MASTER

An optimatizing system for control of the ignition timing of combustion engines

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AN OPTIMATIZING SYSTEM FOR CONTROL OF THE IGNITION TIMING OF COMBUSTION ENGINES.

R. van Lutterveld

Rapport van het afstudeerwerk
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onder leiding van ir. C.Huber

Note

This volume is composed of three separate reports which were prepared independently but consecutively. The titles of these parts are:

I Investigations of possible optimalizing systems for control of combustion engines.

II An optimalizing system for control of the ignition timing of combustion engines.

III Improvements of the ignition timing optimalizing controller and measuring results.

REPORT I

Investigations of possible optimalizing systems for control of combustion engines.

R. van Lutterveld

Summary:

This report outlines the background of optimalizing control in which an automatic unit is placed in the feedback branch of a system to function in the manner of a human operator in searching out and holding the best performance of a controlled system, in spite of any reasonable change of the output level or environmental operating conditions.
A number of typical systems are discussed.
It is shown that the peak holding optimalizing controller is easier to adapt than other types when applying a controller to controlled systems with strong interferences.

C O N T E N T S

1. Introduction

Forcing a system to produce its maximum output at a minimum cost of the basic inputs is ordinarily done by use of manual adjustments or by means of automatic regulators.

In systems using manual adjustments the operator determines the instantaneous optimum condition by a process of trial and error, and adjusts the controlled inputs accordingly. This means that the operator carries out the function of a feedback branch in a closed-loop system.

This report outlines the background theory of optimalizing control in which an automatic unit is placed in the feedback of a system to function in the manner of a human operator in searching out and holding the best performance from a controlled system, in spite of any reasonable change of the output level or environmental operating conditions.

Controllers of this kind may be designed for any operating system that actually exhibits an optimum performance condition as its inputs are varied. An internal combustion engine is an example of a system with characteristics that permit the realization of an optimum operating condition. Figure 1 is a three dimensional model showing the performance surface that represents the relationships between brake mean effective pressure as the dependent output and ignition timing and fuel-air ratio as independent variables, subject to the conditions that engine speed and fuel flow rate are both held constant.

An optimalizing controller applied to this engine would operate by searching out the optimum point through changes in spark advance and fuel-air ratio, made in response to a feedback signal representing the brake mean effective pressure as the essential controlled system output.

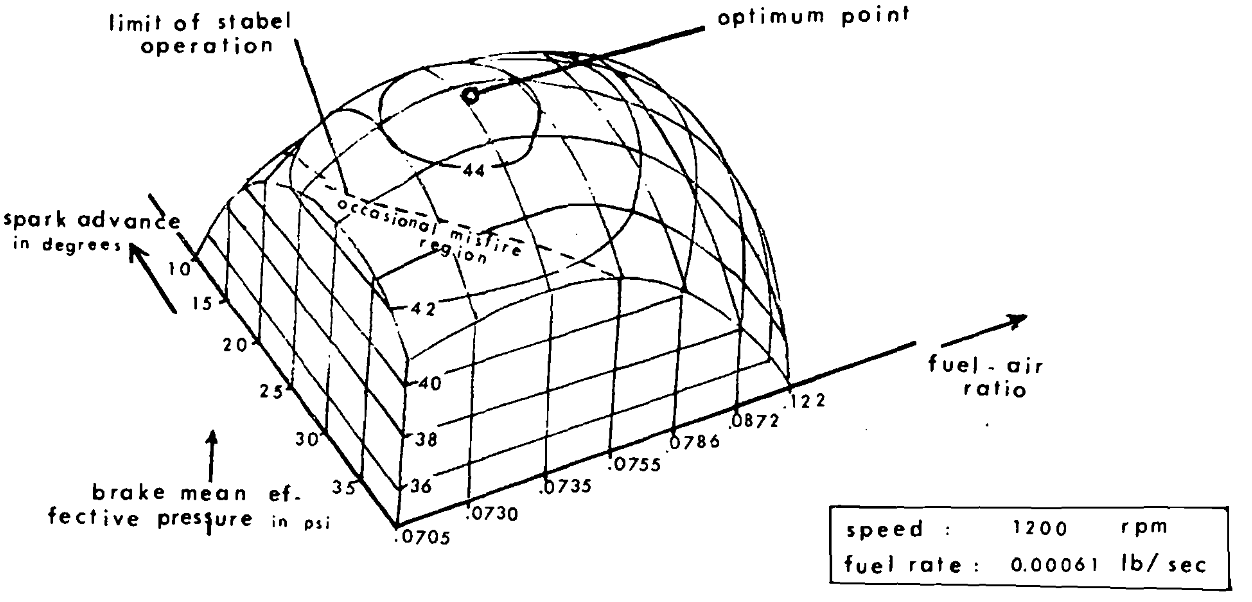


Fig.1. Static performance characteristics of a combustion engine

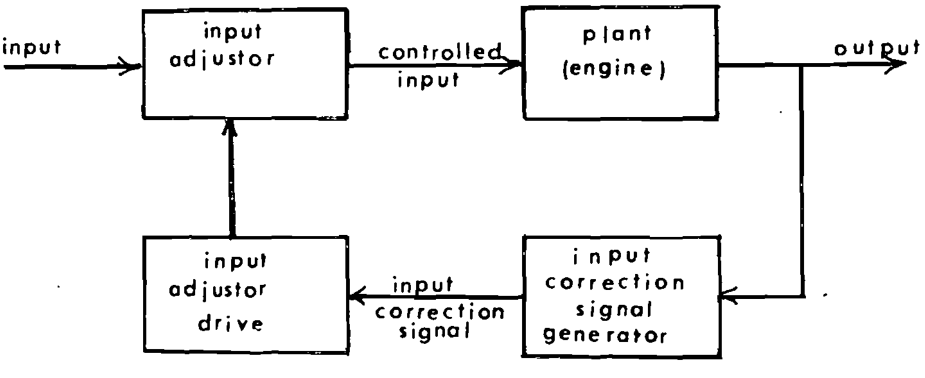


Fig. 2

Fig. 2 is a functional diagram showing the essential components of a generalized optimalizing controller applied in a typical system.
In practice, optimalizing control action may be required for a number of inputs, but to facilitate the present discussion the controlled system of Fig. 2 is shown with a single output depending upon a single controlled input. This means that the diagram applies only to situations in which all other inputs except the controlled input are constant.
Optimalizing controllers may be divided into two classes depending upon the type of input signal that is used. These classes, first proposed by Draper and Li (see page 28) are listed below:

a) Input- output sensitivity operated controllers

The input-output sensitivity is by definition equal to the partial derivative of the output with respect to the controlled input. All optimalizing controllers of the input-output sensitivity operated type work by using the controlled system itself to generate a signal that represents its controlled input-output sensitivity, and then taking the deviation of this signal from zero to produce the controller input signal.

b) Peak holding controllers

Optimalizing controllers of the peak holding type operate by continuously searching for an optimum level, which is used in the generation of an output deviation signal.

These two controller types are discussed in more detail in the following sections.

2. Input-output sensitivity operated controllers

2.1 Sensitivity signal input optimalizing controllers

Optimalizing control based on the direct measurement of controlled system sensitivity is possible if the test function is a simple, constant rate variation of the controlled input that may be reversed in direction. When the controlled system sensitivity is positive, an increase in the controlled input causes a corresponding increase in the output. At the instant the optimum point is passed, the sensitivity reverses and the output starts to decrease, even though the input continues to increase. When this reversal has existed long enough for its presence to be definitely distinguished from interference effects, the direction of the controlled input change may be changed by the controller so that the controlled input starts to decrease. As this decrease in the input continues, it affects the system output through the performance characteristics to cause a reduction in output that causes the controller cycle to start anew. An optimalizing controller may be designed so that the sequence of events described in the preceding paragraph is repeated indefinitely, causing the output of the controlled system to remain within some "hunting zone".

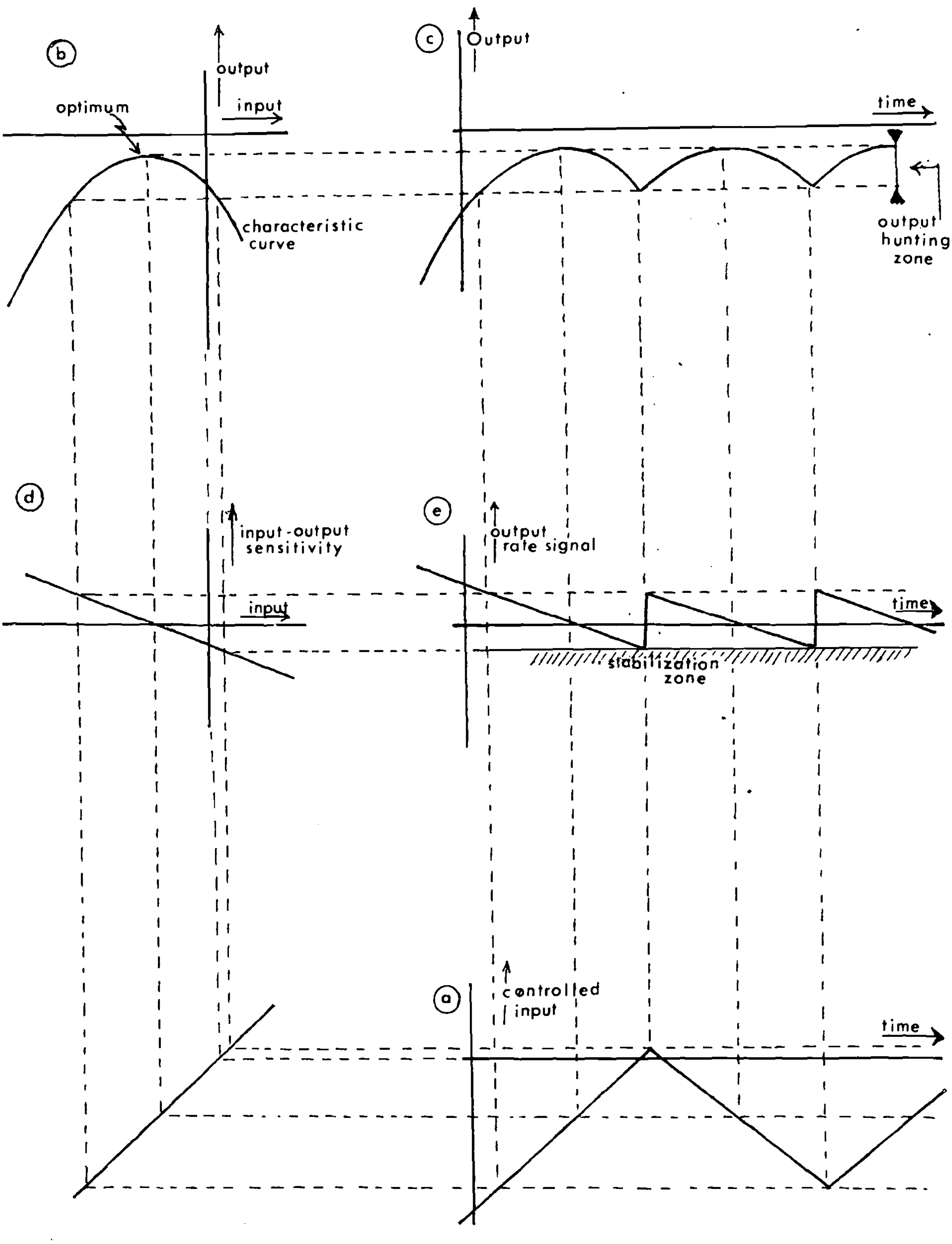
Fig. 3 gives a typical control diagram for the sensitivity signal type of controller. The functional diagram of Fig. 2 applies directly to the sensitivity signal type of controller.

The curves (b) and (d) at the left-hand side of Fig. 3 are the characteristic curves for the output signal and the controlled input-output sensitivity, respectively, plotted against controlled input as the independent variable. To facilitate discussion the plot origin of Fig. 3b is located in the region of primary interest (near the optimum point).

The curves (a), (e) and (c) to the right in the figure are the controlled input, the input correction signal and the output signal, respectively, all plotted as functions of time.

The controlled input variation with time, represented in Fig. 3(a) is generated by a constant speed change of the input with reversals at points determined by operation of the controller. Variable input rates may be used when desired.

The time rate of change of the output rate signal is a direct representation of the input-output sensitivity of the controlled system, and can be obtained graphically by projecting the corresponding points from Fig. 3d to Fig. 3e. The signal representing the output rate is used as the input correction signal for optimalizing control.



b
output
input
optimum
characteristic curve
c
Output
time
output hunting zone
d
input-output sensitivity
input
e
output rate signal
time
stabilization zone
a
controlled input
time

Fig. 3

When this signal level reaches the stabilization limit, the input rate is reversed by the controller. After this input rate has continued for a sufficiently long time, the output signal curve will pass the optimum point and then decrease so that the input-output sensitivity of the controlled system again becomes negative.
The corresponding change in the input correction signal continues until it becomes equal to the stabilization zone limit. When this limit is reached, the direction of the input change is reversed, and the sign of the input correction signal again becomes positive. The stabilisation zone limit is chosen at a level greater than the input correction signal changes that may be caused by the interference components present in the output signal.
The size of the output hunting zone depends upon the size of this stabilization zone.

Limitations

The sensitivity signal type of optimalizing controller described in Figs. 2 and 3 represents the simplest design for a system of this kind. The basic difficulty with the sensitivity signal controller input is that the controller input is generated by differentiation of the output signal. A general effect of any differentiation process is that it increases the relative effects of high-frequency interference components. This means that comparatively large stabilization zones must be used.

2.2. Continuous test signal optimalizing controllers

Continuous test signal optimalizing controllers operate by superimposing a continuous variation of relatively small amplitude on the input. The component of the output signal produced by the effect of this test signal is separated from the resultant output variation by filtering and is then compared with the input test signal itself.
The comparison signal, representing the difference between the output signal test component and the test signal, may be made to have an algebraic sense with respect to the input test signal that depends upon whether the average input level is above or below that for the optimum

point, and to approach zero when the controlled system is working at the optimum point. After it has been subjected to proper smoothing and other modifications the comparison signal may be used as the input for controlling the input adjustor. This adjustor changes the average input in a way that drives the controlled system operation to approach its optimum condition.

Because of the ease with which it may be generated and applied in optimalizing controllers, a simple sinusoidal wave form is generally desirable for the test signal. Among other advantages, a signal of this kind may have its frequency adjusted to lie in a band that is relatively free from interference components.

Fig. 4 illustrates the effect of the characteristic curve shape on the steady-state output variation component produced by a simple sinusoidal input variation. To demonstrate clearly the response characteristics that are important for optimalizing controller operation, single input cycles are shown applied to three different segments of the characteristic curve (Fig. 4). The first segment is assumed to be a straight line located on the low-input side of the optimum point and corresponding to a positive input-output sensitivity for the controlled system. The second characteristic curve segment has a parabolic shape with symmetry about the output axis and the vertex located at the optimum point. This parabolic is continued to the right of the optimum point to give a non-linear segment (segment 3) corresponding to a negative input-output sensitivity.

Fig. 4a shows the axis of the first input cycle at a_{in}.
Its intersection with the lineair characteristic curve segment of Fig. 4b. establishes the location of the corresponding output axis a_{out} on which the output cycle 1_{out} is based. Over regions in which the characteristic is linear, the action of the operating system is to produce an instantaneous increment of output level, measured from the axis a_{out}, that is proportional to the corresponding instantaneous increment of input level, measured from the axis a_{in}.
The output cycle 1_{out} has a simple sinusoidal shape in phase with the input cycle 1_{in}.

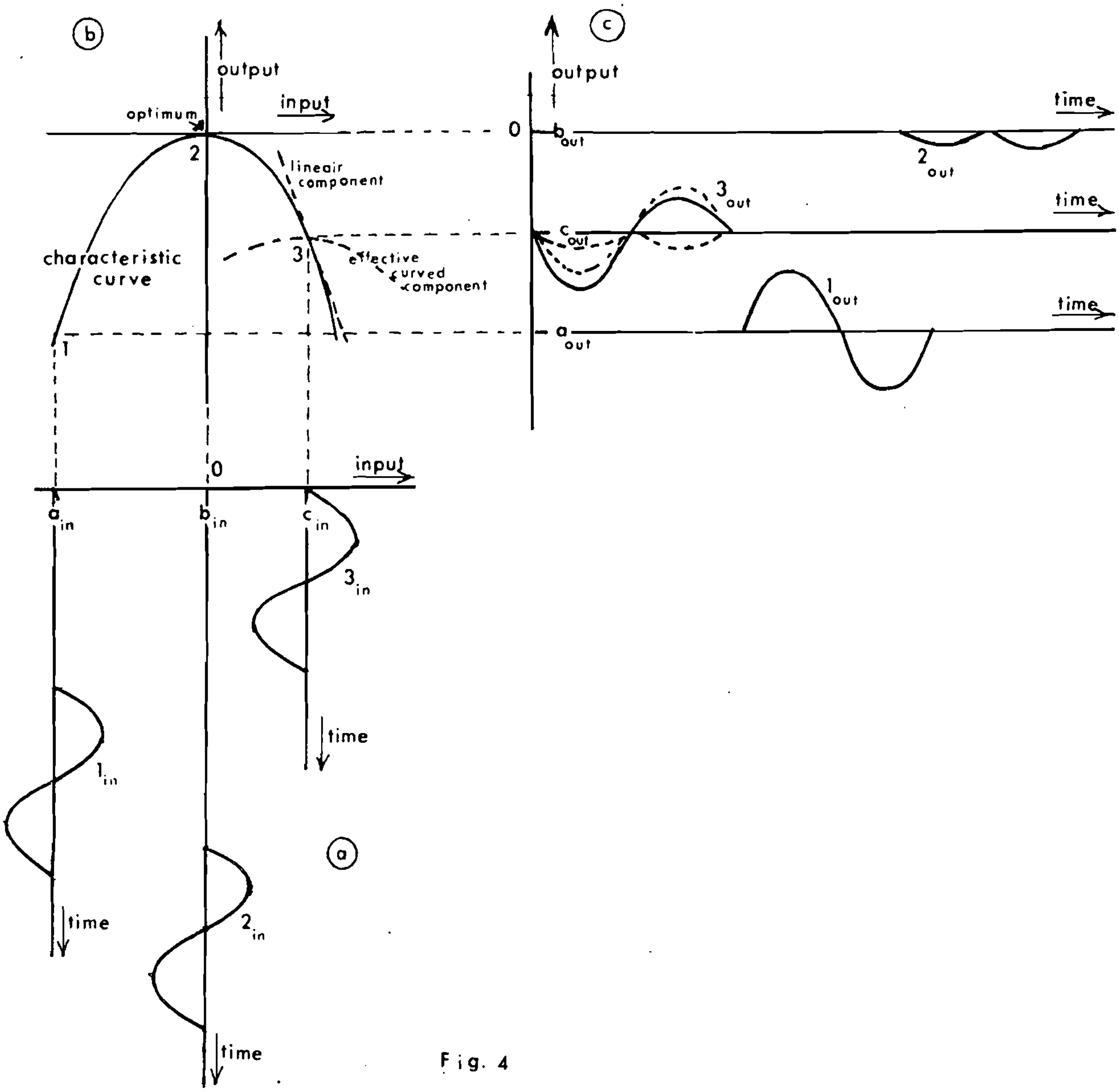


Fig. 4

In Fig. 4a the axis b_{in} for the input cycle 2_{in} is assumed to be identical with the optimum point input level. The corresponding output cycle is determined by the parabolic characteristic curve, which effectively squares the sinusoidal input variation and multiplies this square by a constant. The result of this action is that the output variation has completed two cycles while the input change completes one. This result is shown graphically by curve 2_{in} and 2_{out} of Fig. 4a and 4c. The output curve 2_{out} has a complete cycle for each half-cycle of the input curve 2_{in}. The amplitude of this second-harmonic output curve is proportional to the square of the input cycle amplitude.

The effect of the characteristic curve segment 3 on the input cycle 3_{in} is a combination of the action of a straight line tangent to the characteristic curve at the mid-point of the segment combined with a curved component. The straight line and curved component are shown as dashed lines intersecting at the level of the line c_{out} in Fig. 4b. The straight-line part of the characteristic curve acts to produce an output component with the same frequency as the input cycle and with an amplitude proportional to the product of the input amplitude and the average sensitivity. The behaviour is identical with that already explained for segment 1 of the characteristic. An essential difference between the output determined by segment 1 and the output determined by segment 3 depends upon the fact that segment 3 slopes downward while segment 1 slopes upward. This situation is represented by 3_{out} and 3_{in} in Fig. 4a and 4c which show the resultant effect that the first-order component of the output wave is 180 degrees out of phase with the input wave. In Fig. 4b the parabolically curved deviation from linearity of segment 3 of the characteristic curve acts in the way already explained for segment 2 to cause a second harmonic component in the output. This component and the resultant output curve 3_{out} are shown in Fig. 4c.

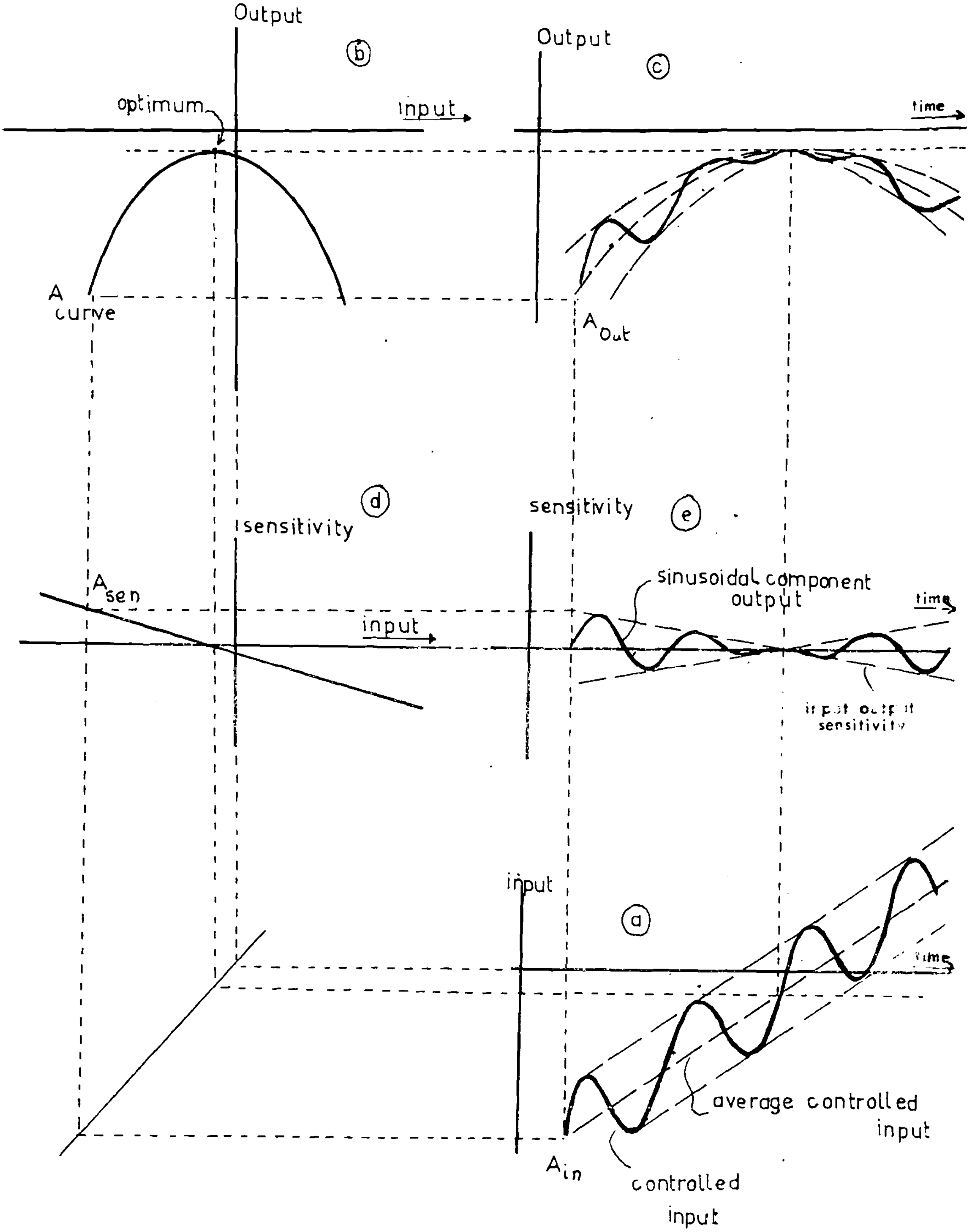
In general, the content of higher-order components that appear in the output will increase as the curvature of the segment increases. From the point of view of optimalizing control, the important fact is that no matter what shape the characteristic curve may have, so long as it is adapted for control of this type, the output will always contain a component with its frequency identical with the frequency of a simple sinusoidal input variation. In practice the higher order components can be removed by proper filtering. The fundamental output component will always be in phase with the input wave when the controlled system is operating on the low-input side of the optimum point and will always be out of phase with the input wave when operation is on the high-input level side of the optimum point.

The diagram of Fig. 5 illustrates the effects of a relatively small amplitude sinusoidal component superimposed on a linear change of the input to an uncontrolled system which has a static characteristic shape suitable for optimalizing control.

Fig. 5a represents the input variation. A typical point A_{in} on the controlled input curve corresponds to the points A_{curve}, A_{sen} and A_{out}. The combination of the individual plots of Fig. 5 shows that the linear component of input changes acts through the downward concave shape of the characteristic curve to give an output component that, as a function of time, increases toward the optimum level and then decreases. The relatively small-amplitude sinusoidal input component of Fig. 5a does not materially affect the smoothed level of the output, but it does produce an output component that has characteristics depending upon the existing deviation of the output level from its optimum level. The principles that control these characteristics are explained by the relationships illustrated in Fig. 4. For the reasons discussed in connection with Fig. 4, the sinusoidal component of the output in Fig. 5c will contain a fundamental of the input frequency. This fundamental is:

1) in phase with the input wave for output levels below the optimum point
2) zero at the optimum point
3) 180 degrees out of phase with the input for input levels above the optimum point.

Although the output will contain higher-order components to an extent depending upon the effective curvature of the system characteristic, the plot of Fig. 5e is drawn to show only the fundamental component of the output variation. This output component curve is related to the sinusoidal input curve component at any point of the characteristic curve by the tangent to the performance characteristic. The amplitude of this fundamental oscillatory component of the output is proportional to the system sensitivity. The straight lines drawn through the oscillatory component peaks of Fig. 5e represents the variations in the controlled system sensitivity. This fact makes it possible to use



Output
(b)
optimum
input
A
curve
Output
(c)
time
A Out
(d)
sensitivity
A sen
input
sensitivity
(e)
sinusoidal component
output
time
input
(a)
time
average controlled
input
A in
controlled
input

Fig 5

the fundamental oscillatory component of the output for the generation of the input correction signal for optimalizing control purposes.

Proportional input rate test signal controller

Fig. 6 is a functional diagram for the combination of a controlled system and a typical optimalizing controller of the continuous test signal type. Fig. 7 is a typical performance diagram showing the essential actions that occur when the system of Fig. 6 is in operation. The test signal generator of Fig. 6 produces a sinusoidal input test signal of constant amplitude and frequency, which is shown as a function of time in Fig. 7a. This signal is superimposed on the average level of the controlled input. This input test variation is shown as the sinusoidal component of the controlled input variation plotted in Fig. 7b. The controlled system receives this sinusoidal input component and produces a corresponding test signal output component depending on the characteristic curve of the controlled system. This test signal output is shown in Fig. 7e.

The action by which the test signal output component is generated is identical with that discussed in connection with Fig. 4 and 5. The output signal is shown as the full-line curve of Fig. 7c. This signal is supplied to the filter of Fig. 6, which separates the fundamental test signal component, suppresses the interference components in the output signal, and reduces the smoothed output level to a zero reference level. This fundamental output test-signal is passed through a phase adjustor, which compensates for undesirable phase shift effects that may have been introduced by operation of the controlled system.

The phase adjusted fundamental output test signal is supplied as an input to the rectifying multiplier of Fig. 6 which also receives the input test signal directly from the test signal generator.

The rectifying multiplier takes the product of these two signals and gives the result an algebraic sign by using phase-sensitive detection of the fundamental output test signal with respect to the input test signal. In order to use this instantaneous varying signal as the controlling effect for the input adjustor, it is passed through a

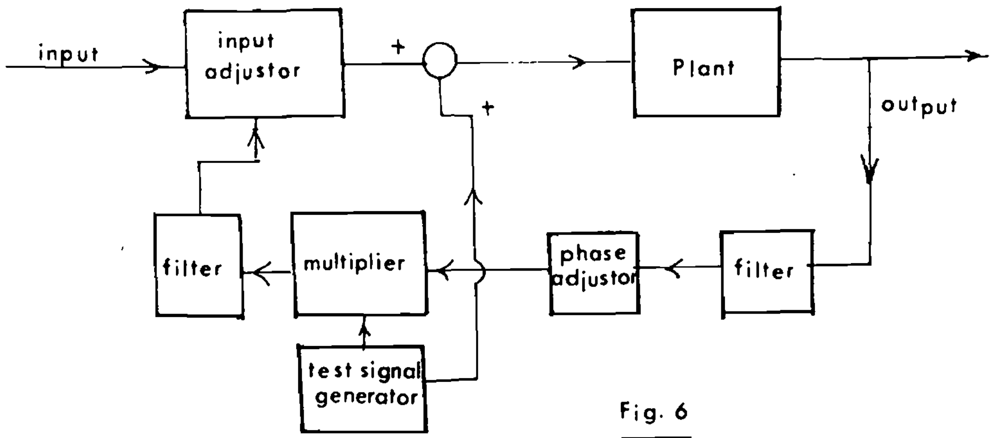

input
input adjustor
+
+
Plant
output
filter
multiplier
phase adjustor
filter
test signal generator

Fig. 6

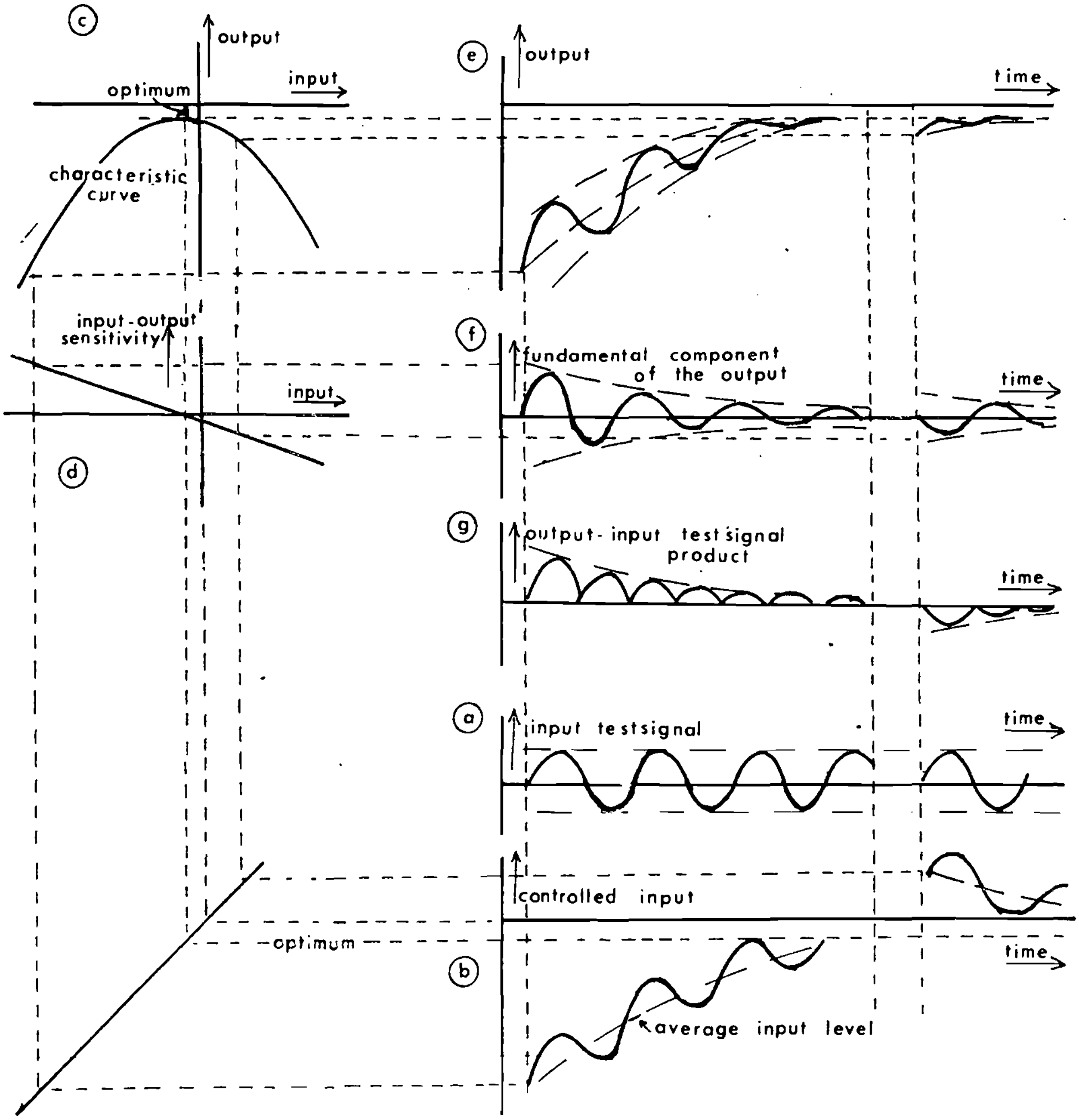

c
output
input
optimum
characteristic curve
input-output sensitivity
input
d
e
output
time
f
fundamental component of the output
time
g
output-input test signal product
time
a
input testsignal
time
controlled input
optimum
b
time
average input level

Fig 7

smoothing filter shown in Fig. 6. The resultant effect on the controlled input is shown in Fig. 7b as the dashed line representing the average input level. By properly connecting the operation components of Fig. 6, the average input level may be made to change in the way necessary to fulfil the general purpose of optimalizing control. In Fig. 7b the plot of controlled input is shown in two sections. In the first section the controlled input is started at an arbitrary initial disturbance below the input level corresponding to the optimum output level. In the second section the controlled input is shown as starting from an initial disturbance above the optimum point input. The resulting effect of the controller, as shown in Fig. 7b, is to bring the input variation toward the optimum point, whether the initial disturbance is below or above the optimum point.

These test signal control systems, which use an input adjustor to change the average input level at a rate proportional to the magnitude of the input correction signal, are called proportional input rate test signal controllers.

2.3. Output sampling optimalizing controllers

Output sampling type controllers are operated by an output rate signal that is generated on the basis of differences taken between output signal levels for successive equal sampling periods. The effect of controlled system operation is to make this output rate signal proportional to the product of the controlled input rate and the input-output sensitivity of the controlled system. For this reason when the input rate is arbitrarily given a constant magnitude between reversals, a series of discrete points, separated in time by the sampling period, are produced to represent the input-output sensitivity of the controlled system. Fig. 8 illustrates the discontinuous generation of an output rate signal by use of the output sampling technique. The example chosen is based on the assumption of a parabolic performance characteristic for the controlled system and a controlled input rate that is maintained constant during the time interval shown on the plots. Because of the constant input rate, the output signal curve of Fig. 8a has a parabolic shape.

The shaded region bounded by the line for $t=0$, the performance characteristic curve, the line $t=T_s$ (where T_s is equal to the constant sampling period) and the controlled input axis is proportional to the time integral of the output signal curve between 0 and T_s. The average value of the output signal for the first sampling period is equal to the value of the integral representing this area divided by the sampling period. This average level, as shown in Fig. 8a, is a line segment projecting from the average signal level point for the first sampling period and drawn between the time interval limits for the second sampling period. The average output signal level for the second sampling period is established in the same way as the average level for the first sampling period, and is drawn between the time interval limits for the third sampling period. The difference between the average output signal levels for the second and first sampling periods gives the point on the output rate signal curve of Fig. 8b for the instant $t=2T_s$. Because it is necessary to have output signal averages for two successive sampling periods before a difference can be taken, the indicated output rate signal points are always behind the true output rate by one sampling period. Fig. 8a shows the relationship between the actual variation of the output signal with time and the step-wise approximation to this variation, which is represented by averages over a continuous sequence of sampling periods. In Fig. 8b the dashed line connecting the discrete points that represent differences between successive averages over individual sampling periods gives the sampling period average difference signal, which is parallel to, but displaced from, the true output rate signal.

For the special case of a constant controlled input rate, the output rate signal is proportional to the controlled input-output sensitivity of the controlled system, that may be used as the essential input for an optimalizing controller. In practice, the use of the output sampling method to generate a signal for the controlled system sensitivity is particularly useful for situations in which the output contains strong erratic interference effects.

These effects may be greatly reduced in any given case by a choice of the sampling period that makes the integrated effects of interference small compared with the difference between the sampling period averages required to reverse the controlled input rate.

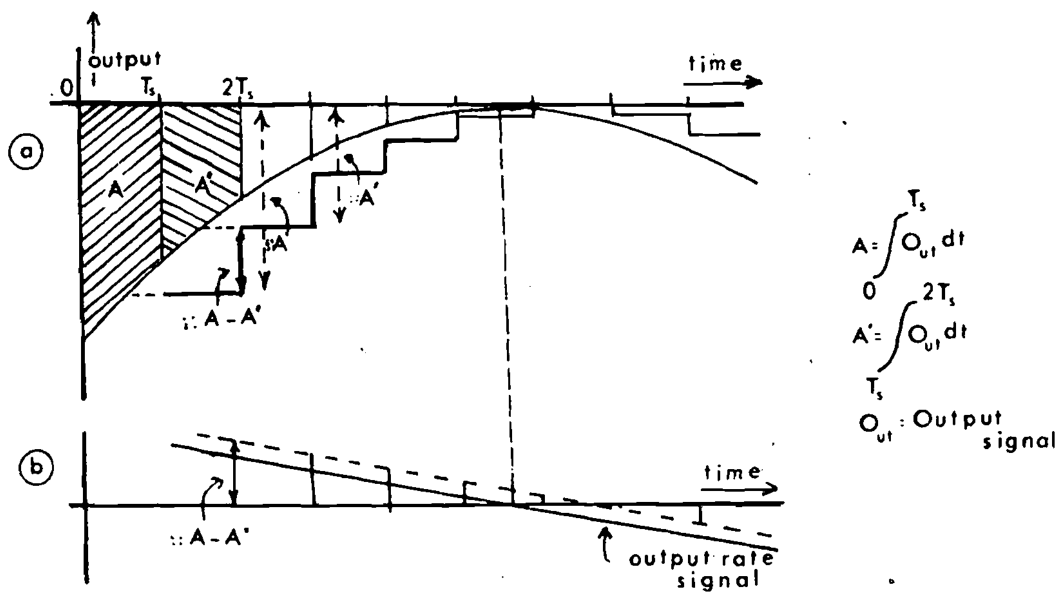


Fig 8

Fig. 9 is a functional diagram showing a typical output sampling type optimalizing controller based on the use of a discontinuous output rate signal generated by the method illustrated in Fig. 8. The plots of Fig. 10 show the essential relationships among the quantities involved in the operation of the control system of Fig. 9. The plots of Fig. 8 are based on the assumption that the output of the controlled system depends on a flow rate that is treated as the controlled input. The plot of Fig. 10a shows that the input rate has a constant magnitude but reverses its direction at certain instants. The corresponding time variation of the system depends on the instantaneous input level and the performance characteristic curve of Fig. 10b. The output signal is averaged over successive test periods. At the end of each test period this average output signal is applied to a switching system, which is also connected by a synchronizing drive to the reference signal holding system and a comparator. One function of the switching system is to apply the present average output signal to the reference signal

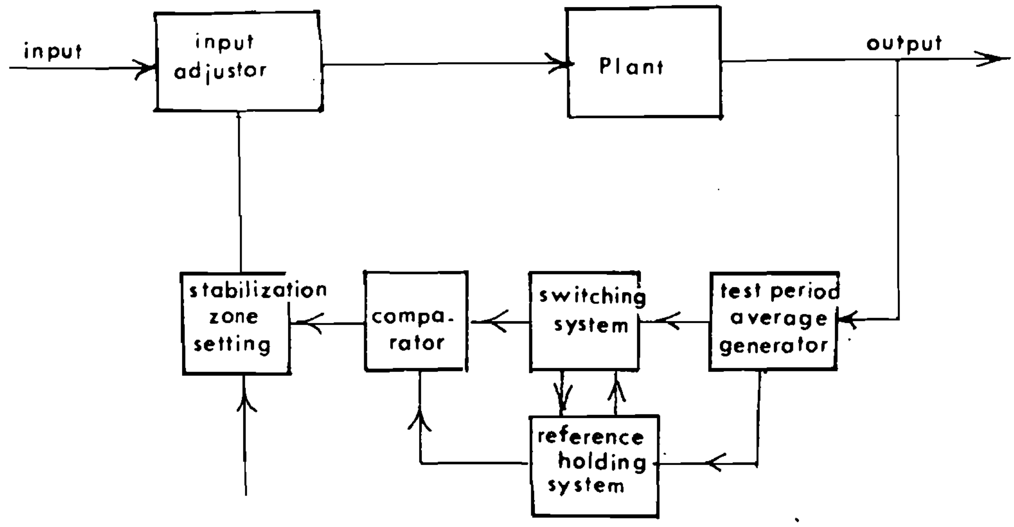

input
input adjustor
Plant
output
stabilization zone setting
compa. rator
switching system
test period average generator
reference holding system

Fig.9

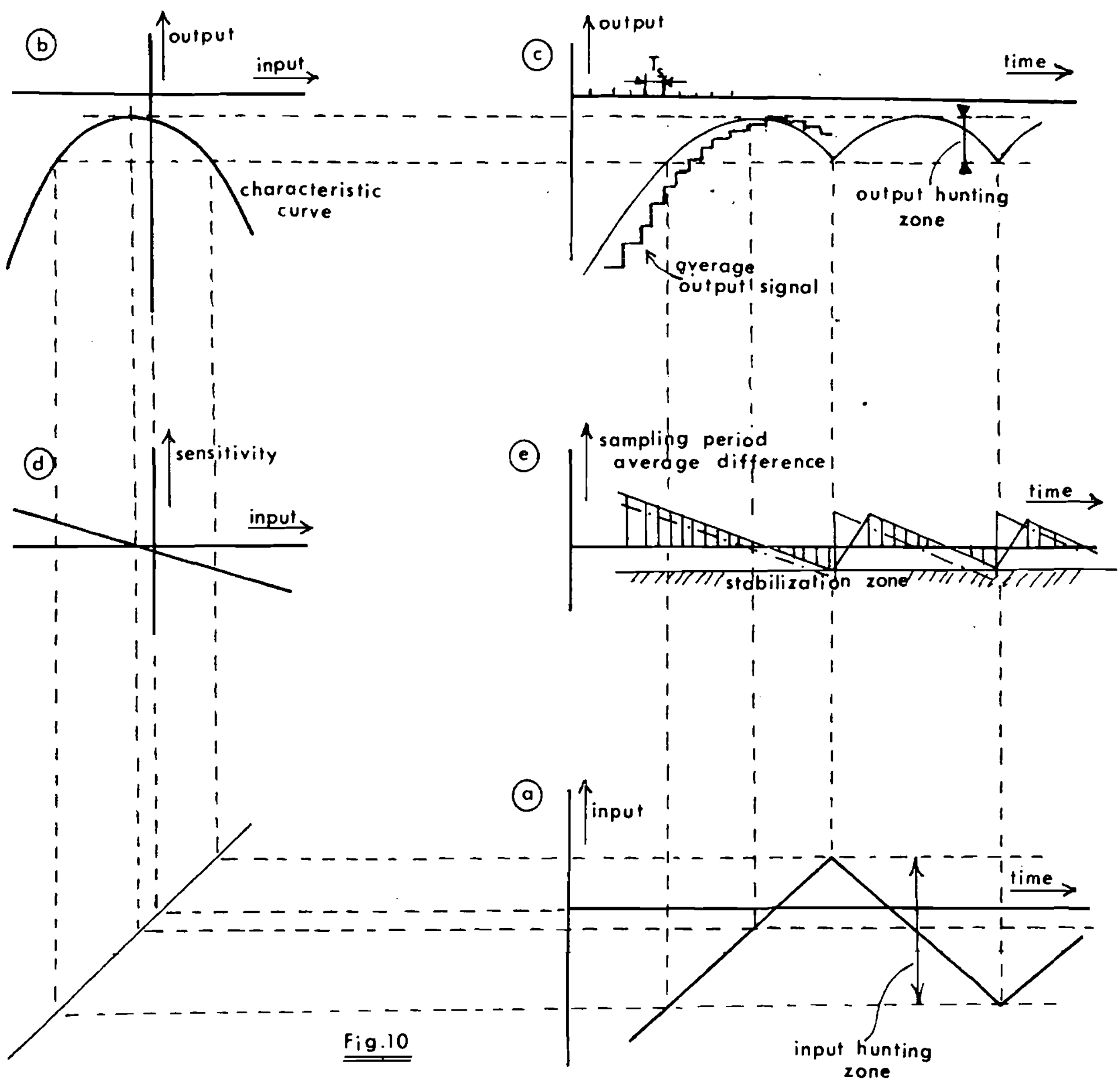

b
output
input
characteristic curve
c
output
T_s
time
output hunting zone
average output signal
d
sensitivity
input
e
sampling period average difference
time
stabilization zone
a
input
time
input hunting zone

Fig.10

holding system and to the comparator. The connections carrying out these operations are made at the end of each sampling period. A second function of the switching system is to take the past average output signal (which is the present test period average output signal for the sampling period immediately preceding the test period just ended) from the reference signal holding system and apply it to the comparator. At the same time the switching system wipes out the past test period signal in the reference signal holding system and substitues for it the present test period signal. The comparator in effect substract the past test period signal from the present test period signal, so that at the end instant of each sampling period its output signal is proprotional to the sampling period average difference (output rate signal) shown in Figs. 10e and 8b. For reasons apparent from the plots of Fig. 8, the sign associated with this signal is positive or negative depending upon whether the controlled system is operating on the low-input side or the high-input side of the optimum point. The signal has a magnitude that increases with the separation of the operating point from the optimum point. This average difference signal is used to cause the input adjuster to change the input at a constant rate with reversals in direction at the instants when the average difference signal is equal to the stabilization zone limit (Fig. 10e). A certain tolerance for interference effects may be designed into the controlled system by the use of this stabilization zone. As indicated in Figs. 10a, 10c and 10e, a sequence of control cycles is continued indefinitely with the controlled input varying between the limits of the input hunting zone and the output varying between limits corresponding to the output hunting zone.

Proportional input rate control

Optimalizing control may be based on the use of a controlled input rate that is algebraically proportional to the input-output sensitivity of the controlled system. Control of this type differs from that provided by the arrangement of Fig. 9, which uses a constant input rate that reverses in direction when the controlled system sensitivity changes its sign. Proportional input rate control depends on the fact that the controlled system sensitivity is defined as the ratio of the output rate to the input rate, i.e.

$$S = \frac{d\, O_{ut}}{d\, I_{in}} = \frac{\mathring{O}_{ut}}{\mathring{I}_{in}} \quad \cdots (1)$$

O_{ut} = output signal
I_{in} = input signal

This means that a sensitivity signal suitable as the input for the controlled input adjustor may be obtained by multiplying the output rate signal by a signal representing the reciprocal of the controlled input rate. A difficulty appears if the controlled input rate goes to zero, so that the denominator of Eq (1) vanishes. A zero input rate implies a zero output rate for the controlled system, so that the expression for sensitivity becomes indeterminate. This condition may be avoided in practice by designing the control system so that the input rate is prevented from decreasing below some properly chosen minimum level. The functional diagram for a proportional controlled input rate optimalizing control system of the output sampling type is shown in Fig. 11. With a single exception the organization components of this diagram is identical with that shown in Fig. 9. The single exception is that a rate signal ratio generating system is placed between the average output signal comparator and the controlled input adjustor. This ratio generating system receives the output rate signal and the input rate signal as its two inputs and produces the controlled input rate command signal as its output. The controlled input setting is made proportional to this signal by the input adjustor drive generator. This action closes the chain of optimalizing control for the system of Fig. 11.

The plots of Fig. 12 illustrate the control action of an output sampling type of controller with proportional input rate control.

Fig. 12a is a plot showing a typical variation of the controlled input. This input variation acting through the characteristic curve of Fig. 12b produces the output signal curve of Fig. 12c. The output signal sampling arrangement of Fig. 11 produces a stepped average output curve, shown as the dashed line in Fig. 12c. The corresponding output rate signal curve generated by the process described in the discussion of Fig. 8 is given in the plot of Fig. 12e. The ratio generating system of Fig. 11 receives the output rate signal shown in the plot of Fig. 12e and the input rate signal of Fig. 12g, which is taken from the input adjustor. The output of the ratio generating system is the input rate command signal shown in the plot of Fig. 12f.

For reasons discussed above, this signal represents the controlled input-output sensitivity of the controlled system.

The input adjustor drive generator receives this command signal and produces the input adjustor drive signal which causes the input adjustor and the input controller to produce the input rate signal shown in the plot of Fig. 12g as proportional to the input rate command signal.

The effect of this rate change on the controlled input itself is shown in the plot of Fig. 12a. The variation of the controlled input closes the operation loop around the closed chain system of Fig. 11.

A system for which the input rate is made proportional to the controlled system sensitivity causes deviations in the output level to decrease exponentially with time. A basic difficulty with the exponential type of system response is that the input and output rates become very small as the deviations approach zero.

With small input and output rates, system operation tends to become unsatisfactory because of interference effects. In addition to this trouble, the generation of the input rate command signal on the bases of dividing the output rate signal by the input rate signal fails as the input rate approaches zero, for reasons discussed above.

The interference effects and the small input rate difficulty can both be overcome by the use of the constant input rate zone illustrated on the plots of Fig. 12a and 12g. Within the constant input rate zone, the input rate has a constant amplitude which is reversed in sign at the instants when the input rate command signal exceeds limits established for the stabilization zone shown by the dashed lines in Fig. 12f. The stabilization zone determines the output hunting zone, which is illustrated in Fig. 12c. By a proper choice of the constant input rate, a tolerably small output hunting zone may be achieved.

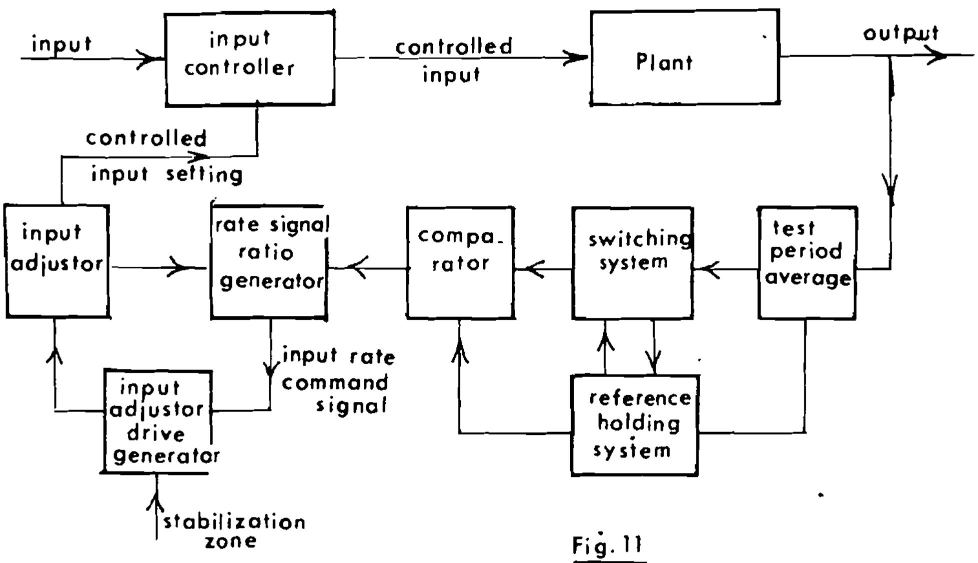

input
input controller
controlled input
Plant
output
controlled input setting
input adjustor
rate signal ratio generator
compa-rator
switching system
test period average
input rate command signal
input adjustor drive generator
reference holding system
stabilization zone

Fig. 11

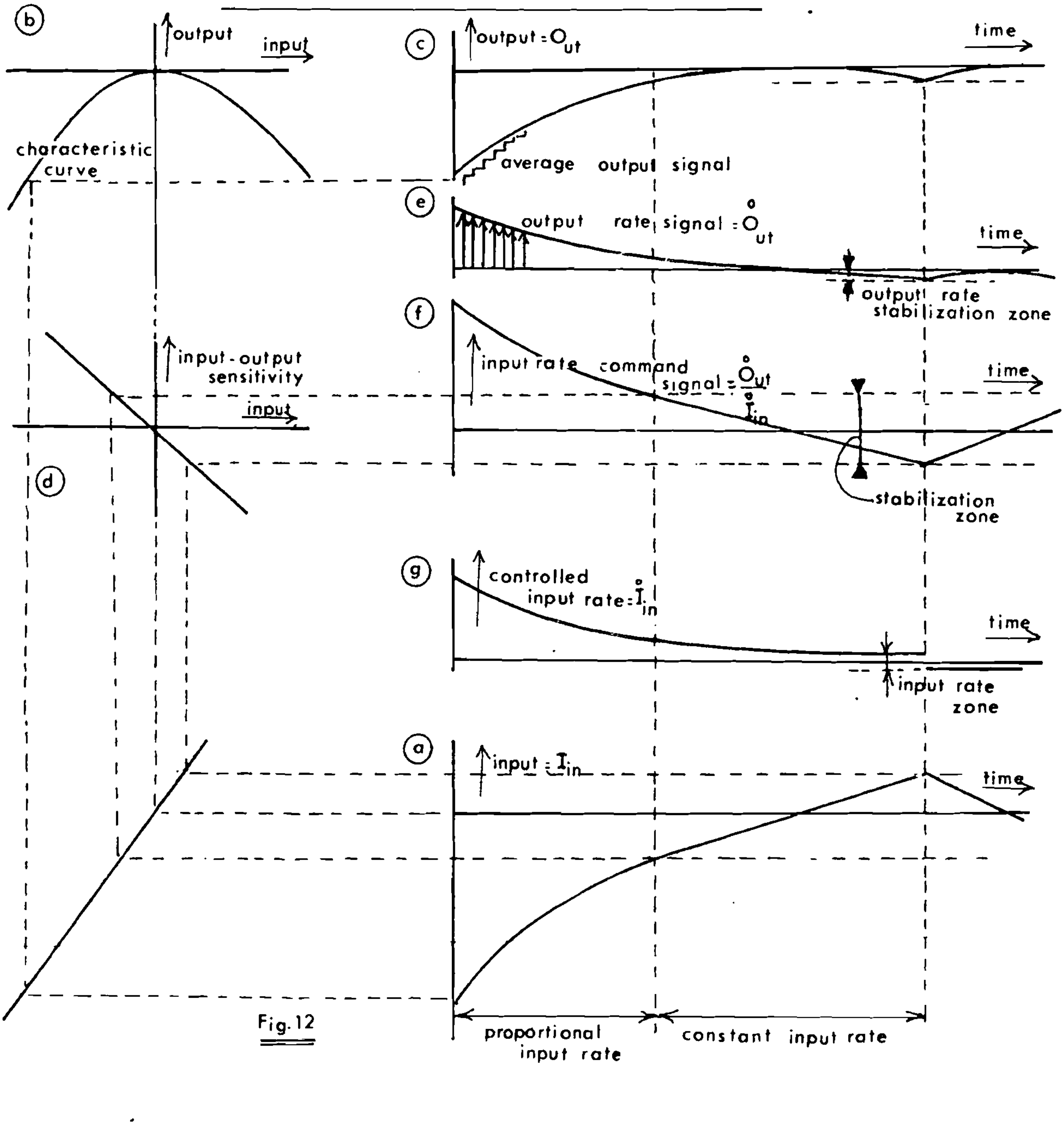

b
output
input
characteristic curve
c
output = O_{ut}
time
average output signal
e
output rate signal = $\mathring{O}_{ut}$
time
output rate stabilization zone
f
input-output sensitivity
input
input rate command signal = $\mathring{O}_{ut}/\mathring{I}_{in}$
time
d
stabilization zone
g
controlled input rate = $\mathring{I}_{in}$
time
input rate zone
a
input = I_{in}
time
proportional input rate
constant input rate

Fig. 12

3. Peak holding optimalizing controllers

Optimalizing control systems of the peak holding type, proposed by Draper and Li, (page 29), differ from the systems already described. In the systems so far described, the input correction signal has been directly related to the input-output sensitivity of the controlled system. In systems of the peak holding type, the input correction signal is based on the difference between a formerly obtained optimum output signal as a reference quantity and the instantaneous output signal as the compared quantity. The correction signal is generated to vary with the time integral of this signal. A system design is used in which the indicated optimum output signal is carried along with the output signal as long as the signal magnitude is increasing, but remains constant at the highest level reached when the output signal starts to decrease. When the magnitude of the input correction signal exceeds the limit established by a stabilization zone, the controlled input rate is reversed to drive the output towards its optimum level. This action results in a series of cycles in which the output signal varies between the limits of its hunting zone while the input changes along a corresponding series of straight-line segments. Fig. 13 is the functional diagram for a typical optimalizing system of the peak holding type using a constant input rate magnitude. The corresponding performance characteristics are illustrated in the plots of Fig. 14. The input adjustor drive generator operates to change the input at a constant rate from some typical level like that indicated at point A on the plot of Fig. 14a. The constant input rate operating through the characteristic curve of Fig. 14b causes the output signal curve to have the shape illustrated in Fig. 14c. As long as the output signal (shown as a solid line in the plot of Fig. 14c) is increasing, the indicated optimum output signal (indicated by the dashed line in Fig. 14c) remains identical with the output signal itself.

When the magnitude of the output signal passes the peak corresponding to the optimum output level and starts to decrease, the peak signal is held by the optimum generator as the output signal reference level

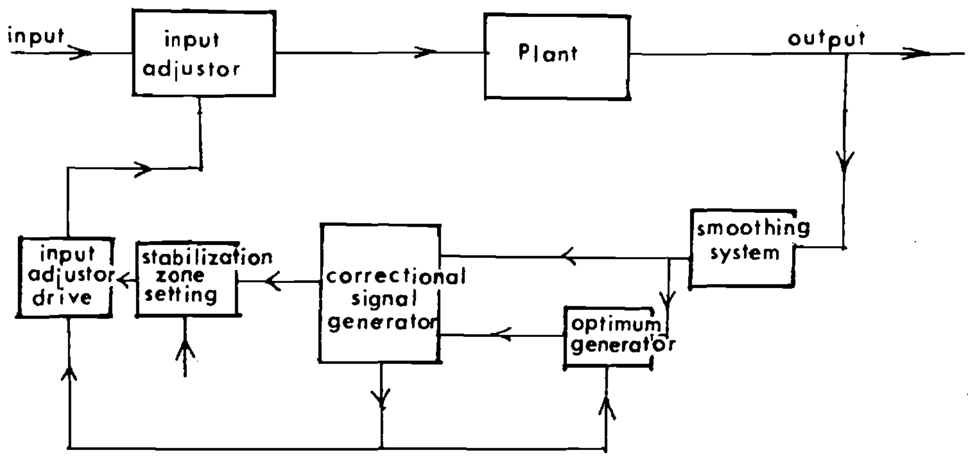

input
input adjustor
Plant
output
smoothing system
optimum generator
correctional signal generator
stabilization zone setting
input adjustor drive

Fig.13

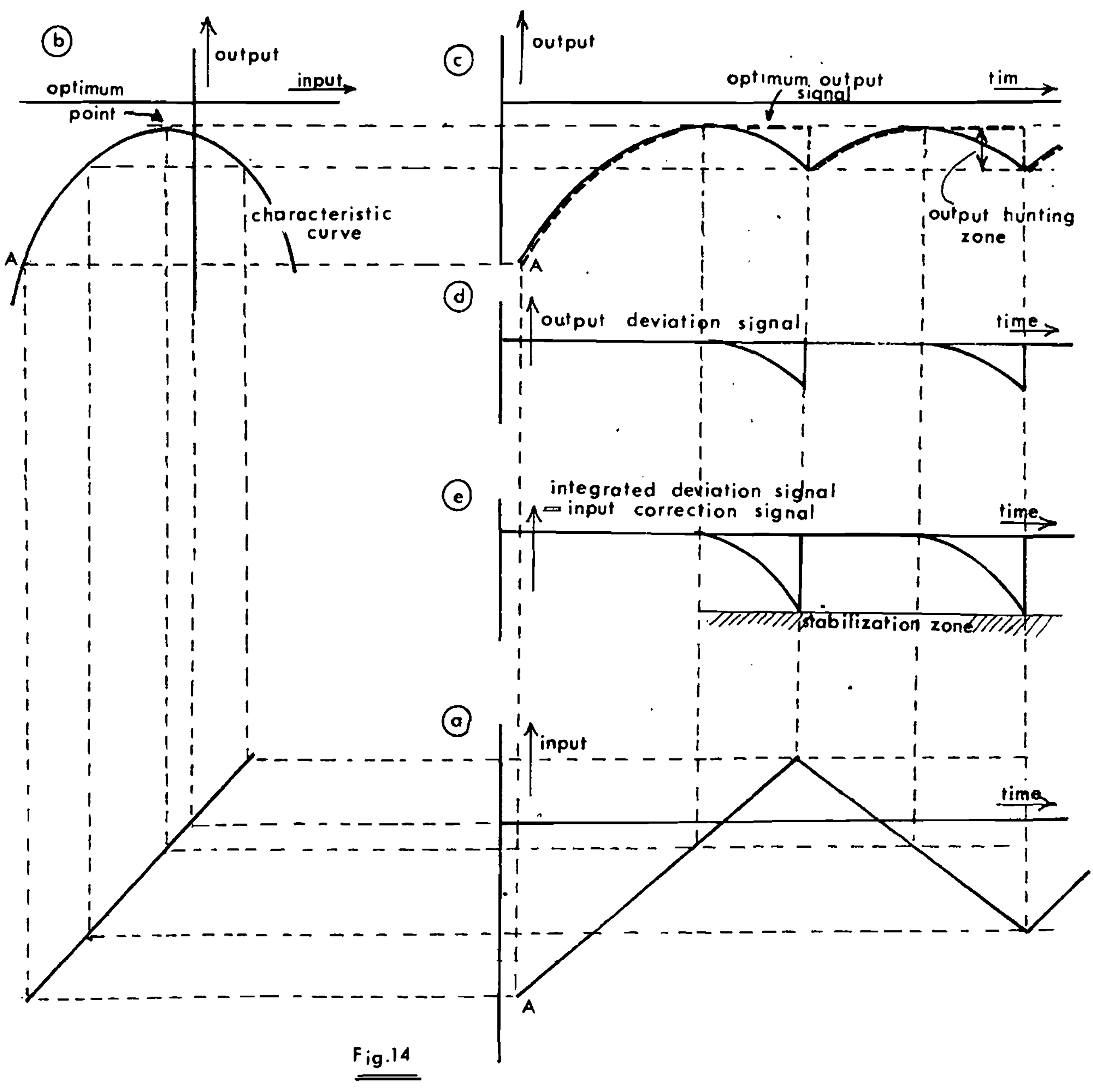

b
output
input
optimum point
characteristic curve
A
c
output
optimum output signal
tim
output hunting zone
d
output deviation signal
time
e
integrated deviation signal = input correction signal
time
stabilization zone
a
input
time
A

Fig.14

and becomes the indicated optimum output signal. The indicated optimum output signal is supplied as one of the inputs to the correction signal generator, which also receives the smoothed output signal. The difference between the output signal and the indicated optimum output signal is the output deviation signal shown in Fig. 14d. Fig. 14e shows the time integral of this deviation signal as it builds up in the correction signal generator of Fig. 13. The signal that represents the integrated signal is applied to the stabilization zone setting.
The output of this system causes the input adjustor drive and input adjustor to vary the controlled input at a constant rate with reversals at the instants when the input correction signal reaches the stabilization zone limit shown in Fig. 14e.
The results of the interactions among the operation components of Fig. 13, that are summarized by the plots of Fig. 14, is that the output of the controlled system remains within the limits of the output hunting zone.
Proportional input rate control, rather than the constant input rate assumed for the system of Figs. 13 and 14, may be applied to optimalizing controllers of this peak holding type controller. With proportional input rate control, the indicated output deviation signal is used to determine the magnitude of the controlled input rate. The necessary reversal of the direction for the input rate may be based on the integral of the output deviation signal in the way described in the discussion of Fig. 14 and 15.
Because the discussion already given for the output sampling controller applies directly to the peak holding controller type, no additional treatment of the peak holding type of optimalizing controller with proportional input rate variations is given here.

4. Conclusion

The peak holding type optimalizing controller described in the last section offers one decisive advantage over the input-output sensitivity operated controllers: the peak holding controller achieves its function without the requirement of a test, or sampling frequency. In the application of the controller to controlled systems with strong interferences, this means that a peak holding type controller is easier to adapt then other types.

5. Consequences

In order to optimalize the performance of an interal combustion engine a controller will be developed. Torque load of the engine should be selected as the output quantity to be optimalized by the controller through adjustments of ignition timing, under the condition of constant fuel-air ratio.

The optimalizing controller will be a peak holding type controller, and is selected because of its ability to operate satisfactorily in systems with strong interference components in the output.

Later on the optimalizing controller may be extended.

Torque load of the engine will then be optimalized through adjustments not only of the ignition timing, but also of the air flow under the conditions of constant fuel flow. Besides this, a detonation detector will be added to the controller to cause the controller to drive the input adjustments away from operating within the intolerable detonation range.

R. van Lutterveld

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Olle I. Elgerd : Control systems theory. Mc. Graw-Hill electrical and electronic engineering series, Mc. Graw-Hill: Tokyo, Kogakusha, 1967, page 436.

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REPORT II

An optimalizing system for control of the ignition timing of combustion engines.

R. van Lutterveld

Summary:

The ignition system of an internal combustion engine has to provide a high voltage spark just before a piston reaches the upper dead point, so that maximum pressure occurs just after this u.d.p.
The correct point at which the spark occurs, relative to the position of the piston, is most important and varies according to engine speed, the load on the engine, engine temperature, and a number of other factors.
In the conventional way, two systems are used to determine the point of ignition, one sensitive to engine speed and the other to throttle opening en engine load. However, there is no feedback branch to verify whether the ignition really occurs at the correct point.
This report describes a (peak holding) optimalizing controller which functions as a human operator in searching out and holding the optimum ignition timing through changes in spark advance, made in response to a feedback signal representing the torque as the essential controlled engine output.
In this way, ignition takes place at the correct moment in spite of any change of output level or environmental operating conditions.

C O N T E N T S

1. Introduction

Optimalizing controllers of the peak holding type operate by continuously searching for an optimum level (see report I)
A simple constant rate variation of the ignition advance is used as a test signal. Carburettor setting and torque load on the engine are kept constant. As long as this constant rate variation of the ignition advance causes an increase in torque of the engine, the direction of the ignition timing change is not reversed.
At the instant the optimum point is passed, the torque starts to decrease. When this reversal has existed long enough for its presence to be definitely distinguished from interference effects, the controller reverses the direction of the ignition timing-change, so that the torque of the engine starts to increase again. When the optimum point is passed again, the torque starts to decrease and the controller reverses the direction of the ignition timing change: the controller cycle starts anew.

Fig. 2.1 is the functional block diagram showing the essential components of the optimalizing controller. The corresponding performance characteristics are illustrated in the plots of Fig. 2.2. (page R2).
The function generator causes the pulse generator to generate a constant rate variation of the ignition advance (see Fig. 2.2a and 2.2b).
This change of ignition timing operating through the characteristic curve of Fig. 2.2c causes the output signal curve to have the shape illustrated in Fig. 2.2d. As long as the output signal is increasing, the deviation signal remains constant (Fig. 2.2e).
When the output signal passes the peak corresponding to the optimum output level and starts to decrease, the deviation signal will proportionally decrease. As soon as this deviation signal exceeds the limit, established by a stabilization zone, the switch reverses the constant rate variation of the output signal of the function generator and resets the descent detector.
In this way, the descent detector and the switch causes the function generator and the pulse generator to vary the ignition timing at a constant rate with reversals at the instants when the deviation signal exceeds the stabilization zone limit.

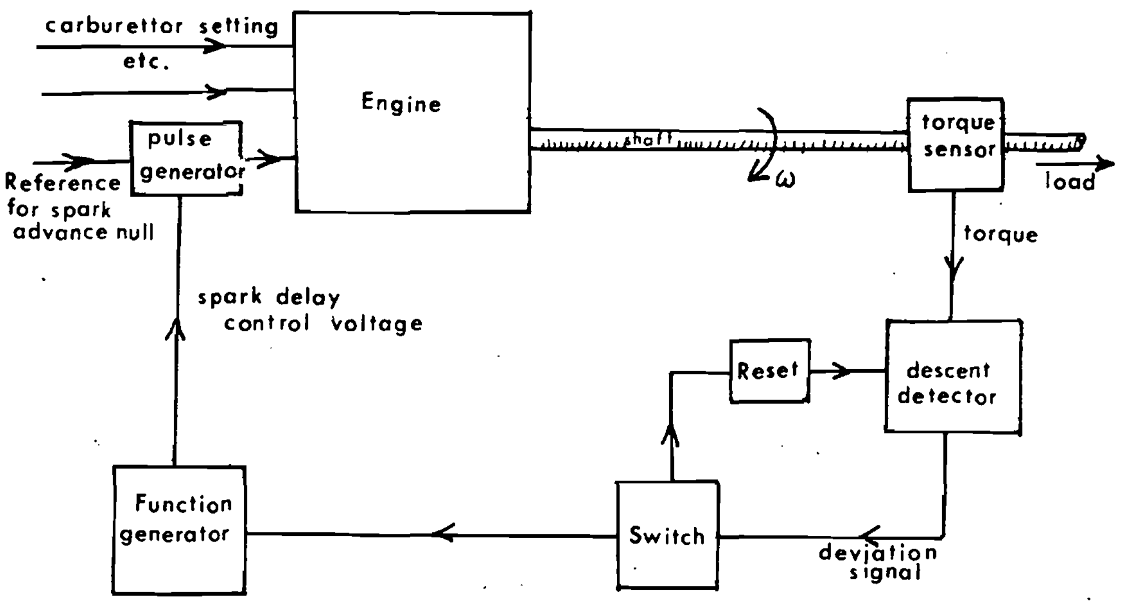


Fig.2.1: Functional block diagram

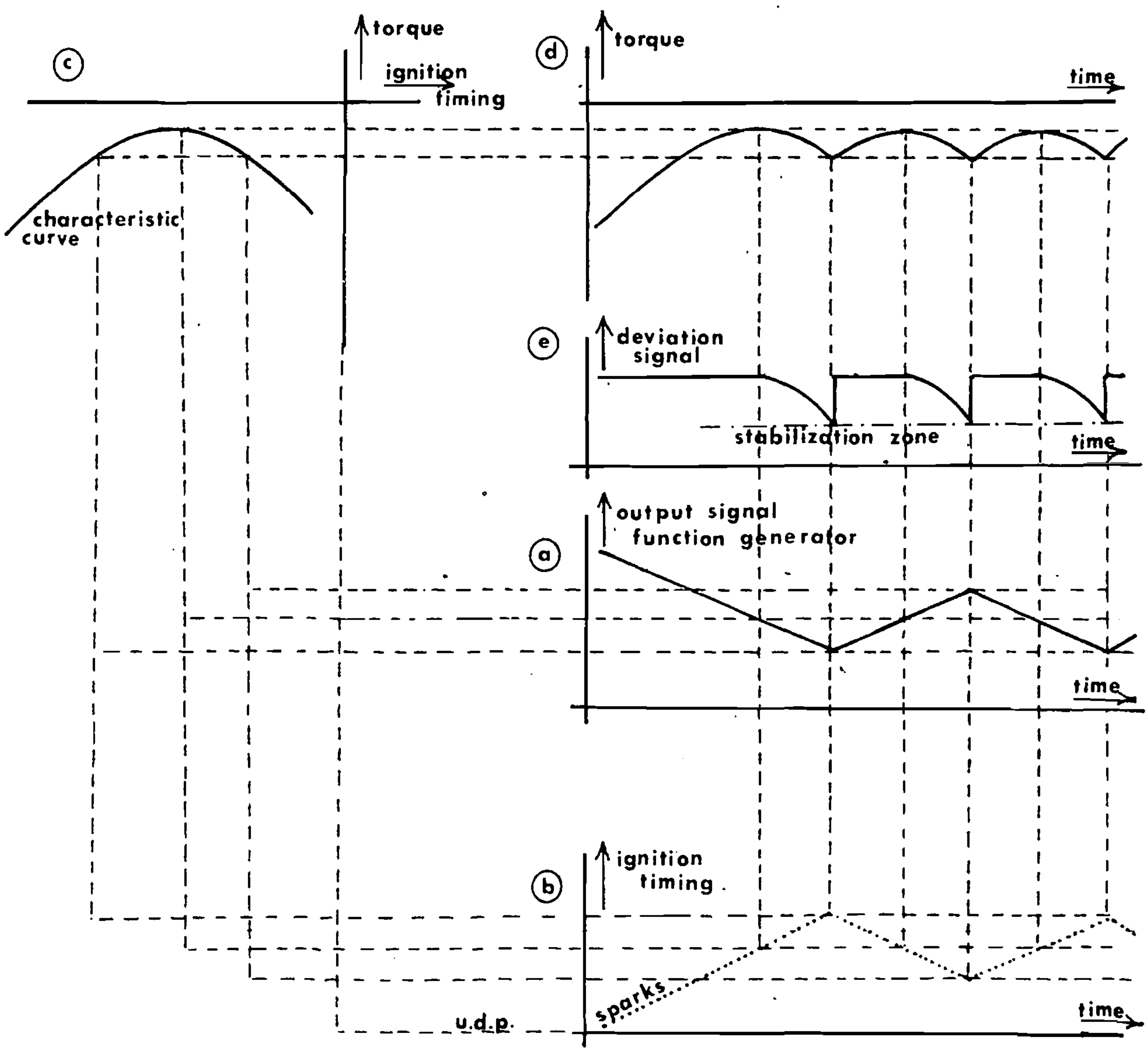


Fig.2-2 Performance characteristics

In order to keep the ignition timing within some working zone, a special system is added to the controller.
Within the zone, established by this working zone setting system, the optimalizing controller will continuously search for an optimum operating performance condition.

Fig. 2.3 shows the functional diagram of the complete system. Each function, shown in Fig. 2.3 is discussed in more detail in the following sections.

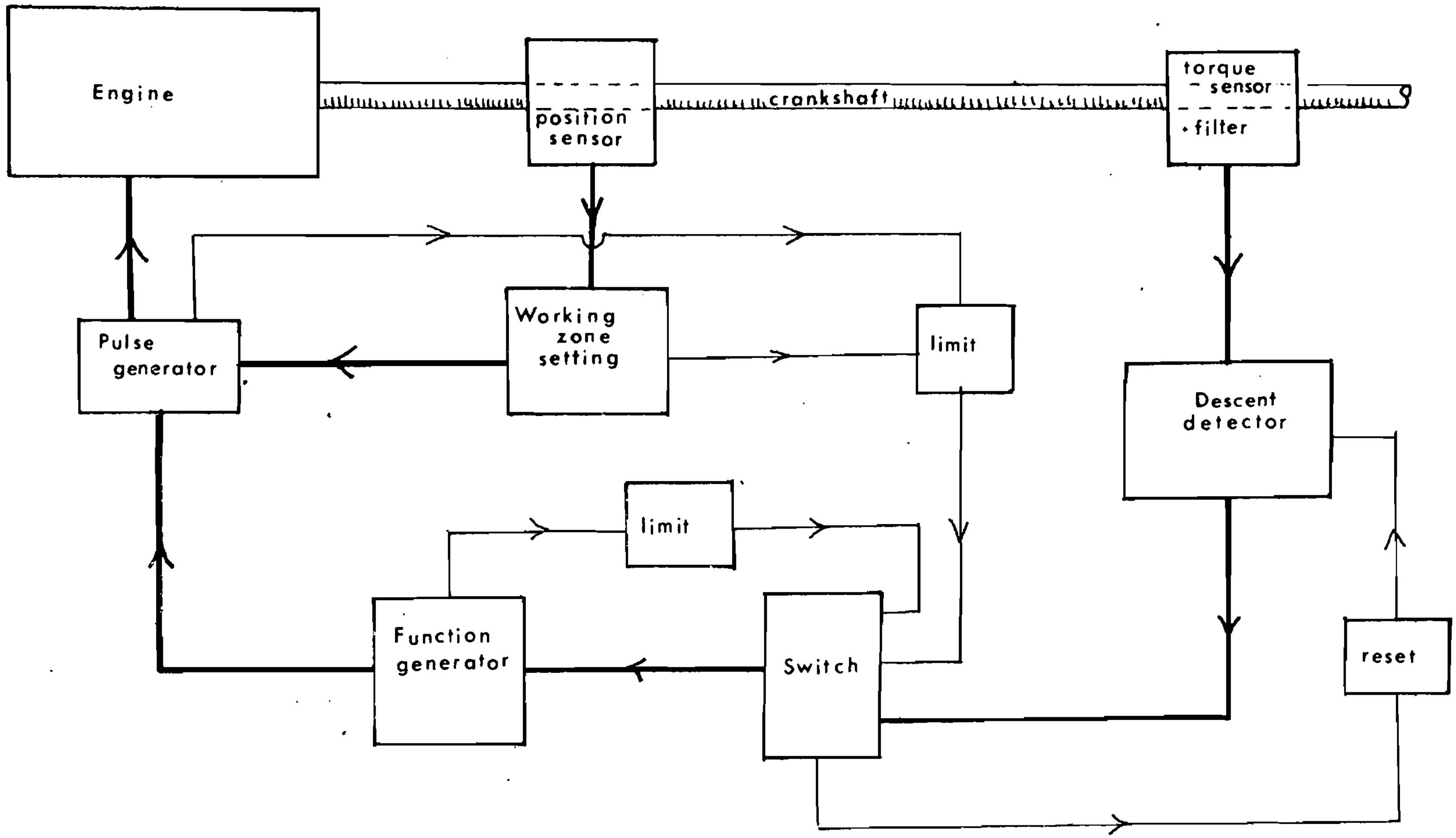


Fig. 2.3: Functional diagram of the peak holding optimalizing controller

2. Circuit description

2.1 Torque sensor and filter

The output torque of the engine is measured by means of an electronic strain-gauge instrument (Peekel type 540DNH).
This instrument measures the resistance variation which occurs in strain-gauges owing to the deformation of the material to which the gauges are cemented (see Fig. 2.4).

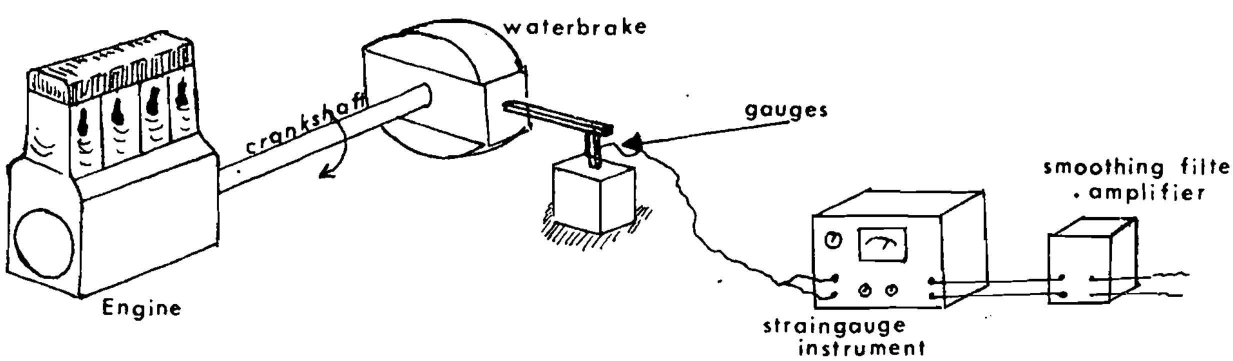


Fig. 2.4 Engine and strain-gauges

A hand-operated Wheatstone bridge is built-in with which it is possible to compensate the static component to be measured. The principle employed in this strain-gauge instrument is the carrier frequency method. Also a low-pass filter is built-in, which suppresses the carrier frequency so that only the modification appears at the output terminals. The output of the strain-gauge instrument is passed through a smoothing filter, which suppresses the unwanted interference signals. The output signal of the smoothing filter is amplified and applied to the descent detector.

2.2 Descent detector

The descent detector may be divided into two parts (see Fig. 2.5).

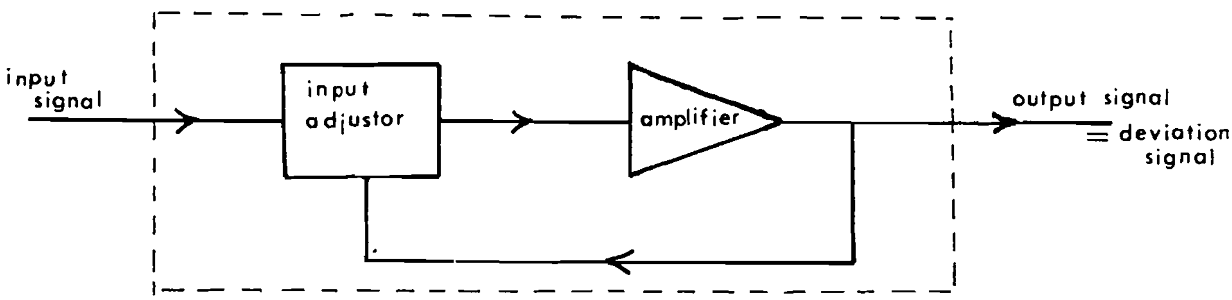


Fig. 2.5 The descent detector.

As long as the input signal is increasing, the input adjustor makes the descent detector have a constant output signal, fixed at a particular reference level. When subsequently the input signal of the descent detector starts to decrease, the input adjustor stops functioning and the output signal decreases below the reference level. The decrease in output signal is directly proportional to the decrease in input signal.

A) The input adjustor

The electronic circuit is given in Fig. 2.6.

Suppose transistor T_6 is non-conducting and U_{input} is increasing. Then U_A and thus U_{output} will increase, until the voltage level at the base of T_1 (= U_{output}) reaches the constant voltage level U_{bT_2} at the base of T_2:

$$U_{bT_2} = \frac{R_3}{R_3 + R_2} U_B$$

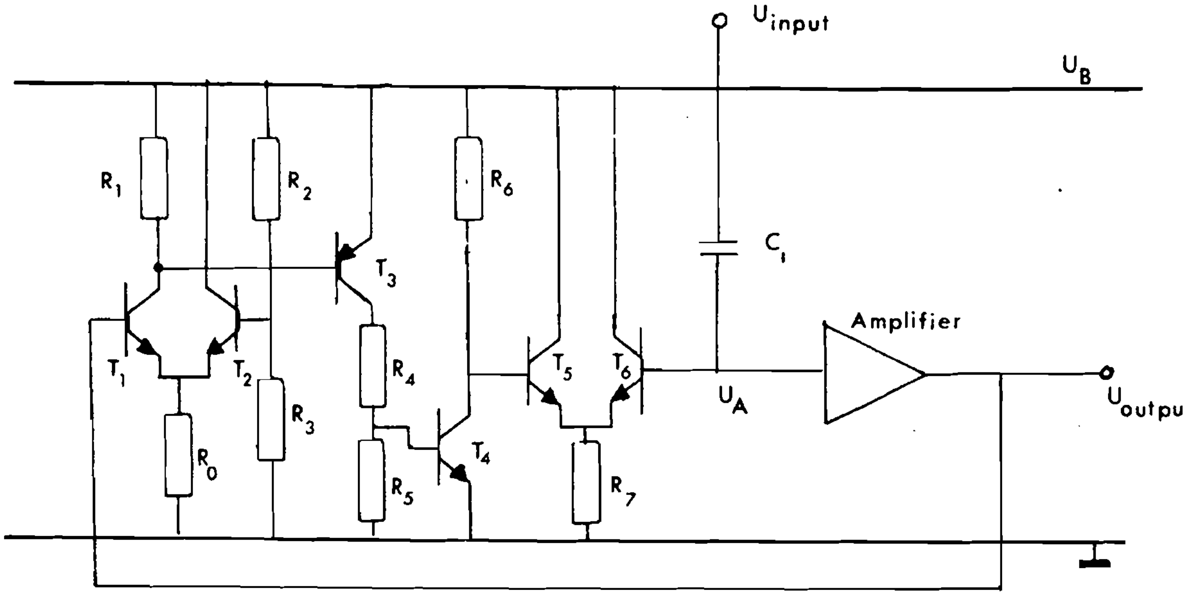


Fig. 2.6 The input adjustor.

As U_{bT_2} is in the order of 3 V and the margin on U_{bT_1} from just conducting to fully conducting is about 0.1 V, the transistors T_1, T_3, T_4 and T_6 start conduction when $U_{bT_1} \approx U_{bT_2}$.

Consequently, from the moment that $U_{bT_1} \approx U_{bT_2}$, the base current of T_6 discharges the capacitor C_1.
The total effect is that whenever U_{input} increases, U_A assumes a fixed voltage level, in accordance with $U_{output} \approx U_{bT_2}$. When subsequently U_{input} remains constant the base current of T_6 continues to discharge C_1 for a moment. Hence U_A and thus U_{output} decreases. As the margin on U_{bT_1} from fully conducting to non conducting is about 0.1 V, the decrease in U_{output} causes T_1, T_3, T_4 and T_6 to stop conduction at once.
In this way U_A is kept constant when U_{input} remains constant or increases. When subsequently U_{input} is lowered, U_A and thus U_{output} are proportionately lowered as T_1, T_3, T_4 and T_6 are not conducting.

B) The Amplifier

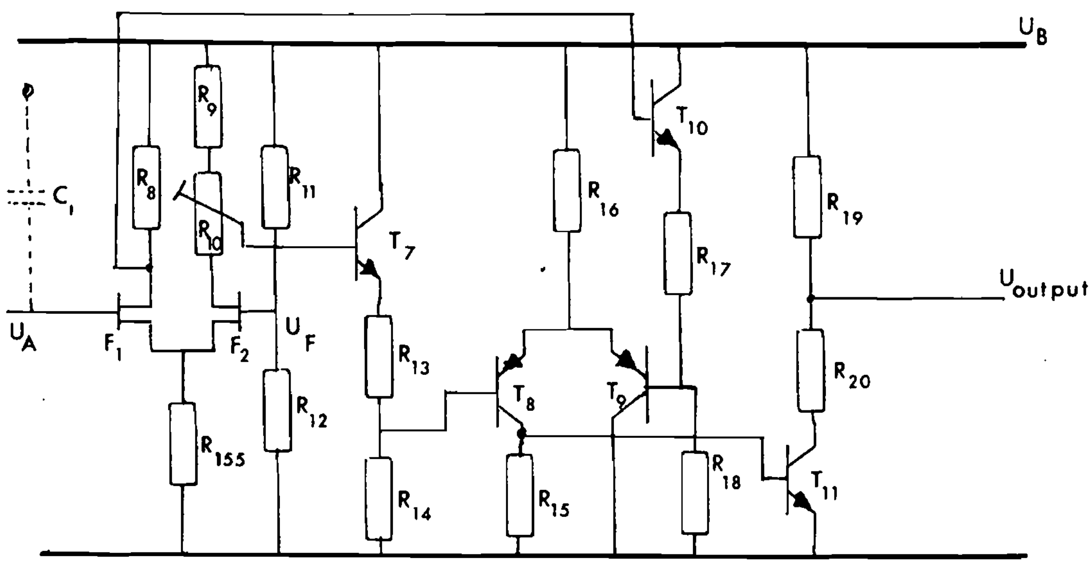


Fig. 2.7 The amplifier.

Because of their high input impedance, two FET's F_1 and F_2 are used to form a differential amplifier.
The gate of F_2 has a fixed voltage level:

$$U_{gF_2} = U_B \cdot \frac{R_{12}}{R_{11} + R_{12}}$$

Via the emitter-followers T_7 and T_{10}, the voltage $U_{bT7} - U_{bT10}$ is amplified by the differential amplifier formed by T_8 and T_9.

Consequently, a small change of U_A results in a considerable change of U_{output}, when the value of the differential voltage $U_A - U_F$ is such that $U_{cesat\ T_{11}} < U_{output} < U_B$. $(R_{20} \ll R_{19})$.
When U_{output} is below some typical level ($U_{stab.}$), a switch causes a reset system to increase rapidly the voltage level of U_A so that $U_{output} = U_B$ when the reset systeem stops operation.

Immediately after the reset, the input adjustor (described in the previous section) causes U_A to decrease until U_{output} becomes equal to the voltage level at the base of T_2 (see Fig. 2.6). In short:

U_{output} remains fixed at the level determined by U_{bT_2} until U_{input} starts to decrease.

When U_{output} decreases below the voltage level of U_{stab}, the switch and the reset system are brought into operation.

2.3 Switch and Reset system

The circuit is illustrated in Fig. 2.8.

The switch consists of a single J.K. Master Slave Flip-Flop.

The output signal of the descent detector, called the deviation signal, is supplied to the T terminal of the flip-flop.

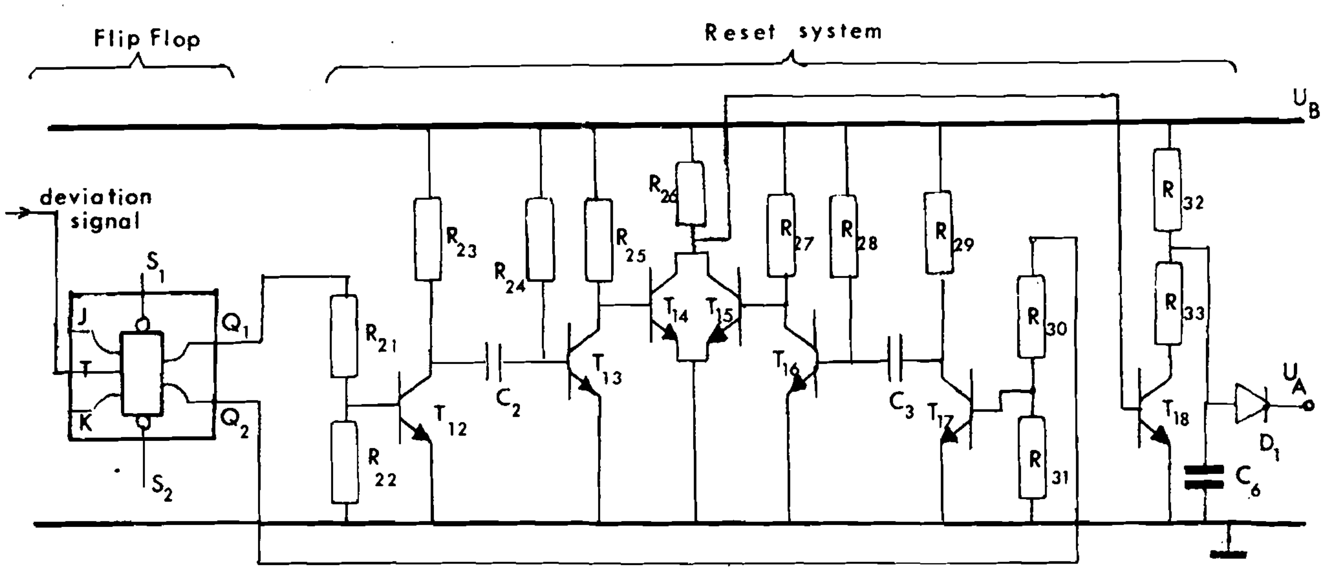


Fig. 2.8 Switch and Reset system.

The J, K, S_1 and S_2 terminals of the flip-flop are high:

$U_J = U_K = U_{S_1} = U_{S_2} = U_B$.

Hence the operation of the flip-flop depends on the voltage level of the T terminal. Rise and fall times are immaterial.

Suppose the input signal of the descent detector increases. Consequently the deviation signal remains high, as stated in a previous section, and the outputs of the flip-flop are not reversed: Q_1 or otherwise Q_2 remains high.

Now suppose the input signal of the descent detector starts to decrease, i.e. the torque of the engine decreases. Consequently the deviation signal U_T will also decrease.

When U_T decreases below some particular level U_{stab}, the flip-flop reverses the levels of Q_1 and Q_2.

For example Q_1 becomes high and Q_2 becomes low : $U_{Q1} = U_B$ and $U_{Q2} = 0$ V.

Hence T_{12} starts conduction. The fall of collector voltage of T_{12} is used as a trigger signal for the monostable multivibrator formed by R_{24}, C_2, T_{13} and R_{25}. The output pulse of this monostable multivibrator has a constant width: 0.3 msec.

During the monostable pulse, T_{13} stops conduction, while T_{14} starts conduction. In this way T_{18} is cut-off by lack of base current during the monostable pulse and the capacitor C_1 (see Fig. 2.6) of the input adjustor is charged via R_{32} and D_1, until the voltage level of U_A becomes equal to the voltage level of U_B. Consequently the voltage level of the deviation signal ($=U_T$) assumes the level of U_B.

When the monostable pulse ends, U_A is lowered and U_T assumes the level of U_{bT_2} through the arrangements of the input adjustor of the descent detector.

The low leakage diode D_1 prevents T_{18} from discharging C_1 when the monostable pulse is ended. $[R_{33} \ll R_{32}]$. U_T remains equal to the voltage level of U_{bT_2} until the input signal of the descent detector starts to decrease. When the decrease in torque of the engine is such that U_T becomes low, the flip-flop reverses the levels of Q_1 and Q_2 so that Q_2 becomes high, and T_{17} starts conduction. T_{12} stops conduction and C_2 is charged via R_{23}: T_{13} continues conduction.

The fall of collector voltage of T_{17} is used as a trigger-signal for the monostable multivibrator formed by C_3, T_{16}, R_{28} and R_{27}. During the output pulse of this monostable multivibrator, T_{18} stops conduction and the capacitor C_1 of the input adjustor is charged as described before.

Resuming: the total effect is that whenever U_T becomes low, the outputs of Q_1 and Q_2 are reversed and U_A is increased during a small time interval, causing U_T to become high and to assume the voltage level of U_{bT_2}.

2.4 The function generator

The function generator has to change the input of the pulse generator at a constant rate, causing a constant rate variation of the ignition timing.

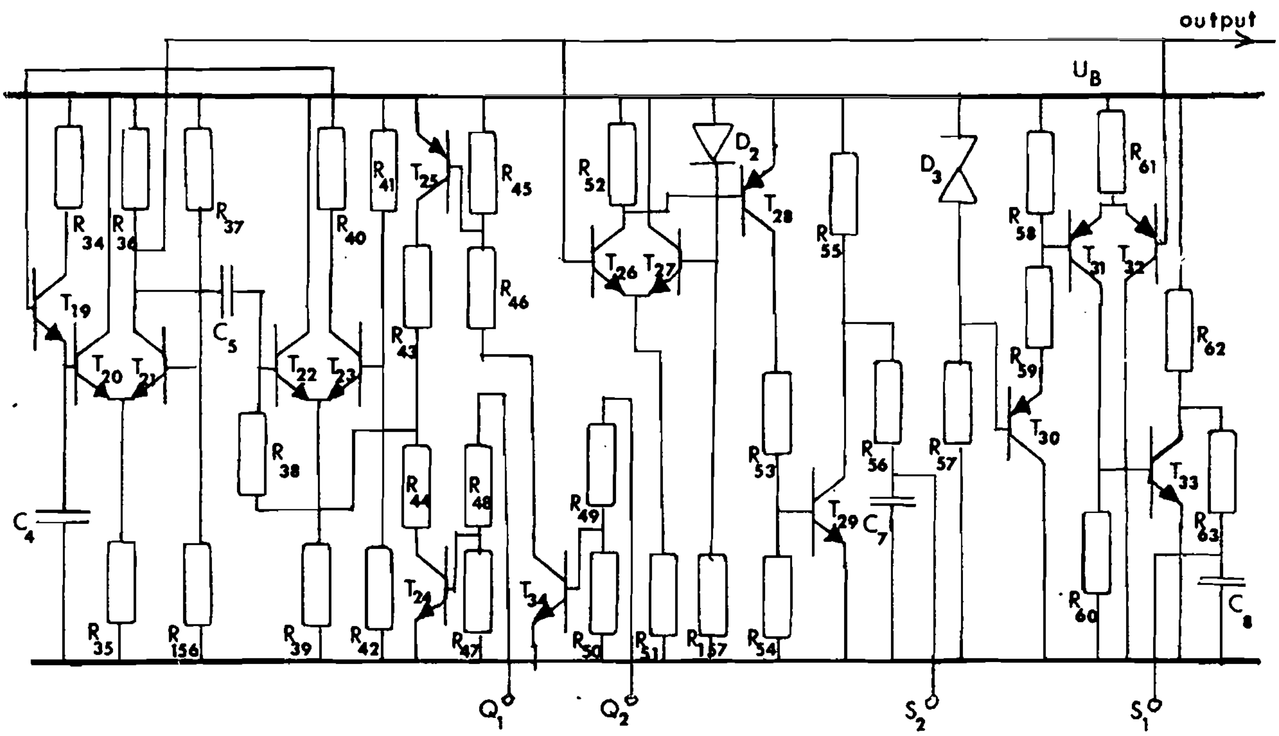


Fig. 2.9 The function generator.

The circuit is illustrated in Fig. 2.9. Q_1 and Q_2 are the outputs of the flip-flop, described in section 2.3, S_1 and S_2 are the set inputs of the flip-flop.

Either Q_1 or alternatively Q_2 is high.
When Q_1 is high, T_{24} conducts and a current equal to:

$$I_{C_5} = \frac{U_{bT_{22}} - U_{cT_{24}}}{R_{38} + R_{44}}$$ charges the capacitor C_5.

On the other hand, when Q_2 is high, a current equal to $I_{C_5} = \frac{U_{bT_{22}} - U_{cT_{25}}}{R_{38} + R_{43}}$ discharges the condensor C_5.

Suppose C_5 is discharged, i.e. Q_2 is high, so that $U_{bT_{22}}$ increases.
At the instant $U_{bT_{22}} = U_{bT_{23}}$, T_{22} starts conduction, as the margin on $U_{bT_{22}}$ from just conducting to fully conduction is about 0.1 V.
From the moment at which T_{22} starts conduction, a small increase in $U_{bT_{22}}$ causes a considerable decrease in collector current of T_{23}. Then, owing to the fact that T_{20} and T_{21} form a differential amplifier, the emitter current of T_{20} decreases, while the collector current of T_{21} increases.
As a result $U_{bT_{22}}$ is lowered, causing $U_{bT_{22}}$ to keep constant, while the constant current I_{C_5} discharges C_5.

Now suppose C_5 is charged, i.e. Q_1 is high.
Then the feedback branch formed by T_{23}, T_{19}, T_{20} and T_{21} causes $U_{bT_{22}}$ to remain constant in the same manner as described before.
Hence $U_{bT_{22}}$ remains constant when C_5 is charged or discharged by the constant current I_{C_5}: U_{output} rises at a constant rate when Q_1 is high, whereas U_{output} decreases at a constant rate when Q_2 is high.

The ignition advance varies according with the output level of the function generator.
As the operation of the flip-flop depends on the voltage level of the T terminal, the constant rate variation of the output signal of the function generator (U_{output}) is reversed whenever the input signal of the descent detector causes U_T to become low: i.e. whenever U_{output} passes the level corresponding to the optimum ignition timing.

U_B and $U_{bT_{21}}$ impose limits on the magnitude of U_{output}. Suppose the descent detector is unable to find an optimum ignition advance, which corresponds to an output level of the function generator somewhere between U_B and $U_{bT_{21}}$. Then the constant rate variation of U_{output} is reversed by means of two level detectors, whenever U_{output} approaches the level of U_B or $U_{bT_{21}}$.

The first level detector is formed by T_{26}, T_{27}, T_{28} and T_{29}.
Suppose U_{output} is increasing i.e Q_1 is high.
As soon as U_{output} reaches the level of $U_{bT_{27}}$, the transistors T_{26}, T_{28} and T_{29} start conduction.
As a result of its conduction, T_{29} makes the S_2 terminal of the flip-flop, become low, so that the flip-flop reverses the levels at Q_1 and Q_2. Hence Q_1 becomes low, while Q_2 becomes high and U_{output} starts to decrease.

In the same way, the second level detector, formed by T_{30}, T_{33}, T_{31} and T_{32}, causes Q_1 to become high whenever U_{output} decreases below the level fixed by U_b T_{31}. The total effect is that U_{output} varies at a constant rate with reversals at the instants when U_T becomes low and when U_{output} exceeds the limits established by the two level detectors.

The output signal of the function generator determines the point before the u.d.p. at which the pulse generator has to initiate a pulse. This pulse is used as a trigger signal for a transistor assisted ignition unit.

2.5 Working zone setting

Before the optimalizing controller was tested on a Simca Rush Engine (4 cyl. 4 stroke), the performance of this engine was measured to find the optimal ignition area to achieve maximum torque.

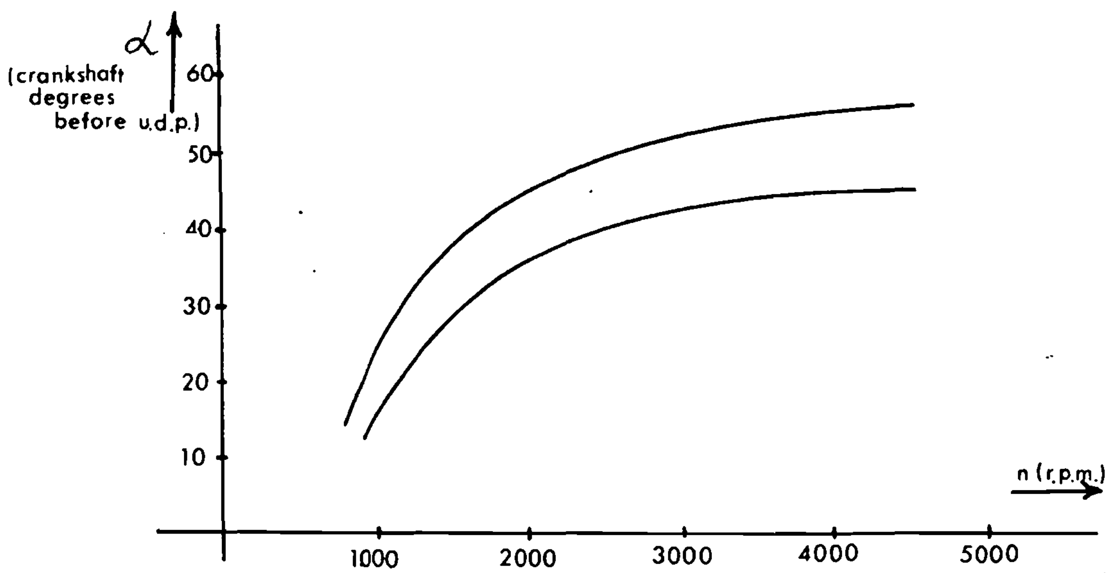


Fig. 2.10 Optimal advance as measured.

The measuring results are given in Fig. 2.10; α is the spark advance in crankshaft degrees before the upper dead point. The area between the solid lines represents the optimal ignition area for the engine (as measured).

In Fig. 2.11 the same data of Fig. 2.10 are given, but with α transferred to msec before the upper dead point.

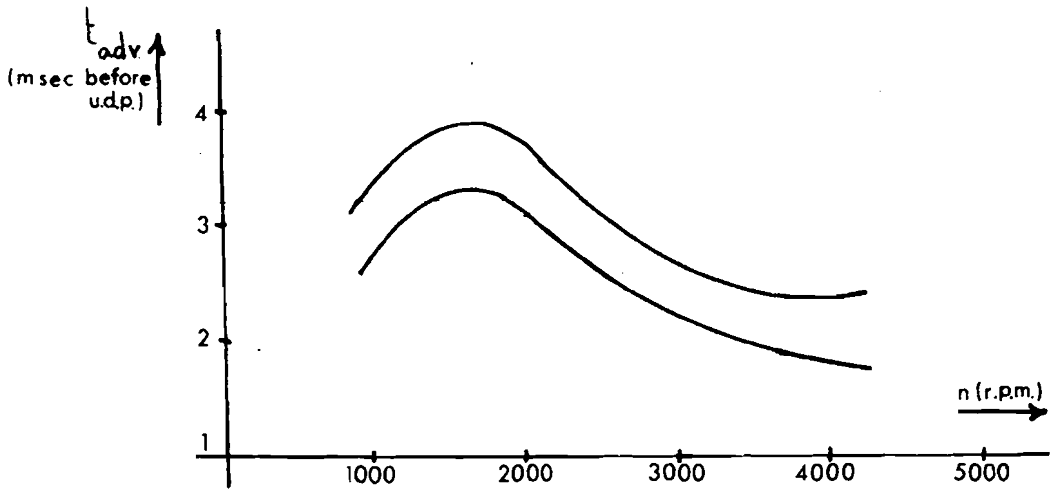


Fig. 2.11 Optimal advance as measured.

Under all conditions the optimal ignition advance t_{adv} is less than 5 msec. Consequently the optimalizing controller behaves well, if it operates by searching out the optimum ignition timing in the area starting 5 msec before the u.d.p. is reached and ending when the u.d.p. is reached. This area is fixed by the working zone setting.

Fig. 2.12 is a functional diagram showing the essential components of the working zone setting.

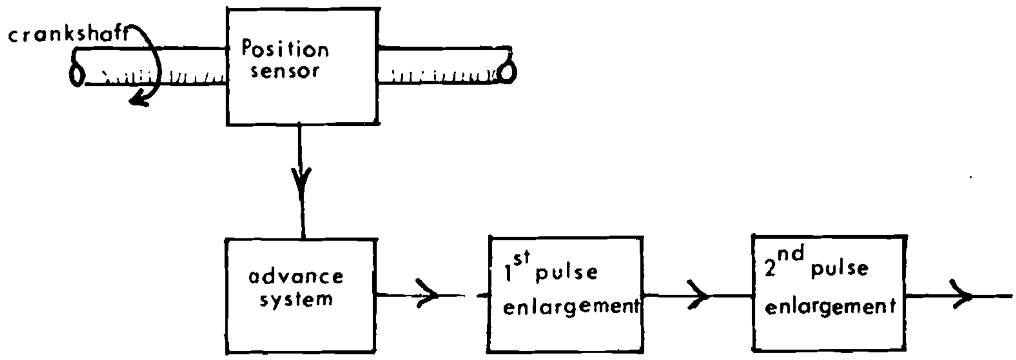


Fig. 2.12 Functional diagram of the working zone setting.

The position sensor

A disk is fixed to the crankshaft of the four stroke Simca Rush engine. As this engine has 4 cylinders, two sparks per revolution of the crankshaft are needed. Therefore the disc contains two magnets spaced at 180°.
A Hall generator with integrated amplifier
is fixed at the body of the engine, opposite to the disc. When the end of a magnet, like that indicated at point A on the plot of Fig. 2.13 turns along the Hall generator a piston reaches the upper dead point.

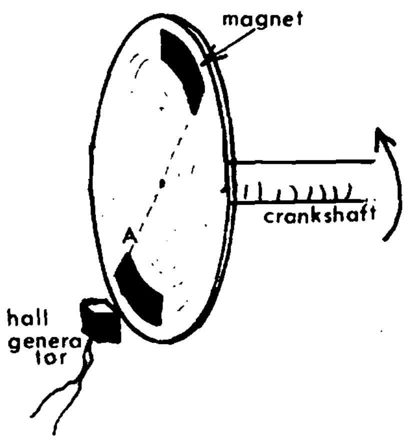


Fig. 2.13 Position sensor.

The Hall generator produces a signal, as long as a magnet is opposite to the Hall generator.

The advance system

The output signal of the Hall generator is applied to the advance system (see Fig. 2.12).
The advance system initiates a pulse, $\tau = 5$ msec before top dead centre is reached, whereas this pulse ends when this top dead centre is reached.

This pulse sets the area in which the optimalizing controller searches out the optimum ignition timing. The advance system is shown in Fig. 2.14

Owing to the limited width of the magnets, τ is lowered at high speeds, while on the other hand at very low speeds τ becomes zero.

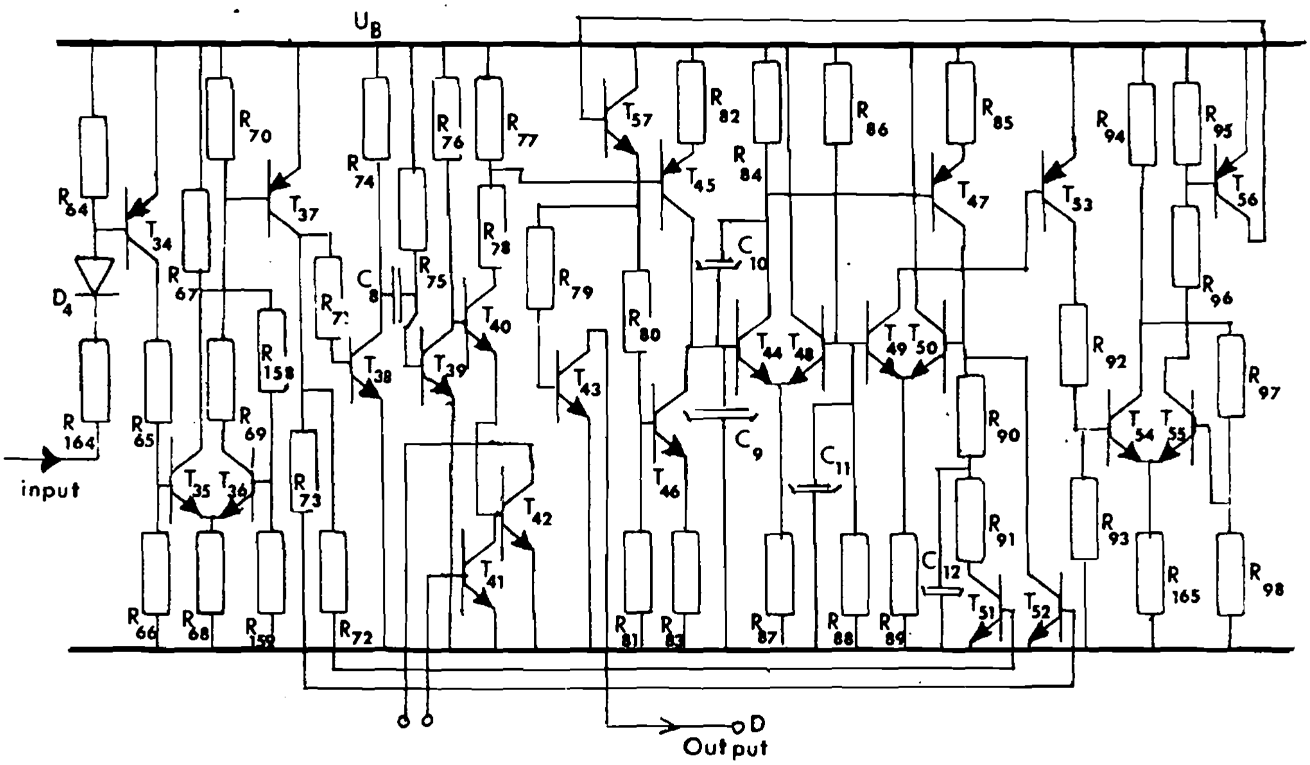


Fig. 2.14 The advance system.

During the output pulse of the advance system, transistor T_{43} is conducting. The function of T_{41} and T_{42} will be discussed in a following section. Before it is applied to the pulse generator, the output pulse of the advance system, ending at upper dead point, is extended.

First pulse enlargement

Fig. 2.15 shows the electronic circuit.

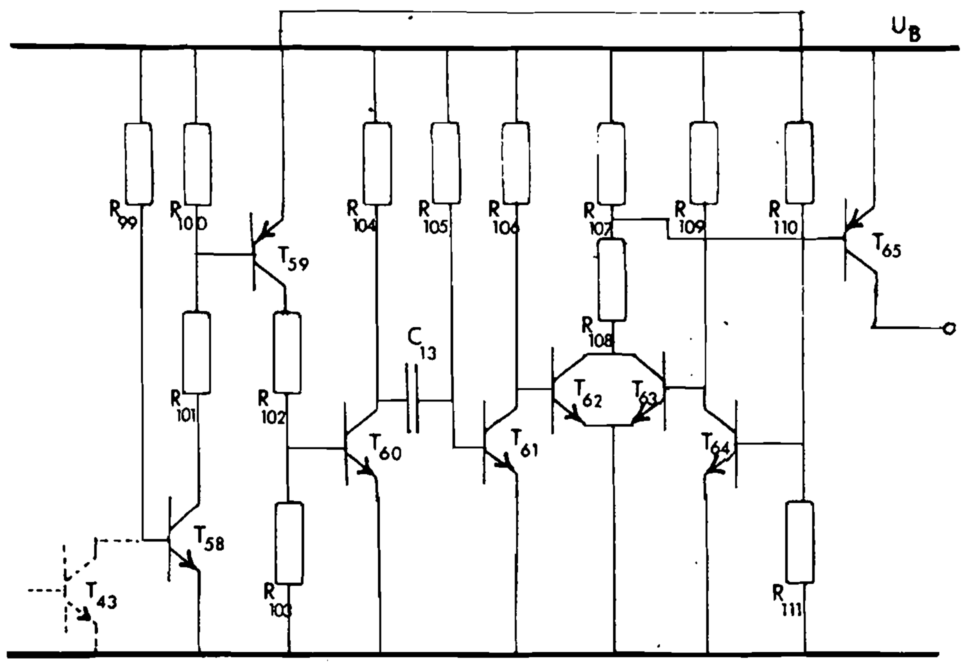


Fig. 2.15 First pulse enlargement circuit.

During the output pulse of the advance system, T_{43} causes the transistors T_{58}, T_{59}, T_{60} and T_{64} to stop conduction, so that T_{63} and thus T_{65} are conducting. When the upper dead point is reached, the output pulse of the advance system is ended and T_{43} stops conduction, whereas T_{58}, T_{59}, T_{60} and T_{64} start conduction.

The fall of collector voltage of T_{60} is used as a trigger signal for the monostable multivibrator formed by C_{13}, R_{105}, R_{106} and T_{61}. The pulse generated by this monostable multivibrator has a constant width (1 msec). During this pulse T_{62} and T_{65} are conducting, since T_{61} is cut-off. When the monostable pulse is ended, T_{61} and T_{64} cause T_{65} to stop conduction until the instant at which T_{64} stops conduction, i.e. until the instant at which the advance system initiates a following pulse.

Resuming: T_{65} starts conduction 5 msec before upper dead point is reached and stops conduction 1 msec after this upper dead point.

Second pulse enlargement

Fig. 2.16 shows the electronic circuit.

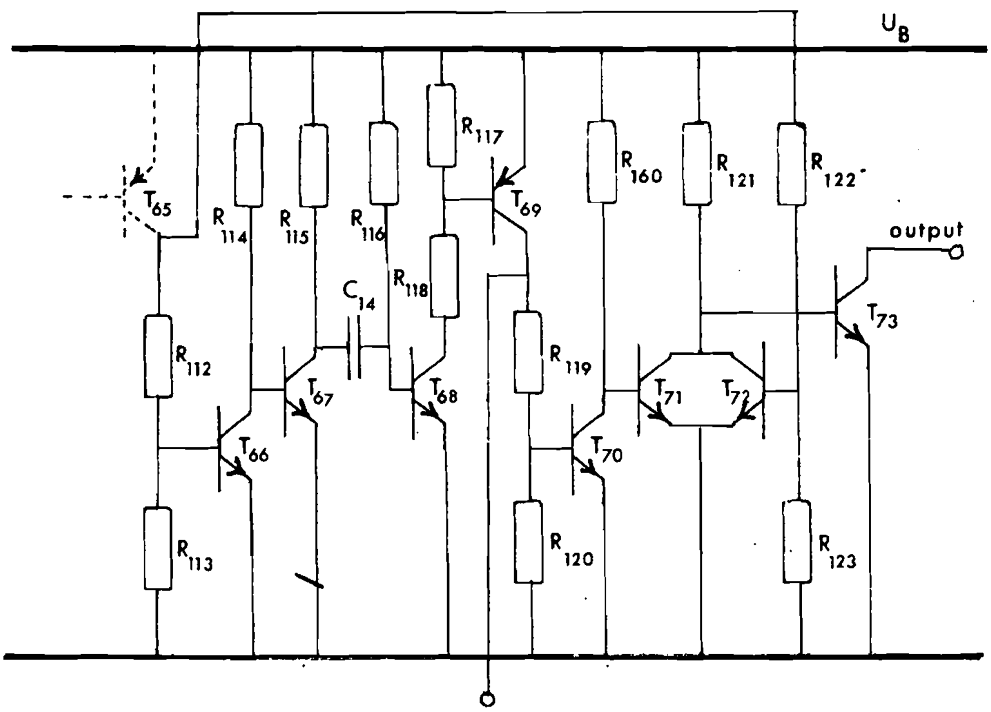


Fig. 2.16 Second pulse enlargement circuit.

The second pulse enlargement circuit differs from the first one in its extra output: the collector of T_{69}. In this way, the output pulse of the monostable multivibrator, formed by C_{14}, T_{68}, R_{116}, R_{118} and R_{117}, can be used to prevent the sparks from being initiated after the upper dead point. This will be described in a following section.

The output pulse of the monostable multivibrator is initiated 1 millisecond after the u.d.p. and is ended 2 milliseconds after the u.d.p.

Because the discussion already given for the first pulse enlargement circuit applies directly to the second pulse enlargement circuit, no additional treatment is given here.

Resuming: at the output of the second pulse enlargement circuit, T_{73} is cut-off from 5 milliseconds before the u.d.p. is reached, until 2 milliseconds after the u.d.p.

The output pulse of the second pulse enlargement circuit is applied to the pulse generator.

2.6 The pulse generator

Whenever the working zone setting produces a pulse, the pulse generator forms a pulse after more or less time, depending on the output signal of the function generator. The output pulse of the pulse generator triggers a transistor assisted ignition system ,

so that at the instant the pulse generator initiates a pulse a spark occurs.

Consequently the ignition advance varies in accordance with the output signal of the function generator.

Fig. 2.17 shows a part of the pulse generator.

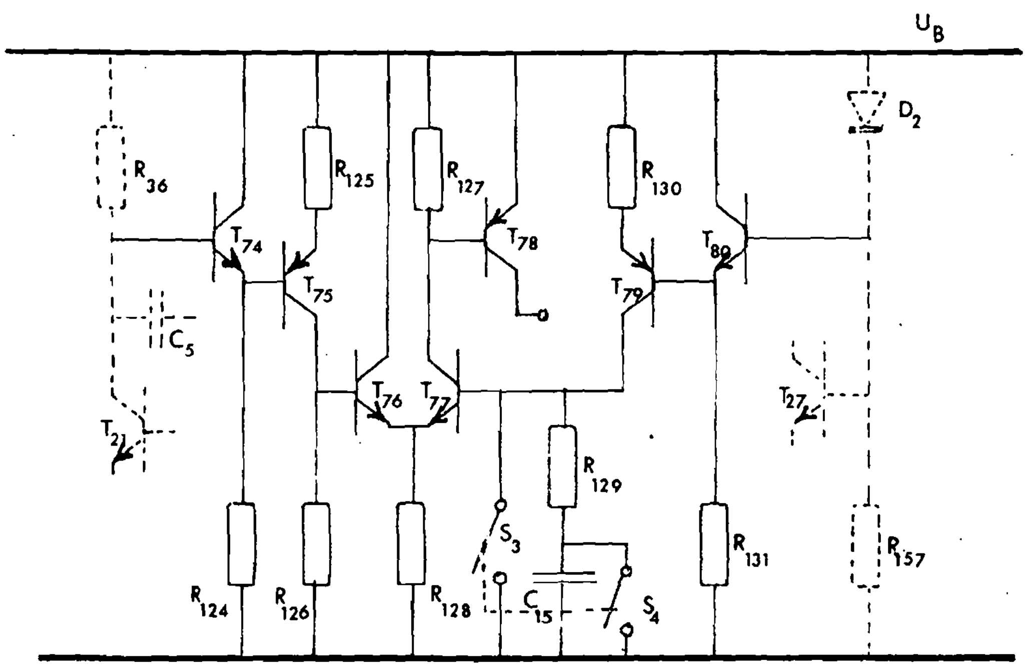


Fig. 2.17 A part of the pulse generator.

The output signal of the function generator, $U_{cT_{21}}$, is applied to the base of T_{74}. Since T_{74} and R_{124} act as emitter follower, T_{75} generates a collector current $I_{cT_{75}}$ proportional to the output signal of the function generator.

T_{80} and R_{131} act also as emitter follower. The constant voltage level at the base of transistor T_{27} is applied to the base of T_{80}. Consequently

T_{79} generates a constant collector current $I_{cT_{79}}$, while on the other hand $I_{cT_{75}}$ changes proportional to the output signal of the function generator.
As stated in a previous section, $U_{bT_{27}}$ sets the maximum level of the output signal of the function generator, so that $I_{cT_{79}} \leq I_{cT_{75}}$.
During the output pulse of the working zone setting, S_3 and S_4 are opened. When S_3 and S_4 are closed, T_{77} is non conducting, as its base voltage is too low.
As soon as S_3 and S_4 are opened, the voltage at the base of T_{77} rises step-wise by $I_{cT_{79}} \cdot R_{129}$ and gradually by $\frac{(I_{cT_{79}}) x t}{C_{15}}$. As the margin on $U_{bT_{77}}$ from just conducting to fully conducting is about 0.1 V, T_{77} and T_{78} change state from non-conduction to fully conduction when $U_{bT_{76}} = U_{bT_{77}}$.

T_{77} and T_{78} subsequently stop conduction when the output pulse of the working zone setting is ended; i.e. 2 msec after the u.d.p. The time needed to reach at the base of T_{77} a voltage level equal to that at the base of T_{76} varies in accordance with the output signal of the function generator. This output signal changes very slowly as compared with the repetition frequency of the output pulse of the working zone setting.
Suppose the output of the function generator has assumed its maximum level; i.e. $I_{cT_{79}} = I_{cT_{75}}$.

Owing to the fact that $R_{126} = R_{129}$, T_{77} and T_{78} start conduction whenever the working zone setting initiates a pulse i.e. 5 msec before the u.d.p.
In case the output of the function generator has assumed its minimum level that is ever possible, the value of C_{15} is such that the time needed to reach at the base of T_{77} a voltage equal to that at the base of T_{76} is 5 msec: i.e. the pulse generator initiates a pulse at the u.d.p.
T_{78} serves to trigger a monostable multivibrator. The output pulse of this monostable multivibrator is used as a trigger-signal for a transistor assisted ignition system. Hence the ignition system initiates a spark whenever T_{77} starts conduction.

The complete circuit of the pulse generator is shown in Fig. 2.18.

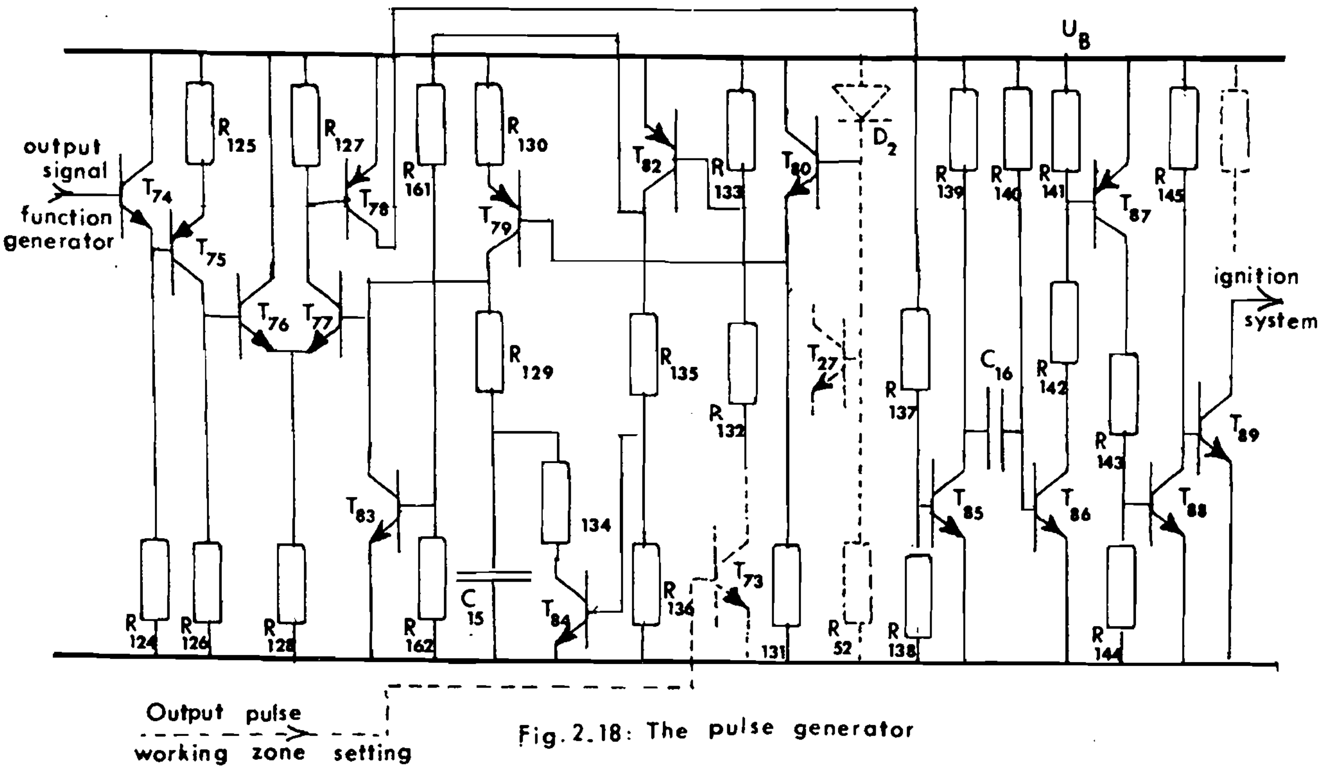


Fig. 2.18: The pulse generator

T_{82}, T_{83} and T_{84} act as switch S_3 and S_4.
The monostable multivibrator is formed by C_{16}, R_{140}, T_{86}, R_{141} and R_{142}.
During the output pulse of this multivibrator T_{89} conducts. Hence, the ignition system produces a spark whenever T_{77} and thus T_{78} start conduction.

Resuming, the total effect is that Δt msec before the u.d.p. is reached the pulse generator initiates a pulse and a spark occurs. The value of Δt is determined by the output signal of the function generator.

Fig. 2.19 is a typical performance diagram showing the essential actions that occur when the pulse generator is in operation. It is assumed that the speed of the crankshaft is very low, and that the descent detector is switched off.

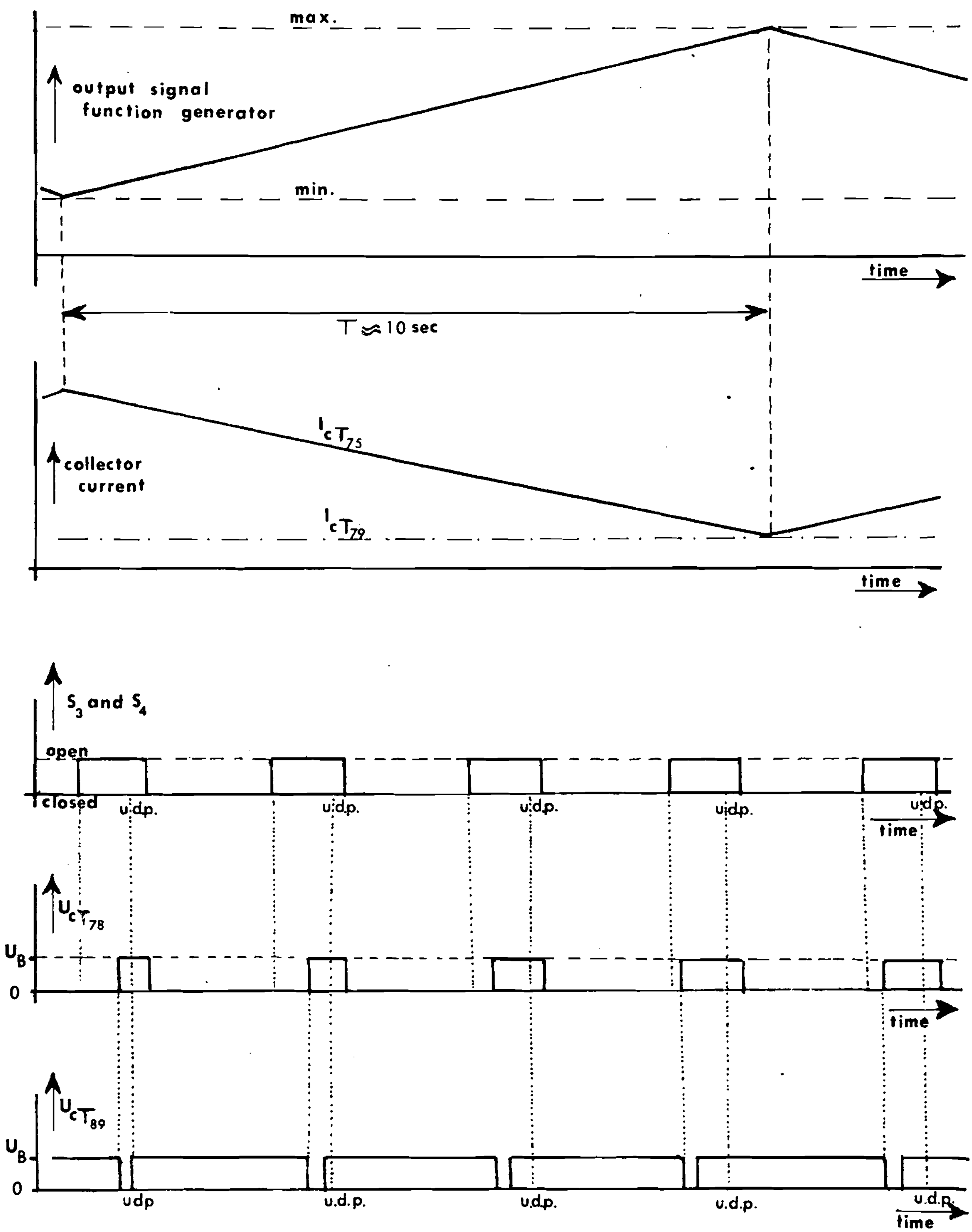


Fig. 2.19 Performance diagram of the pulse generator.

Special provisions

A) In order to prevent the sparks from being initiated after the u.d.p. a special system is added to the optimalizing controller.
This system forces the function generator to advance the ignition timing by means of the S_1 terminal of the flip-flop, whenever the sparks start to occur after u.d.p.

Fig. 2.20 shows the electronic circuit of this system.

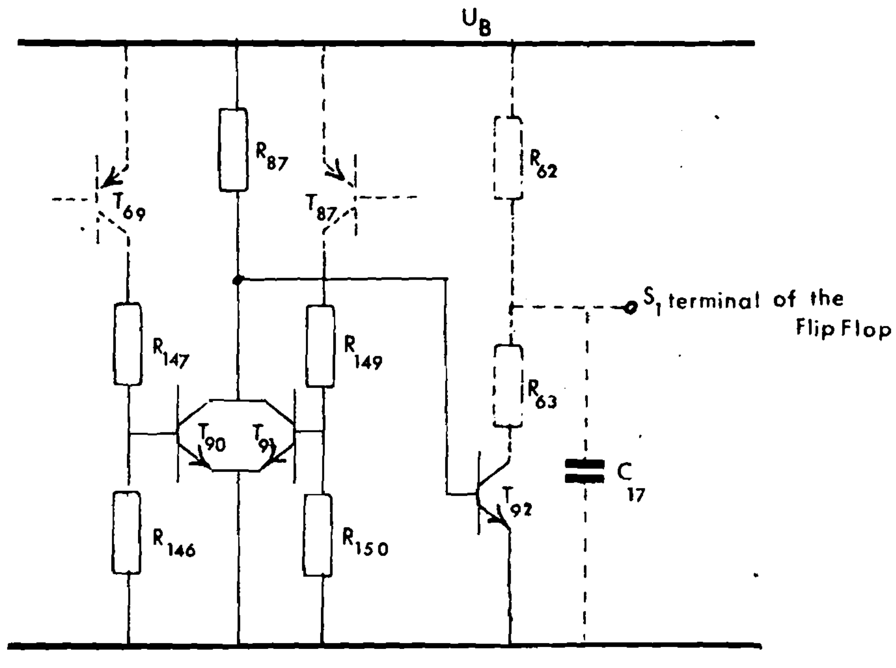


Fig. 2.20

T_{69} is cut-off from 1 msec after the u.d.p. until 2 msec after the u.d.p. (see page 50). T_{87} is cut-off during the output pulse of the pulse generator, which has a constant width (1 msec).
When a spark occurs before the u.d.p. the output pulse of the pulse generator is ended before the second monostable multivibrator of the working zone setting initiates a pulse. Consequently T_{90} or else T_{91} prevents T_{92} from starting conduction: S_1 remains high.

When a spark is initiated after the u.d.p.,the output pulse of the second monostable multivibrator of the working zone setting is initiated before the output pulse of the pulse generator is ended.
Consequently, at the instant the multivibrator of the second pulse enlargement initiates a pulse, T_{90} and T_{91} are cut-off simultaneously, and T_{92} starts conduction: S_1 becomes low. T_{92} stops conduction when the output pulse of the pulse generator is ended. In this way, when a spark is initiated after the u.d.p., S_1 becomes low and the flip-flop forces the function generator to advance the ignition timing, until the sparks occur before the u.d.p.
The S_1 terminal of the flip-flop overrides the T input of the flip-flop. Hence the T terminal is immaterial when the sparks occur after the u.d.p.

Fig. 2.21 is a performance diagram showing the essential actions that take place when the sparks occur after the u.d.p.
The assumption is made that the speed of the crankshaft is very low.

B) Whenever the engine is running very slowly, the advance system of the working zone setting stops operation (see page 48). In order to compensate for this, T_{41} and T_{42} are interposed in the advance circuit (see Fig. 2.14). Suppose the advance system stops operation, as the engine is running very slowly.

At the instant, the u.d.p. is reached, the advance system still generates its standard pulse. Via T_{42} this pulse is used to cause the monostable multivibrator, formed by C_{16}, R_{140}, T_{86}, R_{141} and R_{142}, to initiate a pulse. In this way, the sparks occur at the u.d.p. when the engine is running very slowly.
When the advance system is operating, T_{42} is cut-off by means of T_{41} and the sparks occur whenever the pulse generator initiates a pulse.
The complete function diagram and the complete electronic circuit of the optimalizing controller are shown in Fig. 2.22 and 3.13

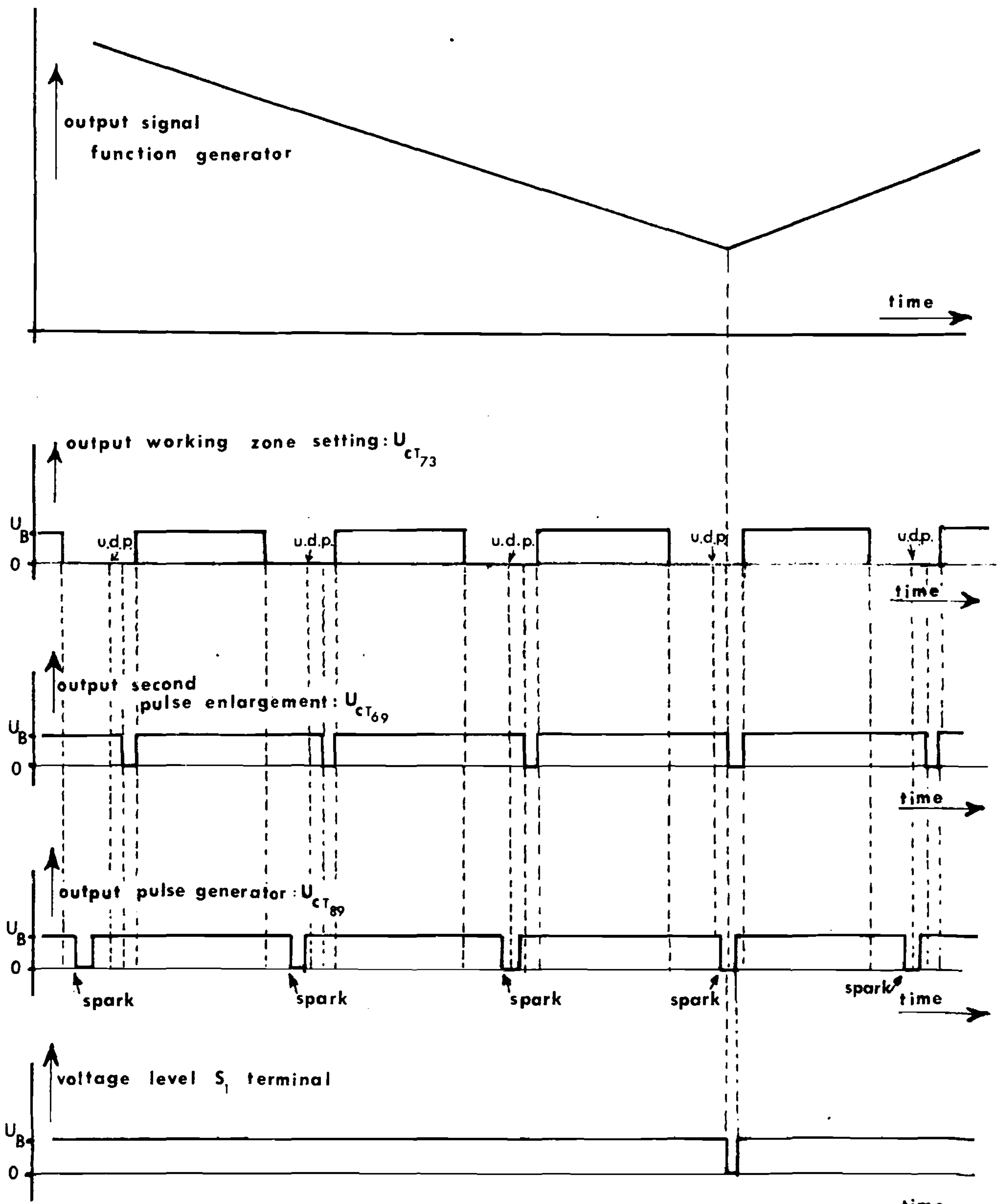


Fig. 2.21: Performance diagram; the essential actions that take place when the sparks start to occur after u.d.p.

3. Advantages

1) Ignition takes place at the correct point, in spite of any change of carburettor setting, type of fuel, engine temperature, condition of combustion chamber, engine load, etc.

2) The conventional advance mechanics are superfluous.

3) The controller may be used in combination with any electronic ignition unit.

4) The controller may be applied to any operating system that actually exhibits an optimum performance condition as its inputs are varied.

5) The optimalizing controller behaves well, even if the torque sensor is not linear.

Improvements

The following improvements of the foregoing tentative circuit will have to be considered.

- the electronic circuit of the optimalizing controller has to be simplified.

- the torque has to be measured in another way.

- dependent on the choice of this torquo sensor, a special smoothing filter and amplifier have to be developed (see page 36).

- A means should be provided for optimalizing the speed of the engine, whenever the torque produced by the engine decreases below a particular level.

- A misfire detector has to be added to the controller to cause the controller to drive the ignition timing away from operating within the intolerable misfire range.

Besides these improvements, some measurements have to be taken, in order to determine the behaviour of the controller under various conditions.

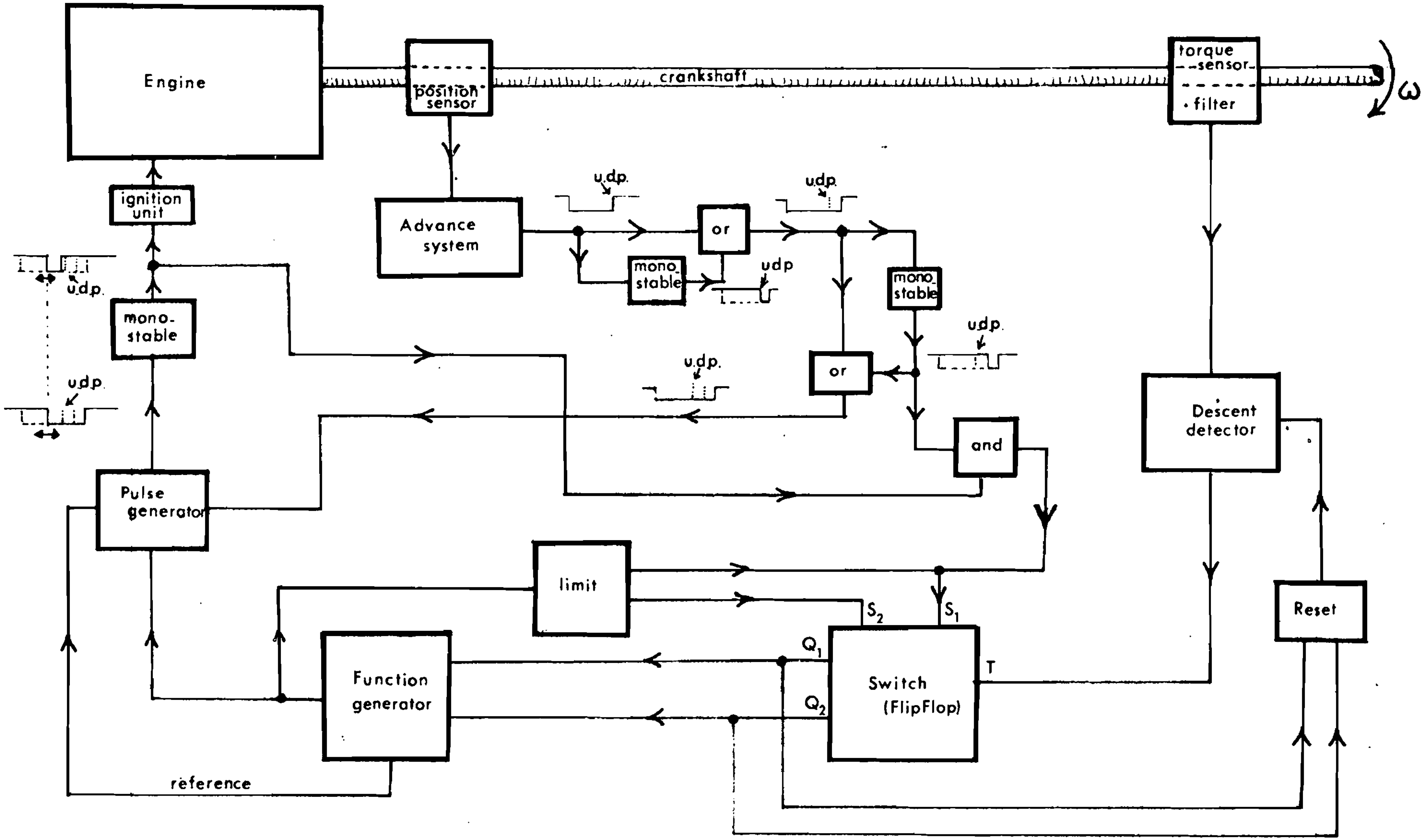


Fig 2.22 Function diagram

Parts List:

All resistors: $\frac{1}{4}$ Watt

NPN transistors: BC147 or BC107

PNP transistors: BC177

Flip-flop : FCJ111

F_1 and F_2 : Matched N-channel FET's; BFS21A

C_6, C_7, C_8 and C_{18} serve to reduce the effects of high-frequency interference signals.

R. van Lutterveld

REPORT III

Improvements of the ignition timing optimalizing controller and measuring results.

R. van Lutterveld

Summary:

In continuation of report II, the following is discussed:

- a specially designed amplifier and smoothing filter for the torque sensor

- a switch system, which causes the optimalizing controller to optimalize the ignition timing with respect to the speed of the engine, whenever the torque of the engine decreases below a particular level

- some measuring results of the performance of an engine which is equipped with the optimalizing controller.

C O N T E N T S

1. Amplifier and smoothing filter

A) The Amplifier

The amplifier has to amplify the output signal of the straingauge instrument, as shown in Fig. 2.4 of report II

The functional diagram of the amplifier is illustrated in Fig. 3.1

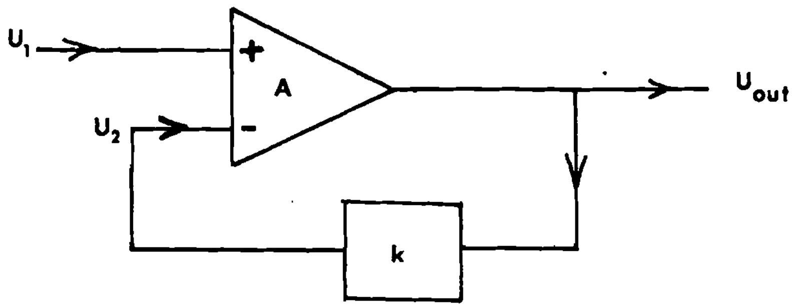


Fig. 3.1 Functional diagram of the amplifier.

Properly speaking, the amplifier is a feedback system: a part k of the output signal is subtracted from the input signal U_1. ($k \leqslant 1$).

As a result $$U_{out} = (U_1 - k\,U_{out})A \qquad (1)$$

or $$U_{out} = A \frac{U_1}{1 + k.A}$$

in which $A \gg 1$.

Since $1 \ll k.A$, equation (1) may be reduced to

$$U_{out} = \frac{U_1}{k}$$

Hence the voltage gain G_v of the amplifier is constant and depends only on k:

$$G_v = {}^1/_k$$

Fig. 3.2 shows the electronic circuit of the amplifier.

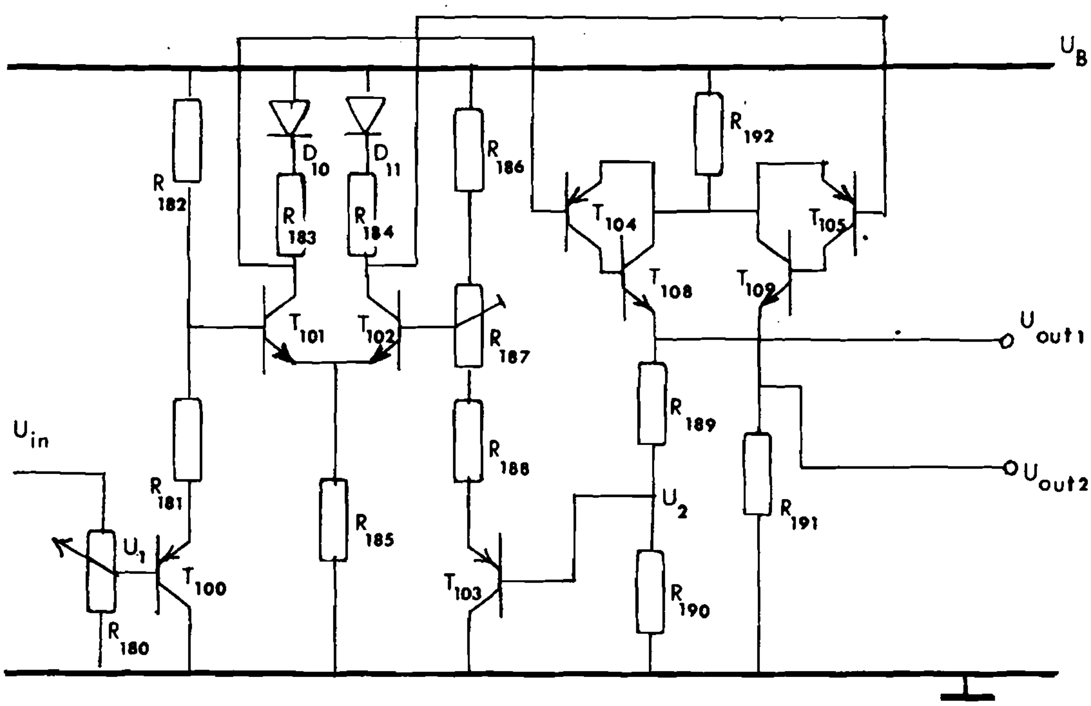


Fig. 3.2 <u>The amplifier</u>

Via the emitter-followers T_{100} and T_{103}, the voltage U_1-U_2 is amplified by two differential amplifiers.

The first differential amplifier is formed by T_{101} and T_{102}, the second is formed by T_{104}, T_{108}, T_{105} and T_{109}.

Hence

$$U_{out_1} = A(U_1 - U_2) \qquad (2)$$

Because of $U_2 = \frac{R_{190}}{R_{190} + R_{189}} U_{out_1}$, we can write equation ② as

$$U_{out_1} = A\left(U_1 - \frac{R_{190}}{R_{190} + R_{189}} U_{out_1}\right) \quad ③$$

When equation ① (see page65) is compared with equation ③ , we get

$$k = \frac{R_{190}}{R_{190} + R_{189}}$$

and the constant voltage gain is

$$G_v = \frac{1}{k} = \frac{R_{190} + R_{189}}{R_{190}}$$

As a result $\Delta U_{out_1} = G_v \, \Delta U_1$

and $\Delta U_{out_2} = -G_v \, \Delta U_1$ $(R_{191} = R_{189} + R_{190})$

The offset voltage is adjustable to zero by means of R_{187}.
The output signal of the amplifier has to be filtered in order to suppress the unwanted interference signals. Therefore, the emitter current $I_{e\,T_{109}}$ is passed through a smoothing filter.

B) Smoothing filter

The optimalizing controller was tested on a four stroke, four cylinder, engine. In this engine, two sparks are required during each revolution, so that, when the engine's speed is n rounds per minute, $\frac{2n}{60}$ combustions per second take place.
As a result of the regular sequence of combustions in the cylinders, the torque M of the engine consists of a constant plus a frequency part:

$$M = M_o + \Delta M \sin \omega_c t$$

in which

$$\omega_c = 2\pi f_c = 2\pi \frac{2n}{60} \frac{rad}{sec}$$

f_c varies from 20 Hz to 200 Hz, according to the speed of the engine. The sinusoidal component of M has to be suppressed, since it may cause the optimalizing controller to reverse the ignition timing change before the optimum ignition timing is reached. For this reason, the emitter current of T_{109} of the output of the amplifier is smoothed by the smoothing filter, shown in Fig. 3.3.

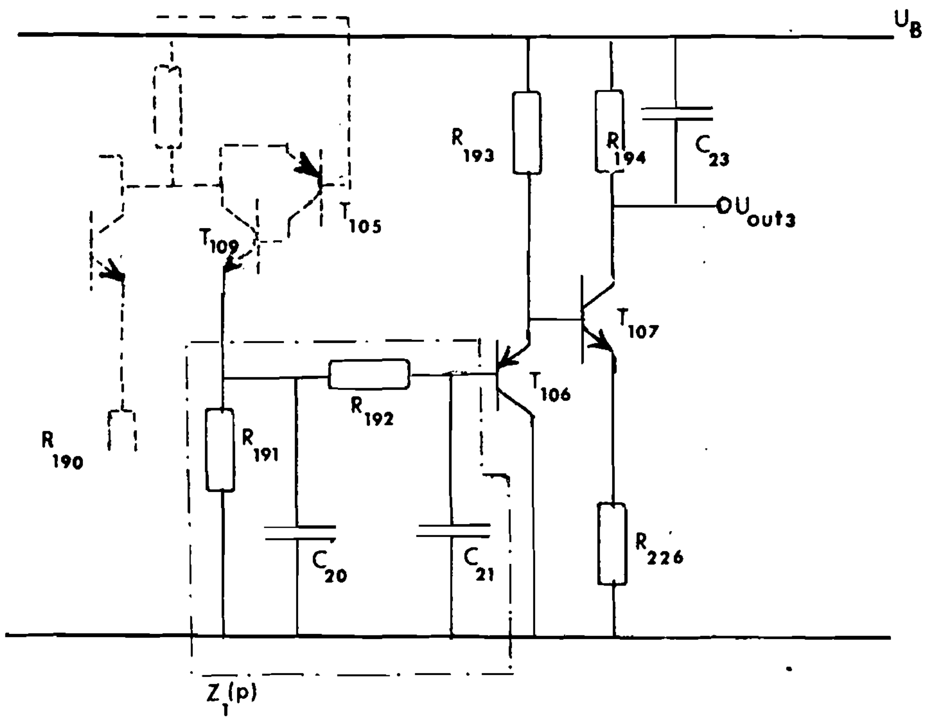


Fig. 3.3 The smoothing filter

The emitter current of T_{109} is passed through the impedance $Z_1(p)$, composed of two simple RC filters.

In view of the fact that $R_{192} \gg R_{191}$, we can neglect the influence of the second RC filter (R_{192} and C_{21}) on the first RC filter (R_{191} and C_{20}) and the impedance $Z_1(p)$ will be:

$$Z_1(p) = \frac{R_{191}}{(1+p\,R_{191}\,C_{20})\,(1+p\,R_{192}\,C_{21})}$$

T_{106} and T_{107} invert the output signal of the second RC filter. The collector current of T_{107} is passed through the third RC filter, formed by R_{194} and C_{23}.

As a consequence, we can write the transfer function of the smoothing filter in the form:

$$\frac{\Delta U_{out\ 3}(p)}{\Delta U_{out\ 1}(p)} = K \cdot \frac{1}{(1+p\,R_{191}\,C_{20})\,(1+p\,R_{192}\,C_{21})\,(1+p\,R_{194}\,C_{23})}$$

$$\text{with} \quad K = \frac{R_{191}}{R_{190}} \cdot \frac{R_{194}}{R_{226}}$$

The Bode plot of this transfer function is illustrated in Fig. 3.4.

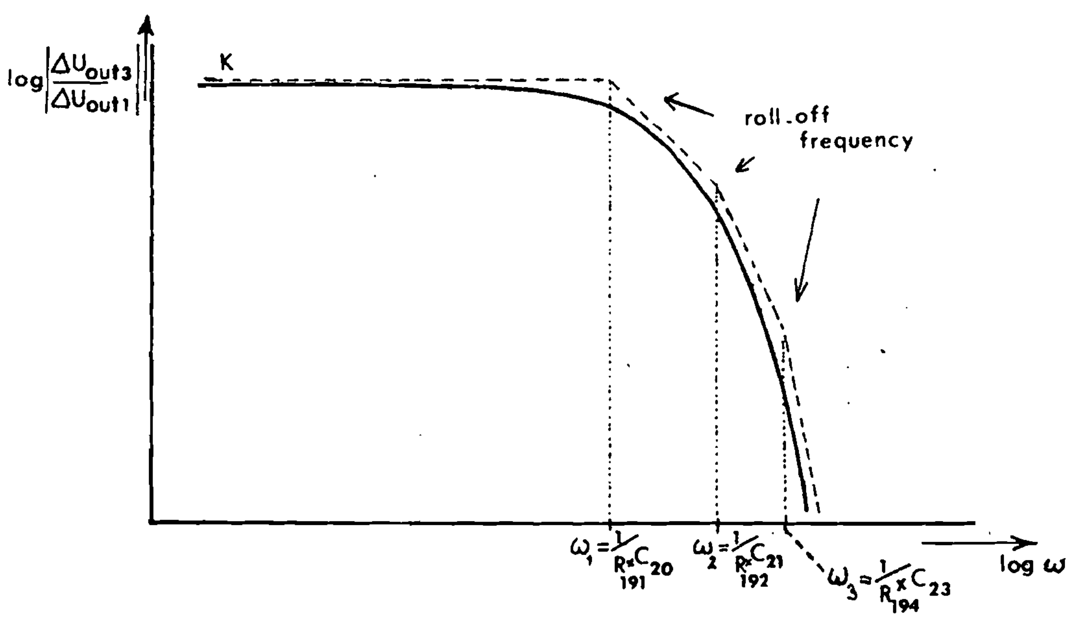


Fig. 3.4 Bode plot of the smoothing filter

The total effect is that the smoothing filter suppresses the signals with radian frequency $\omega > \omega_1$.

2. Switch system

The **descent** detector (see page 37 report II) is unable to find an optimum performance condition whenever the load of the engine in the measuring set up is turned off (see Fig. 2.4).
Therefore, a tachometer and a switch are added to the optimalizing controller. The tachometer generates a D.C. signal proportional to the speed of the engine. This signal is applied to the **descent** detector by means of the switch, whenever the torque decreases below a particular level.
As a result, **when the torque decreases below that particular level, the** optimalizing controller starts to optimalize the ignition timing with respect to the speed of the engine, instead of the torque of the engine.

A) Tachometer

The tachometer makes use of the output pulses of the second pulse enlargement circuit, which generates two pulses during each revolution of the crankshaft (see page50)

Fig. 3.5 illustrates the electronic circuit.

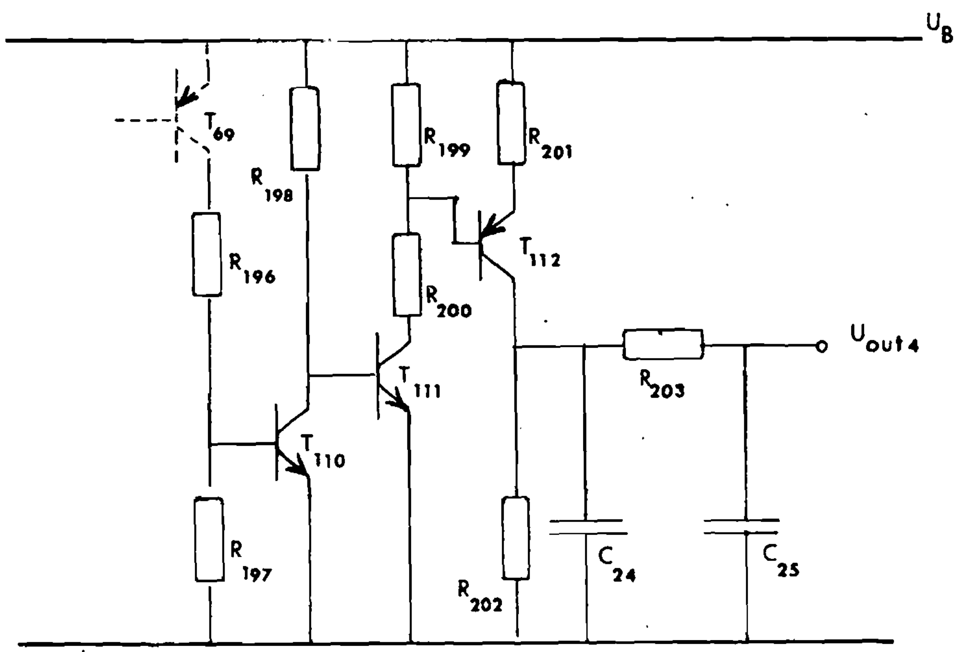


Fig. 3.5 The tachometer

During the output pulse of the second pulse enlargement circuit, T_{69} and T_{110} are cut-off, whereas T_{112} conducts a current

$$I_c\, T_{112} = \frac{U_{R_{199}} - U_{be}\, T_{112}}{R_{201}}$$

On the other hand, T_{111} and T_{112} stop conduction:

and $I_c\, T_{112} = 0$, when the output pulse of the second pulse enlargement circuit is ended.

Because the output pulse has a constant width, the average collector current of T_{112} corresponds to the speed of the engine. Therefore $I_c\, T_{112}$ is passed through a filter, which is composed of two RC filters.

Owing to $R_{203} \gg R_{202}$, the impedance $Z(p)$, set by the two RC filters, will be

$$Z(p) = \frac{R_{202}}{(1+p\, R_{202}\, C_{24})\,(1+p\, R_{203}\, C_{25})}$$

The corresponding Bode plot is shown in Fig. 3.6.

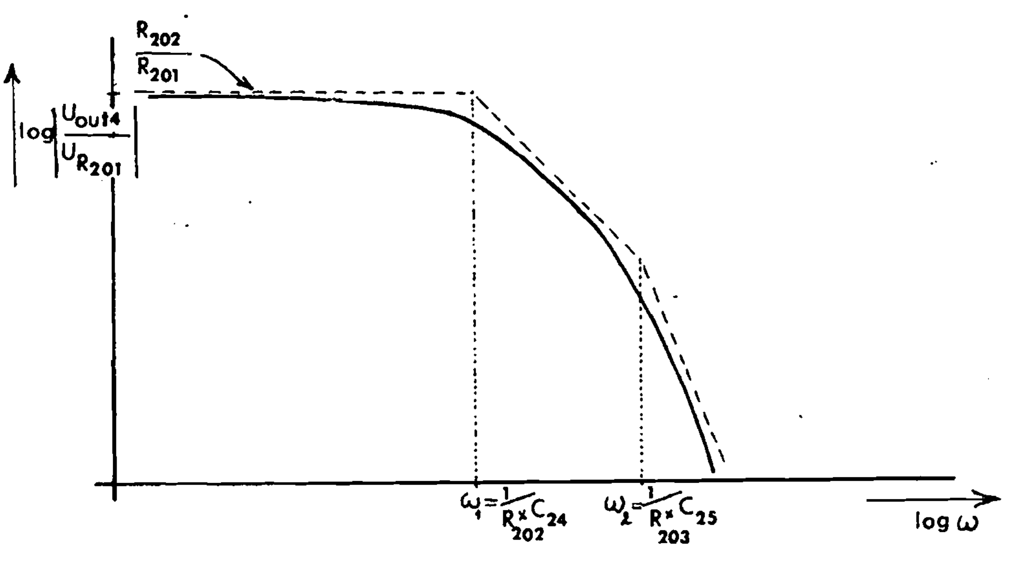


Fig. 3.6 Bode plot

In this way, the output of the tachometer is a smoothed signal which only varies with the speed of the engine.

B) **Switch**

The output of the smoothing filter of the torque sensor, $U_{C\ T_{107}}$ is compared with a fixed voltage level.
Whenever $U_{C\ T_{107}}$ decreases below that fixed voltage level, the output of the tachometer is applied to the input of the **descent** detector and replaces the output of the smoothing filter.

The switch is composed of two parts.
Fig. 3.7 shows the first part of the switch.

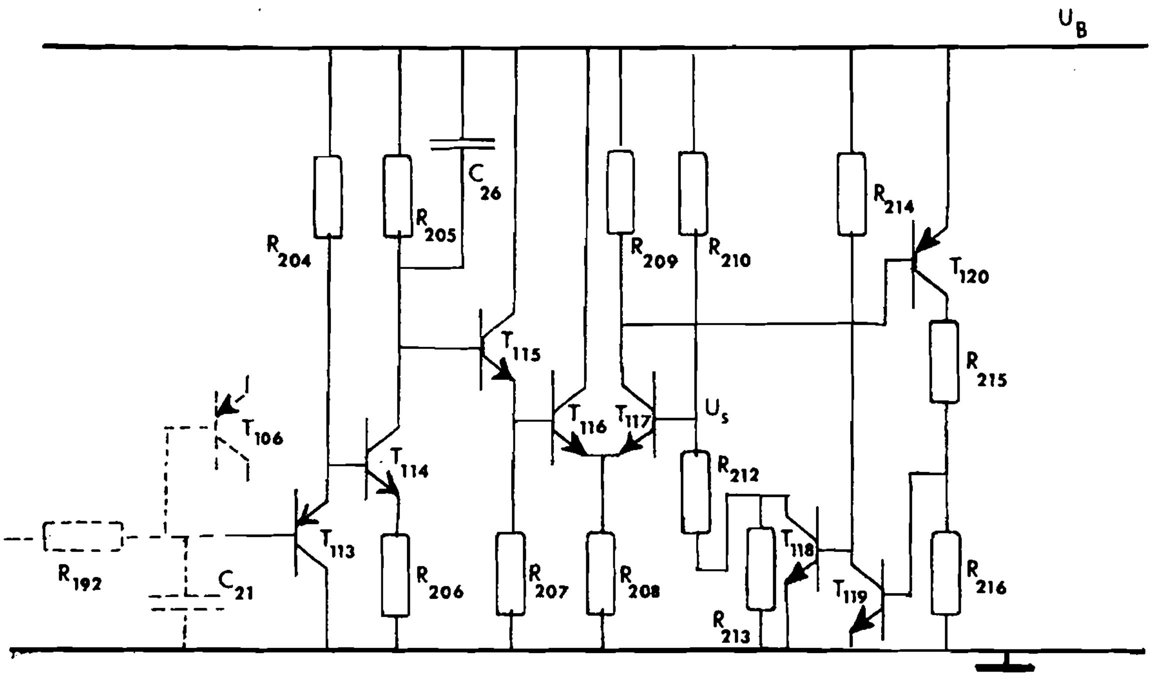


Fig. 3.7 First part of the switch

The voltage level at the collector of T_{114} is proportional to the voltage level at the output of the smoothing filter.

Via T_{115}, the voltage level of $U_{C\ T_{114}}$ is compared with the voltage level U_s at the base of T_{117} by means of the differential amplifier formed by T_{116} and T_{117}.

When the voltage level of $U_c\ T_{114}$ is such that $U_b\ T_{116} < U_b\ T_{117}$, T_{117}, T_{119} and T_{120} are conducting whereas T_{118} is cut-off by lack of base current.

As a result, the voltage level U_s at the base of T_{117} will be

$$U_S = U_M$$

$$\text{with} \quad U_M = \frac{R_{212} + R_{213}}{R_{212} + R_{213} + R_{210}} U_B$$

If subsequently $U_c\ T_{114}$ increases and $U_b\ T_{116}$ rises above the level of U_M, then T_{117}, T_{120} and T_{119} change state from conduction to non-conduction. Hence T_{118} shortcircuits the resistor R_{213} and U_S assumes a lower level:

$$U_S = U_L$$

$$\text{with} \quad U_L = \frac{R_{212}}{R_{210} + R_{212}} U_B$$

T_{118} shortcircuits R_{213} until the moment that $U_b\ T_{116}$ decreases below the level of U_L.

The transfer characteristics of the switch are illustrated in Fig. 3.8:

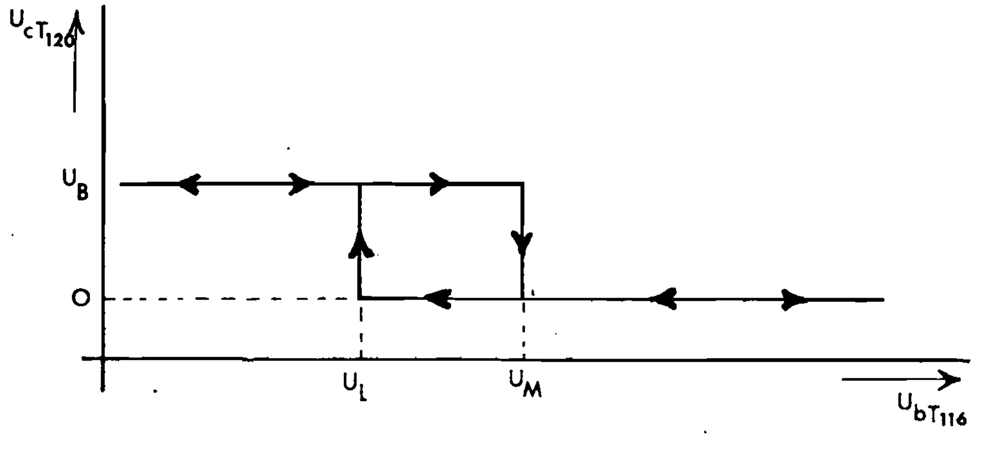


Fig. 3.8 Transfer characteristics of the switch

Fig. 3.9 shows the second part of the switch.
This part causes the input of the **descent** detector to vary with the output of the tachometer, whenever T_{120} starts conduction.

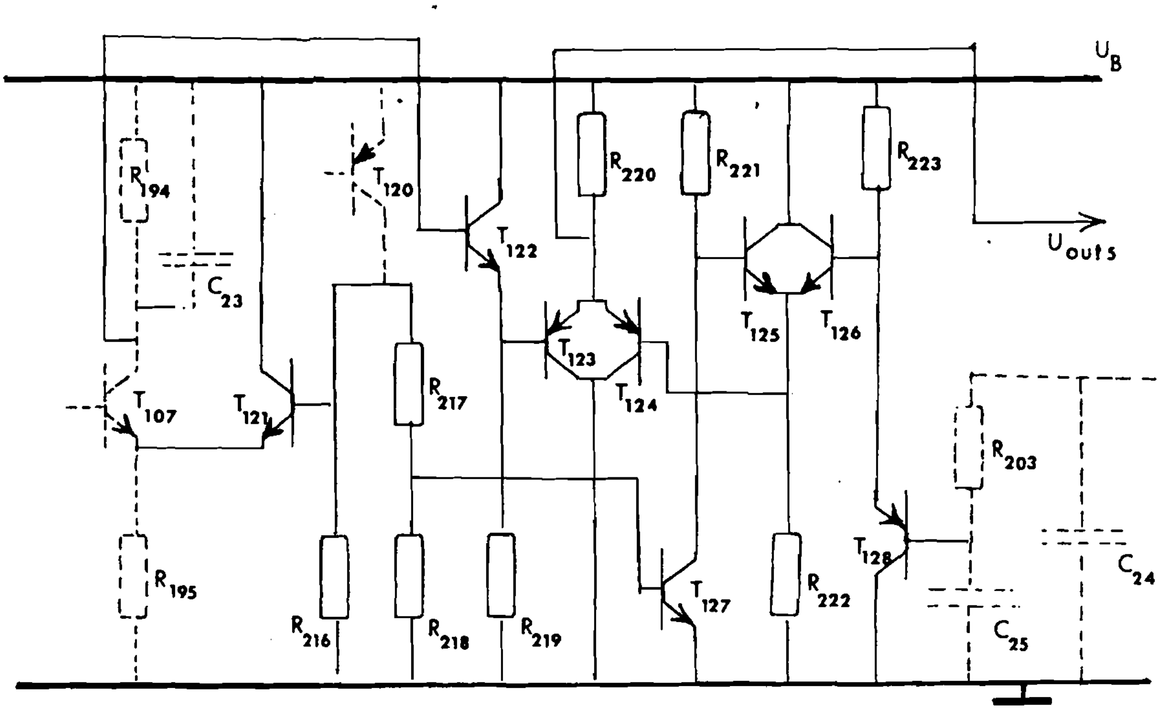


Fig. 3.9 Second part of the switch

Suppose the torque of the engine is such that T_{120} starts conduction. Then $U_b\ T_{121} \approx U_B$ and T_{107} stops conduction as the maximum level of $U_b\ T_{107}$ is in the order of 2 V.

Consequently $U_c\ T_{107}$ assumes the level of U_B.

At the same time, T_{127} starts conduction and T_{125} is cut-off by lack of base current. As a result the output of the tachometer $U_b\ T_{128}$ is applied to the base of T_{124} via the emitterfollowers T_{126} and T_{128}.
Owing to the fact that the maximum voltage level of $U_b\ T_{128}$ is in the order of 4.5 V, the voltage level $U_b\ T_{124}$ is always below the voltage level of $U_b\ T_{123}$. Hence the output of the switch varies according to $U_b\ T_{128}$: i.e. according to the speed of the engine.

Now suppose the torque of the engine increases, so that T_{120} stops conduction. Then T_{127} stops conduction and $U_b\ T_{125}$ assumes the level of U_B.

Hence

$$U_b\ T_{124} \approx U_B - U_{be}\ T_{125} \qquad (4)$$

At the same time, T_{120} causes T_{121} to stop conduction and $U_c\ T_{107}$ varies according to the torque of the engine.

Via the emitter follower T_{122}, the output signal of the smoothing filter $U_c\ T_{107}$ is applied to the base of T_{123}.
As the maximum level of $U_c\ T_{107}$ is in the order of U_B, the maximum level of $U_b\ T_{123}$ will be

$$(U_b\ T_{123})_{max} = U_B - U_{be}\ T_{122} \qquad (5)$$

When we compare equation (4) with equation (5) we get

$$U_b\ T_{123} \leqslant U_b\ T_{124}$$

Consequently $U_{out\ 5}$ varies according to the output of the smoothing filter of the torque sensor.
$U_{out\ 5}$ is applied to the input of the descent detector.

The total effect is that the optimalizing controller starts to optimalize the ignition timing with respect to the speed of the engine, whenever the torque of the engine decreases below the level, which corresponds to the voltage level of U_L.

Fig. 3.13 shows the complete circuit of the amplifier, the smoothing filter and the switch system.

3. Measuring results

Before the ignition timing optimalizing controller is tested on a Simca Rush engine, the performance of this 4 stroke, 4 cyclinder engine is measured as a function of carburettor setting and ignition advance angle.

The measurements are taken under static working conditions. The cooling watertemperature is kept within 70°– 80°C and the load on the engine is kept constant: i.e. the water-brake setting is not changed during the measurements.

The measuring results are illustrated in Fig. 3.10. The torque is given in per cent of the torque that is available when the ignition takes place at the optimum moment. The dotted lines and the striped lines represent the lines of oonstant advance angle.

After these measurements, the engine is equipped with the ignition timing optimalizing controller.

C_2 and C_3 are chosen to be:

$$C_2 = 560 \text{ nF}$$
$$C_3 = 440 \text{ nF}$$

(see page 40)

As a result, the reset-time will be 0.5 sec after the moment of ignition timing change reversion, when the ignition timing is too advanced. On the other hand, the reset-time will be 0.4 sec after the moment of ignition timing change reversion, when the ignition timing is too retarded.

T is chosen to be 10 sec by adjusting R_{38}:

$$R_{38} \approx 200 \text{ kOhm} \quad \text{(see Fig. 2.19)}$$

The controller varies the ignition timing at a constant rate. When the optimum ignition point is passed, the torque starts to decrease. As soon as the value of this decrease in torque ΔM exceeds a particular value ΔM_{max}, the controller reverses the direction of the ignition timing change.

In this way, the ignition timing varies within a hunting zone (see Fig. 2.2)

Fig. 3.11 illustrates the behaviour of the engine and the controller at a particular carburettor setting. The torque and the ignition advance are shown as a function of time. The dotted lines represent the boundaries of the ignition timing hunting zone. As the measurement shows, the controller sometimes reverses the ignition timing change within the hunting zone. This is effected by the irregularities which occur in the torque signal.

When the boundaries of the ignition timing hunting zone are measured as a function of carburettor setting and are compared with the measuring results of Fig. 3.10, the minimum level as shown in Fig. 3.12 is found. As a result of using the optimalizing controller, the torque of the engine varies within the area between the bold lines. The average torque is represented by the dotted line.

4. Consequences

The measuring results show that under static working conditions the controller behaves very well: the ignition timing varies at a constant rate within a hunting area around the optimum point.

It is clear that the measurements have to be extended in order to determine the behaviour of the engine and the controller under variable working conditions. This has to be the subject of the forthcoming research. Besides these measurements the torque has to be measured by another torque sensor.

R. van Lutterveld

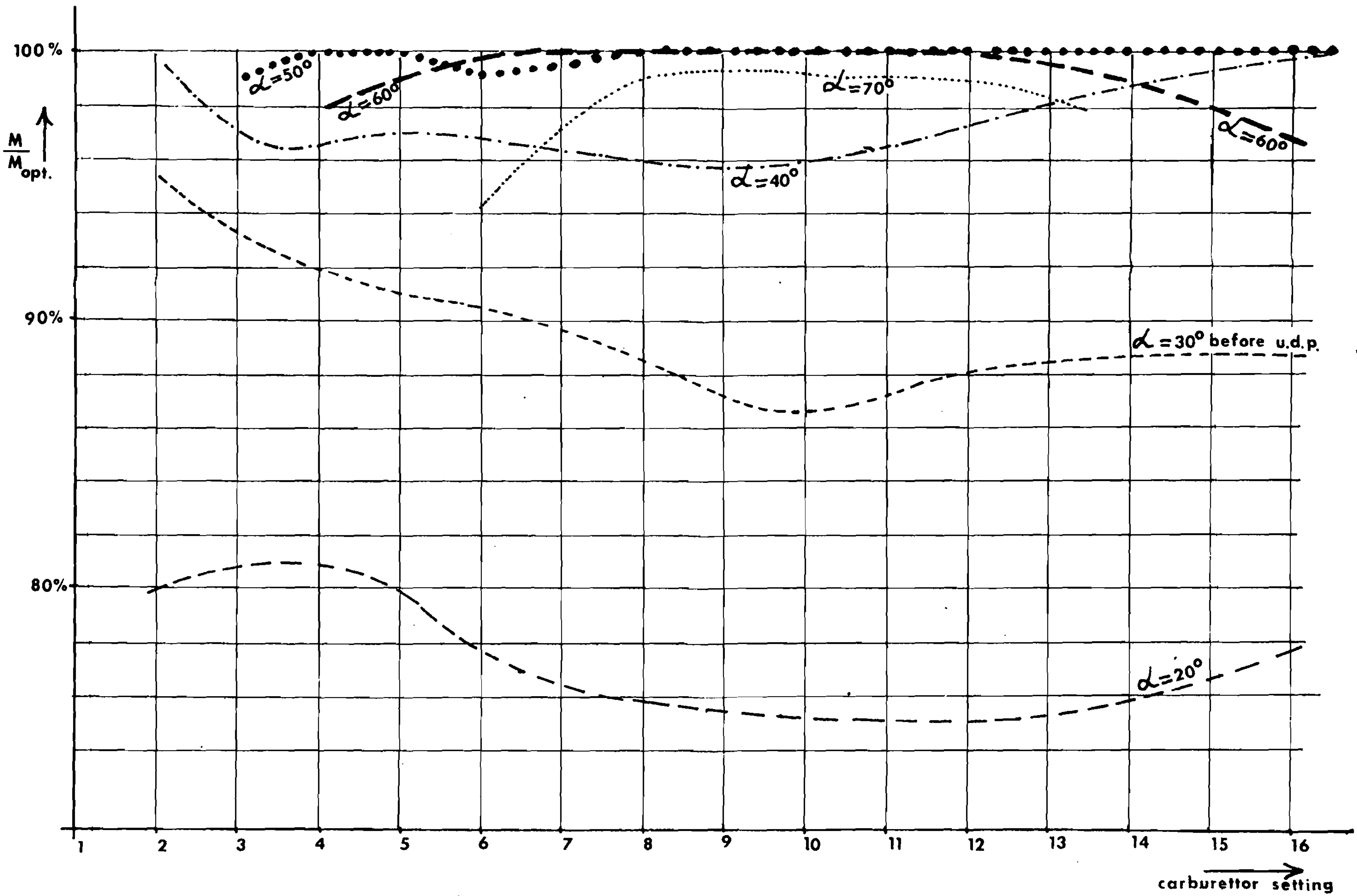


Fig.3.10: constant load performance of the engine.

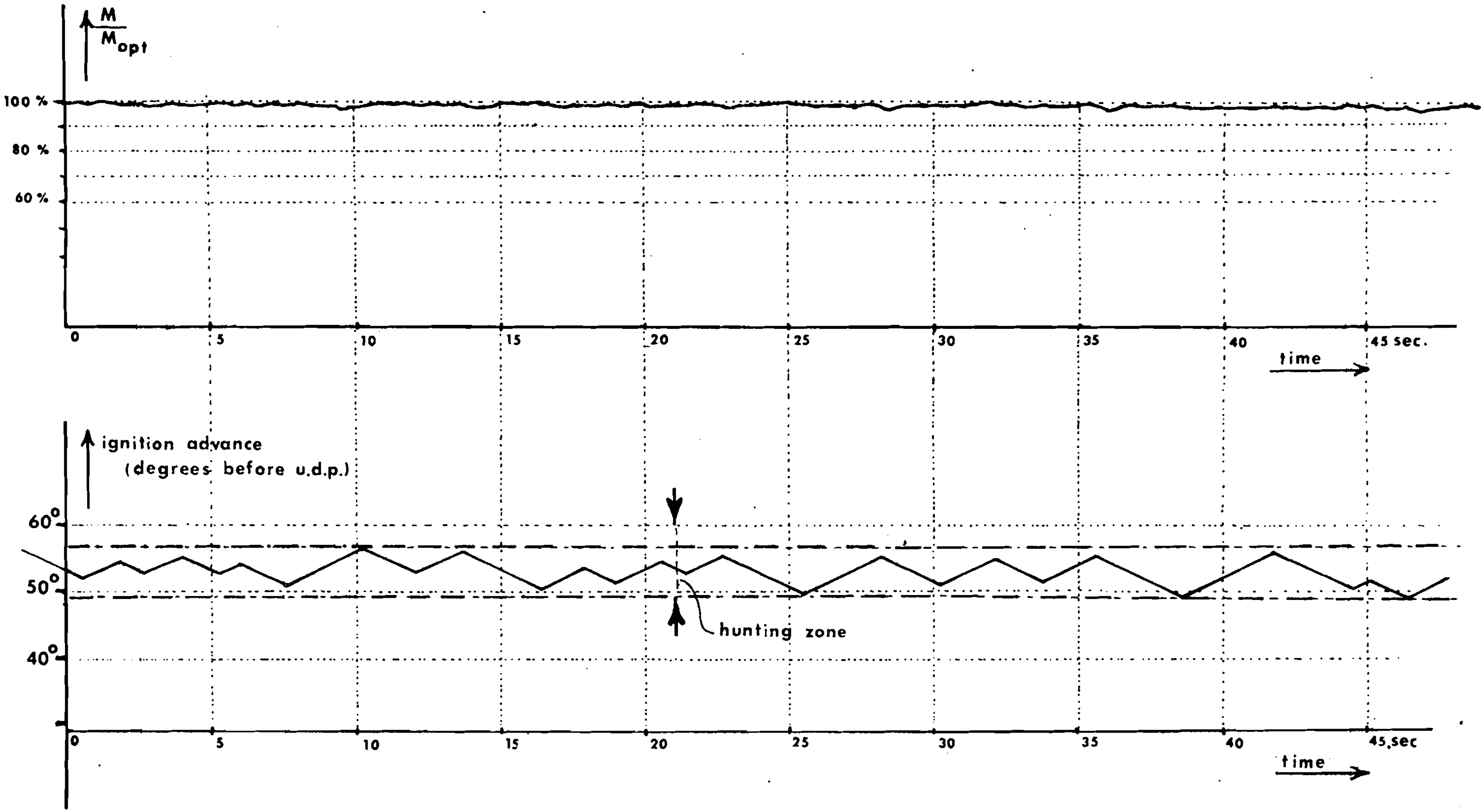


Fig 3_11: performance of the engine and the ignition advance when the optimalizing controller is used.

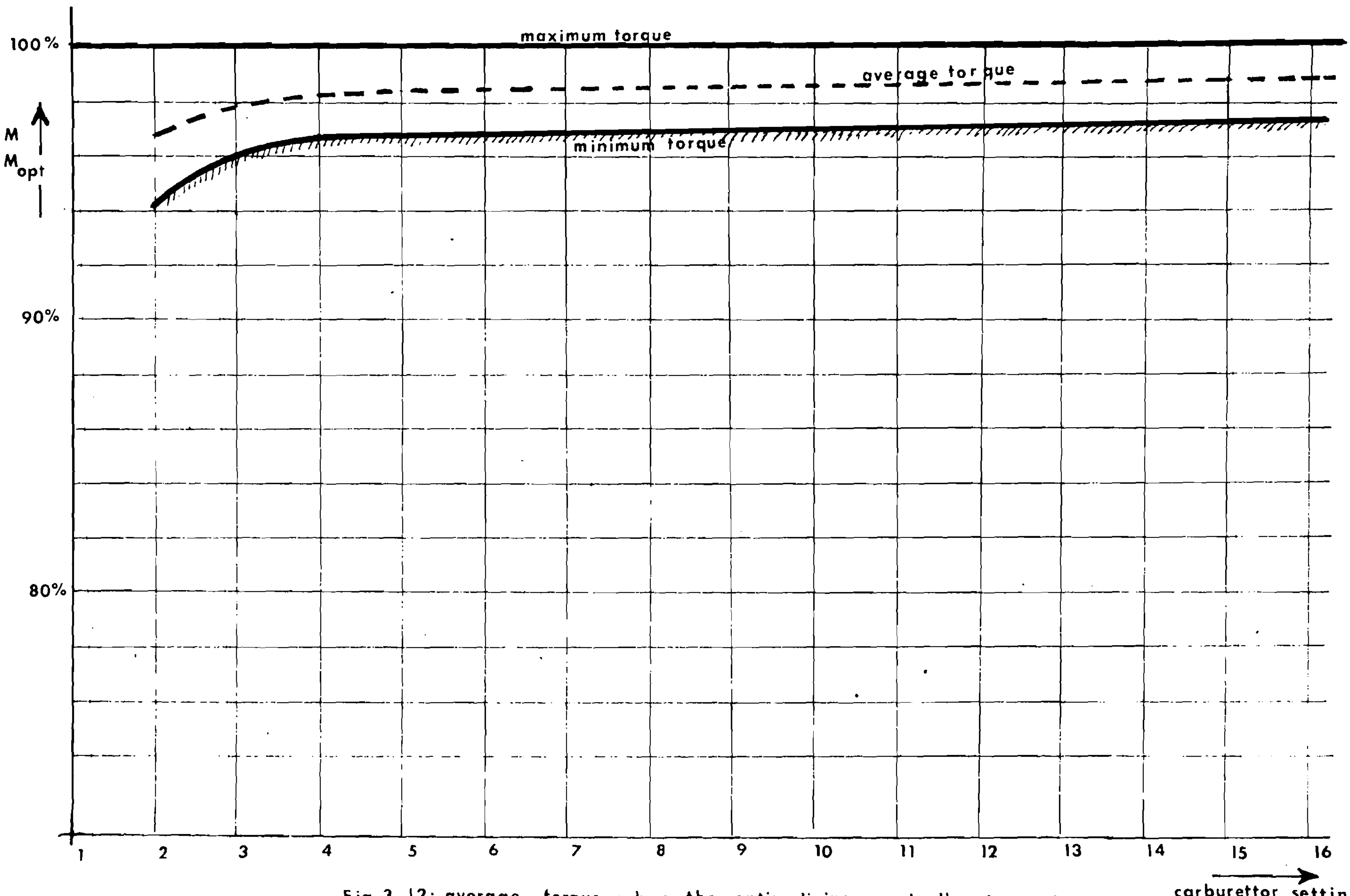
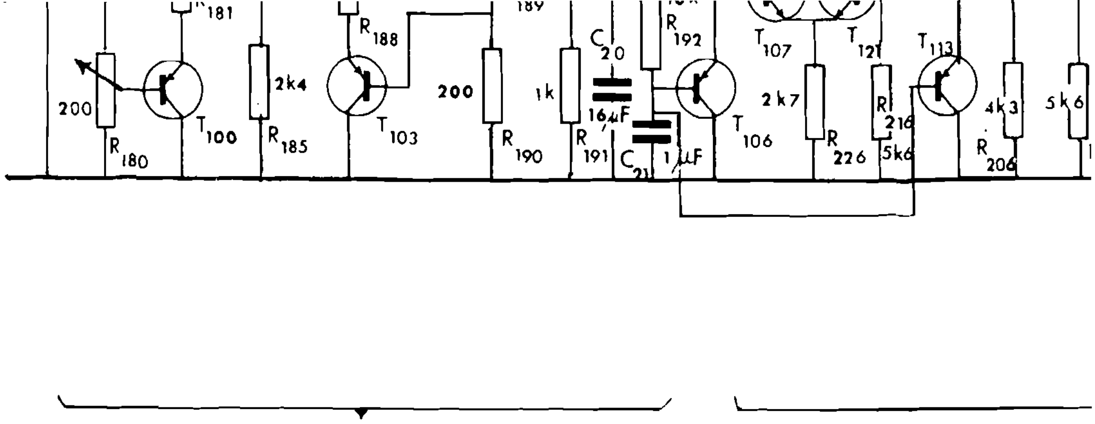
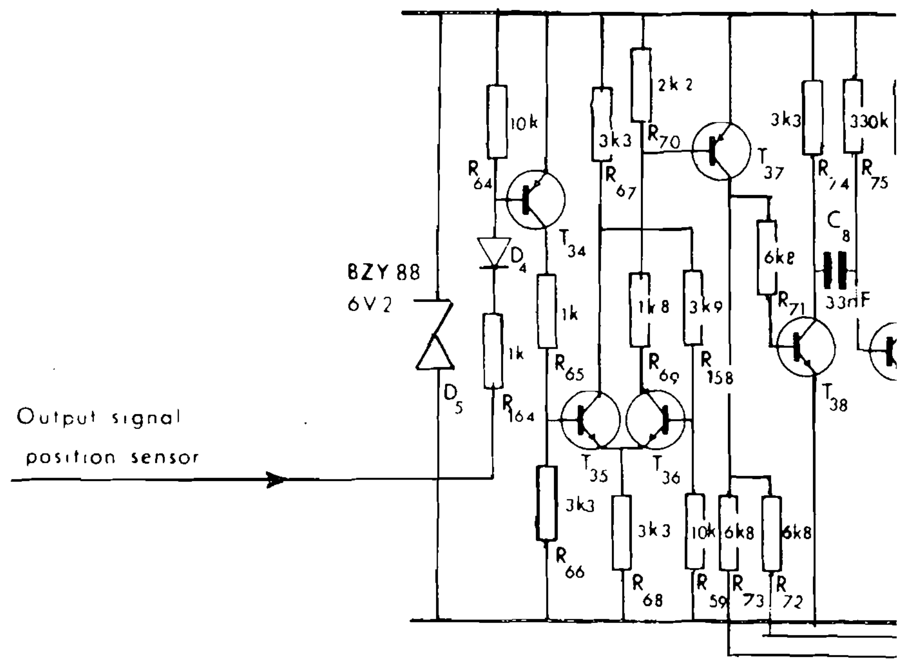


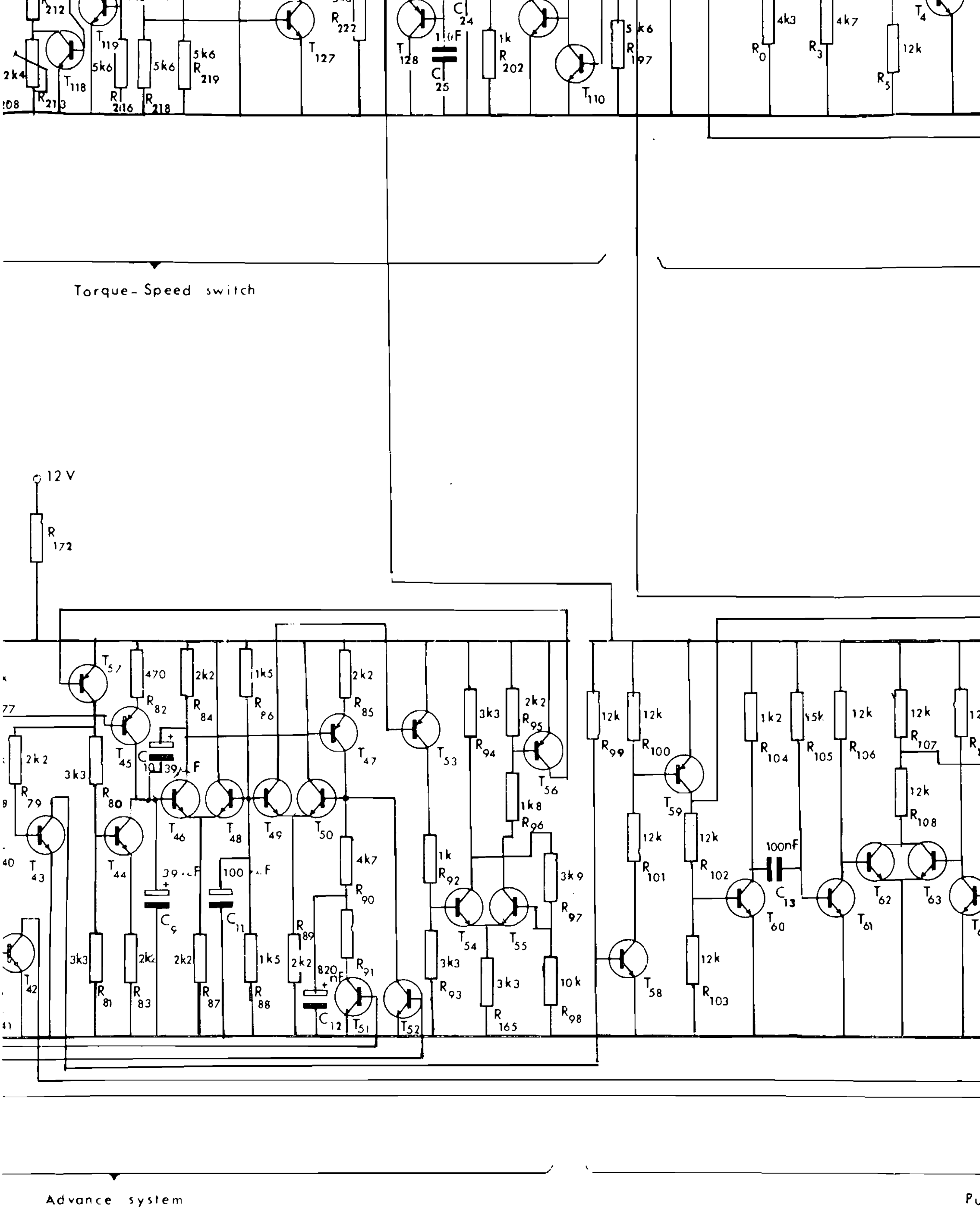
Fig.3.12: average torque when the optimalizing controller is used.



Amplifier + filter

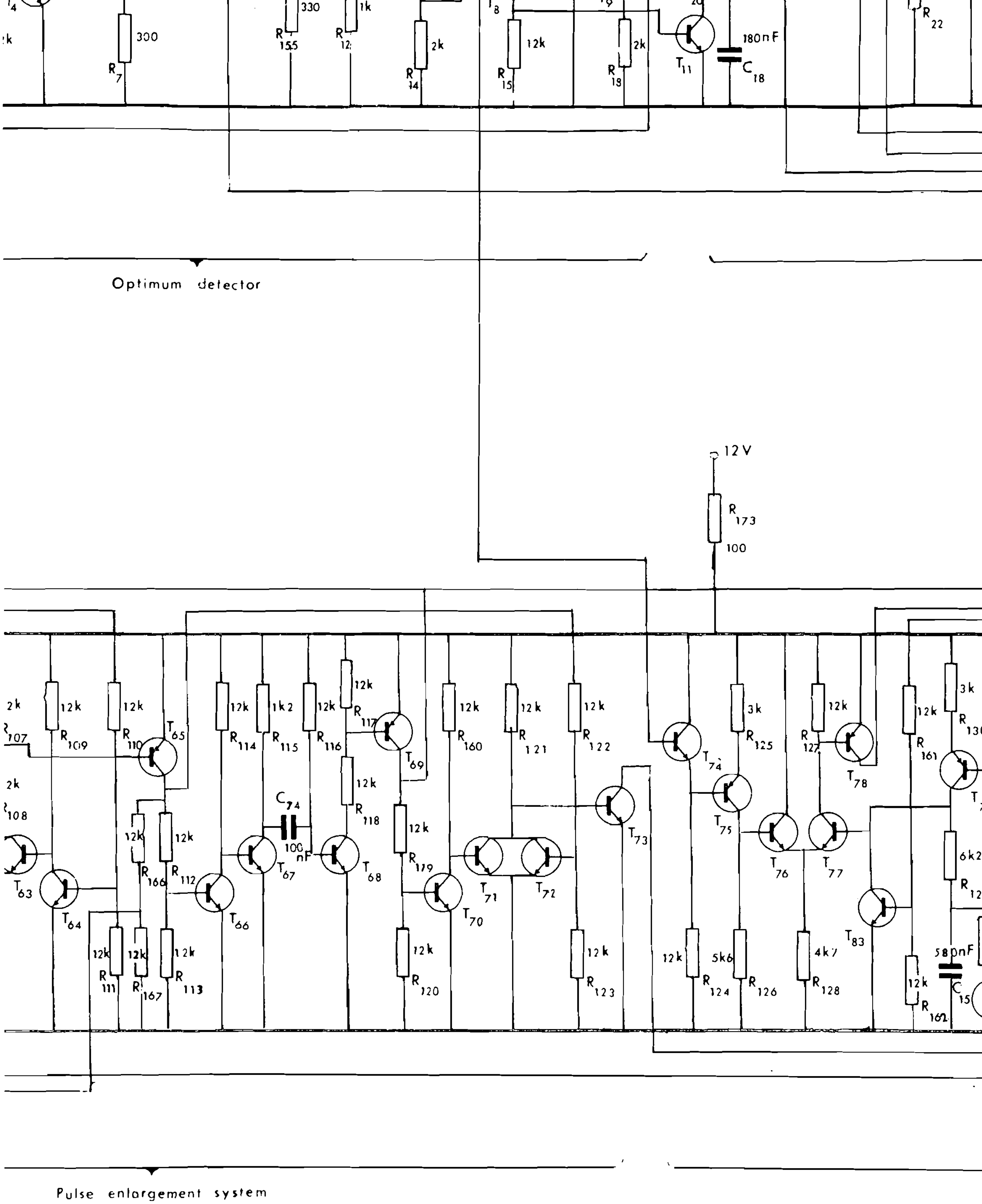


1

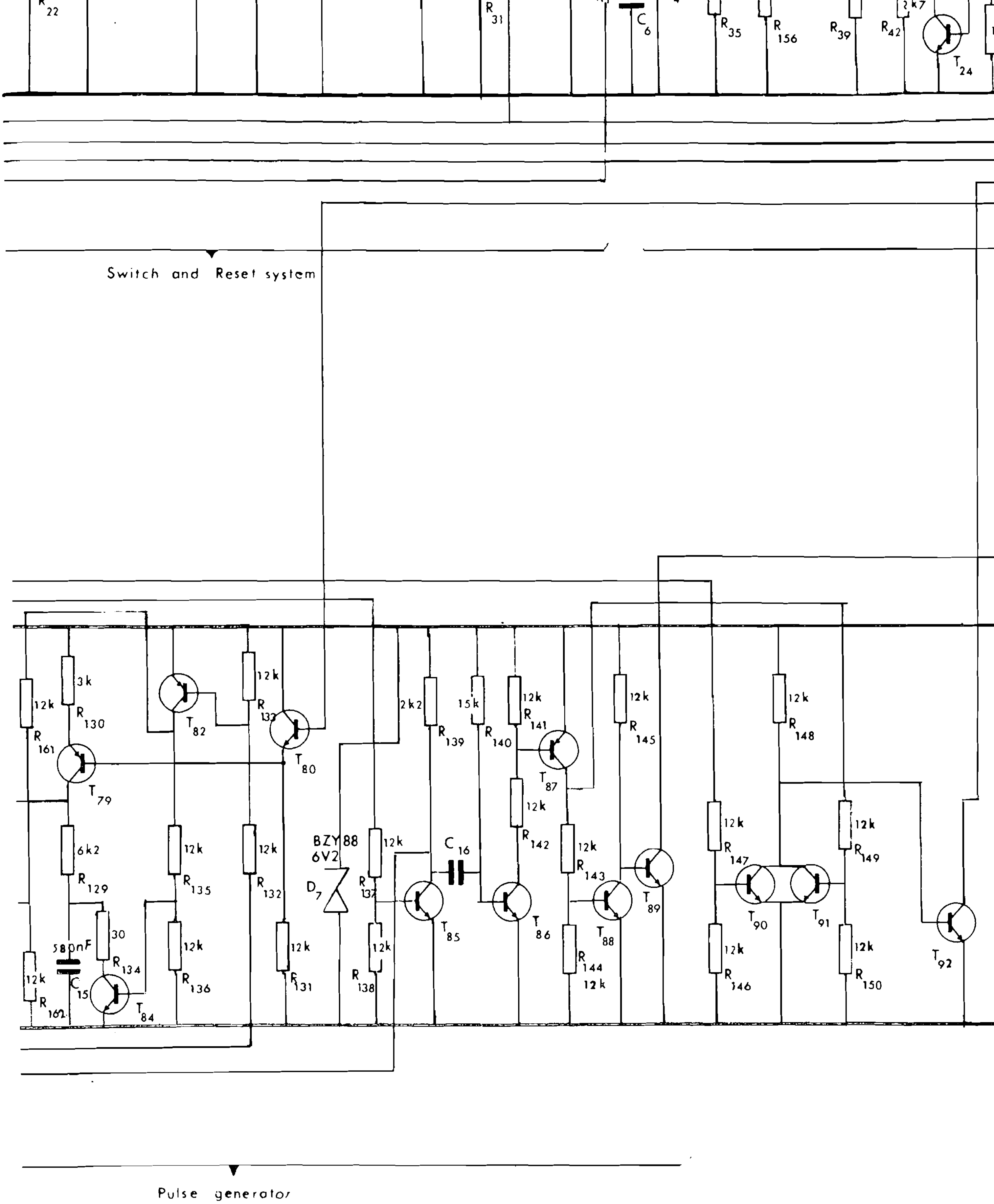


Torque-Speed switch
12 V
R 172
Advance system
T 57
470
R 82
2k2
R 84
1k5
R 86
R 85
T 45
T 46
T 48
T 49
T 50
T 47
T 53
3k3
R 94
2k2
R 95
T 56
1k8
R 96
3k9
R 97
10 k
R 98
T 54
T 55
3k3
R 165
1k
R 92
R 93
4k7
R 90
R 89
R 91
820 nF
C 12
T 51
T 52
C 9
C 11
100
R 87
R 88
R 81
R 83
3k3
R 80
T 44
2k2
R 79
T 43
T 42
12k
R 99
R 100
T 59
R 101
12k
R 102
R 103
T 58
1k2
R 104
R 105
12k
R 106
100nF
C 13
T 60
T 61
R 107
R 108
T 62
T 63
R 212
T 119
T 118
2k4
R 213
5k6
R 216
R 218
R 219
T 127
R 222
C 24
T 128
C 25
1k
R 202
T 110
5 k6
R 197
4k3
R 0
4k7
R 3
12k
R 5
T 4

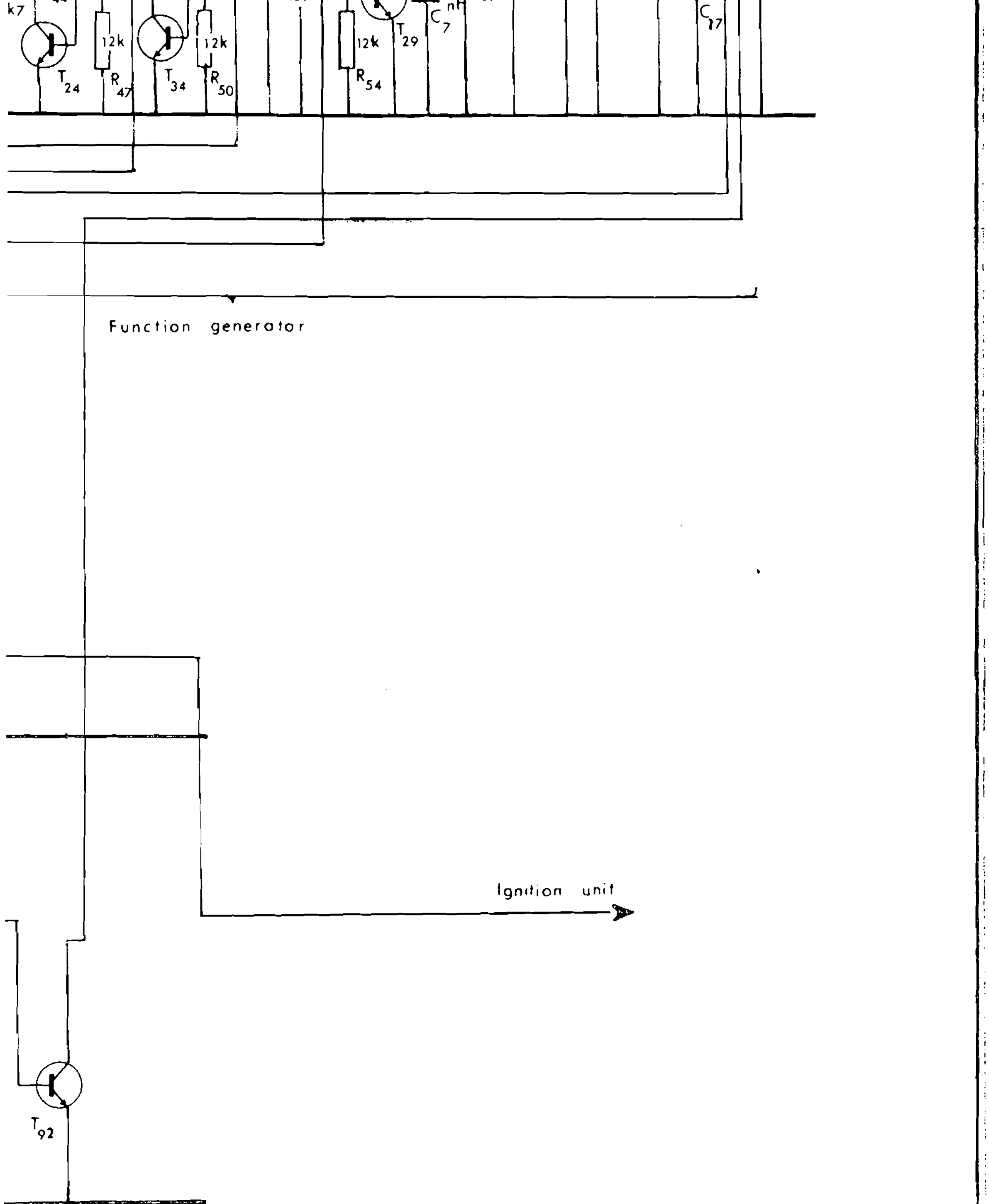
2



3

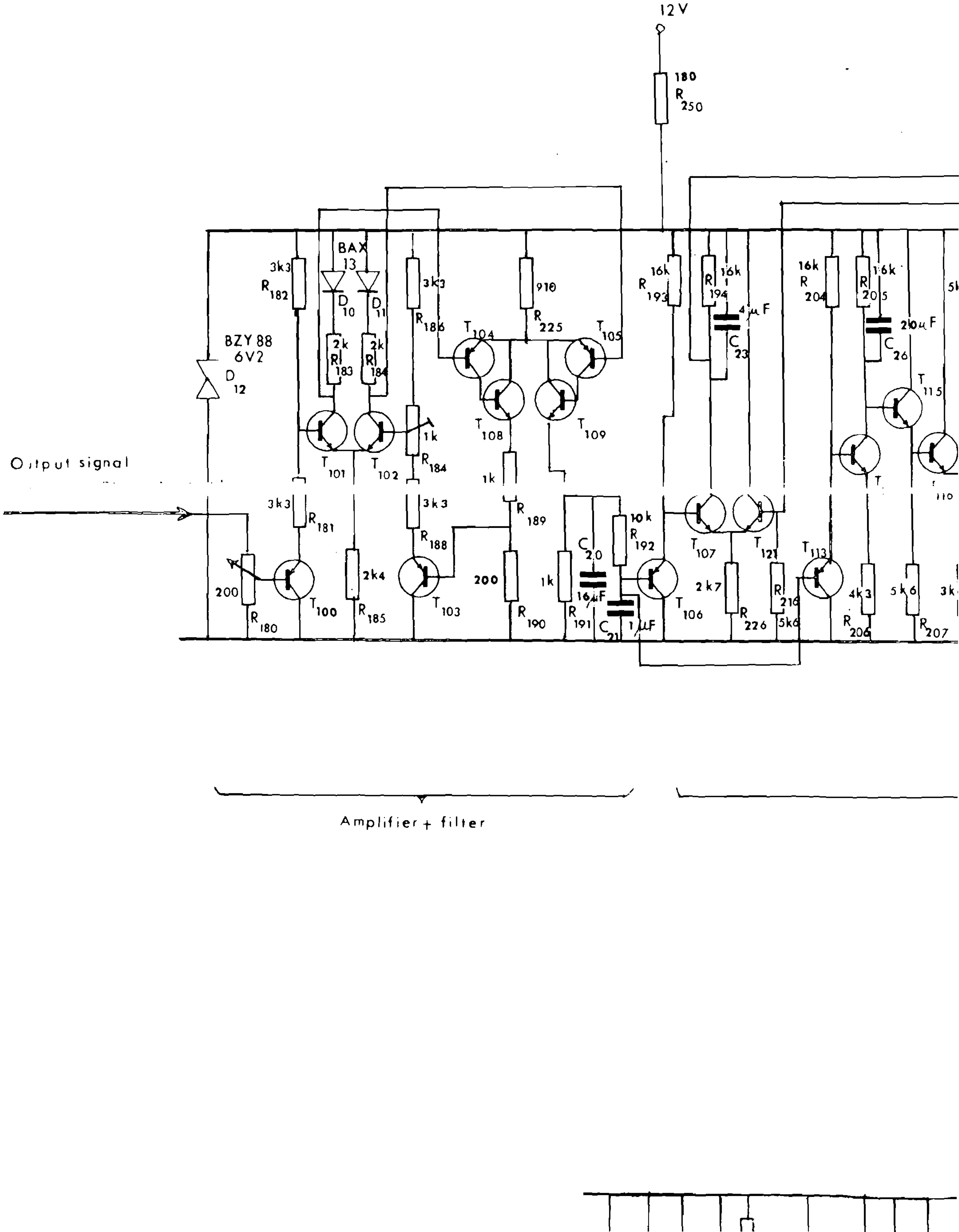

R22
R31
C6
R35
R156
R39
R42
2k7
T24
Switch and Reset system
12k
3k
R130
R161
T79
T82
R133
T80
6k2
R129
12k
R135
R132
30
580nF
R134
C15
T84
R136
R131
R162
BZY88
6V2
D7
R137
R138
2k2
R139
15k
R140
C16
T85
R141
T87
R142
T86
12k
R143
R144
T88
R145
T89
R147
T90
T91
R148
R149
R146
R150
T92
Pulse generator

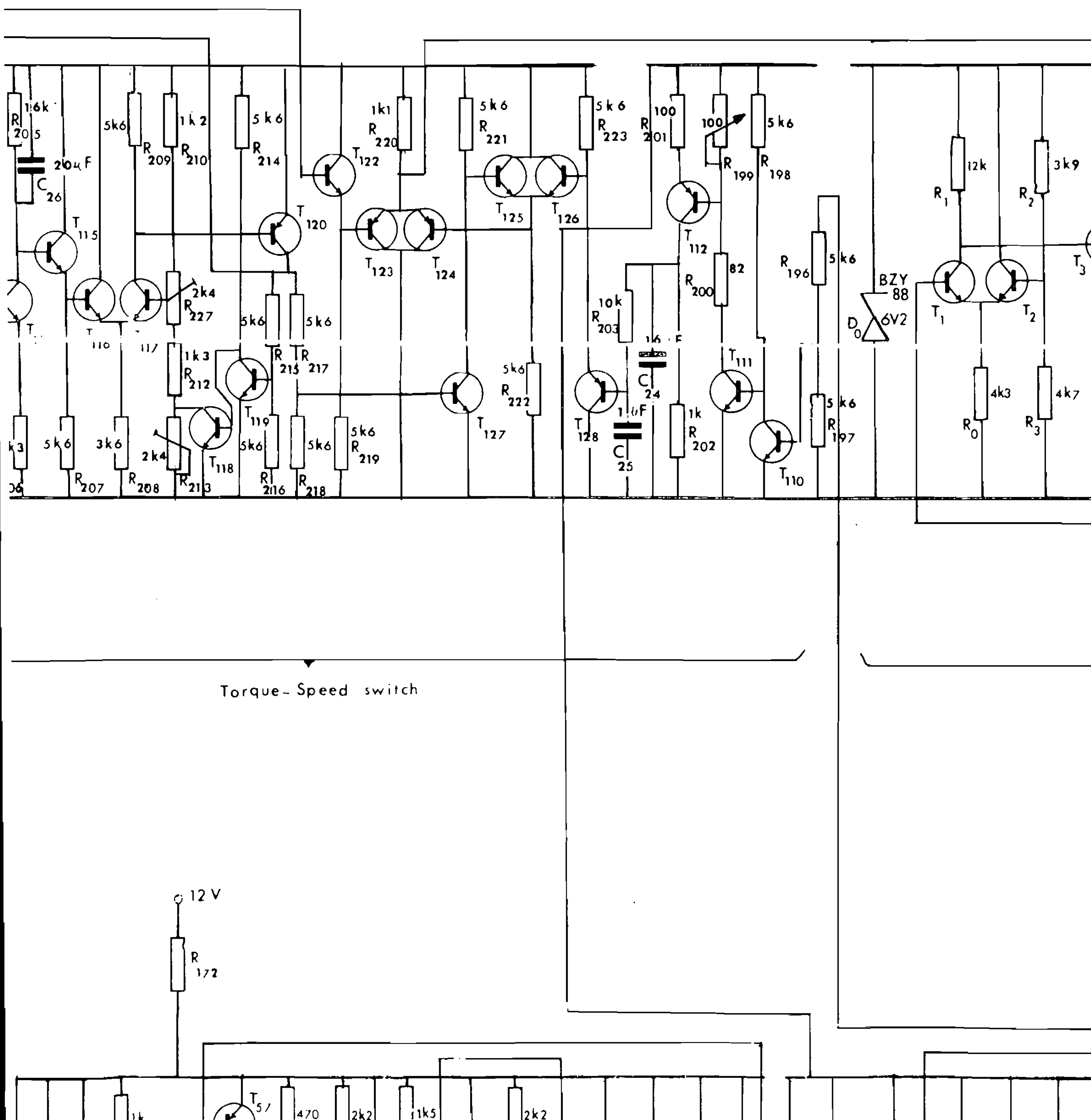
9



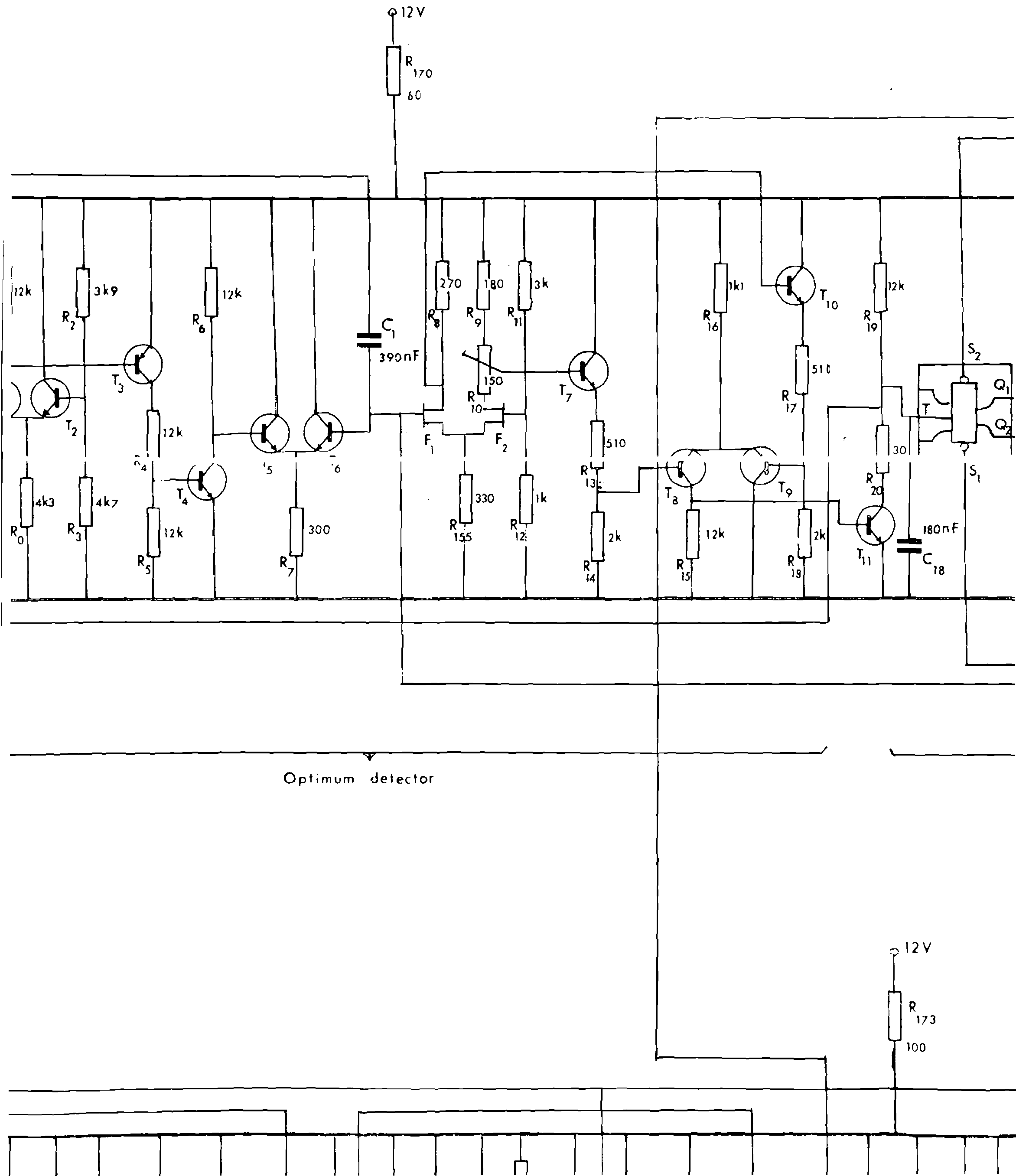
S

Fig 3.13 Complete circuit

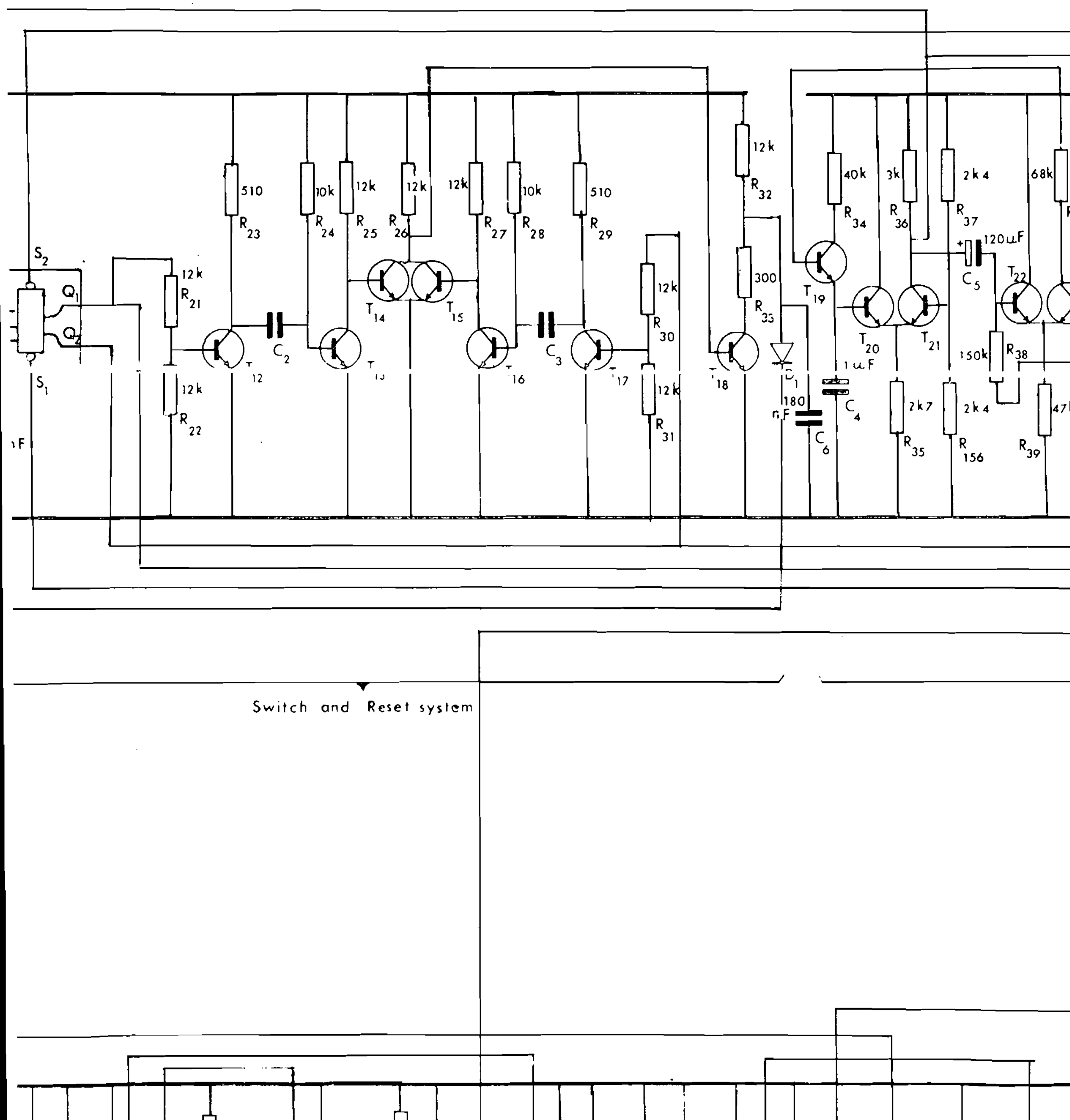

12 V
180
R250
Output signal
BZY 88
6V2
D12
BAX
13
D10
D11
3k3
R182
2k
R183
2k
R184
T101
T102
1k
R184
3k3
R181
200
R180
T100
2k4
R185
3k3
R186
3k3
R188
T103
910
R225
T104
T105
T108
T109
1k
R189
200
R190
1k
R191
C20
16μF
C21
1μF
10k
R192
T106
16k
R193
16k
R194
4μF
C23
T107
T121
2k7
R226
R216
5k6
T113
16k
R204
16k
R205
20μF
C26
T115
4k3
R206
5k6
R207
Amplifier + filter



R 205
16k
20μF
C 26
T 115
5k6
R 209
1k2
R 210
5k6
R 214
T 120
T 122
1k1
R 220
5k6
R 221
T 123
T 124
T 125
T 126
5k6
R 223
R 201
100
100
R 199
5k6
R 198
T 112
82
R 200
R 196
5k6
BZY 88
D 0
6V2
12k
R 1
3k9
R 2
T 1
T 2
T 3
4k3
R 0
4k7
R 3
2k4
R 227
1k3
R 212
5k6
R 215
R 217
5k6
T 119
T 118
2k4
R 213
5k6
R 216
5k6
R 218
5k6
R 219
T 127
5k6
R 222
T 128
10k
R 203
C 24
C 25
1k
R 202
T 111
T 110
5k6
R 197
5k6
R 207
3k6
R 208
Torque-Speed switch
12 V
R 172
T 57
470
2k2
1k5
2k2

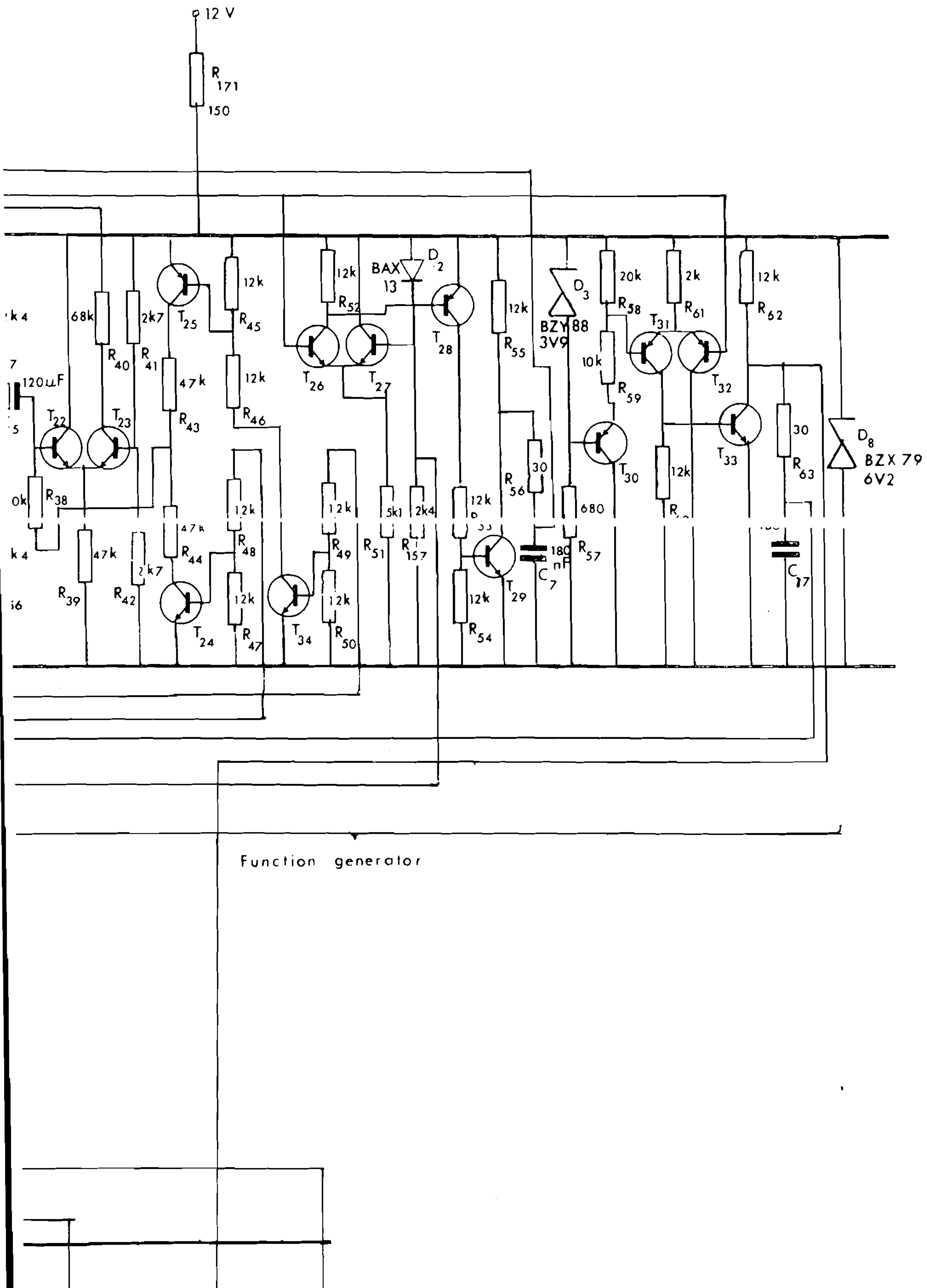

12 V
R 170
60
12k
3k9
R2
12k
R6
C1
390nF
270
R8
180
R9
3k
R11
150
R 10
T3
T2
T7
T10
1k1
R 16
12k
R 19
510
R 17
S2
Q1
Q2
T
S1
12k
T4
F1
F2
510
R 13
30
R 20
4k3
R0
4k7
R3
12k
R5
300
R7
330
R 155
1k
R 12
2k
R 14
T8
T9
12k
R 15
2k
R 18
T11
180nF
C18
Optimum detector
12 V
R 173
100

7



Switch and Reset system

6



Function generator