2 dB over the 20 dB limiting range of the device.

A 50 μs pre-emphasis time-constant can be introduced in the control chain when used for FM transmissions.

The nominal attack time is 1.8 ms and there is a range of fixed recovery time-constants selected by a front panel control. An input gain control enables an increasing amount of dynamic range compression to be introduced with a standard input level.

A further development of the device, the AM6/3A, enables the flat-topped limiting characteristic to be changed to a sloping compression law over part of the control range.

5.2 The dynamic characteristics of limiters for sound-programme circuits

5.2.1 General

The dynamic characteristics of the limiters so far described grew out of the conditions obtaining at MF transmitters at the time. In 1964 the subject was re-examined with a view to specifying the dynamic characteristics of the next generation of limiters. This work led to the introduction of the non-overshoot type of limiter which has been described fully elsewhere[3]. For the sake of completeness, however, the main points will be repeated here.

5.2.2 The effects of limiter overshoot

It has already been mentioned that, in the absence of wide-band loudspeakers, overloading on transient limiter overshoot was unlikely to cause significant impairment. However, with the loudspeakers available by the mid-sixties it was noticed that audible distortion could result from the clipping of a momentary overshoot if there was insufficient headroom between the steady-state output limiting level of a limiter and the overload point of following equipment. The headroom necessary to avoid audible impairment depended on the nature of the programme material and on a number of other factors, but values of 3dB or more were typical. In general the headroom required decreased as the limiter attack time was reduced but a condition was reached, as the attack time was still further reduced, where audible distortion was detectable on critical programme material, irrespective of the amount of headroom provided. It was

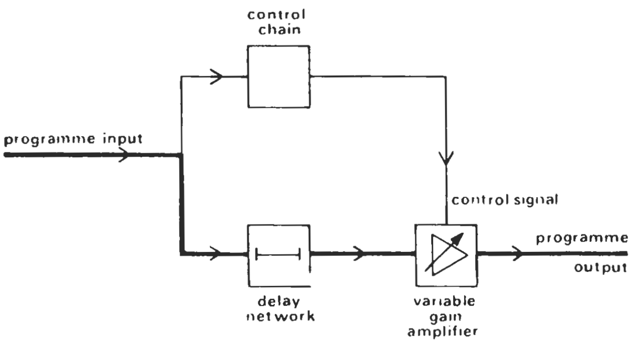

Fig. 6 Input-controlled limiter with delay network.

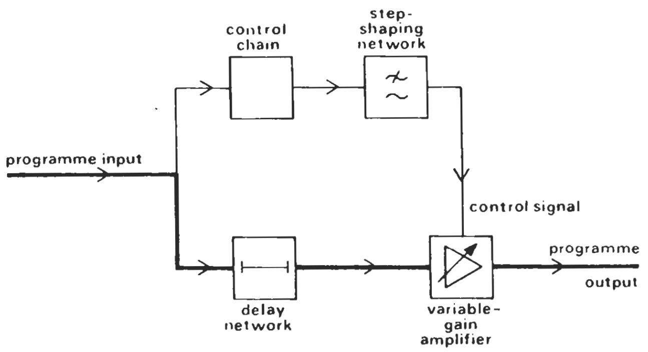

Fig. 7 Input-controlled limiter with step-shaping and delay networks.

concluded that this distortion — which will be referred to as modulation distortion — was an unavoidable consequence of over-rapid change of gain. Further investigation indicated that, to make impairment from this source inaudible, the gain reduction period had to extend over a few hundred microseconds — long enough for there to be a risk of audible impairment due to overloading of following equipment unless adequate headroom was provided.

5.2.3 Elimination of overshoot

Overshoot in a limiter can, in principle, be reduced to any desired extent by introducing an appropriate delay network in the programme path ahead of the variable-gain element so that, by the time the programme signal reaches this point in the chain, the gain reduction effected by the control circuits is substantially complete. It is clearly essential with this arrangement that the limiter be input controlled, that is that the gain control system is operated by the input signal to the limiter and not by the signal at the output. The resulting circuit is shown in a simplified block schematic form in figure 6.

To eliminate overshoot with all types of signal the peak detection and smoothing system which provides the control signal for the variable-gain element must have a sufficiently short charging time to register fully the crest value of the shortest peak likely to occur — ideally, the shortest peak which the bandwidth of the system will allow to pass. However, in practice, the very rapid change of gain which this implies can itself cause audible distortion in the manner described in the previous section.

By a slight refinement to the system of figure 6 it was found possible to avoid both overshoot and modulation distortion. In figure 7, which shows the new arrangement[4], the control system is made sufficiently rapid in action to register the crest value of the shortest incoming pulse. The rate of rise of the control signal reaching the variable-gain element is then restricted by a low-pass filter, or 'step-shaping network', so that the resulting rate of change of gain is not so rapid as to cause audible modulation distortion. In practice the attack period adopted was about 300 μs. To avoid overshoot, the arrival of the programme signal at the variable-gain element has to be delayed, as before, for a time sufficient for the control signal to reach its full value, i.e. by about 300 μs. The new arrangement thus avoids both momentary overshoot and over-rapid gain variation, together with the impairments which these effects may cause.

The circuit shown in figure 7 requires a variable-gain element having a particular gain/bias law, arranged so that the desired static characteristics, illustrated in figure 2, are obtained. It may not always be simple to achieve this required law, but the same performance can be produced using the circuit shown in figure 8, which requires two variable-gain stages that have the same gain/bias law but does not demand a particular law. This duplicate variable-gain stage arrangement was used in the experimental non-overshoot limiters and was adopted for the first production version, the AM6/7, described later.

5.2.4 The effects of limiter gain-recovery time

The operation of a limiter may impair the programme quality by the introduction of effects which, while not classifiable as distortion in the ordinary sense of the word, can nevertheless be aesthetically objectionable. These impairments, which increase in severity with the degree of gain reduction, depend largely on the rate of gain recovery.

If the gain-recovery period extends over several seconds it will be observed that occasional exceptionally high signal levels, momentary in duration and in some cases making little direct impact on the ear, produce a sudden and prolonged gain reduction. At the other extreme, if gain recovery is substantially complete within a syllabic period, say less than 0.2 second, other, but equally disturbing, effects may be apparent, particularly if the limiter is deliberately operated above the normal level to reduce the dynamic range of the programme. In speech, breath noises and some initial consonants will be exaggerated by the rise in gain between sentences or even between words. In music, sustained choral or orchestral passages may suffer a fluttering due to the variations of gain produced by the irregular crests of the signal; during sustained piano notes the natural fall in level is opposed — the net result may even include a temporary *rise* in level — and a similar effect occurs during the decay of sound in reverberant surroundings. The rise in gain at every pause in the programme accentuates background noise, such as studio rumble, tape hiss, or 'print-through'. Operation in this manner during a sporting commentary will mean that the level of any crowd noises in the background will follow the fluctuations in gain, an effect commonly known as gain pumping.

Syllabic compression may be introduced at the studio in the production of some 'pop' music, for artistic reasons, or at AM transmitters to increase the mean modulation depth and thus improve reception under adverse conditions. In these examples the effects of rapid gain recovery may be regarded either as desirable in themselves, or as the price paid to achieve a desirable end. The discussion which follows is, however, concerned with the more difficult case of a protective limiter, the function of which is, like that of a human operator, to apply such overall corrections to the programme level as may be necessary to prevent overload of the transmission system without reducing the mean level of modulation, while making the minimum possible change in the short-term dynamic range.

5.2.5 Double- and triple-time-constant circuits

To avoid the more extreme effects described above, it is usual to arrange, as a compromise, for the recovery time-constant of the control circuit in a simple limiter to be of the order of 0.5 s to 1 s. There is, however, no single relationship between gain recovery and time by which all of the effects described above can be avoided, and various attempts have therefore been made to achieve a better compromise by making the effective recovery time-constant vary automatically with the nature of the signal. One such device introduced in early BBC limiters, gave, in effect, a double time-constant, the gain-recovery period being automatically prolonged according to the amount and duration of the gain reduction which preceded it. While appreciably ameliorating the situation this still failed to bridge the gap between the more extreme requirements, and the 1964 investigations included experiments aimed at extending the range of conditions over which satisfactory operation was possible.

It was found that some of the difficulties associated with a long recovery time could be overcome by making the time-constant dependent on output signal level; a recovery time-constant far in excess of that normally permissible can be allowed, provided that the system is arranged to revert automatically, over a period of about a second, to the usual compromise value of 0.5 s to 1 s during pauses or quiet passages in the programme.

There remained the problem of achieving a sufficiently rapid gain recovery after the limiter had been activated by a signal of less than syllabic duration, while at the same time avoiding flutter effects on sustained passages. These two requirements are in direct conflict; a useful compromise can, however, be achieved by a double-time-constant circuit having fixed parameters, so designed that part of the gain recovery is effected very rapidly, after the limiter has been activated by a signal peak of short duration, leaving the remainder to be restored at a slower rate.

The circuit arrangement finally adopted incorporated both the artifices described in the preceding paragraphs, so that the overall effect might be loosely described as that of a triple time constant[5].

5.2.6 Recovery time-constant parameters selected

Figure 9 shows the essential elements of a peak-detection and smoothing circuit giving a triple-time-constant recovery characteristic. The values of the parameters given below are those originally chosen on the basis of subjective assessments by only a few listeners using a variety of selected programme material; however, no significant changes have been found necessary in field trial or service use during the intervening years.

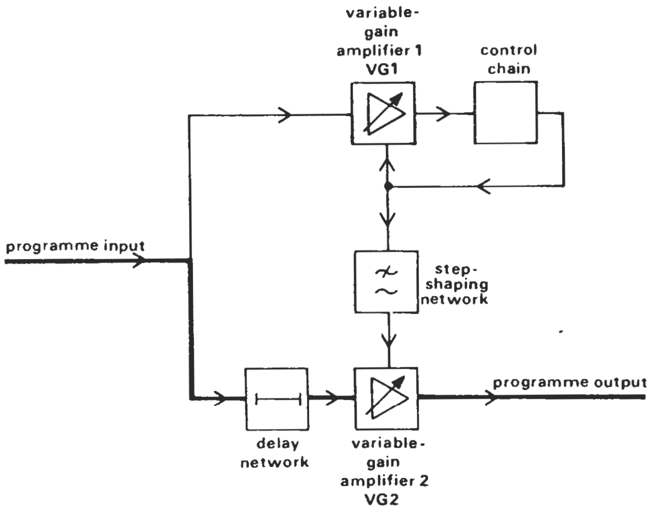

Fig. 8 Duplicate variable-gain stage limiter with step-shaping and delay networks.

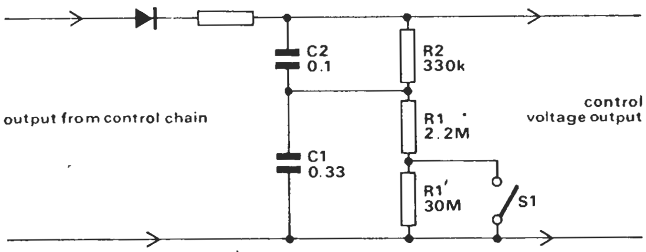

Fig. 9 Peak detection and smoothing system with triple time-constants.

The longest effective time-constant is formed by $C_1(R_1+R_1')$; this product was made about 10 s. For programme levels below a prescribed changeover point, R_1 is short-circuited electronically — a process symbolised in figure 9 by the switch S1 — leaving an intermediate value of time-constant C_1R_1 for which the best compromise was found to be about 700 ms. The shortest time-constant, formed by C_2R_2, was made 33 ms. The values of C_1 and C_2 were chosen so that about three-quarters of the control voltage arising from a momentary overload was allowed to be discharged at the 33 ms rate.

The signal level at which the change of time-constant takes place has to be set sufficiently low to avoid appreciably interfering with the 'tail' of a long reverberation process, yet not so low that gain recovery at the intermediate rate is virtually excluded. For programmes including classical music covering a wide dynamic range, a suitable changeover point was found to be that at which the output signal falls to 20dB below its limiting value.

5.3 A production non-overshoot limiter

The design of the AM6/7 limiter, developed in the late

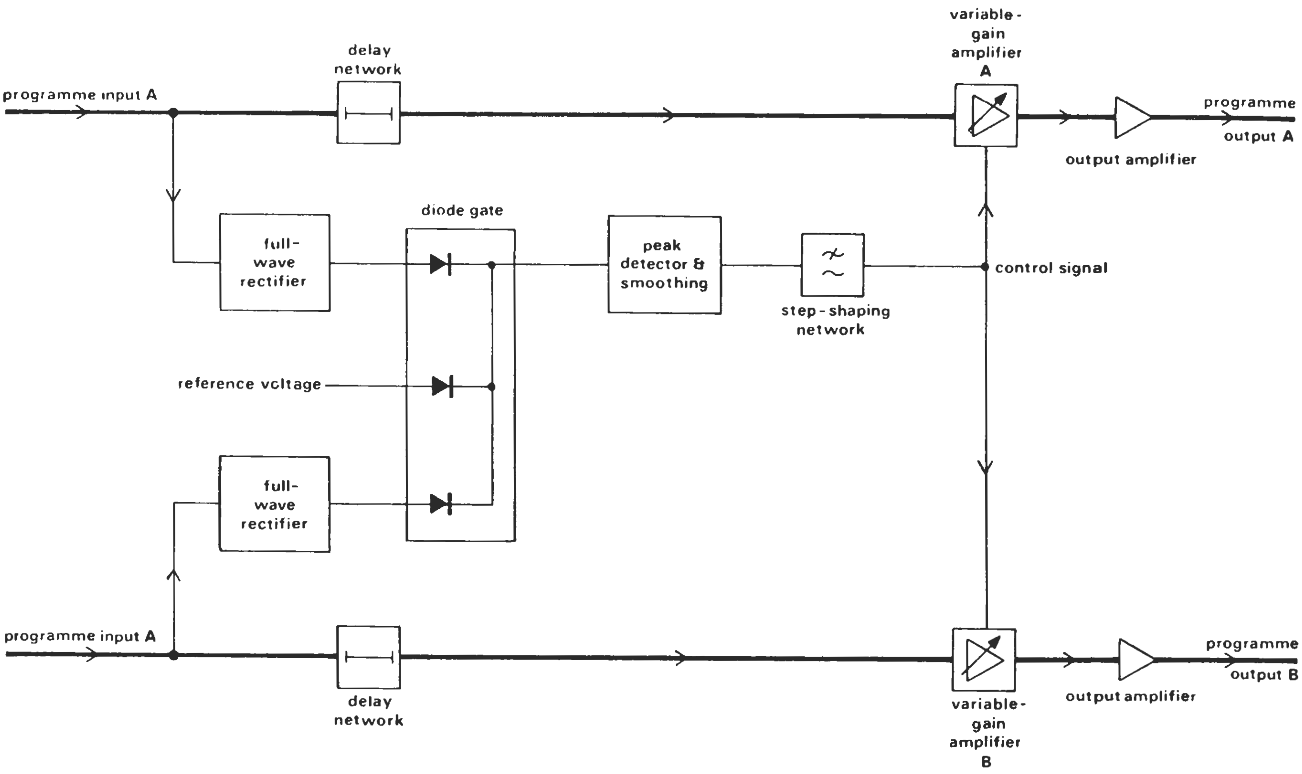

Fig. 10 Stereophonic limiter arrangement.

sixties, was based on the results of the investigations described above. With its introduction it became possible to eliminate transient overshoot entirely, without risk of introducing impairment in the process.

As indicated earlier the AM6/7 limiter used the method of duplicate variable-gain stages shown in figure 8. The control signal was derived in a fast-acting feed-back limiter circuit, and was transferred at an appropriate rate, controlled by a step-shaping network. to the programme-channel variable-gain element. A lumped-constant delay network having a group delay of about 300μs provided time for the gain in the programme channel to be reduced before the arrival of any programme peak which required control.

The variable-gain elements were selected matched pairs of field-effect transistors (FETs) acting as variable shunt resistors in L-section attenuators.

5.4 Requirements for stereophony

So far only brief mention has been made of stereophony. Stereophony places additional requirements on limiters that were difficult to meet with earlier designs. First, it is essential that, in order to avoid image shift, the two limiters used as a stereophonic pair should be matched and ganged so that they have equal gains at all times: there is experimental evidence that gain matching both statically and dynamically to within about 2dB is required, and clearly matching even more closely than this is desirable within a single link in a transmission circuit. Second, if the output of neither limiter is to exceed its maximum defined level it follows that the common control during gain reduction should be derived from whichever limiter in the pair has the greater input at the time.

These additional requirements could be met with limiters of the AM6/7 type (see section 5.3), but not without some practical difficulties which were costly to overcome. The most successful ganging technique investigated with this type of limiter was relatively complex: a composite signal, derived from the two programme input signals by time-division multiplex, was used to determine the amount of control effected by the limiters in the two channels.

If, however, the limiters were of the type shown in figure 7, two such devices could conveniently be connected for stereophony in the manner shown in figure 10. Here, each input is full-wave rectified and, by simple diode gating, the greater of the two rectified signals is fed to the remainder of a common control chain. As discussed earlier this approach requires a particular gain-versus-bias characteristic for the variable-gain element in order to achieve the ideal flat-topped static characteristic shown in figure 2b. Where the control signal is linearly related to the limiter input signal, the gain of the variable-gain element must be inversely proportional to the control signal if the desired characteristics are to be achieved. Then, as the input signal exceeds the limiting threshold, the increasing control signal causes the variable-gain element to reduce gain to compensate exactly, and a constant level is maintained at the limiter output. This process may be regarded under steady-state conditions as an arithmetic division of the programme signal by a direct control voltage which, for inputs beyond the limiting threshold, is proportional to the peak of the input waveform.

Such an analogue divider was readily instrumented with the advent of the integrated-circuit multiplier. A multiplier in the negative-feedback path of an amplifier with a high loop gain, as shown in figure 11, results in a variable-gain element of the required type. Any departure from the ideal limiting characteristic depends only on the control circuit and multiplier linearity.

A stereophonic limiter using this technique, the AM6/11, was developed in 1972. The dynamic performance was similar to that of the AM6/7 but the gains could readily be matched within 0.3dB over a 20dB control range with a departure from a flat-topped characteristic of less than 0.5dB.

This form of ganging enables any number of devices to be accurately coupled together and subsequent designs, e.g. the AM6/14, have consisted of monophonic units which, for stereophony, can be ganged to any unit of like design by a simple wire link.

5.5 Variable-emphasis limiters

5.5.1 General

Where a flat-spectrum* limiter is used to control pre-emphasised sound signals for FM radio in the manner described in section 4.3, limiting action which is necessary to regulate the emphasised high-frequency components of programme — even though that programme was correctly controlled at source — also depresses the level of low- and medium-frequency components. In some circumstances this action can give rise to an objectionable subjective effect, often referred to as gain ducking. In these circumstances, it has been a common practice for broadcasting organisations to attenuate the signal applied to the limiter until gain ducking is reduced to acceptable proportions — a practice which necessarily reduces the effective service area of the transmitter. In 1971/72 work began on the development of a limiter which, even with full-level signals applied, substantially eliminates impairment due to gain ducking on emphasised sound signals and which prevents overmodulation, even of a momentary nature.

Overloading as a result of high-frequency pre-emphasis can be prevented by a limiter which simply reduces the amount of emphasis as required, without affecting the level of lower-frequency components[6]. Impairment due to gain ducking can thus be made much less obtrusive, and the audible effect of limiter action need be no more than a momentary loss of 'top', generally imperceptible unless unprocessed programme is available for reference.

By its nature a limiter stage of this kind cannot, however, give protection against overloading by low-frequency signal components of excessive level; it must therefore be preceded by a flat-spectrum limiter stage of the non-overshoot delay-line type[4]. The combination of the two limiter stages, plus any necessary emphasis network, will be referred to as a two-stage variable-emphasis limiter.

The arrangement was developed for 50 μs pre-emphasis operation, principally with FM radio and television sound in mind, but it can be applied in other situations where the effective overload level decreases with increasing signal frequency. The principle can be applied to systems having other than 50 μs pre-emphasis, though its performance would have to be reassessed if greater values were being considered. It has found application in association with the BBC's PCM system for sound-signal distribution.

Here the sound signals are pre-emphasised at the sending terminal and variable-emphasis limiters located at that point can give protection to the PCM channels *and,* because of the gain stability of the PCM system, to *all* the FM transmitters they serve.

*A flat-spectrum limiter can be defined for the present purpose as one which has, at any instant, the same gain for all signal components, irrespective of their frequency.

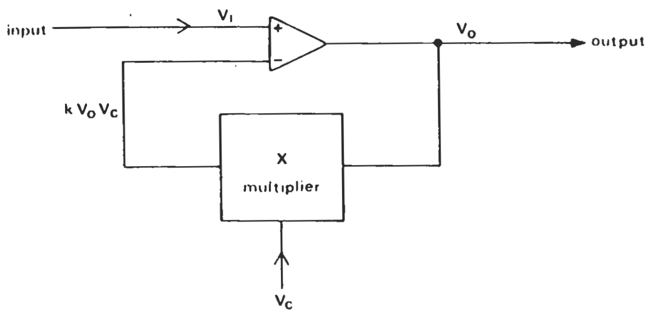

Fig. 11 Voltage-controlled amplifiers. Conventional use of a multiplier in the feedback path of an operational amplifier to produce an analogue divider.

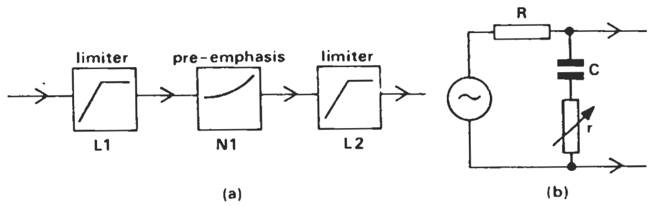

Fig. 12 Experimental two-stage variable-emphasis limiter.
a. Block schematic.
b. Variable-gain element of stage-two limiter

5.5.2 Experimental circuit arrangement

Figure 12a shows the general arrangement of an experimental two-stage variable-emphasis limiter constructed for evaluation. Incoming signals, when of excessive level, are regulated by a non-overshoot flat-spectrum stage-one limiter L1, then applied to a 50 μs pre-emphasis network N1, and finally to the variable de-emphasis stage-two limiter L2. The flat-spectrum limiter used has a complex gain-recovery characteristic, of the type described in section 5.2.5, and can exercise a considerable amount of control with little impairment of quality.

The circuit of the variable de-emphasis element used initially in stage L2 is shown in figure 12b. It comprises an L section with a series arm of resistance R and a shunt arm having capacitance and variable resistance r connected in series — the latter being in fact the drain/source impedance of a field-effect transistor (FET). The value of r, and hence the amount of top-cut introduced by the circuit, can be controlled by varying the voltage applied to the FET gate. Component values were chosen so that, in the limit ($r = 0$), a 50 μs de-emphasis characteristic was applied, just offsetting the effect of the preceding pre-emphasis. The listener thus hears some degree of top cut when programme-signal conditions require L2 to operate.

The subjective effect of this top loss may be minimised by making its duration as short as possible. In flat-spectrum limiters the recovery time-constant is normally made at least several hundred milliseconds in order to avoid audible distortion due to significant gain recovery during the period of one cycle, i.e. 'cycle-following', at low frequencies. The variable de-emphasis stage, however, operates significantly only on high-frequency components, so the rate of gain recovery can be much higher without causing audible distortion; in the experimental apparatus the rate of gain recovery for this stage was set by a circuit having a 25 ms time-constant.

5.5.3 Subjective assessment

Subjective tests were carried out to compare the quality of reproduced programme processed by the experimental arrangement with unprocessed programme and with pre-emphasised programme processed by a conventional flat-spectrum limiter. Three short programme items were used for the investigation — selected because the nature of their high-frequency content made them potentially susceptible to gain-ducking and to degradation due to top loss. Tests were carried out with programme applied to the limiters at normal level and at increased levels such as might occur accidentally in service.

For two programme items having intermittent high-frequency components the subjects showed a marked preference for the experimental arrangement rather than the conventional system. In the item with more continuous high-frequency content, however, the results indicated little difference between the two systems, but in no case was the mean grading of the experimental arrangement worse than that of the conventional arrangement.

The comparisons with unprocessed programme showed that, while the listeners did indeed prefer the unprocessed version of the most stringent test items, the difference was only slight. Programme processed by the variable-emphasis limiter system was, even in these circumstances, less than one grade worse than the unprocessed programme on a seven-point comparison scale running from 'much better' to 'much worse'.

Prototype limiters operating as described above were first subjected to field trial and service use in 1973.

5.5.4 A production design

In the experimental variable-emphasis limiter arrangement non-overshoot delay-line limiters were used for both the stages. Subsequent investigation[7] has indicated that, under the conditions in which the second stage operates, a simplified, non-delay-line arrangement — in which overshoot is prevented by instantaneous clippers — is acceptable provided that the steady-state output limiting level is set about ¾ dB below the clipping level. This arrangement has been adopted in the production limiter instrumentation described below.

The nature of the variable-gain element, too, has been revised during development; the variable-de-emphasis arrangement has been changed to a variable-pre-emphasis arrangement, with the 50 μs fixed pre-emphasis network omitted. As a result the effects on the programme spectrum are somewhat modified but listening tests have indicated that in practice the subjective performance is substantially unchanged.

The experimental two-stage variable-emphasis limiter just described used a field-effect transistor to provide the voltage-controlled resistance, as did the first generation of overshoot-free flat-spectrum limiters, but in the variable-emphasis case the problems of stereophonic ganging are even more acute. Both the flat-spectrum stage-one limiters and the variable-emphasis stage-two device need to be ganged, to an acceptable degree of accuracy, to the corresponding parts of the companion limiter of the stereophonic pair. This requirement makes the use of field-effect transistors in a production design somewhat difficult. Fortunately the needs of the stage-one limiters were met by existing circuits used by the BBC (see section 5.4).

Further development of the stage-two limiter to use multiplier techniques, while still meeting the critical noise requirements of the PCM distribution system, resulted in some modification to the stage-two limiter. Figure 13 shows the basis of the new configuration.

Here the apparent impedance of the network in the emitter circuit of the transistor TR1 depends on the amplitude and phase of the output signal from amplifier A1. This signal is in phase with the input and its magnitude is determined by the control voltage applied to the multiplier. Under normal working conditions this control voltage is zero, and hence there is no signal either at the output of the multiplier or at the output of A1. The system is arranged so that under these conditions the output signal (V) taken from the collector of TR1 has undergone the standard 50 μs pre-emphasis used for FM broadcasting. If, however, the output tends to exceed the defined limiting level, peaks of the full-wave rectified output exceed a reference level and an error amplifier charges capacitor C_2 via a diode and resistor R_4. The resistor and capacitor restrict the attack speed of the control system. The potential difference across the capacitor is fed to the control input of the multiplier and causes a signal in phase with the input signal to appear at the output of A1, increasing the apparent impedance of C_1 and R_3 in the emitter circuit of TR1. This effectively reduces the pre-emphasis time constant until the output assumes a value no greater than the defined maximum. When the rectified output drops below the reference potential, C_2 discharges through R_5 and the standard 50 μs pre-emphasis is restored. The recovery time-constant may be made short for the reason already discussed, and the necessary engineering control is effected with a minimum of subjective disturbance.

The variable-emphasis stage described above is of the non-delay-line type, and clippers are provided, as described earlier, to eliminate momentary overshoot of the pre-emphasised signals. Ganging of two stage-two limiters in a stereophonic arrangement is conveniently carried out by the simple linking arrangement described in section 5.4 for flat-spectrum limiters.

Stereophonic variable-emphasis working on the principles

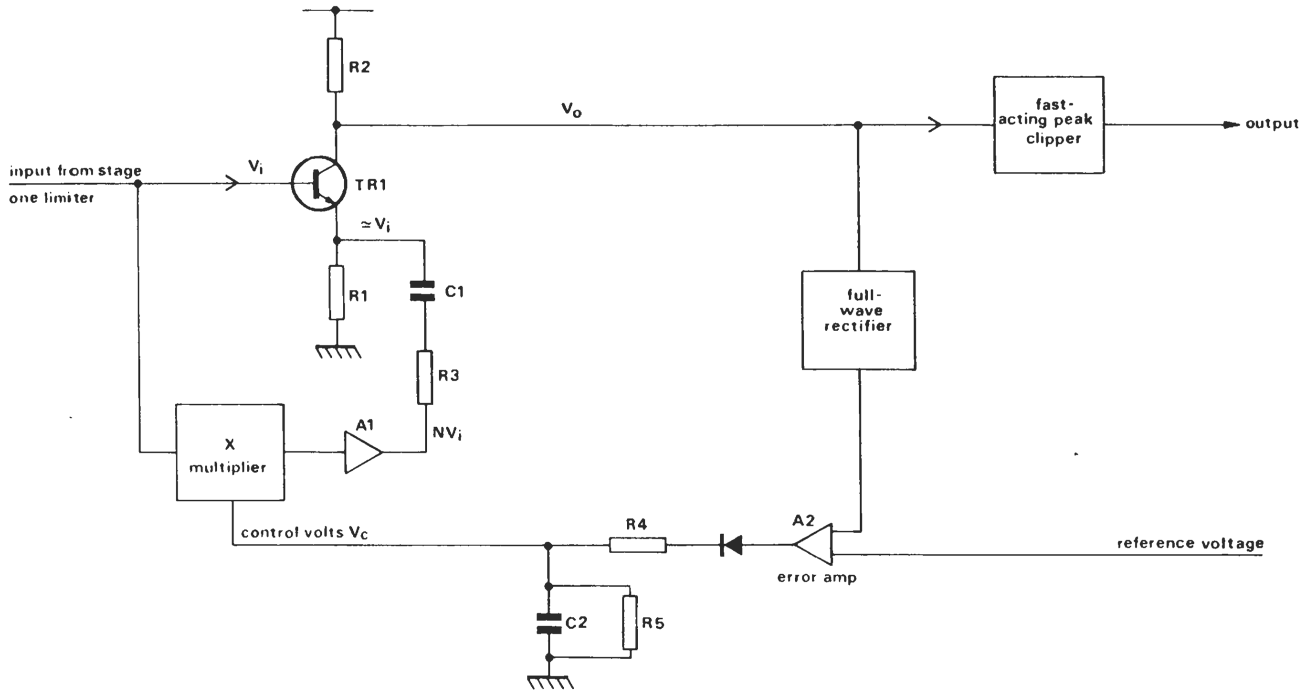

Fig. 13 Stage-two variable-emphasis limiter.

described above were used in service in 1974, and the production design, the AM6/16, came into service in 1975.

6 Conclusions

This review of the development of sound-programme limiters within the BBC mirrors advancing technology and changing requirements.

The physical size of limiters has been reduced, first by the introduction of miniature valves and later by the introduction of transistors and integrated circuits. Limiter size is likely to continue to decrease with the increasing application of integrated circuits.

Limiter performance has been improved by successive refinements of a basic technique, to meet the needs of the day. The special requirements for FM radio and for stereophony have been met and new designs have been introduced to reduce the impairment of programme quality by eliminating momentary overshoot and by minimising the effect of gain fluctuations.

Future developments are less easy to predict, but it seems inevitable that analogue limiters, essentially similar to those described, will continue to be required for the foreseeable future, at least until an economic digital equivalent is developed.

7 References

1. BBC Engineering Division Training Manual, 1942, pp 105-107.
2. Patent No. 509,309 (application date January 12 1938).
3. SHORTER, D. E. L., MANSON, W. I. and STEBBINGS, D. W. The dynamic characteristics of limiters for sound-programme circuits. BBC Engineering Division Monograph No. 70, October 1967.
4. Patent No. 1108413.
5. Patent No. 1172310.
6. DASNES, A. A sibilant limiter for FM broadcasting systems. EBU Review, 77A, February 1963.
7. MANSON, W. I. Frequency-dependent limiters for FM sound broadcasting: optimisation of attack period and of delay length in the variable-de-emphasis stage. BBC Research Department Report No. 1975/22.

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