MPS/Int-ED 67-5
NSB/amm - 29.6.1967

THE MEAN SPEED REGULATION SYSTEM

FOR THE NEW

C.P.S. MOTOR/ALTERNATOR SET

by

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1. INTRODUCTION

Under normal operating conditions of the CERN Proton Synchrotron (i.e. CPS), the main magnet field and hence current delivered by its associated Power Supply has the form shown in Fig. 1a. The Power Supply is a controlled rectifier installation, which is supplied from a motor driven alternator set (i.e. M/A set). The corresponding rotational speed variation of the M/A set during a CPS cycle, for a constant motor input power, is shown in Fig. 1b. It will be seen from Fig. 1, that as the CPS magnet current rises the speed of the M/A set falls, caused by the transfer of kinetic energy of the set into magnetic energy in the CPS magnet. The speed of the set continues to fall until completion of the magnet current rise. During the flat-top period of the CPS magnet field (i.e. constant current), the set speed remains essentially constant. However, a slight fall in speed does occur during the flat-top as a result of power dissipation losses in the CPS magnet coils. At the end of the flat-top period the CPS magnet is de-excited, current falls and the M/A set accelerates as the magnetic energy is recovered in the reverse energy transfer process.

In the absence of power losses in the magnet, the set speed would rise to the value which pertained just before the excitation of the magnet. The power input to the M/A set would then only be that to cover the mean rotational losses of the set. However, the magnet power losses are not negligible, and a power input to the set in excess of the rotational losses is required to accelerate the set during the idle period (i.e. between pulses) to the same speed as at the start of the previous pulse, in order to have a reproducible speed variation with time. This excess input power depends critically on the CPS magnet current waveform and repetition period. A too high excess power input results in a gradual rise in the set mean speed and vice-versa. The total speed variation during a whole CPS repetition period depends upon the magnet current waveform, being at a maximum for a peak rated current pulse in the magnet. In any case, the total deviation is not permitted to exceed about ± 3 o/o of the M/A set synchronous speed.

An electro-optical system is coupled to the alternator shaft of the M/A set, and produces a train of "CERN standard" machine pulses (i.e. M pulses, + 40V - 1 μsec). Using this M pulse train, electronic counting equipment derives a series of designated pulses (eg:M0, M30, MT, etc), according to their position relative to the CPS cycle, as shown in Fig. 2. The designated pulses are used to programme the controlled rectifier installation (i.e. CPS Power Supply) and hence the magnet current waveform.

When the set is running at synchronous speed, the frequency of the M pulse train is 300 cps. However, since the M pulses are produced proportional to the set rotational speed, then the speed variation per cycle produces a corresponding frequency variation in the M pulse train. It will be seen later that this fact is used to measure, and eventually to control the M/Aset mean speed.

In order to have an accurately reproducible PS magnet field cycle, it is required that the M/A set runs at constant speed. However, such a condition implies a prohibitively large M/A set flywheel.

The most economic method of having an accurately reproducible field cycle is to allow a reasonable speed variation during a CPS cycle and control the M/A set mean speed to within the desired precision. The purpose of the "mean speed regulation system" described in this report is to maintain the average speed of the M/A set per cycle at a predetermined value within specified limits.

For most PS programmes, it is required that the mean speed is regulated to be that corresponding to the M/A set synchronous speed. However, it will be seen later that the system described affords adjustment to have a mean speed slightly higher or lower than synchronous as required. It is foreseen that such a facility may eventually be used in conjunction with a closed-loop system to lock the mean speed in synchronism with the CERN electrical network mains frequency. However, with the present network mains frequency stability (slipping at a rate of up to 10^{-4}/sec), this could only be achieved at the expense of CPS magnet field reproductibility, since it is of the same order as the required precision.

2. POWER/SPEED REGULATION SYSTEM

Before analysing in detail the mean speed regulation system, it is first necessary to know the dynamic relationship or transfer function between the power input and speed of the motor/alternator set. The power/speed regulation system is supplied by the M/A set manufacturers (i.e. Siemens). In so far as its influence on the mean speed regulation system is concerned, it has two main functions:

a) restrict the M/A set speed to within the limits ±3% of synchronous speed.

b) provide a feedback measurement of the motor active power (i.e. torque) which is limited to 6 MW.

2.1 Control schematic

The control schematic of the Siemens power/speed regulation system is known to take the form of that shown in Fig.3. The purpose of the mean speed regulation system is to regulate the power input signal P in order to have a predetermined mean speed output N. Thus, Fig.3 is a schematic of the system to be controlled and the overall transfer function is required.

It is known that the transfer functions of G_3 and G_4 are of the form

$$G_3 = \frac{A_3}{(1 + sT_r)} \quad , \qquad G_4 = \frac{1}{sT_m}$$

where A_3 = rotor power gain,

T_r = rotor electrical time constant,

T_m = set mechanical time constant,

s = Laplace operator.

With this condition, the open-loop frequency response of loop A must be of the form shown in Fig. 3a, which implies that

$$G_2.G_3.G_4 = \frac{A_a}{sT_r(1+sT_r)} \qquad \ldots\ldots\ldots\ldots\ldots(2.1)$$

Substituting for G_3 and G_4 in equation (2.1), there obtains

$$G_2 = \frac{A_a \cdot T_m}{A_3 \cdot T_r}$$

The closed-loop transfer function of loop A is given by the expression

$$G_A = \frac{G_2 \cdot G_3 \cdot G_4}{1 + G_2 \cdot G_3 \cdot G_4}$$

which after substitution gives

$$G_A = \frac{1}{sT_{r/A_a}(1+sT_r) + 1}$$

With this result, the schematic of Fig.3 may be reduced to that shown in Fig.4.

The open-loop transfer function of the schematic of Fig.4 is given by the expression

$$\frac{G_1 \cdot G_A}{G_4}$$

Now, by substitution

$$\frac{G_A}{G_4} = \frac{sT_m}{\frac{sT_r}{A_a}(1+sT_r) + 1}$$

The highest frequency lag of this expression is for

$$\omega = \frac{1}{T_{r/A_a}}$$

Therefore, to have a good frequency response let it be defined that the open-loop response is of the form

$\frac{1}{sT_{r/A_a}}$, as shown in Fig.4a.

With this condition, then

$$G_1 = \frac{\dfrac{1}{sT_{r/A_a}}}{G_A/G_4}$$

$$= \frac{(1+sT_r) +,1}{sT_m}$$

Now

$$\frac{N}{P} = \frac{G_1 . G_A}{1 + \dfrac{G_1 . G_A}{G_4}} \quad , \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

Substituting for G_1, G_4 and G_A in equation (2.2), there results that

$$\frac{N}{P} = \frac{1}{sT_m \, (1 + sT_{r/A_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

The frequency response of $\frac{N}{P}$ according to equation (2.3) is shown in Fig.5. T_m is of the order of seconds and T_r of the order of msecs, so that the lag from $\frac{1}{(1 + sT_{r/A_a}}$ is very much higher than the 0db crossing point (i.e. $\omega = \frac{1}{T_m}$)

2.2 Estimate of the M/A set mechanical time constant Tm

It is readily shown that, for a rotating system,

Torque T = Inertia I x rate of change of rotational speed.

For the M/A set, this may be written as

$$T = \frac{GD^2}{4g} \cdot \frac{d\omega}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4)$$

where T = shaft torque,

$\frac{GD^2}{4g}$ = inertia,

$\frac{d\omega}{dt}$ = rate of change of shaft angular speed,

ωs = M/A set angular speed (rads/sec)

Dividing out equation (2.4) by the M/A set maximum torque T_o and normalizing the differential, there results

$$\frac{T}{T_o} = \frac{GD^2}{4g} \cdot \frac{\omega s}{T_o} \cdot \frac{d\,(\omega/\omega s)}{dt}$$

which may be rearranged in the form

$$\frac{T/T_o}{\omega/\omega_s} = s\left(\frac{GD^2}{4g} \cdot \frac{\omega s}{T_o}\right) = sT_m ,$$

where s = Laplace differential operator.

Therefore, the M/A set mechanical time constant is given by the expression

$$T_m = \frac{GD^2}{4g} \cdot \frac{\omega s}{T_o} \quad \dots\dots\dots\dots \qquad (2.5)$$

For the motor/alternator set,

GD^2 = 170 ton-m^2
ωs = 105 rads/sec (ie: synch.speed = 1000 rpm)
T_o = 5000 Kg.m
and g = 9.81 m/sec^2

Substituting these values into equation (2.5), we obtain that

$$T_m = 89 \text{ seconds.}$$

2.3. Rate of change of M/A set speed when maximum torque is applied.

It is required to know the rate of change of set speed when maximum torque is applied, corresponding to maximum power input to the motor (ie:6MW),

Equation (2.4) may be rearranged to give for maximum torque

$$\frac{d\omega}{dt} = \frac{T_O}{GD^2/4g}$$

Substituting for T_O, GD^2 and g as given in the previous sub-section, we obtain

$$\left(\frac{d\omega}{dt}\right)_{max} = 11.2 \text{ rpm/second} \quad \dots\dots \qquad (2.6)$$

This corresponds to 1 o/o/second for a synchronous speed of 1000 rpm.

3. MEASUREMENT OF MEAN SPEED DEVIATION

In the previous Section, it has been shown that the transfer function between M/A set power input and speed is essentially a simple integration, having a time constant equal to that of the M/A set. Before a mean speed control system can be established, it is first necessary to have a method by which the mean speed/PS cycle can be accurately measured. The foregoing describes the method employed.

3.1. "Speed error" - "Time" relationship.

Let it be supposed that the CPS has been programmed to have a desired repetition period Trep, which would normally be set as a multiple of 100 msecs between say 1 and 5 seconds. The machine repetition period, together with all the designated pulses in the PS cycle (ie : M0,M30 etc), is derived from counting the M pulse train. If the machine repetition period is to correspond to the preselected value, it requires that the mean M pulse frequency is 300 cps. This in turn requires that the mean M/A set speed is synchronous.

The time period between any given designated M pulse (eg: M0), is a measure of the actual CPS repetition period $Trep_m$.

Let the real time difference between the desired Trep and actual machine repetition period $Trep_m$ be δt as indicated in Fig. 6. It is shown in Fig. 6 that for small deviations δN of the mean set speed/cycle, about synchronous speed N_s, the following equation is valid ;

$$\frac{\delta t}{Trep} = \frac{\delta N}{N_s} \qquad \ldots\ldots\ldots\ldots \qquad (3.1)$$

Equation (3.1) implies that the time error δt_r between the desired and actual repetition periods is directly proportional to the corresponding mean speed deviation δN. To have an acceptable reproducibility of the CPS magnet field cycle, the mean speed is required to be accurate within the limits of $\pm 10^{-4}$. For a repetition period of 1 second, this corresponds to a time deviation of ± 100 μsecs. If the time error δt_r is measured to an accuracy of 10 μsecs, then it is an order less than the desired mean speed precision. To achieve this result, let the MO pulse start a counter driven from a 100 Kc/sec crystal controlled oscillator. An output pulse TR is produced after the desired repetition period Trep. The time error between the TR and the next MO pulse, will be a measure of the mean speed deviation from synchronous. Since the mean speed can swing above and below synchronous, then it will be seen from the waveform/time diagrams of Fig. 7, that two such counters are required in order to have a measurement/cycle of the mean speed deviation.

Fig. 7 indicates the method used and is also a schematic diagram of the U. 1545 "GENERATEUR DE L'IMPULSION DE REFERENCE". The MR pulse is used to "gate" the MO start pulse, so that the 100 Kc/sec counters are operated alternatively. The relevant waveform/time diagrams for the machine mean speed being under and over-synchronous are also shown in Fig. 7. The schematic of the 100 Kc/sec counter units is shown in Fig. 8.

4. MEAN SPEED CONTROL ANALYSIS .

In the previous Section, the method has been described by which the M/A set mean speed deviation/cycle is measured. The time period between the reference pulse TR and a machine pulse MO represents the mean speed deviation, and the order (re: MO before TR or vice-versa), is an indication of whether the machine is running too fast or too slow. It is apparent that the two pulses may be used to produce an analogue signal (eg: by a time to. voltage converter integration process), the level of which is proportional to the time period between the pulses and the "sign" according to their order. The analogue signal can then be used to provide a correcting action of the M/A mean speed. The open-loop schematic of such a method of control is shown in Fig. 9.

4.1. Open-Loop Schematic.

Consider the schematic of Fig. 9. G_1 represents the normalized transfer function between the M/A set power input and speed. G_2 is the transfer function of the sampling process of measuring the mean speed deviation per CPS repetition period. G_3 is the transfer function of an integration and "hold" circuit, which stores the deviation measurement and uses it to provide corrective action during the following repetition period. G_4 is the transfer function of a control regulator which may or may not be frequency dependant, depending upon the stability when the closed-loop is formed by negative feed-back connection of "B" to "A". It is desired to know what form the open-loop frequency response of the mean speed regulation system may take.

The transfer function of the sampler may be shown to be

$$G_2(s) = \frac{1}{Trep} \varepsilon_{k=-\infty}^{k=+\infty} (s + jk\omega_r), \text{ ....} \qquad (4.1)$$

where $\omega_r = 1/Trep$;

and that of the zero-order hold circuit

$$G_3(s) = \frac{(1-e^{-sTrep})}{s} \qquad \text{................} \qquad (4.2)$$

The frequency response of $|G_2\ (j\omega)|$ is shown in Fig. 10, for positive frequencies and $k = 0$.

In order to recover the input signal, the sampling frequency should be larger than or equal to twice the highest frequency component of the input signal.

$$\text{ie:}\quad \omega_r \geqslant 2\,\omega$$

$$\frac{1}{Trep} \geqslant 2\,\omega$$

$k = 0$ is the case of interest, higher frequency sidebands being ignored.

Consider the modulus of the hold circuit, which may be shown to be given by the expression

$$|G_3\ (j\omega)| = Trep \frac{\sin(\omega Trep/2)}{\omega Trep/2} \qquad \text{..............} \qquad (4.3)$$

The frequency response defined by equation (4.3) is indicated in Fig. 11.

Considering both $|G_2(j\omega)|$ and $|G_3\ (j\omega)|$ together for the case of $k = 0$ (ie: only case of interest from the sampler). It will be observed that $|G_2(j\omega)|$ is the function that determines the frequency response of $|G_2(j\omega) \cdot G_3(j\omega)|$. This means that in order to have a stable closed-loop, the overall frequency response of the open-loop schematic of Fig. 9 must have a gain $\leqslant 0$db for frequencies $\geqslant \omega_r/2$ (ie: 1/2 Trep).

Fig. 12 shows the frequency response of $|G_1(j\omega) \cdot G_2(j\omega) \cdot G_3(j\omega)|$. The break point due to $1/(1 + s\,Tr/Aa)$ in G_1 is well above the frequency range of interest, and is therefore neglected. In order to satisfy the condition for closed-loop stability, G_4 may have a proportional gain k having a maximum value k_{max}, such that the response of Fig. 12 becomes that shown dotted. Since that part of the frequency response above 0db is falling off at 20 db/decade, it is readily shown that ;

$$k_{max} = \frac{Tm}{2Trep} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (4.4)$$

However, this is a maximum value. In practice it should be slightly less, to avoid the risk of conditional stability.

4.2. Mean Speed Regulation System Transient Control Loop.

The preceding section has shown that in order to maintain a good frequency response of the mean speed control system, the loop gain must be changed inversely proportional to the repetition period Trep.

The mean speed deviation is measured as a real time difference between TR and MO, irrespective of Trep. It is apparent from equation (3.1) that the output from the "hold" circuit must be made inversely proportional to the repetition period for a given real time error, to obtain the corresponding speed error. This result implies that the total loop again must be changed inversely proportional to the square of Trep.

A practical schematic of the mean speed transient control loop can now be established and is shown in Fig. 13, wherein the more important waveform/time diagrams are also indicated. Fig. 13 is also a main schematic of the mean speed electronic chassis "U. 1546 - CONVERTISSEUR TEMPS/TENSION ET REGULATEUR".

In the schematic of Fig. 13, an additional operational amplifier has been added in parallel after the main regulating amplifier. This amplifier provides a transitional lag giving increased gain to reduce low frequency speed variations. The effect of such a transitional lag on the open-loop frequency response is shown in Fig. 14.

The MW designated machine pulse, occurring some 30msecs before MO, has been used to initiate the resetting of the time/voltage converting integrator. For a synchronous mean speed at a 1 sec repetition period, resetting with MW has the effect of introducing a negligible gain defficiency error of only 3 o/o (ie : 30 msecs/Trep), being proportionally less for higher repetition periods.

It is important to note that the "fine" control signal of the control system schematic shown in Fig. 13, is zero when the M/A set mean speed is synchronous, giving a +ve or -ve signal to have more or less power depending upon whether the set is running under or over synchronous respectively. Thus, the system described provides transient correction of mean speed deviations. However, a mean power input setting is required (constant for a given CPS programme), in order to obtain that the set runs at approximately synchronous speed. This mean power reference input (Pr in Fig. 13) depends upon the CPS programme, mainly the repetition period and magnet current pulse flat-top current.

4.3. Some Additional Remarks about the Mean Speed Regulation System.

Starting conditions require that just prior to pulsing, the M/A set should be running at its upper speed limit (ie: 3 o/o above synchronous). As explained earlier, the limits of ± 3 o/o are controlled by the power-speed regulation system of the M/A manufacturers. This condition implies that the power reference signal is initially at a maximum.

Irrespective of the CPS programme (ie: heavy or light), the set is running at 3 o/o above synchronous when pulsing begins. The mean speed regulation system is required to progressively reduce and then to maintain the set mean speed at synchronous.

The above conditions necessitate a coarse control system (ie: providing the reference signal P_r), to set within a few o/o the average power demands of the M/A set.

4.4. Mean Speed Regulation System Coarse Control Loop.

It has been shown that a power reference signal is required to provide the steady-state power demands of the motor-alternator set. For a given CPS programme the power reference signal P_r is constant. However, it can have any value corresponding to between several o/o and 100 o/o of the motor maximum power input $P_{max.}$ (6MW), and is required to be set automatically.

It should be borne in mind that the set mean speed only begins to fall after the power reference signal has dropped below that required for the particular CPS programme. If the coarse control system is arranged to operate whilst the mean speed is outside of specified limits, then it means that when the speed is within the limits a certain reference power error will exist. The value of this error will depend upon the rate at which the reference signal is reduced and the repetition period of the machine. In order that the machine will run synchronous, this power error must be taken over by the transient control loop.

Under normal working conditions, the coarse control system only operates for a short period at the beginning of the CPS pulse programme. An initial period of several minutes has been considered acceptable before the mean speed is within the required precision.

To have a good resolution of the transient control loop, it is desirable that its limits of operation are small. If it is arranged that the "time to voltage converting" integrator integrates linearly for a time error deviation between MO and TR of up to ± 1 o/o of the repetition period, then for a 1 sec Trep this means a linear time to voltage converting integrator output for up to 10 msecs. The particular integrator used (employing a "Zeltex model 145" chopper stabilized d.c. amplifier), saturates at ± 12 V. Therefore, the integrator can be linear to say ± 10.V. A 10^{-4} error in mean speed would then have an output of 100 mV. Clearly, if the band of linear integration is reduced (ie: ± 10 V in < 10 msecs), then the output signal for a 10^{-4} speed error would be proportionately increased.

Although the final steady state offset of power error will be taken over by the "limited gain" integral part of the transient control loop, initially it must be compensated for by the proportional part of the loop. In Section 4.1., it has been shown that the maximum gain of the proportional loop is

$$k_{max} = T_m/2Trep$$

Thus, for a T_m of say 100 secs (ie: calculated value is 89 secs.), then the maximum power which may be applied for say a 1 o/o speed error is 50 o/o P_{max}. Correspondingly, a 5 sec repetition rate limits the applied power to 10 o/o P_{max}, for the same o/o speed error. For practical reasons, it is undesirable to have possible power input swings to the M/A set motor greater than about 10 o/o of P_{max}. (ie: $\leqslant$600 kW). This is achieved by arranging that the saturation level of the final stage summation amplifier of the transient control loop corresponds to 10 o/o P_{max}.

If the bands of integration are reduced to say 0.1 o/o to have a better resolution, then the maximum power which may be applied, before the risk of loop instability and hence "hunting" of the M/A set, at a 5 sec. repetition rate is only ± 1 o/o P_{max}. This would require that the coarse control system sets the mean P_r to within ± 1 o/o. For practical and particularly security reasons, it is desirable that the coarse control system is simple and not too complicated to achieve high accuracy.

Suppose the coarse system sets the mean power P_r to $\leqslant \pm$ 5 o/o of the necessary value. This means that up to 5 o/o must be provided by the transient control loop. At a 1 sec repetition period, 5 o/o power corresponds to a 0.01 o/o speed offset. (only from the proportional part of the loop). The transitional lag of the integral part of the transient control loop having a gain of 10 (ie: one decade, which is about the maximum to avoid having a zone of 180° phase shieft on the open-loop frequency response), would eventually reduce the required offset to 0.001 o/o. This is an order of magnitude less than the required mean speed precision. Similarly, at a 5 sec.repetition period the initial offset would be 0.05 o/o, eventually reducing to 0.005 o/o; which is a factor of two better than the required precision.

Thus, it is sufficient to have a coarse control system which sets the mean power reference P_r to a precision of the order of ± 5 o/o. The reference power error and subsequent compensating offset from the transient control loop, only effects the value of the steady state mean speed. The reproducibility of the CPS magnet current pulse is not influenced by the power error.

The complete control schematic of the mean speed regulation system is shown in Fig. 15, in which the adopted method of coarse control is indicated. Fig. 15 also includes a simple schematic of the mean speed chassis "U . 1547 - POTENTIOMETRE DE REFERENCE".

The waveform/time diagrams of Fig. 15, are those pertaining as the M/A set mean speed is reduced into the transient loop linear operating limits (ie: ± 1 o/o).

4.5. Rate of Change of Power Reference Signal.

It has been shown in Section 2, equation (2.6) that the rate of change of speed when maximum power P_{max} is applied is

$$\left(\frac{dN}{dt}\right)_{max} = 11.2 \text{ rpm/sec} \qquad 1 \text{ o/o } N_s/\text{sec.}$$

For any power applied or removed being x o/o of P_{max}, the corresponding rate of change of speed will be

$$\frac{dN}{dt} = \frac{x}{100} \text{ o/o } N_s/\text{sec.} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.5)$$

The mean speed of the M/A set only begins to fall when the motor input power is less than that for the particular CPS programme.

Let the motor driven power reference signal potentiometer take T_r seconds to reduce from maximum (corresponding to P_{max}), to zero. Therefore, from the time that the power becomes less than the programme requirement and by analogy with equation (4.5), we can write

$$\frac{dN}{dt} = \frac{t}{T_r} \text{ . o/o } N_s/\text{sec} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.6)$$

where t = time elapsed after input power has dropped below required power input.

Integrating equation (4.6), there results

$$N = \frac{t^2}{2T_r} \text{ . o/o } N_s, \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.7)$$

which can be rearranged to give

$$t = \sqrt{2N \text{ o/o. } T_r} \qquad (4.8)$$

Let T_r = 240 seconds, which is achieved by using a "CERN standard" 6 turns/min. motor drive on a 25 turn helipot.

The maximum required reduction of mean speed (ie: for a very light programme), to bring it into the linear operating limits of the transient loop (ie: ± 1 o/o) will be 2 o/o.

Substituting for N = 2 and T_r = 240 in (4.8), we obtain

$$t \approx 30 \text{ seconds.}$$

For a 1 sec. repetition period the reference power motor drive will stop after a maximum of 31 seconds, and for a 5 sec. repetition period after a maximum of 35 seconds. Thus, producing reference power errors of

$$-\frac{31}{240} = -12.4 \text{ o/o, and}$$

$$-\frac{35}{240} = -14.5 \text{ o/o respectively}$$

Whilst the mean speed is above + 1 o/o of synchronous, the transient loop will be saturated giving a -10 o/o power signal. In order that the mean speed will not undershoot the limits of ± 1 o/o, the transient loop must at least be able to compensate the mean power error deficiency. (ie: max. of -14.5 o/o). This condition is satisfied since the transient loop can give from a -10 o/o to +10 o/o power signal (ie: 20 o/o). However, it should be noted that once pulsing has begun, the mean speed will in fact be less than 3 o/o above synchronous, so that the power error when the coarse loop motor drive ceases will be less than 14.5 o/o. A more realistic value would be about 10 o/o, which corresponds to an initial mean speed of say 2 o/o above synchronous. For a 10 o/o coarse loop power setting error, the steady state signal from the transient loop would be very nearly zero.

5. DESCRIPTION OF THE MEAN SPEED REGULATION SYSTEM ELECTRONICS CHASSIS

In the previous Sections, the principle of operation of the mean speed regulation system has been described and the relevant general schematics of individual component chassis indicated. However, for completeness it is felt necessary to include brief comments on the actual chassis equipment to facilitate adjustments and "trouble shooting". The mean speed regulation equipment consists of four 19" rack mounting chassis, each of 4 "standard units" height. A complete comprehensive dossier of drawings exists for each chassis.

ie: U. 1552
U. 1545
U. 1546
U. 1547

5.1. U.1552 - Alimentation du Générateur de l'Impulsion de Référence.

This chassis contains the power supplies for the "U.1545 - Générateur de l'Impulsion de Référence" and all neon pulse indicator lamps. Lack of space in U. 1545 necessitated that its supplies be located in a separate chassis. The electrical wiring diagram of U. 1552 is shown on Drg. 125-1552-3. It will be seen that there are four supply voltages (plus the zero volt line), namely;

+ 170V	(50 mA capacity)
+ 30V(a)	(1A capacity)
+ 30V(b)	(1A capacity)
- 20V	(1A capacity)

As with all the mean speed regulation equipment, the "banana plug" checking points on the front panel are protected through suitable resistors, in this case 4.7 KΩ .

The relay **print** "228P-Exec. 13" provides a closed contact between pins 1 and 2 (SK5 - rear panel), when all except the + 170V supply voltages are present. The +170V is used only for neon pulse indicator lamps in U. 1545 and U. 1546, and is therefore not essential for the functioning of the mean speed regulation. The lamps LP1 and LP2 should be illuminated if the essential supplies (ie : + 30V(a), + 30V(b), - 20V) are present.

5.2. U.1545 - Générateur de l'Impulsion de Référence.

The schematic diagram and more important waveform/time diagrams of this chassis are shown in Fig. 7 of this report. The schematic of the 100 Kc/sec. counter sections of the unit are shown in Fig. 8, and the chassis wiring diagram is given in Drg. 125-1545-0. The counter flip-flops are located on the printed circuit card sockets.

Counter 1 - sockets 33 to 44 inclusive
Counter 2 - sockets 17 to 28 inclusive.

It should be noted that the first two decades of each counter (ie: 100 Kc/sec to 1 Kc/sec., sockets 33 to 36 and 17 to 20 respectively), are fast 1Mc/sec. double counting flip-flops. The remaining flip-flops are slower 10 Kc/sec. double counting flip-flops.

The output (ie: U) of the "Ebauches" crystal controlled oscillator is a 100 Kc/sec., 1 V r.m.s. sine wave. The associated trimming condenser should be adjusted to have exactly 100 Kc/sec. The output signal is amplified by the waveform shaper card (ie: 225P-chassis socket 4) to give a +30V square wave. A potentiometer P_1 is provided on this card to facilitate adjustment to have a unity mark : space ratio of the square wave signal. The potentiometer P2 varies the quiescent operating point of the first stage a.c. amplifier to have optimum gain.

The binary outputs from the last two decades of the two counter strips (ie: 100 msec. and 1 sec. steps, sk 41 to 44 and sk 25 to 28 respectively), are decoded by the 239P diode prints to give the corresponding decimal output. These decimal outputs from each counter are assembled together on the 335P relay cards.

The selected CPS machine repetition period is transmitted by external closing contacts to the chassis relay cards 335P (sk 49, 50, 51 and 52). For example, a selected repetition period of 2.1 seconds, would result in a +30V signal appearing on E (sk.51) and B(sk. 49), which energizes the corresponding decimally arranged relays on the cards.

According to the relays that have been energized by the externally selected repetition period, the decimal signals are gated to produce (alternatively from each counter, as indicated in Figs. 7 and 8) an output coincidence pulse. This coincidence pulse gives a real time reference of the desired repetition period, measured from the previous counter start pulse. The coincidence pulses are used to reset the corresponding counter from which they have been derived, and are then "OR" gated together to give the TR reference pulse every CPS repetition period.

The designated machine pulse inputs to the chassis are :

(a) <u>the MR pulse</u>, which is used to switch the start pulse (ie: machine repetition pulse), alternatively from one counter to the other. The reasons for this have been explained in Section 3 of this report.

(b) <u>the MO ± n 3.3 msecs.</u>

If the M/A set is to have a synchronous mean speed, the pulse of (b) should be that corresponding to the MO machine pulse (ie: n = 0). However, if for some reason it is required that the set runs slightly faster or slower than synchronous mean speed, it is achieved by using later or earlier pulses in the M pulse train (around the MO pulse). For example, at a 1 sec, repetition period and using the next later pulse in the M pulse train (ie: MO + 3.3 msecs.), then the set would be regulated to run at 0.33 o/o slower than synchronous mean speed. Similarly if a pulse from the M pulse train corresponding to two earlier than MO is used (ie: MO - 6.6 msecs.), then the set will have a mean speed 0.66 o/o faster than synchronous.

5.3. <u>U. 1546 - Convertisseur temps/tension et Régulateur</u>.

The electrical wiring diagram of this unit is shown in Drg. 125-1546-1, and the corresponding waveform/time diagrams are given in Drg. 126-1052-0. The function of this unit has been described in Section 4 of this report and its general schematics indicated in Figs. 13 and 15. The upper left hand portion of the wiring diagram shows the two independant power supplies (+30V, 0V, -20V and +15V, $\bar{0}$V, -15V). The upper right hand portion contains the gain switching relay cards. As in the previous unit (ie: U.1545), the relays are energized by external closing contacts according to the selected CPS repetition period. For example, a CPS repetition period of 3.4 seconds results in a +30V energizing signal appearing at R(sk. 39 and 40) and T (sk. 37 and 38).

The "signal flow" of the remaining part of the wiring diagram is from left to right. The cards to the left and including 239P (sk.12) are first pulse adapters (ie: 203P - converting the CERN standard input pulses (+45V, 1μsec.) into +30V, 10 μsec. pulses), followed by the logic circuitry to obtain ;

(a) a +30V pulse of width (MO-TR), only when the set is running over-synchronous and MO occurs before TR.

(b) a +30V pulse of width (TR-MO), only when the set is running under synchronous mean speed and TR occurs before MO.

For the case (a), the integrator pulse adapter 242P (sk.18), converts the +30V pulse into a "-ve pulse" of amplitude such that for a 1 sec. repetition period and 10 msec separation between MO and TR , the integrator output (236P/F - sk. 19) reaches +10V. Adjustment of the amplitude of the "-ve pulse" to achieve this result is by potentiometer P_2 on card 242 P(sk.18). Similarly for thecase (b), the +30V pulse is converted to a "+ve pulse" of amplitude such that for the same repetition period and time separation between TR and MO as previous, the integrator output reaches -10V. The pulse amplitude in this case is adjusted by P_1 on card 242P (sk. 17). It should be noted that by appropriate adjustment of P_1 on card 228P (sk. 33), the integrator input pulse (+ or - going) is automatically reset to zero when the integrator output reaches say ± 11 Volts.

The MW machine pulse initiates the resetting of the "time to voltage converting" integrator (Zeltex, 236P - sk.19). Depending upon whether the integrator output is at a +ve or -ve level (determined by MO occurring before TR or vice-versa respectively), the MW pulse is gated accordingly to initiate the correct polarity of the resetting pulse by turning "on" either the flip-flop of sk. 24 or sk. 23.

The integrator is reset from +10V to zero by a +ve input voltage signal from 242P (sk. 18). The amplitude of this signal is adjusted by P_1 on the card, so that the resetting time is 2.5 msecs. Similarly the resetting from -10V to zero is achieved with a -ve Voltage signal from 242P (sk.17). The amplitude is adjusted by P_2 on the same card to have a 2.5 msec. resetting time. The potentiometer P_1 on card 241P (sk.21) allows the resetted voltage of the integrator (coming from a -ve voltage), to be adjusted very accurately to within a few mV of zero by stopping the +ve input voltage signal to the integrator. The potentiometer P_1 on card 241P (sk.22) is to have the same adjustment on the resetted voltage when the integrator output is coming from a +ve voltage by stopping the -ve voltage input signal to the integrator.

The effective input resistances of the integrator across R_{16} and R_{13}, for positive and negative input pulses respectively,are changed proportionaly to the repetition period by the gain switching relay cards (sk. 39 and sk. 40). The resistance across each for a 1 second repetition period is 10 KΩ.

The "Nexus" amplifier of sk. 26 is the main regulating amplifier of the mean speed regulation system. The gain of this amplifier is made α 1/Trep by changing the effective input resistance across R_{22} proportional to Trep. The appropriate resistance are located on the gain switching relay cards (sk. 39 and sk. 40) and are connected automatically across R_{22} according to the selected CPS repetition period. The resistance across R_{22} is 10 KΩ for a 1 second repetition period. The 50KΩ, 10 turn helipot permits an increase of theloop amplification from one to two times the automatic selected value. The best setting of the helipot will be obtained by "trial and error" to obtain optimum response.

The transitional lag (ie: integral part of the transient control loop), is provided by feedback around the "Zeltex" amplifier of sk.27.

The resistors R_{31} and R_{32} determine the ratio of the control action between the proportional and integral parts of the transient control loop. At present, both are 5.6 KΩ , in order to have equal effect.

Each of the instrument potentiometers should be adjusted to give a full scale reading for 10 Volts applied.

The relay print (ie: 228P, Exec.B - sk.34), provides a closed contact between pins 1 and 2, rear panel SK.6 if all the essential power supply voltages are present (ie: +30V, -20V, +15V, -15V). The lamps LP2 and LP3 should be illuminated accordingly.

5.4. U. 1547 - Potentiomètre de Référence.

The wiring diagram of this unit is shown in Drg. 125-1547-1. The schematic diagram and an indication of the more important waveform/time diagrams are given in Drg. 126-1053-1.

The left hand portion of the wiring diagram shows the independant supply transformers for (a) + 30V and -20V, (b) 20V reference source and (c) 48V a.c. helipot motor drive. The voltage across the helipot is reduced to 10V, by a 3.9 KΩ series resistor, to correspond to 100 o/o power input signal to the power/speed regulation system. The facility is provided to have an initial power reference signal drop from 0 to 8 o/o when pulsing begins. This is achieved by opening the "bridge" between A and B (ss.16), and adjusting the potentiometer on 228P-Ex.16 (sk.15) accordingly. This power drop is recuperated as soon as the helipot motor drive stops (ie: mean speed within the limits of ± 1 o/o of synchronous), and is incorporated to partially compensate automatically the final steady state power error of the coarse control system (as explained in Section 4 of this report). However, tests with prototype equipment have shown this facility may not be necessary. Once a steady mean speed has been achieved automatically, it is recommended that steady state offset is reduced by adjusting the helipot manual control to have a very small output signal from the integral part of the transient control loop (ie: instrument AM2 in U. 1546).

Failure of the +30V, -20V or reference source voltages causes a contact to open between pins 1 and 2 (rear panel SK.6).

Symmetrical triggering of the helipot motor drive relays is achieved by adjustment of potentiometer P_1 on card 235P (sk. 12). The feedback resistor R_{23} of the 243P d.c. amplifier (sk. 11), should be adjusted so that the motor drive operates when the input signal to the amplifier is $\geqslant \pm 10$ V.

The Drg. 126-1054-3 shows the mean speed regulation system chassis interconnections, and connections to "Siemens" and other CERN control equipment.

N.S. Blyth

Distribution :

Open

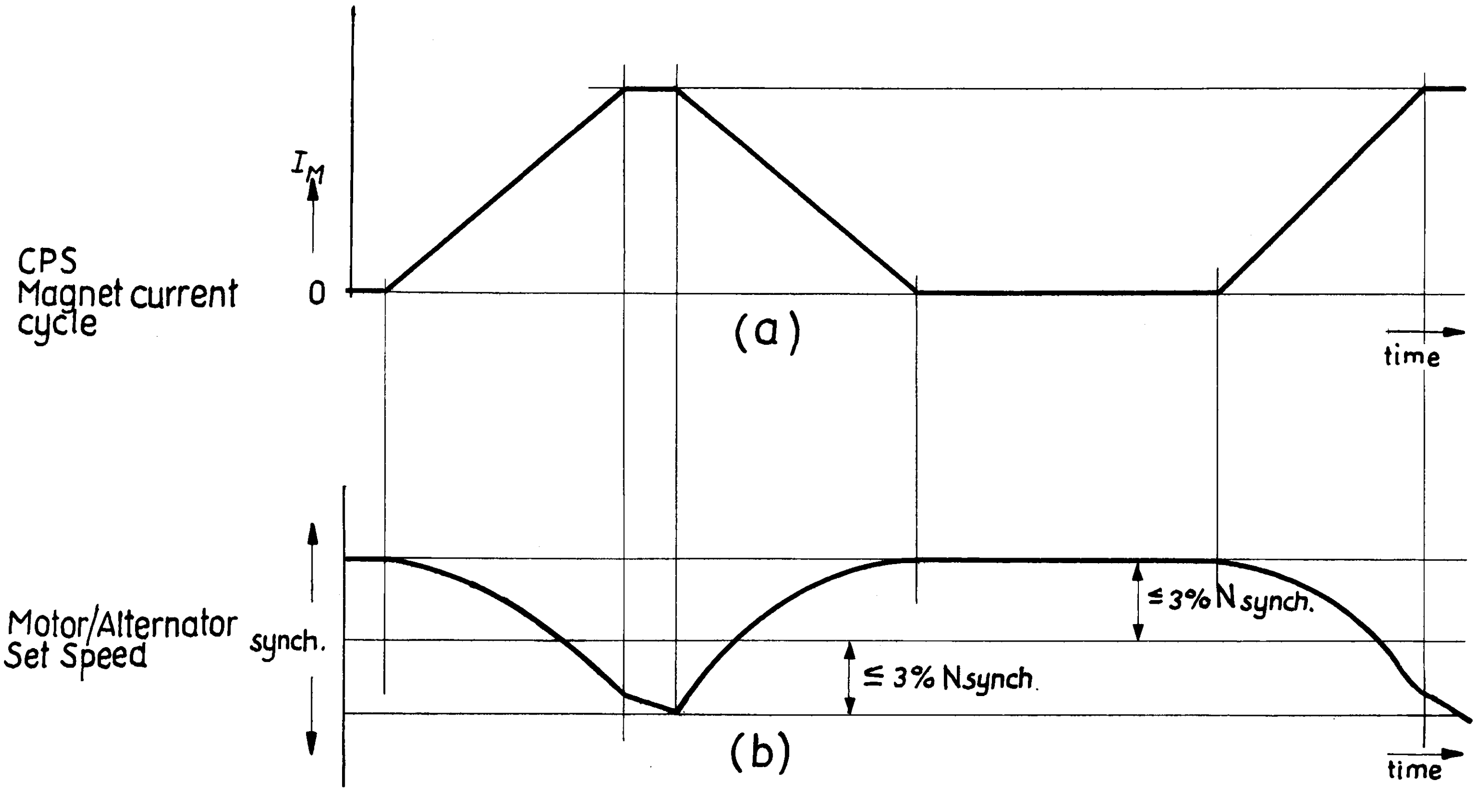
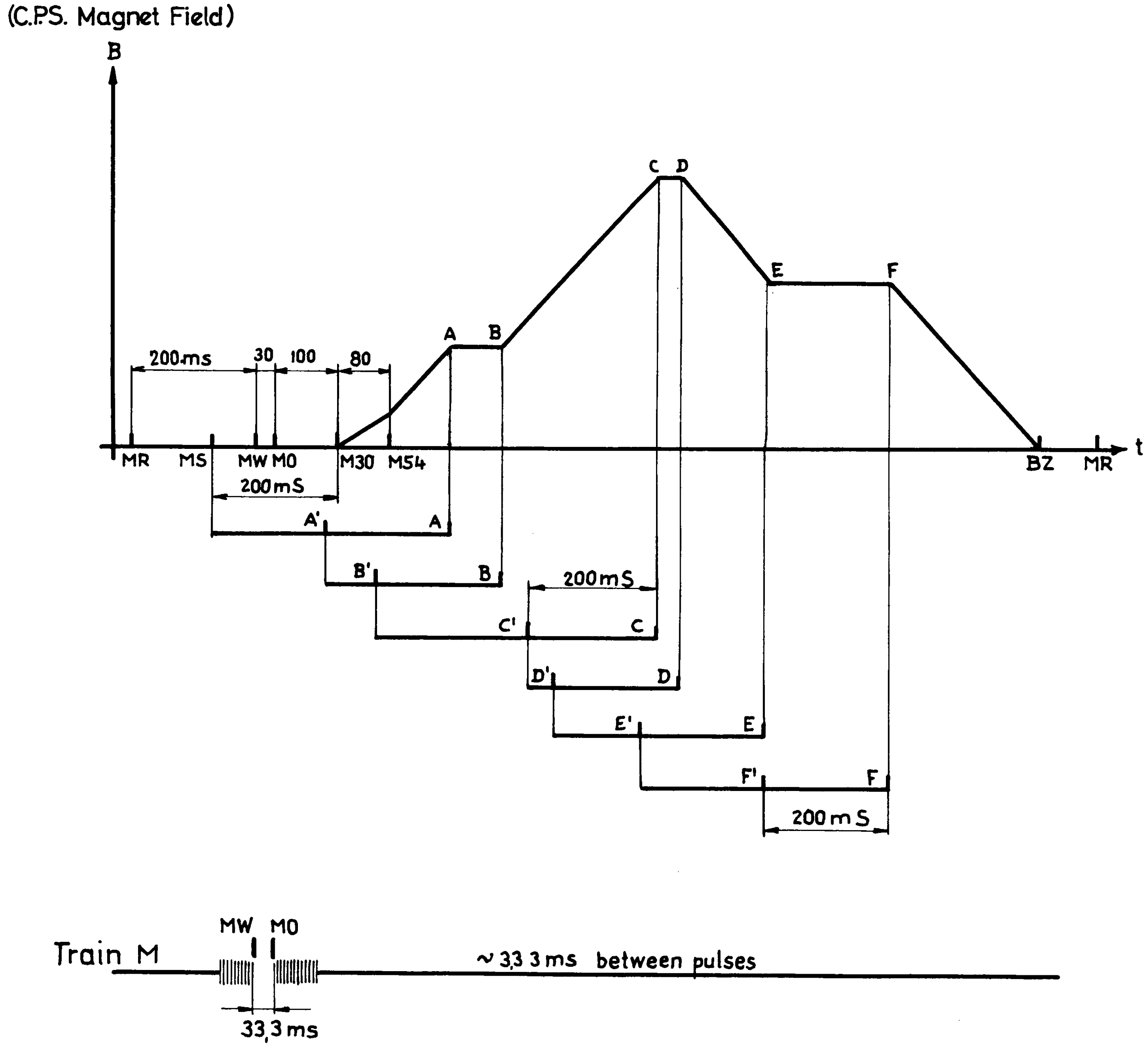


Fig. 1

CERN-MPS 126-1055-4

SIS/R/15396



Timing Pulses of the
New C.P.S. Magnet Power Supply
Fig. 2

CERN-MPS 126-1056-4

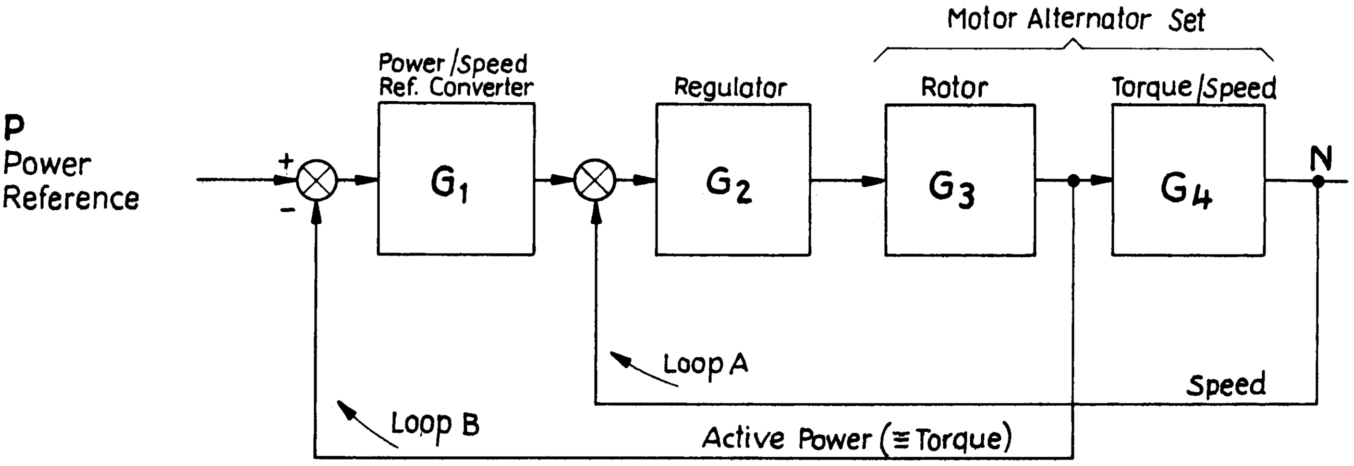

Motor Alternator Set
Power/Speed Ref. Converter
Regulator
Rotor
Torque/Speed
P
Power Reference
+
-
G1
G2
G3
G4
N
Loop A
Speed
Loop B
Active Power (≡ Torque)

Fig. 3

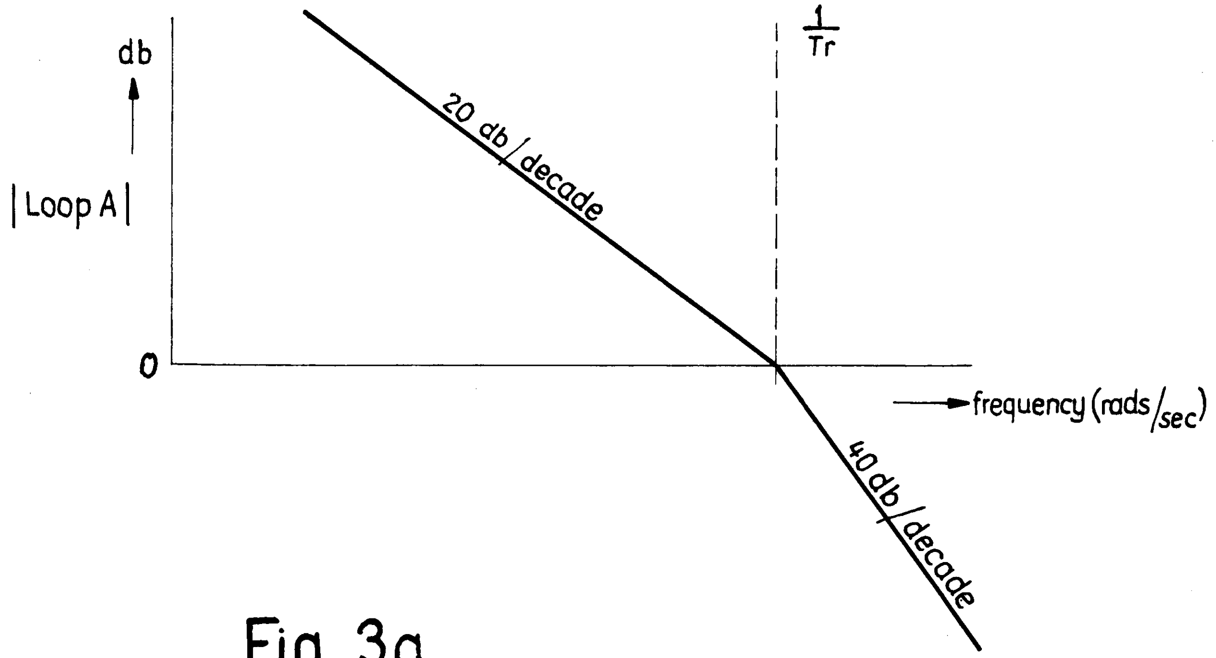

db
|Loop A|
0
1/Tr
20 db/decade
40 db/decade
frequency (rads/sec)

Fig. 3a

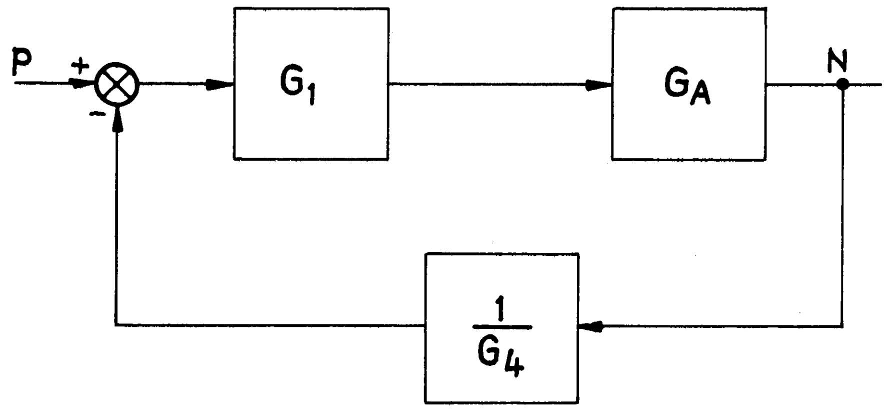

P
+
−
G_1
G_A
N
$\frac{1}{G_4}$

Fig. 4

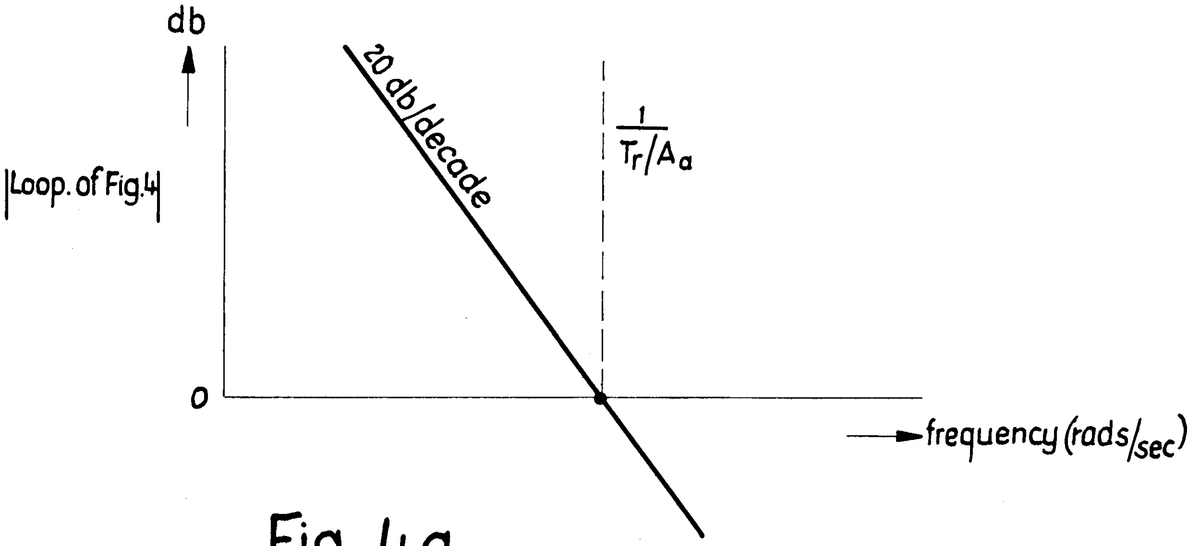
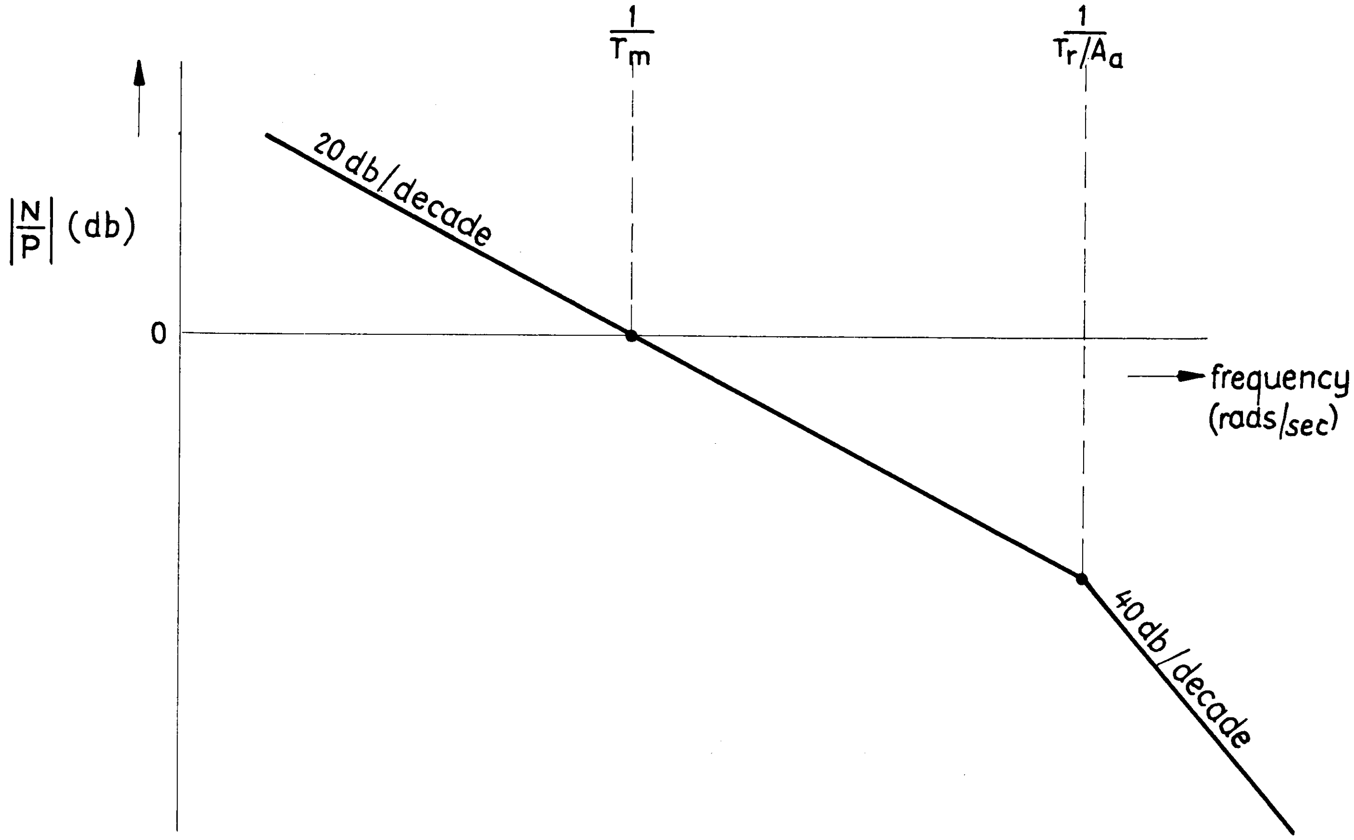
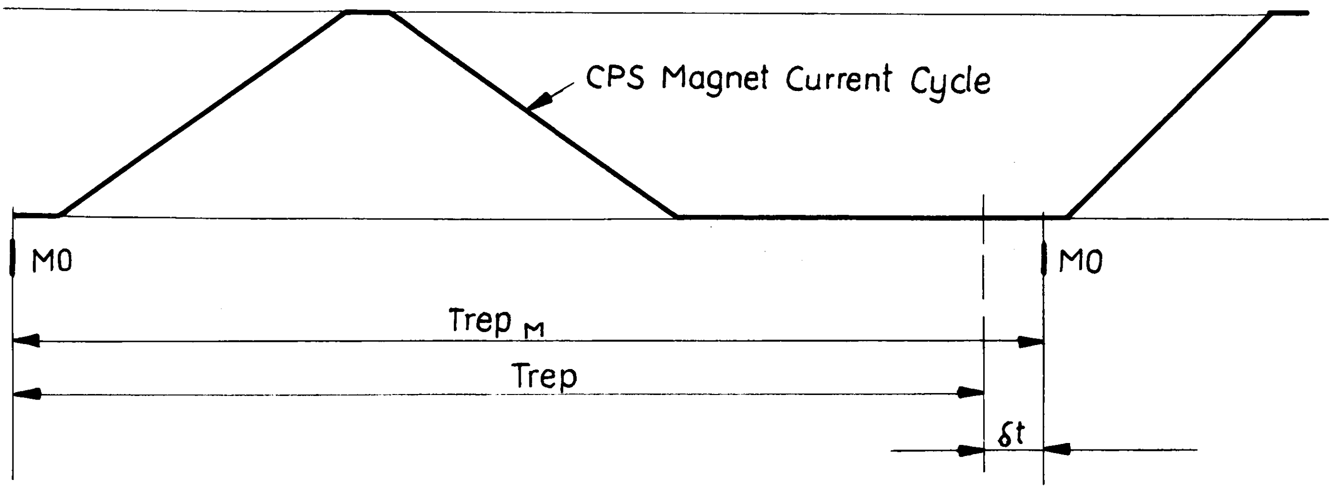

db
|Loop. of Fig.4|
20 db/decade
$\frac{1}{T_r/A_a}$
0
frequency (rads/sec)

Fig. 4a



$\frac{1}{T_m}$
$\frac{1}{T_r/A_a}$
$\left|\frac{N}{P}\right|$ (db)
0
20 db/decade
40 db/decade
frequency (rads/sec)

Fig. 5



$$\delta t = Trep_M - Trep$$

$$\frac{\delta t}{Trep} = \frac{Trep_M}{Trep} - 1$$

$$= \frac{N_s}{N_M} - 1$$

$$= \frac{N_s}{(N_s - \delta N} - 1$$

$$= \frac{1}{\left(1 - \frac{\delta N}{N_s}\right)} - 1$$

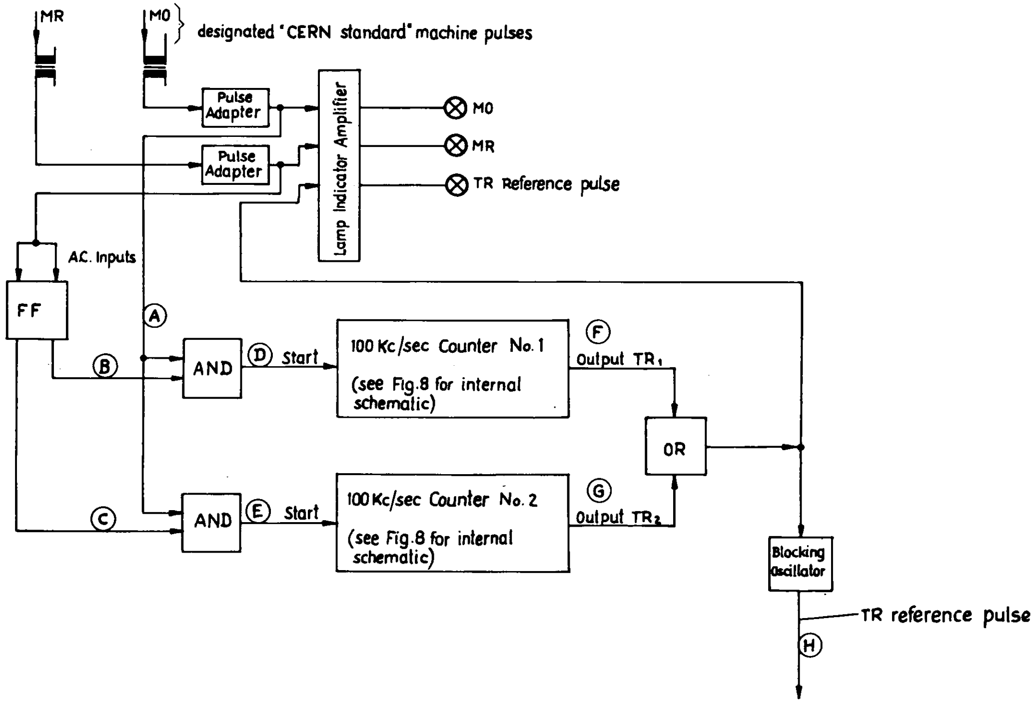
which for small δN, may be approximated

$$\underrightarrow{\frac{\delta t}{Trep} \approx \frac{\delta N}{N_s}}$$

where:

M0 = designated machine pulse/cycle
Trep = desired CPS repetition period
$Trep_M$ = actual machine repetition period
δt = real time error
N_s = M/A set synchronous speed
N_M = M/A set mean speed/cycle
δN = M/A set mean speed deviation from synchronous

Fig. 6



Schematic of U.1545
Générateur de l'impulsion de Référence
(Measurement of Mean Speed Deviation)

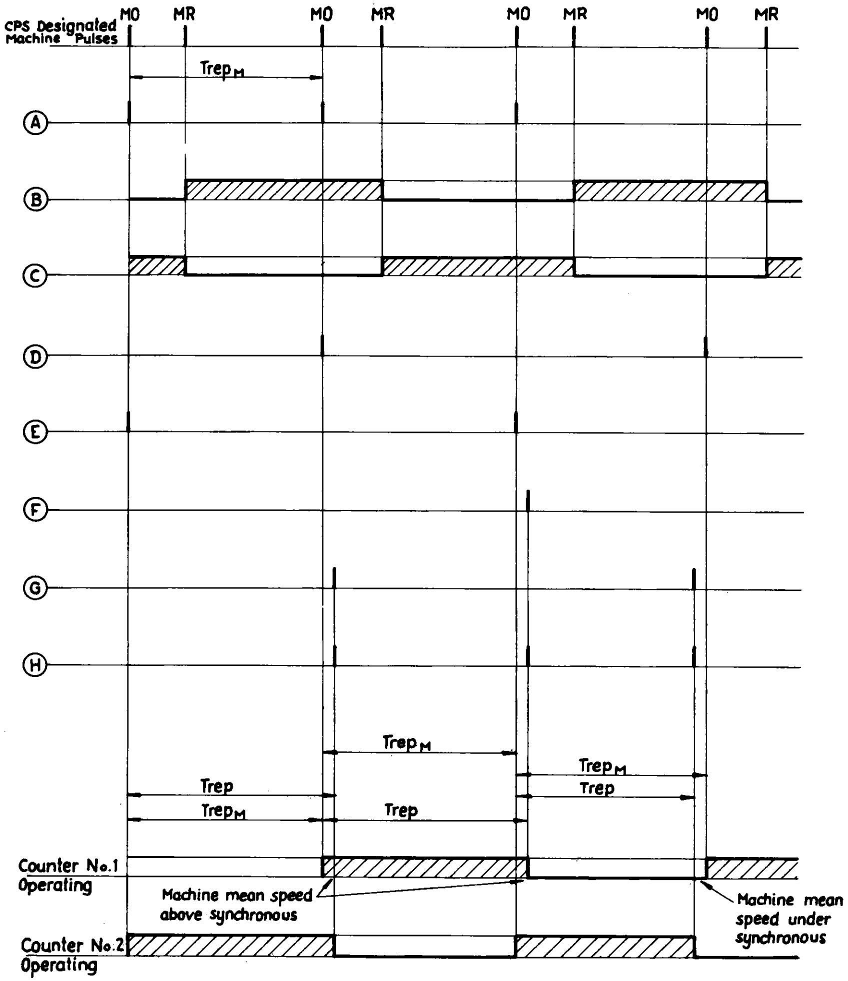
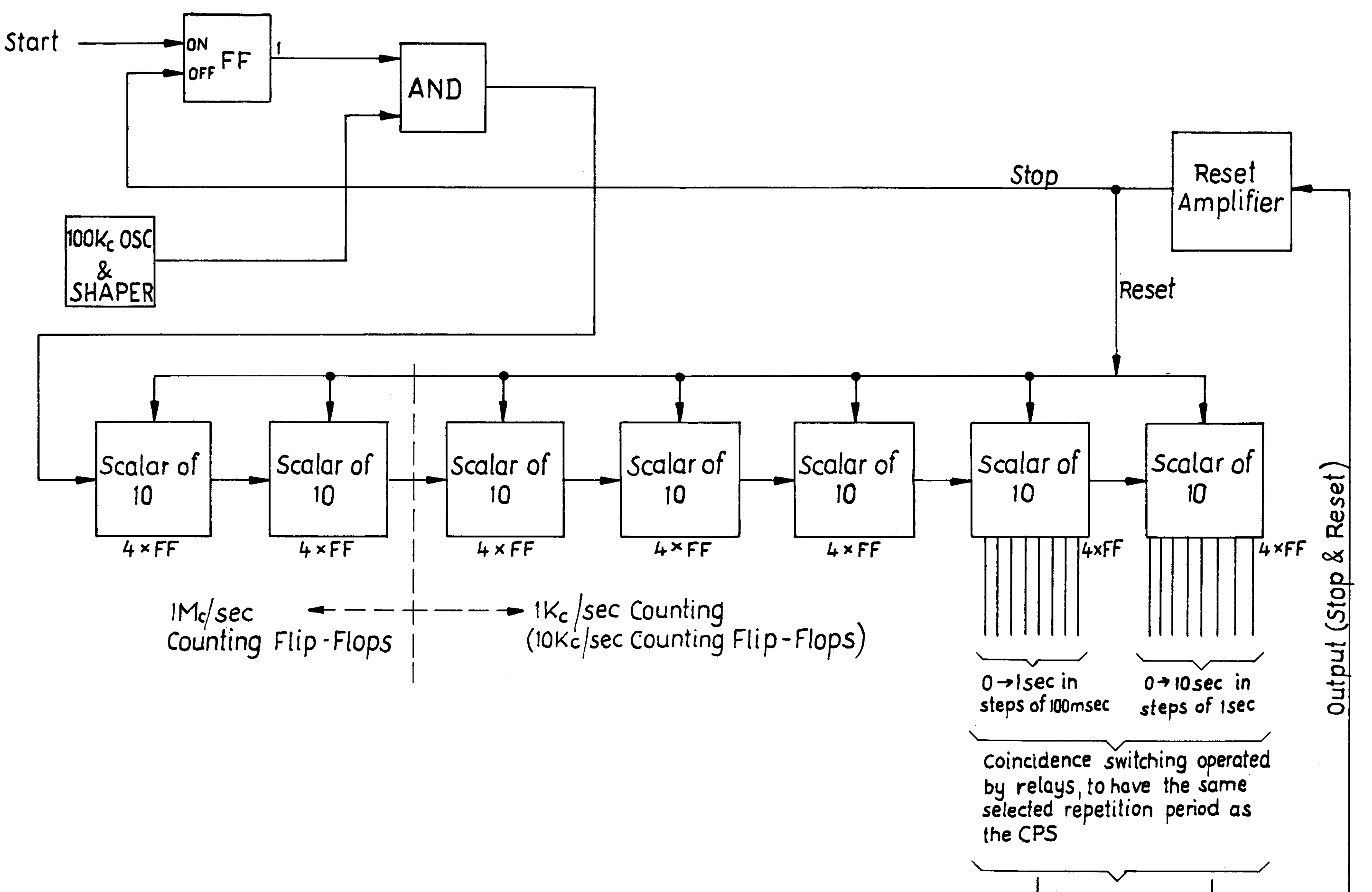


Fig.7

CERN-MPS 126-1061-2



Schematic of 100Kc/sec Counter UNITS

Fig.8

CERN-MPS 126-1062-4

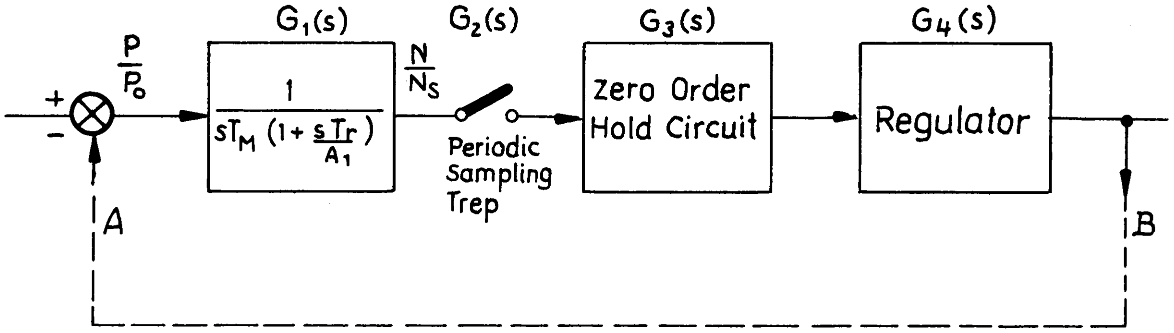


Fig.9

CERN-MPS 126-1063-4

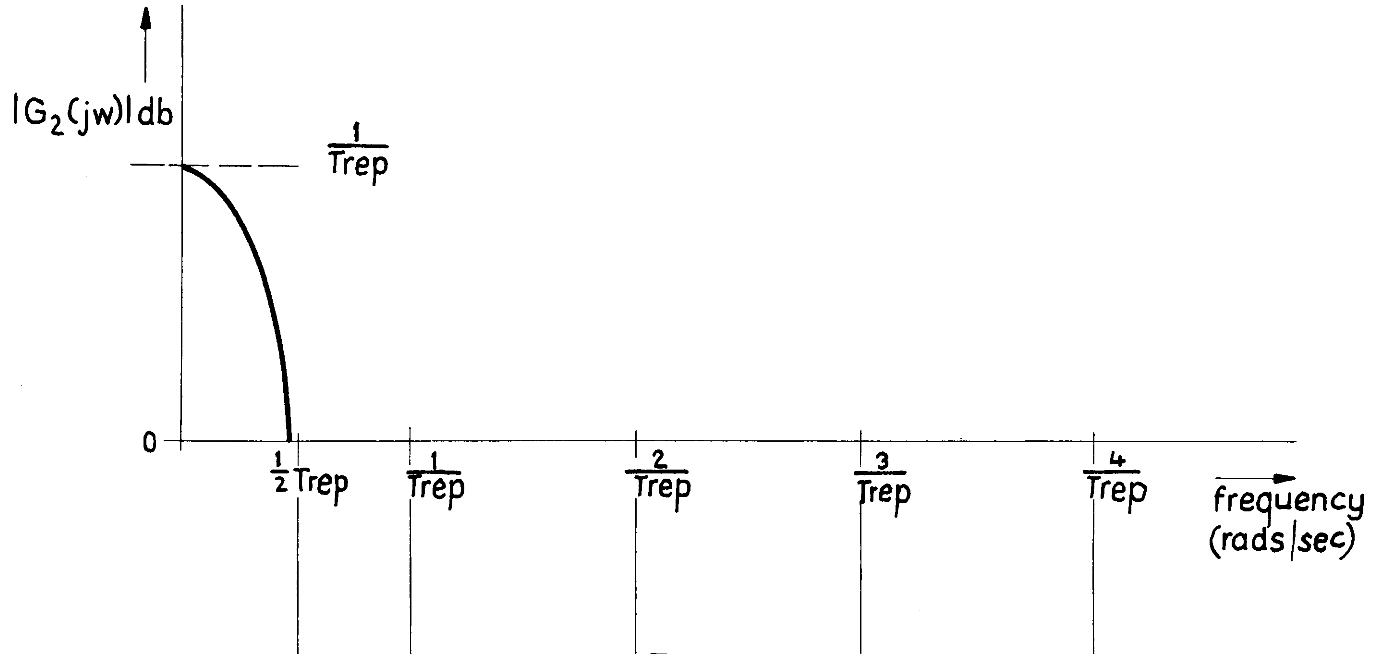

|G₂(jw)| db
1/Trep
0
½ Trep
1/Trep
2/Trep
3/Trep
4/Trep
frequency (rads/sec)

Fig.10

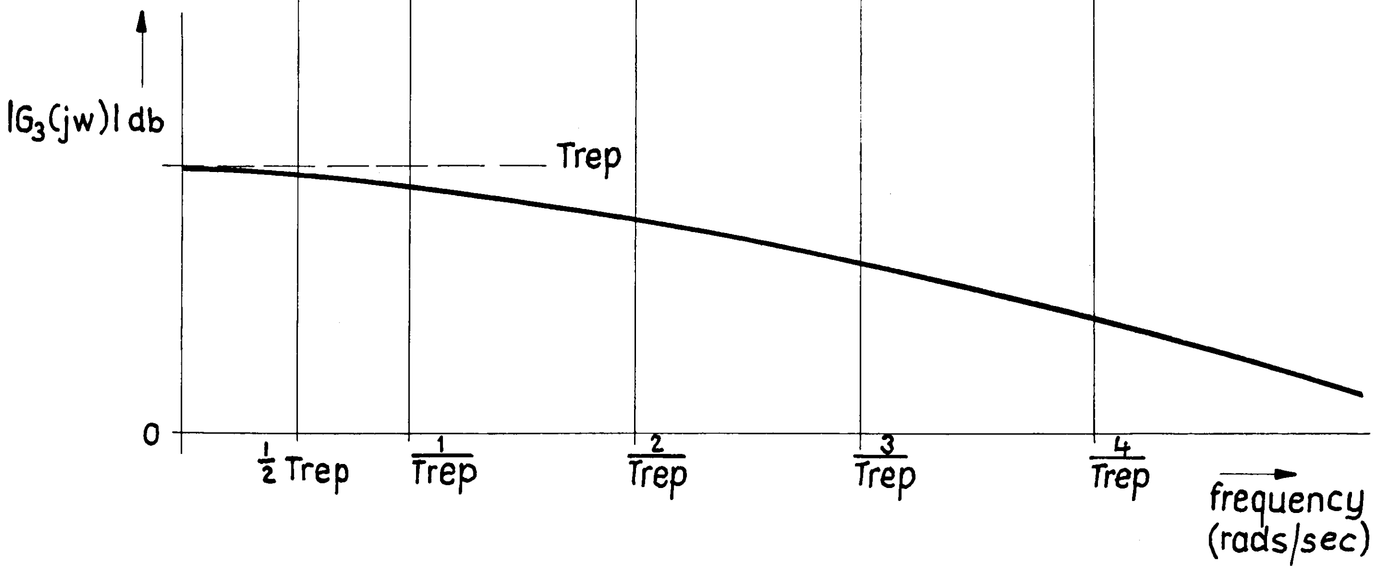

|G₃(jw)| db
Trep
0
½ Trep
1/Trep
2/Trep
3/Trep
4/Trep
frequency (rads/sec)

Fig. 11

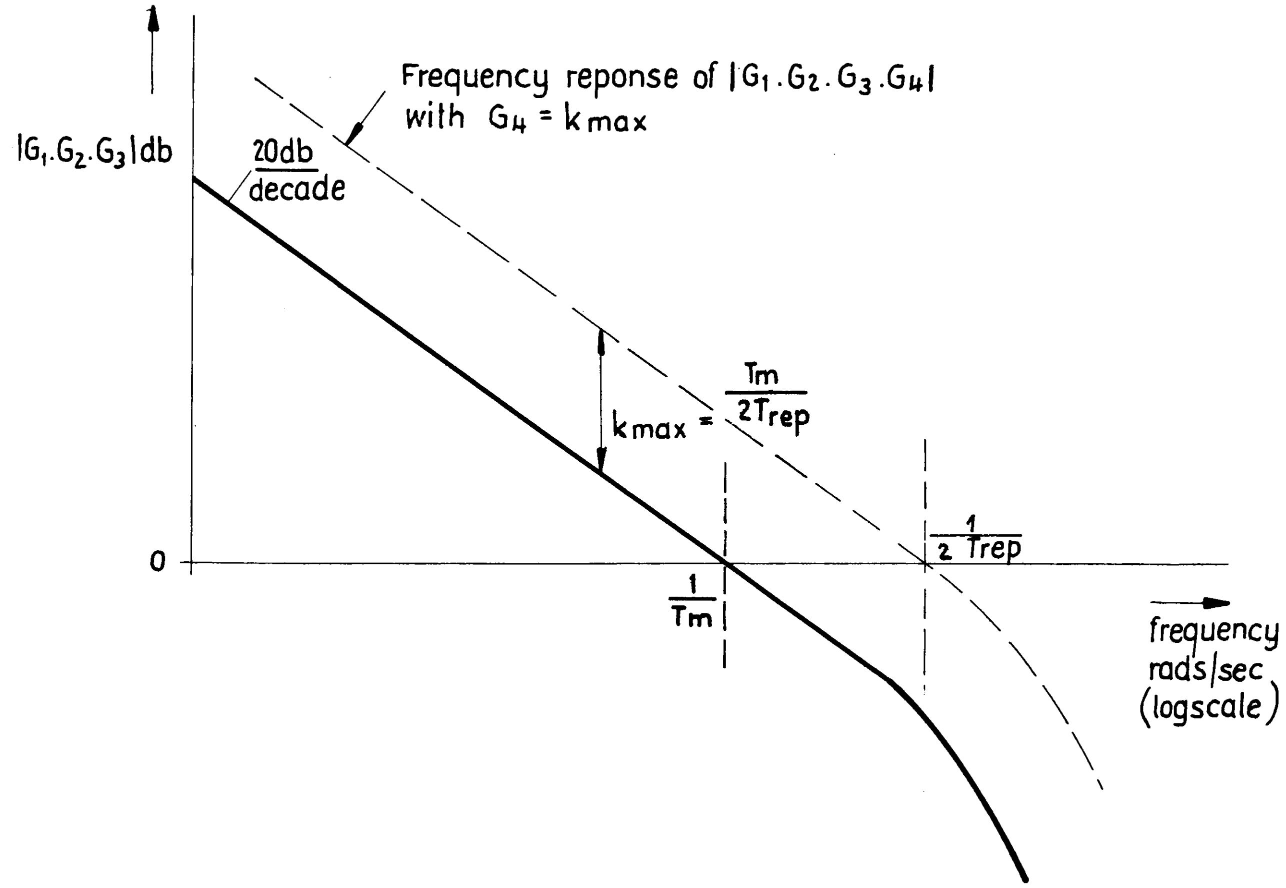
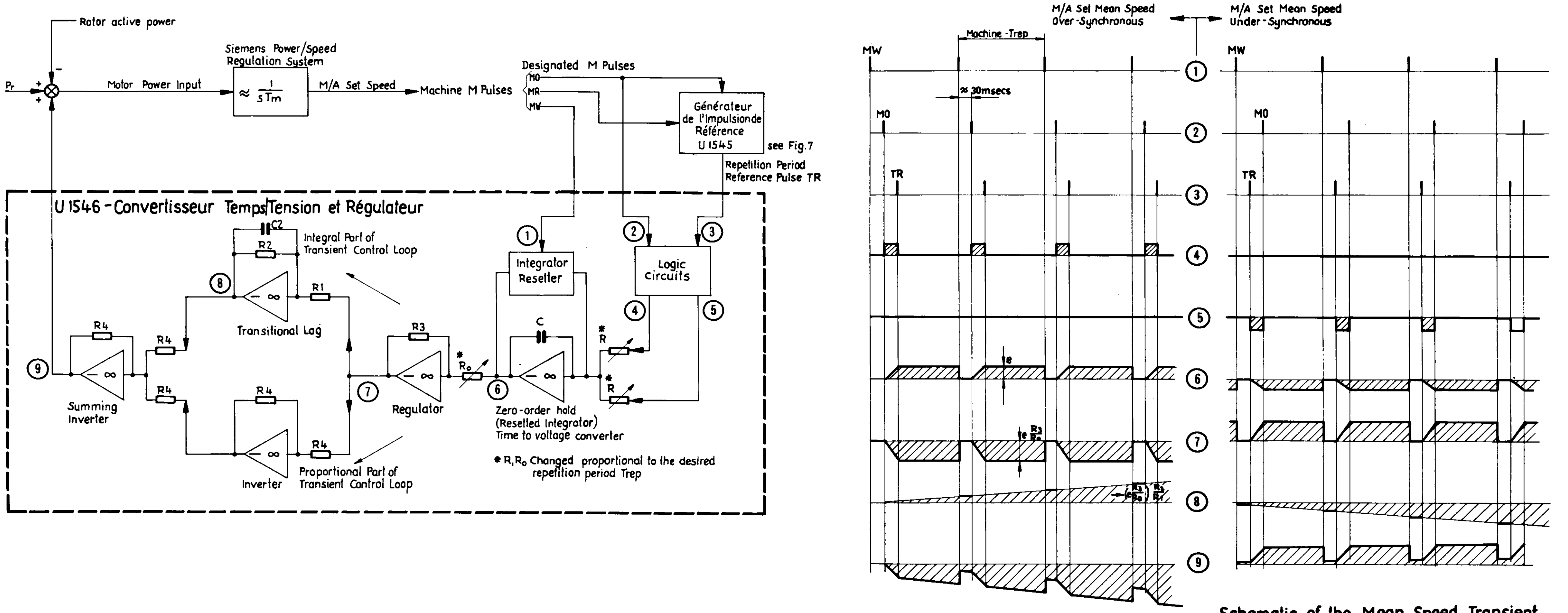


Fig.12

CERN-MPS 126-1065-4



Schematic of the Mean Speed Transient or Fine Control System
Fig.13

CERN-MPS 126-1066-1

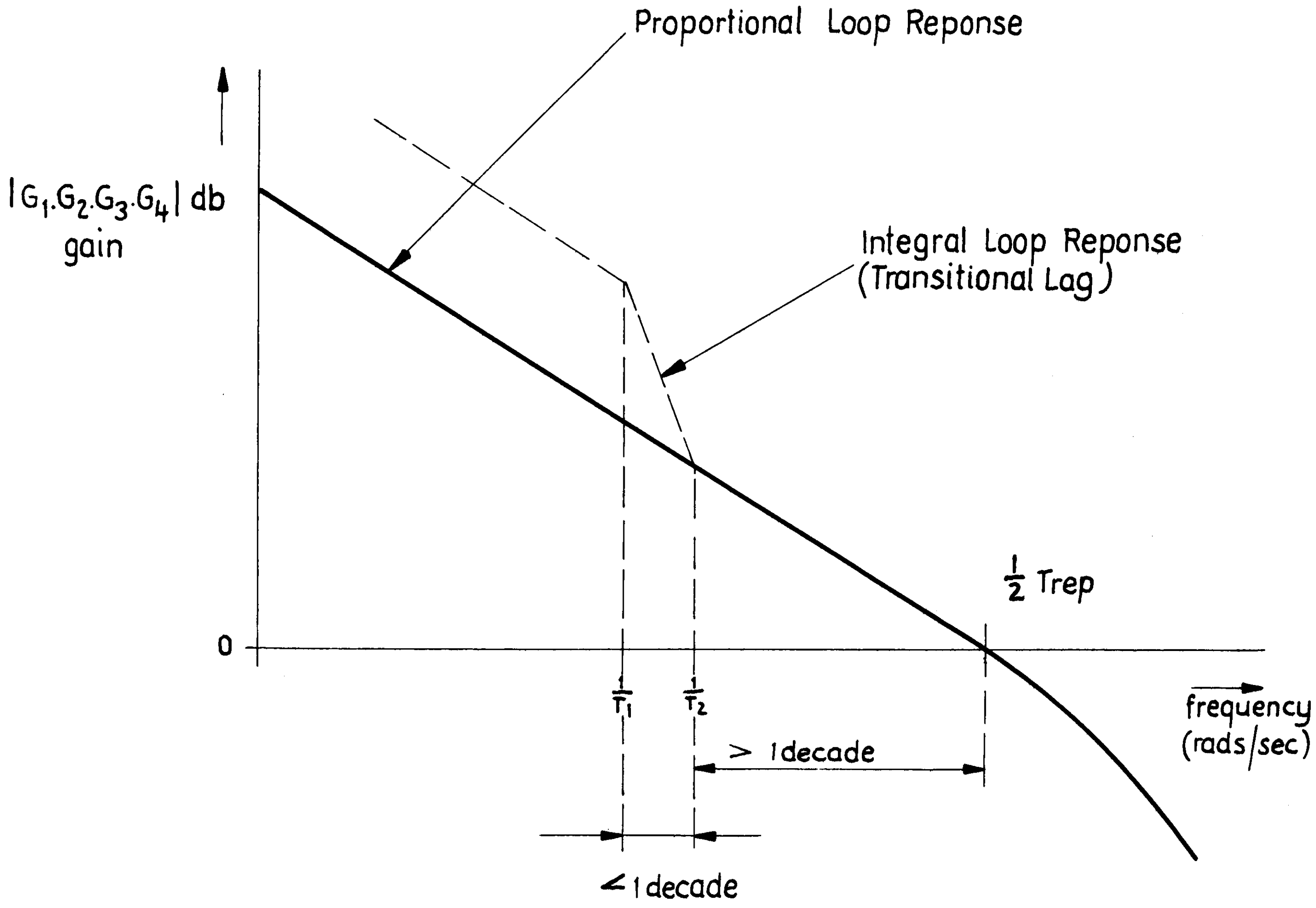
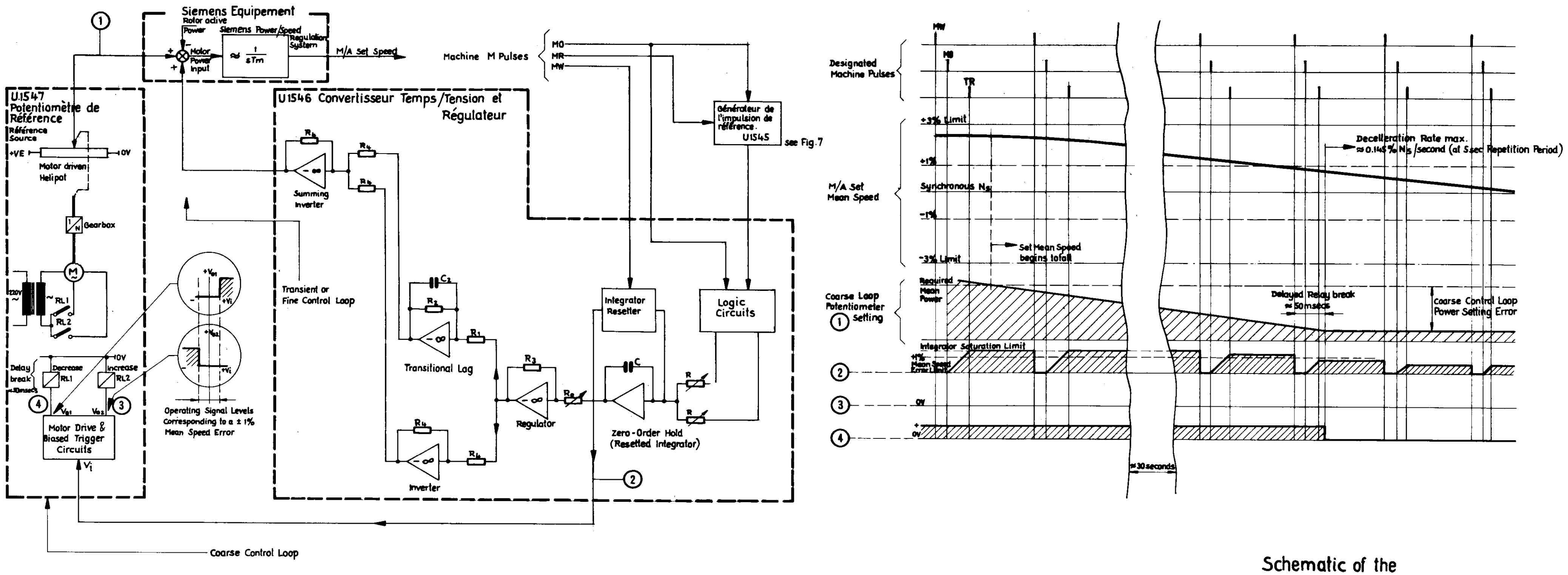
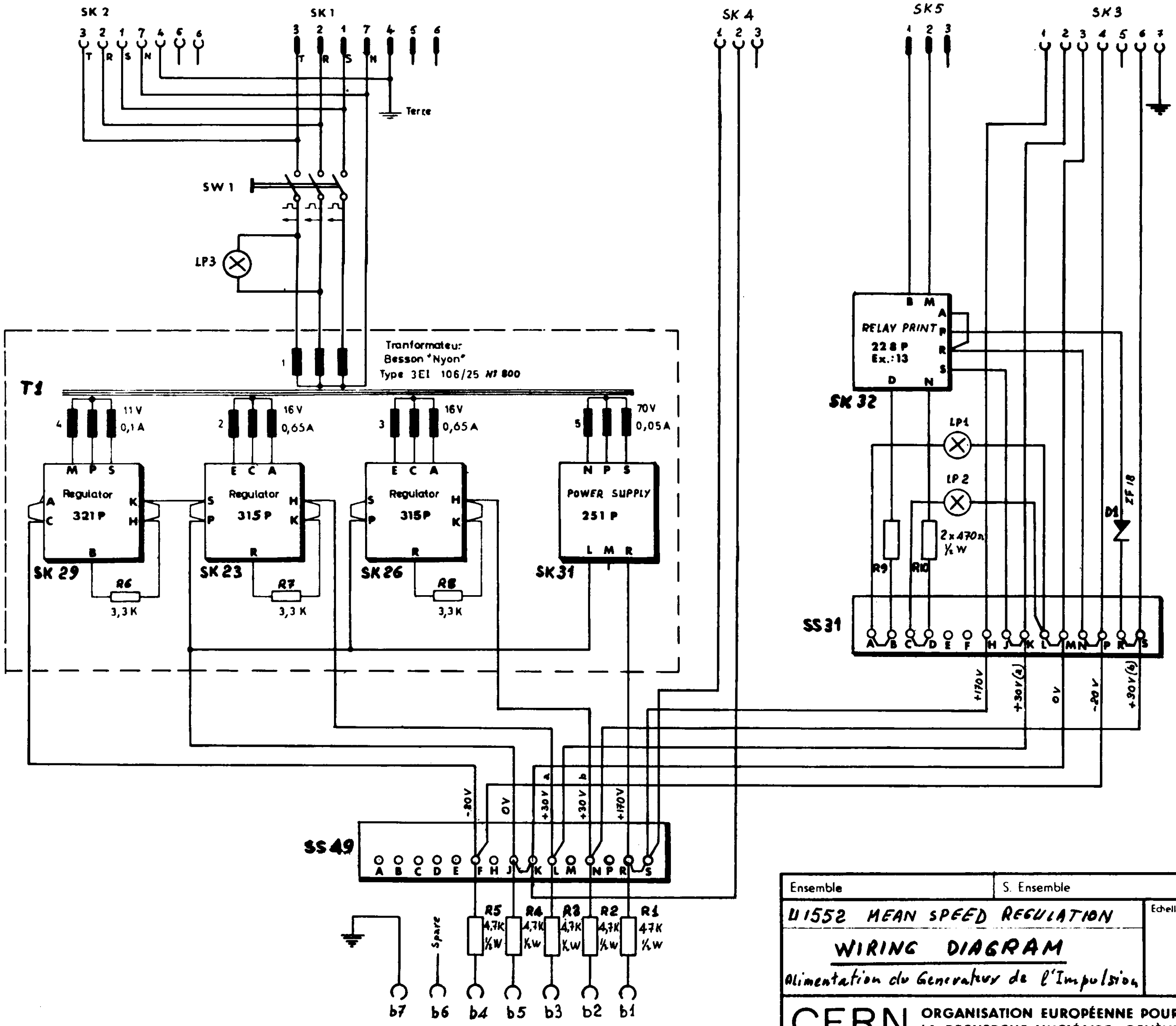

Proportional Loop Reponse
$|G_1.G_2.G_3.G_4|$ db
gain
Integral Loop Reponse
(Transitional Lag)
$\frac{1}{2}$ Trep
0
$\frac{1}{T_1}$
$\frac{1}{T_2}$
frequency
(rads/sec)
> 1decade
< 1decade

Fig. 14



Schematic of the
Mean Speed Regulation System
Fig.15

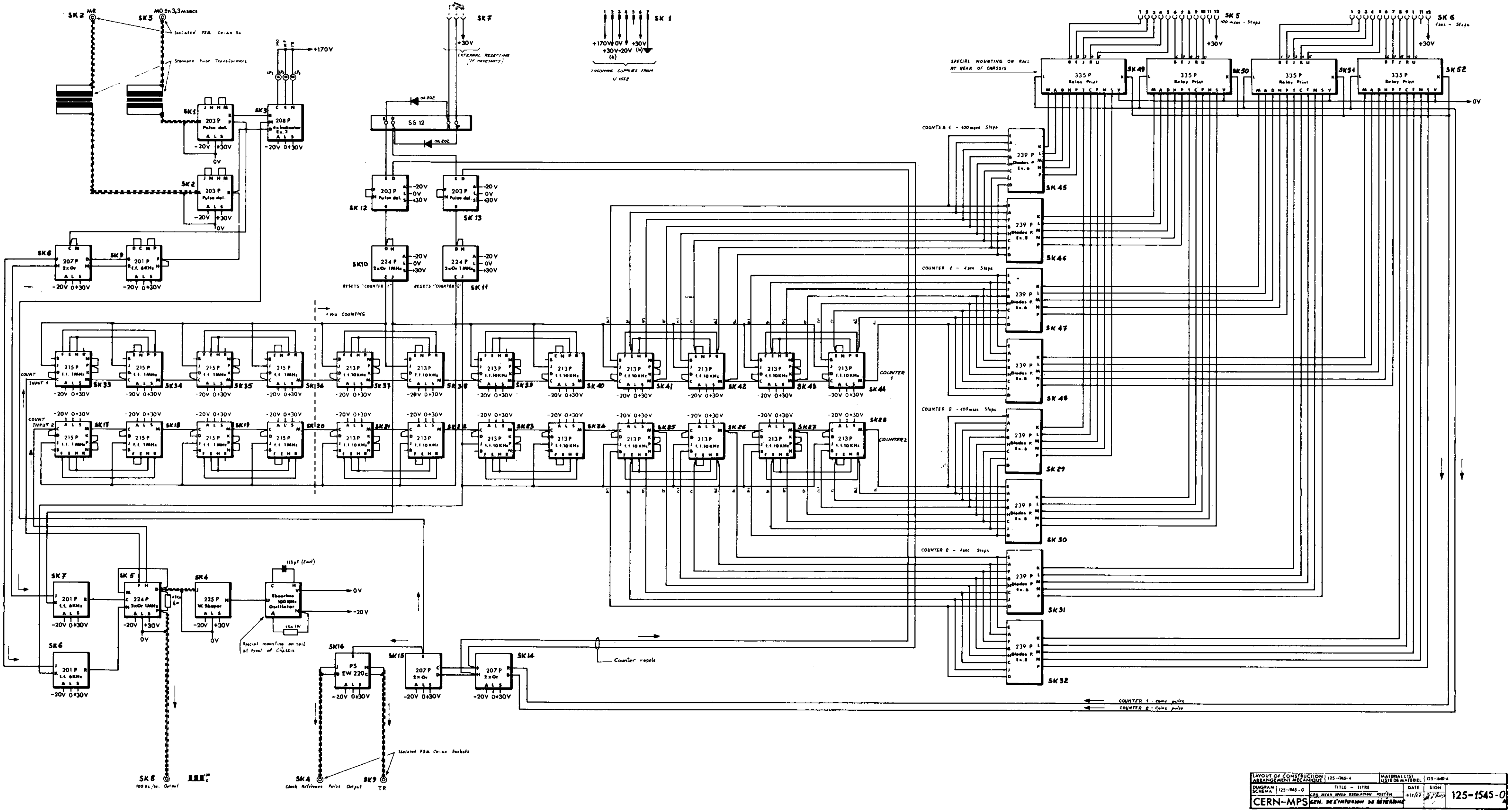
CERN-MPS 126-1068-1



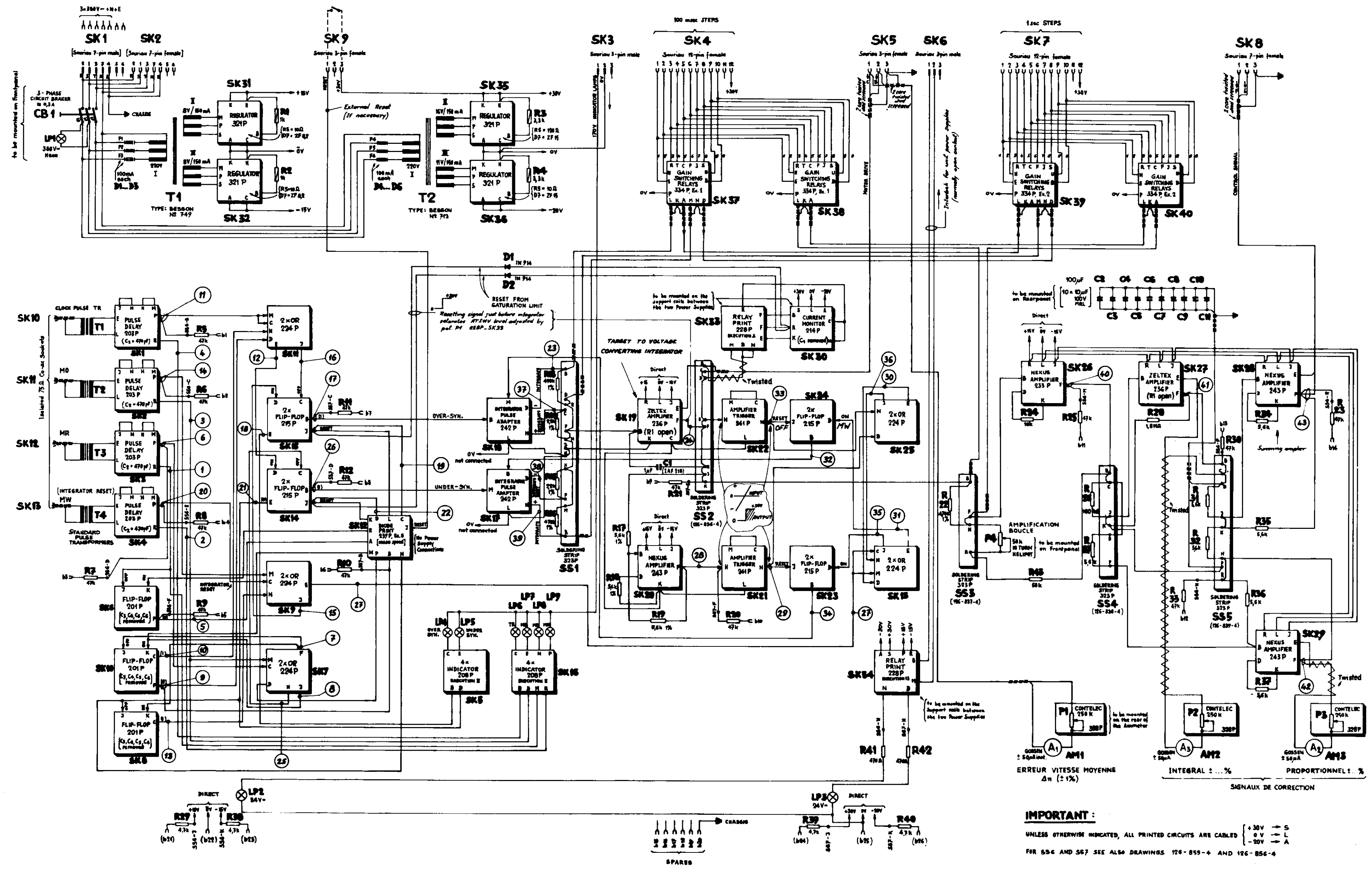
Ensemble	S. Ensemble		Dessiné	6/4/67	M. d'Auria
U1552 MEAN SPEED REGULATION		Echelle	Controlé		
WIRING DIAGRAM			Vu		
Alimentation du Generateur de l'Impulsion			Remplace		
			Remplacé par		
			Reduction		

CERN ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE - GENÈVE

125 - 1552 - 3a



LAYOUT OF CONSTRUCTION ARRANGEMENT MECANIQUE	125-1545-4	MATERIAL LIST LISTE DE MATERIEL	125-1545-4		
DIAGRAM SCHEMA	125-1545-0	TITLE - TITRE	DATE	SIGN.	125-1545-0 A
CERN-MPS		C.P.S. MEAN SPEED REGULATION SYSTEM GEN. DE L'IMPULSION DE RÉFÉRENCE	13/2/67		



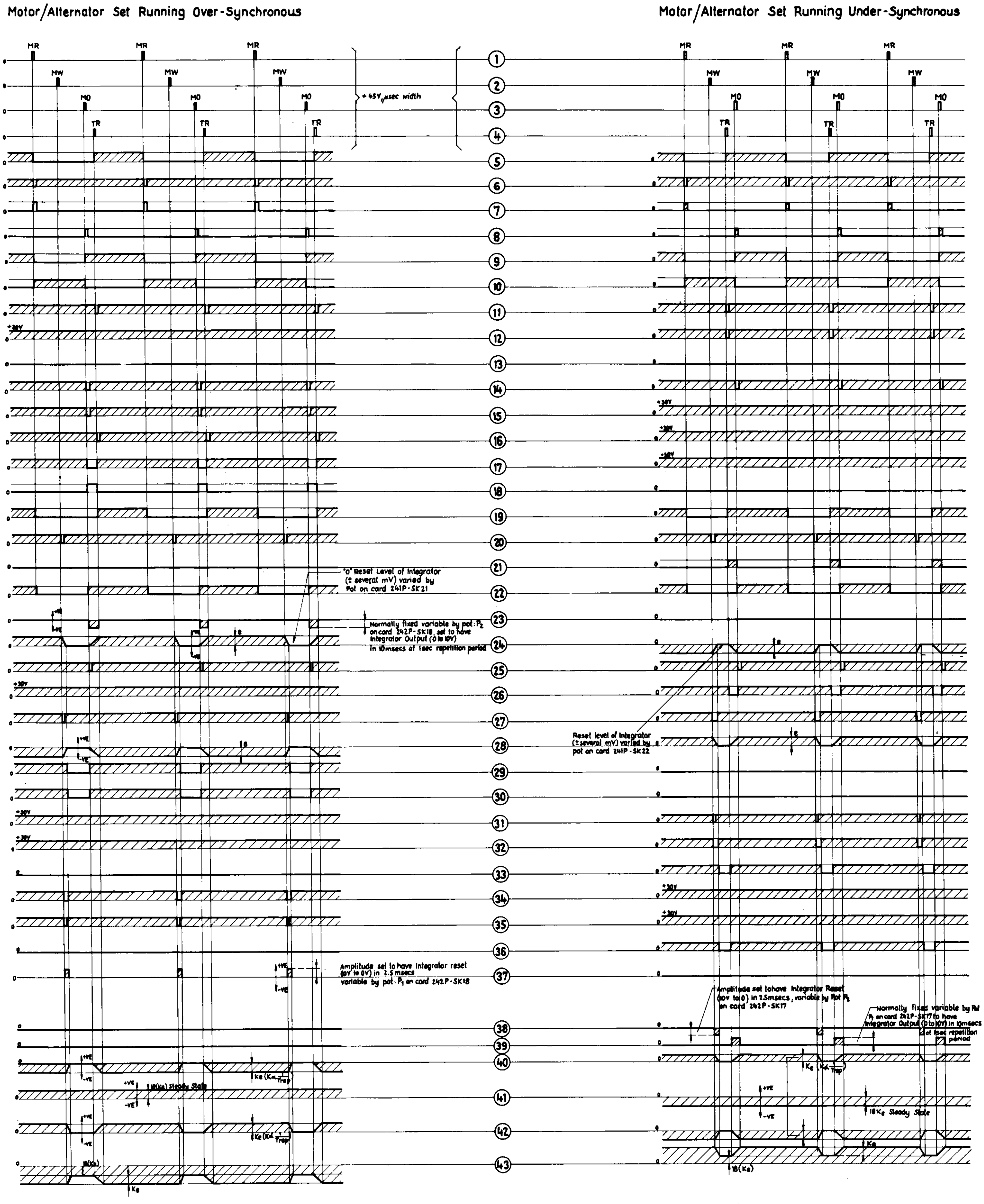
IMPORTANT :

UNLESS OTHERWISE INDICATED, ALL PRINTED CIRCUITS ARE CABLED {+30V → S; 0 V → L; −20V → A}

FOR SS6 AND SS7 SEE ALSO DRAWINGS 126-855-4 AND 126-856-4

* Circled numbers thus ○ refer to the waveform/Time diagram of this unit See Drg Nº 126-1062-0

LAYOUT OF CONSTRUCTION ARRANGEMENT MECANIQUE	125-1946-4	MATERIAL LIST LISTE DE MATERIEL	125-1646-4	
DIAGRAM SCHEMA	125-1546-1			
CERN-MPS	TITLE – TITRE C.P.S. MEAN SPEED REGULATION SYSTEM CONVERTISSEUR TEMPS/ TENSION ET REGULATEUR	DATE 1.8.67.	SIGN.	125-1546-1A


Motor/Alternator Set Running Over-Synchronous

Motor/Alternator Set Running Under-Synchronous

+45V, μsec width

"0" Reset Level of Integrator (± several mV) varied by Pot on card 241P-SK21

Normally fixed variable by pot: P_2 on card 242P-SK18, set to have Integrator Output (0 to 10V) in 10msecs at 1sec repetition period

Reset level of Integrator (± several mV) varied by pot on card 241P-SK22

Amplitude set to have Integrator reset (10V to 0V) in 2.5msecs variable by pot P_1 on card 242P-SK18

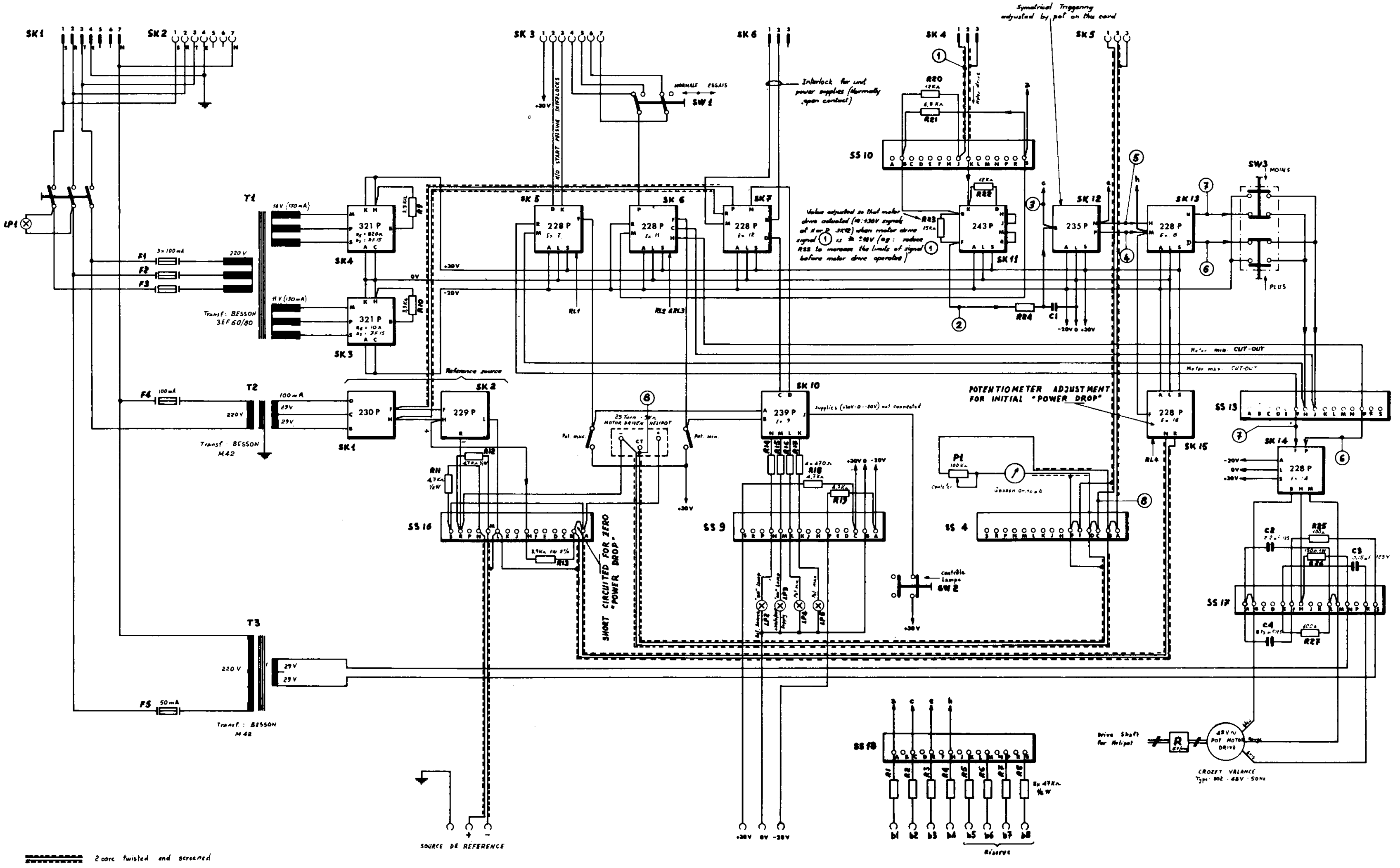
Amplitude set to have Integrator Reset (10V to 0) in 2.5msecs, variable by Pot P_1 on card 242P-SK17

Normally fixed variable by Pot P_2 on card 242P-SK17 to have Integrator Output (0 to 10V) in 10msecs at 1sec repetition period

NB. All logic command pulse widths are 10μsecs
logic high level is +30V
logic low level is 0V

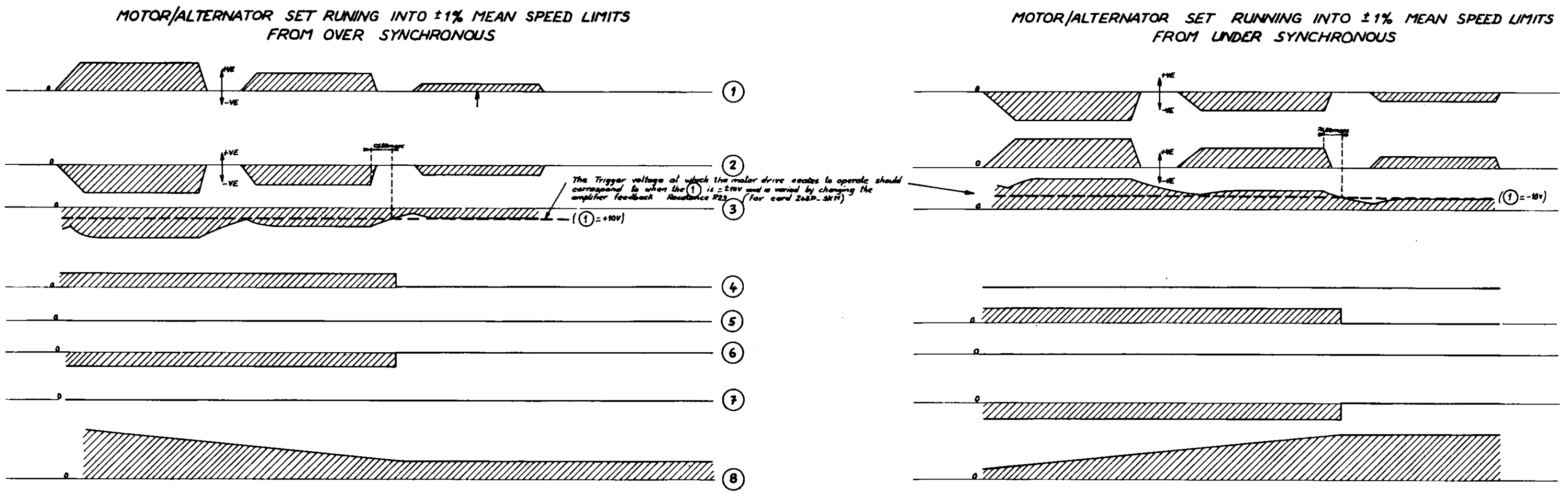
Waveform/Time Diagrams
of the Mean Speed Regulation System U1546
"Convertisseur Temps/Tension et Regulateur".

CERN-MPS 126-1052-1



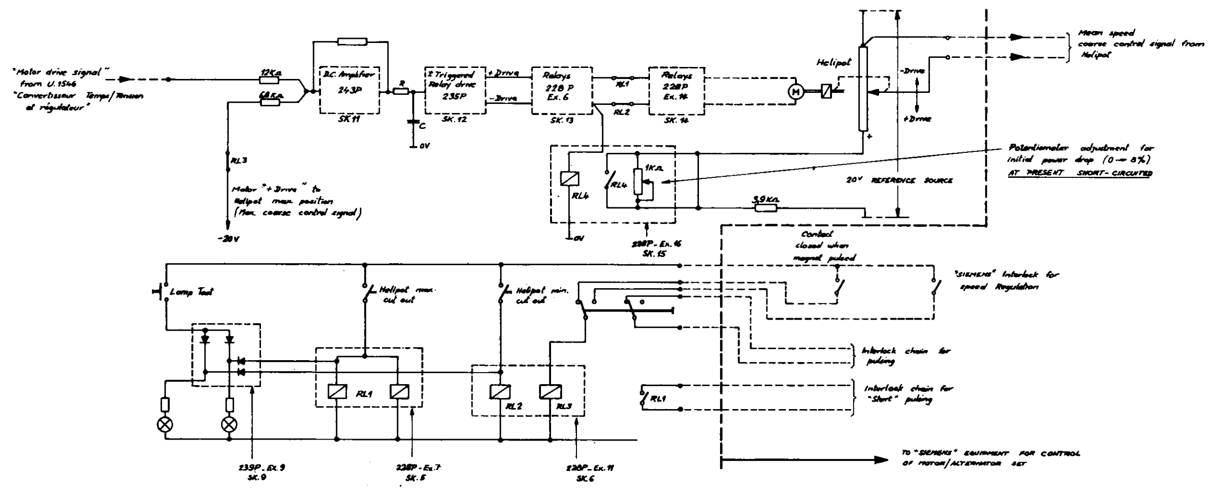
* For waveforms/Time diagram and operating schematic see Drg Nº 125-1853-1

LAYOUT OF CONSTRUCTION / ARRANGEMENT MECANIQUE 125-1547-4
MATERIAL LIST / LISTE DE MATERIEL 125-1547-4
DIAGRAM / SCHEMA 125-1547-1
TITLE - TITRE: POTENTIOMETRE DE RÉF. N 1547
DATE 22/2/67
SIGN
CERN-MPS
125-1547-1


MOTOR/ALTERNATOR SET RUNING INTO ±1% MEAN SPEED LIMITS FROM OVER SYNCHRONOUS

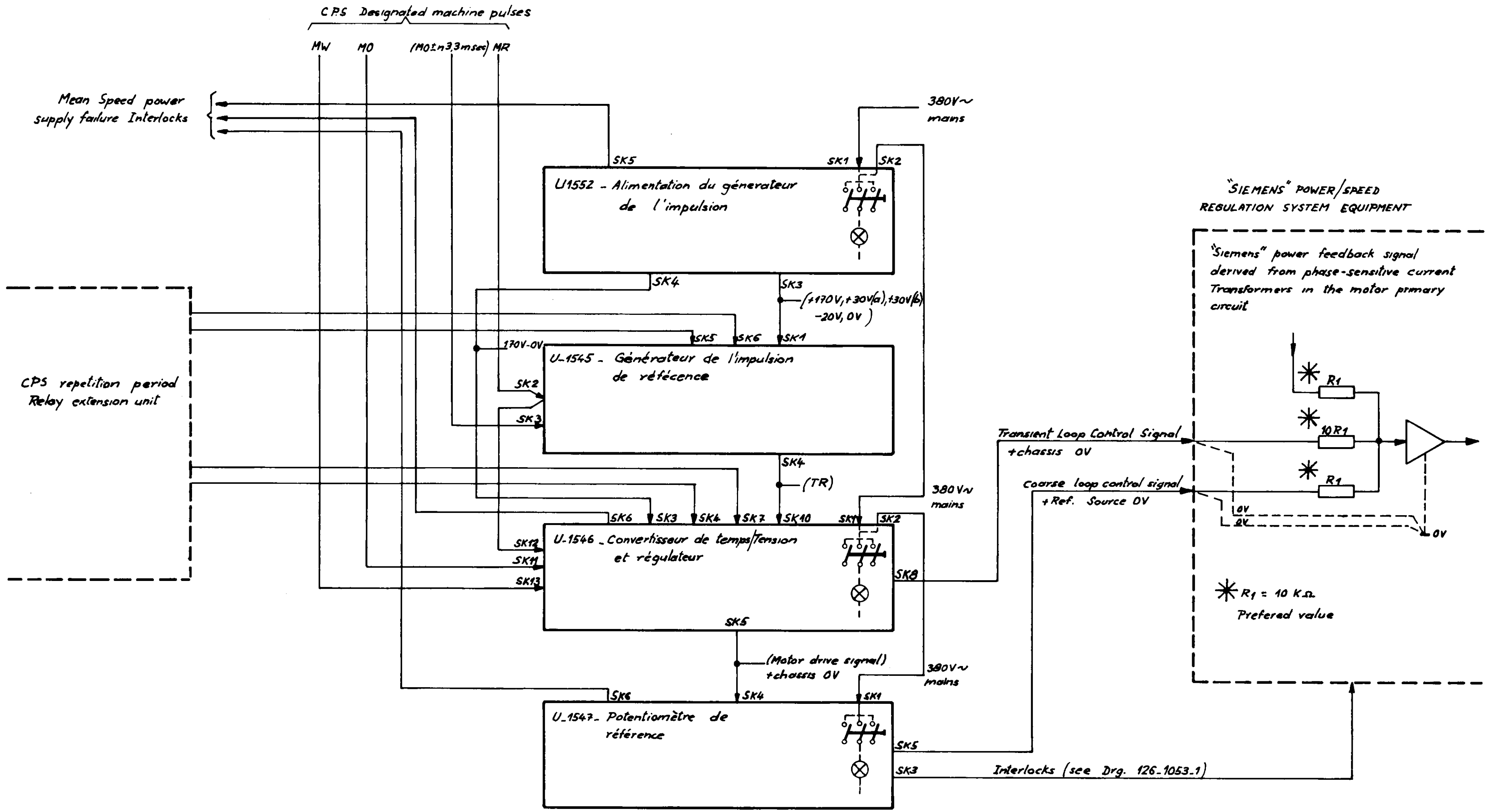
MOTOR/ALTERNATOR SET RUNNING INTO ±1% MEAN SPEED LIMITS FROM UNDER SYNCHRONOUS

The Trigger voltage at which the motor drive ceases to operate should correspond to when the ① is ±10V and is varied by changing the amplifier feedback Resistance R23 (for card 243P - SK11)



WAVEFORM/TIME DIAGRAMS AND GENERAL SCHEMATIC
MEAN SPEED REGULATION SYSTEM
U.1547 "POTENTIOMETRE DE REFERENCE"

126-1053-1



MEAN SPEED REGULATION SYSTEM
CHASSIS INTERCONNECTION

126-1054-3