DISSERTATION

ON

AUTOMATION IN STEEL INDUSTRY

by

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PREFACE

The subject of 'Automation in Steel Industry' is a very wide and diverse topic and it is difficult for one to attempt to squeeze it in a specific dissertation of this nature. During last two decades, there have been considerable advances in the development of Automatic Controls in the various branches of industry. Steel industry has been most sensitive to these developments, on account of its otherwise strategic importance. More of steel in a shorter time is the vital need of the day. The design Engineer of control systems is ever busy in achieving his ideal of instantaneous response and quick steady state..

The field covered by this dissertation has been divided into five chapters. Chapter 1 reviews briefly the fundamental of automatic control and developes mathematical expressions of linear control systems. The characteristics of the transient phenomena associated with the control system regulator have been discussed at length.

Amplifiers which are an important unit of a system of regulation have been dealt with in chapters 2 & 3. In Steel Industry, the most extensively used amplifiers are the D.C. cross field machines also known as rotary amplifiers.

Amongst the various types of cross field machines, that are used in control systems, the 'Amplidyne - Generator' is very extensively used in the steel mills. During the last one decade, the Magnetic Amplifiers have also been successfully used and have exhibited distinct advantages over the amplidynes as regards particular applications.

Chapter 2 has been entirely devoted to the description of amplidynes, from an application stand point. A mathematical expression has been developed for the coefficient of amplification. Effect of machine parameters on the coefficient of amplification is discussed and certain very interesting conclusions drawn therefrom.

Chapter 3 deals with the elementary description of magnetic amplifiers. It discusses the limitations and the scope of the magnetic amplifiers. A typical application of the magnetic amplifier is described.

Chapter 4 is devoted to the study of various control systems, as applied in steel mill practice. Working of some of the control systems, described in this chapter, have been observed and studied by the author at the Zaporostal Plant, Ukraine, U.S.S.R. and the Bhilai Steel Plant (India,Madhya Pradesh) where the author has been working.

The last chapter (chapter 5) deals with the anacom studies made on control systems, with a view to illustrate the effect of the latter, on associated equipment and also concludes the dissertation.

The author thanks the Engineers and Workers of Rolling Mill and Blast Furnace Departments of Zaporostal Steel Plant, Ukraine, U.S.S.R. for their generous help and guidance. My grateful thanks are due to Mr. Sirkar of the Research Library, Tata Iron & Steel Company Ltd., Jamshedpur for helping me to dig out relevant reference material on the subject. I must convey my gratitude to Dr. Z. U. Ahmed of Roorkee University (Now Principal, Regional Engineering College, Srinagar) for his helpful hints and advice. I am also obliged to Shri Hari Ram Sharma, Stenographer of the Regional Research Laboratory, Jammu for the pains he took in typing out this thesis.

BHILAI(M.P.)
March, 1961. A. K. Fotedar.

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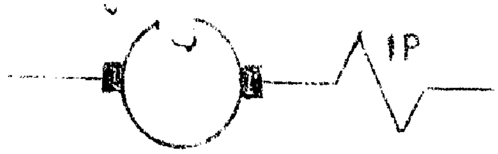
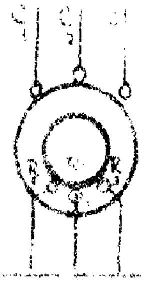
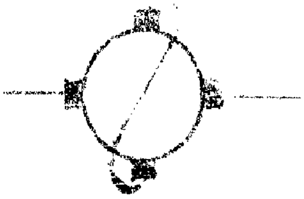
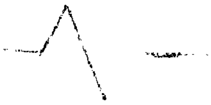
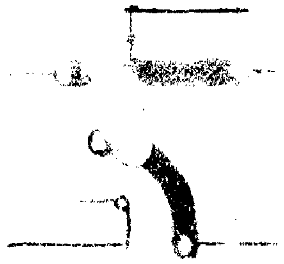
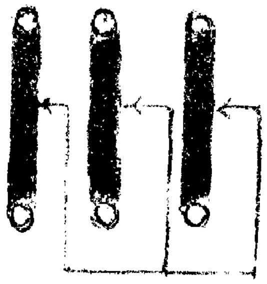
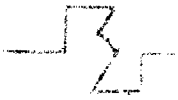
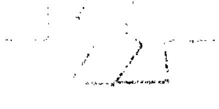
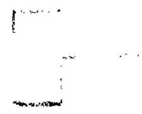
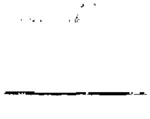
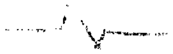
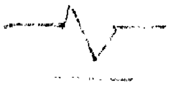
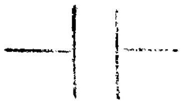
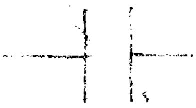
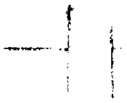
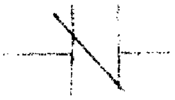
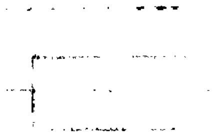
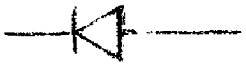
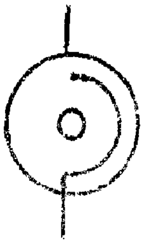
CHAPTER CONTENTS PAGE

SCHEMATIC REPRESENTATIONS

S.No.	Schematic representations	Identification
1.		Armature of a D. C. machine with inter-poles.
2.		Slip ring induction motor
3.		Squirrel cage induction motor
4.		Armature of an amplidyne
5.		Series field winding of a D.C. machine.
6.		Shunt field winding of a D.C. machine
7.		Power circuit resistor.

S.No.	Schematic representations	Identification
8.		Starting rheostats in armature circuits.
9.		Starting rheostats in rotor circuits.
10.		Resistors in control & field circuits.
11.		Closing coil of a shunt contactor.
12.		Connection between two shunt contactors closing coils.
13.		Closing coil of a series contactor.
14.		Relay shunt coil or hold on coil of a contactor.

S.No.	Schematic representation	Identification
15.		Relay series coil, in power Circuit.
16.		Relay series coil, in field and control circuits.
17.		Normally open contact of a contactor.
18.		Normally closed contacts of a contactor.
19.		Normally open auxiliary contact.
20.		Normally closed auxiliary contact.
21.		Normally open auxiliary contact, with magnetic arc quenching coil
22.		Normally closed contact with magnetic quenching coil (Auxiliary)
23.		Signal lamp.

S.No.	Schematic representation	Identification
24.		Condenser
25		Rectifier
26.		Photo-element.

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CHAPTER I

1. AUTOMATIC CONTROL - ITS BASIC ELEMENTS AND THEORY.

Modern technological processes, are often required to maintain constancy of certain functional quantities, or a variation in these quantities according to certain definite law. Supply of electrical energy to different types of undertakings; may for example be required to maintain a constacy in voltage, and frequency. Similarly, rolling of metal in a continuous rolling mill takes place by maintaining a definite relationship between the speeds of the different stands, and so on.

However, majority of the processes do not possess independant characteristics, to regulate themselves according to a certain desired manner, or may be that they only succeed partially. As an example a generator as such may not be able to hold its voltage constant, when there is a change of load at its terminals. Similarly a motor as such would not be able to maintain, its speed constant, when there is a change of load at the motor shaft.

The purpose of Automatic Regulation & Control, consists in maintaining a certain law of variation, are more often a constancy in a particular functional quantity, irrespective of external factors arising out of inherent characteristics of the object under regulation.

The processes thus requiring to be regulated and controlled may be different in character. They may be, thermal, mechanical, electrical, or a combination of these. Undertakings wherein such processes are practically perfected are known as Regulated objects. Any device that regulates a process according to some predetermined condition or law is called an Automatic Regulator. A complete system consisting of the regulator and its object is called a system of regulation.

A system of regulation is characterised by the presence of at least two media, viz., energy and matter. By disturbing the state of equilibrium between the two, the net energy balance is altered, in consequence to which the value of the regulated quantity is altered. The change in the value of the quantity under regulation will in general not be instantaneous, because of the inherent inertia properties of both the objects as well as its regulator. As an example, rise of current in an inductive circuit is related to the circuit time constant while change in the speed of a motor is related to its mechanical time constant. Any disturbance in the normal working of a process will be corrected by the regulator according to some predetermined law, but however such a correction would not be instantaneous, on account of inertia properties of the object and that of its own. In short, any recovery from the disturbed state, will involve a series of transient processess before the steady state has been attained. It therefore would follow, that the length of time of these intermediatory transient processes would depend upon the magnitude of the deviation between the transient and the steady state value of the quantity under regulation. The greater the deviation,the greater the time of these transient processes. The process of regulation could therefore be judged from the following main features:-

a) How far the regulated quantity at the time of disturbance deviates from the steady state value?

b) Process characteristics.

c) Time of intermediatory transient processes.
R

Regulated objects in general may possess, one or more number of simultaneously varying quantities. As an example, a turbo-generator has three simultaneously varying quantities, viz., voltage, frequency and power output. An important characteristic of majority of the objects of regulation is their characteristics property of self regulation. Electrical machines form a large majority in so far as self regulating characteristics are concerned. Thus for example,a generator possesses, positive self regulating characteristics in relation to its terminal voltage. A motor possesses positive self regulating characteristic in relation to its speed at the shaft and so on. The property of self regulation helps to reduce the difference between the quantities under regulation, before and after the disturbance. In that way it reduces the work of the regulator by some appreciable amount.

An automatic regulator may in general consist of the following elements:-

a) Sensitive measuring and transmitting element.

b) Differentiating element.

c) Controlling, executing and stablizing elements.

The transmitting element, is intended to reveal the actual value of the quantity under regulation. The differentiating element will compare the value of the quantity so indicated by the transmitting element, with the desired steady state value, and thereby indicate the difference between the two. The controlling element, amplifies and transmits the 'difference signal' to the executing mechanism of the regulator. In its turn, the regulating mechanism sets itself into action to reduce or totally cancel the difference indicated by the differentiating elements. An ideal regulator would be one in which the executing mechanism would make an instantaneous correction, no sooner there was a disturbance within the object.

Regulators are classified into two classes viz., direct acting, and indirect acting. Regulators of the first type consist of the usual measuring element which directly influences the executing organ. In such cases, the measuring element should supply sufficient power to control the executing organ. Indirect acting regulators will, however, include the amplifying device in addition to the measuring and executing elements. In such cases, the power supplied by the measuring element is amplified by the amplifier so that output of the amplifier would be enough to operate the executing device.

Regulators are further sub-divided into two classes, continuous acting and intermittent acting, depending upon the characteristics of the regulating organ and that of the object. In continuous acting regulators, ~~are~~ regulating organ works continuously corresponding to the variation in the quantity under regulation. In intermittent acting regulators, the regulating organ operates periodically depending upon the periodic variations of the quantity under regulation.

Theoretically, there are four fundamental control responses:

1. Two position
2. Proportional
3. Floating (integeral or reset)
4. Rate

Regulators for each of the above responses, would be defined as follows:

1) Two position regulator:

A two position regulator is that in which the final control element is moved from one of the two fixed positions to the other. Such regulators are desired to limit, the variations in the quantity under regulation between two fixed or set values.

2) Proportional regulator:

A proportional regulator is that in which, there is a continuous linear relation between the value of the controlled variable, and the position of the final control element (executing organ).

3) Floating regulator:

A floating regulator is that in whihh, there is a predetermined relation between value of the controlled variable and state of motion of the final control element (executing organ).

4) Rate regulator;

A rate regulator is that in whihh, there is a continuous linear relation between rate change of the controlled variable and position of the final control element (executing organ).

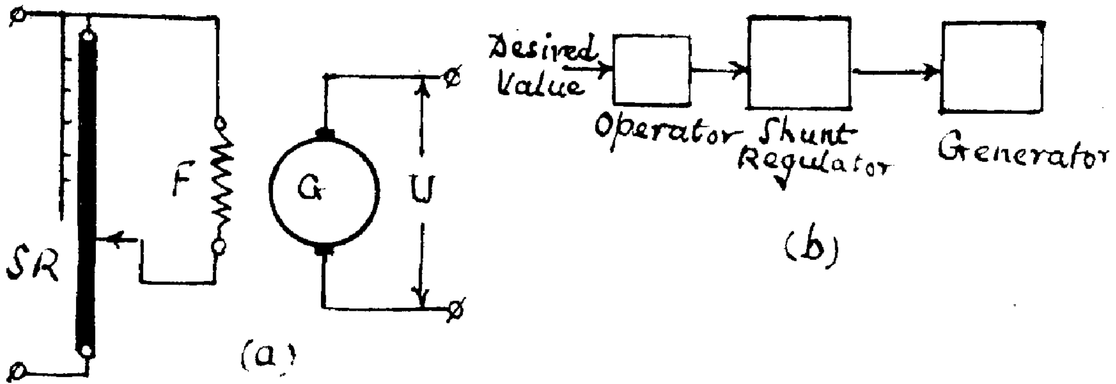
It is sufficient for the scope of this dissertation, to indicate that the use of single mode of regulation, such as two position or floating with its inherent oscillating characteristic and proportional control with its inherent offset characteristic is not satisfactory. Therefore industrial automatic regulator combinations, which incorporate the benefits of more than one control effect are common. The three important controller or regulator combinations are listed below:

1) Proportional plus reset
2) Proportional plus rate
3) Proportional plus rate plus reset

1.1 STRUCTURE OF SYSTEM OF REGULATION.

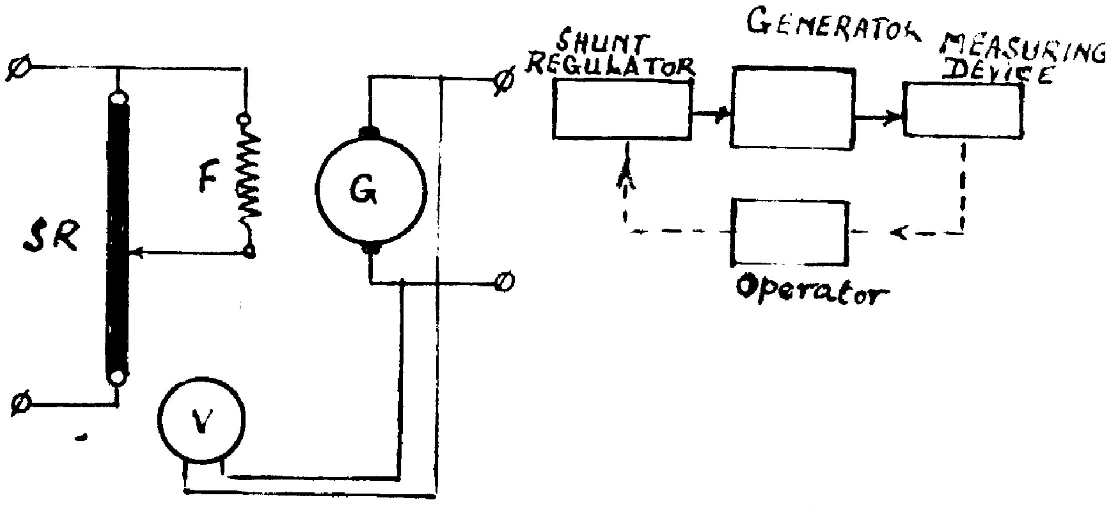
Let us consider the case of a D.C. generator. It is required to control the voltage of the generator with the help of a shunt field regulator (See Fig.1) If the shunt field regulator is calibrated in terms of the voltage across the generator terminals, a human operator can control the generator voltage to any desired value, by adjusting the regulator arm at the desired value. We can thus represent such a system of regulation, as shown in Fig. 1(b). This may be called a straight line or an open loop structure. After the operator sets the voltage at a desired value, it can happen that the voltage changes from the set desired value, due to certain external influences. In such cases, the operator shall not be able to re-adjust the value at the set point, and our straight line or open loop structure will be inaccurate and even false.

OPEN
&
CLOSED LOOP SYSTEMS
OF
REGULATION



(a) (b)

Fig(1) CONTROL OF GENERATOR VOLTAGE



(a) (b)

Fig(2) CLOSED Loop System
OF
REGULATION

Let us now suppose that the control post of the operator is provided with a volt meter, directly connected across the generator terminals. In such a case, any changes in the voltage from the set point, due to external influences, will be indicated by the volt meter and the operator will be able to maintain the set value, by re-adjustment of the shunt field regulator. Such a system of regulation; can be represented by a closed loop as shown in Fig.2. If we are able to replace the human operator, by incorporating additional control elements, which can measure deviations of the generator voltage from the set value and which can make appropriate corrections in the generator voltage, (re-adjustment of the voltage at the set value) we arrive at, what is called the automatic system of regulation.

As an example, Fig.3 shows an elementary scheme of automatic voltage regulation. The generator voltage (U) at any instant is compared with the set or the desired value (U_0). The difference or deviation ($U-U_0$) is amplified by an amplifier, the output terminals of which are connected to the field winding EF of the exciter E. The exciter further excites the generator field GF, which brings about the necessary correction in the voltage across the generator terminals.

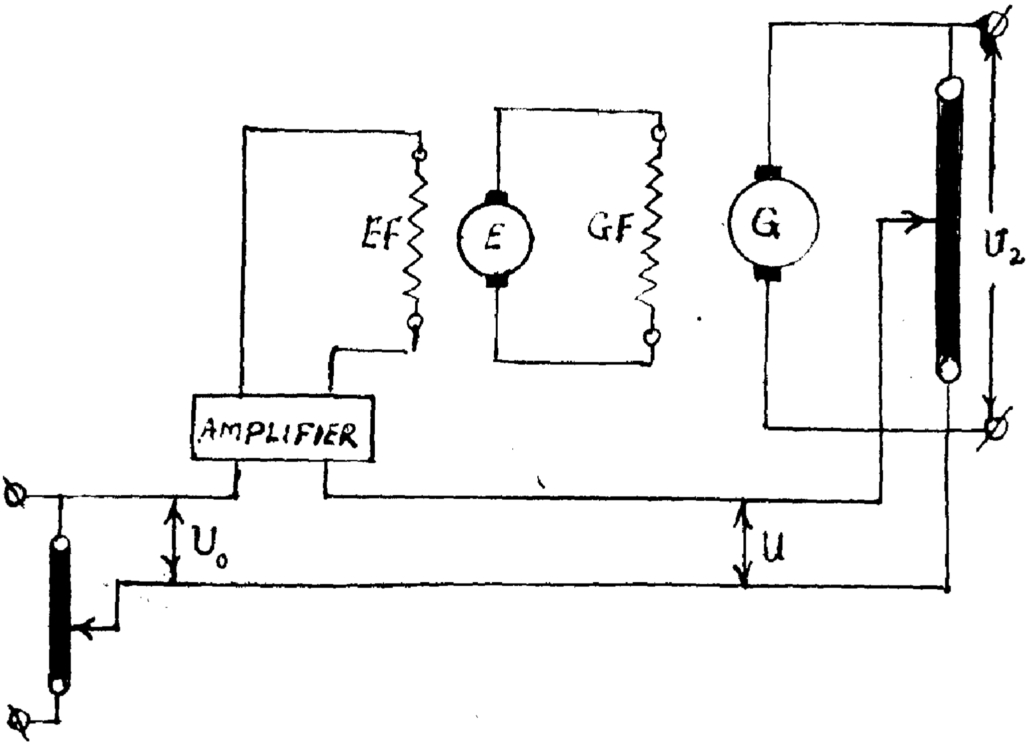
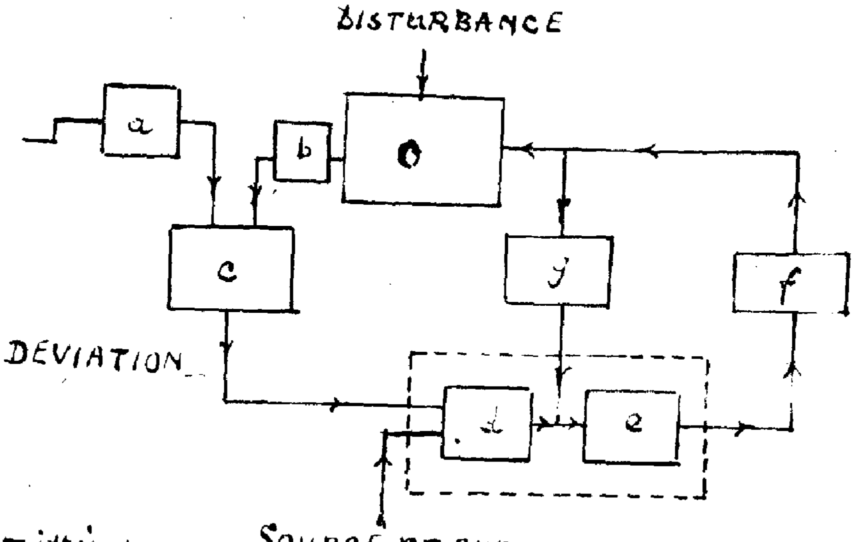


Fig (3)



a - Transmitting element.
b - Sensitive Measuring element.
c - Differenciating element
d - Amplifying element.
e - Rectifying element
f - Regulating organ.
g - Stabilising element
O - OBJECT OF REGULATION

Fig (4)

It will be observed that the above scheme, or for that matter any other scheme of automatic regulation, has three salient features:

1. A system of regulation is characterised by a 'closed loop' wherein any disturbance (deviation of the controlled parameter from the steady state value) is picked up by the sensitive measuring element and transmitted right round the loop, consisting of differentiating, controlling, executing and stablising elements.

2. The transmission of the disturbance, (deviation of the controlled parameter from the steady state value) as picked up by the sensitive measuring element is unidirectional. Refer Figs. 1 & 2 where the directions are indicated by the arrows.

3. The disturbance is so directed and the scheme of regulation so arranged, that the final correction of the disturbed parameter is such as to decrease the difference, between the steady state value and the value at the instant the disturbance took place. Systems where the correcting signal is directed in a direction so as to further widen the gap between the steady state and instantaneous values, are called self exciting systems.

What has been said above, can be very easily exemplified by the voltage regulator of a D. C. generator, shown in Fig. 3. Let us assume that due to some external disturbance, the generator voltage shot up by some amount from its nominal or steady state value. If the scheme of regulation is proper, the above deviation should be directed so as to decrease the exciter voltage, and bring back the generator voltage to the nominal value with reasonable accuracy. If we had arranged the scheme such that, the deviation was directed in a direction so as to further increase the difference between the steady state and instantaneous value, we would arrive at a self exciting system. The generator voltage would continuously rise, and would be limited only by magnetic saturation of the system.

We, therefore, conclude that a system of regulation, is a close dynamic cycle, where any disturbance in the value of the controlled parameter is directed so as to bring about ' a positive correction', in the values of the disturbed parameter. By positive correction, we mean the minimising of the difference between the steady state and instantaneous values. Fig 4 shows a skeleton diagram of a system of regulation in which each of the elements have been shown in blocks. Instantaneous value of the controlled parameter is measured by the sensitive measuring element. The differential element compares the instantaneous value, as measured by the measuring element, with the desired steady state value (also called the set point). The output from the differential element is a function of the deviation, which is fed at the input end of the controlling device. The controlling device consists of amplifying and rectifying elements. Controlling device controls the regulating organ which in turn makes positive correction in the parameter of the object under regulation.

In addition to the elements enumerated above, the system may further contain stabilising and forcing elements (as shown in Fig. 4).

1.2 FUNDAMENTAL ANALYSIS OF A SYSTEM OF REGULATION.

In a system of regulation, the controlled parameter undergoes through a number of physical processes, from the instant the deviation is detected by the measuring and differential elements, till such time it is corrected by the controlling device and the final regulating organ. We shall study these processes as functions or properties. We will later find out how these functions, when synthesised, affect a system of regulation?

a) Amplifying function:

Amplification is defined mathematically by the following equation:

$$x = k.x_1 \qquad (1)$$

where x_1 - output value (or function)

x - input value (or function)

k - coefficient of amplification

In other words the amplifying function should be such that the output is k times the input at all instants of time.

Fig. 5 shows how the output varies with respect to time when there is a continuous disturbance of constant magnitude. An example of such an amplifying function may be any linear amplifier, practically without inertia (as compared with other elements of the system).

b) Inertia function:

Let us consider the switching on processes associated with the exciting windings of direct current electrical machines. Rise of current in such a circuit, would be given by the equation:

$$L\frac{di}{dt} + ri = e \qquad (2)$$

where ,

L - Coefficient of self induction

r - Circuit resistance

e - Applied voltage

when,

$$\left.\begin{array}{ll} t \leqslant 0, & e = 0 \\ t > 0, & e = E \end{array}\right| \qquad (3)$$

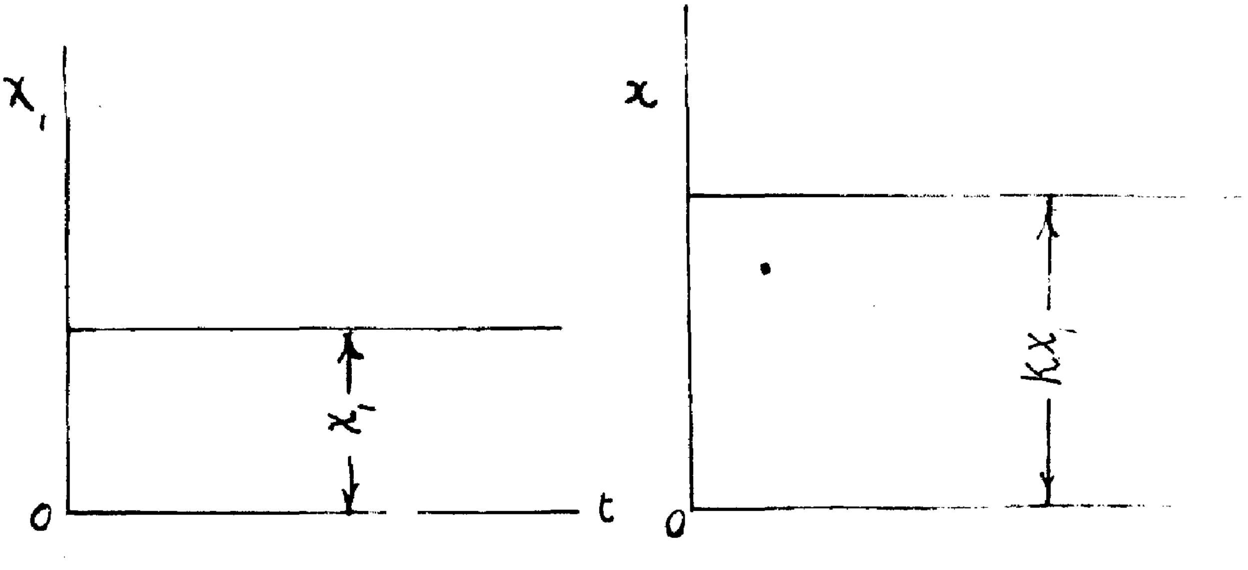


Fig (5a)

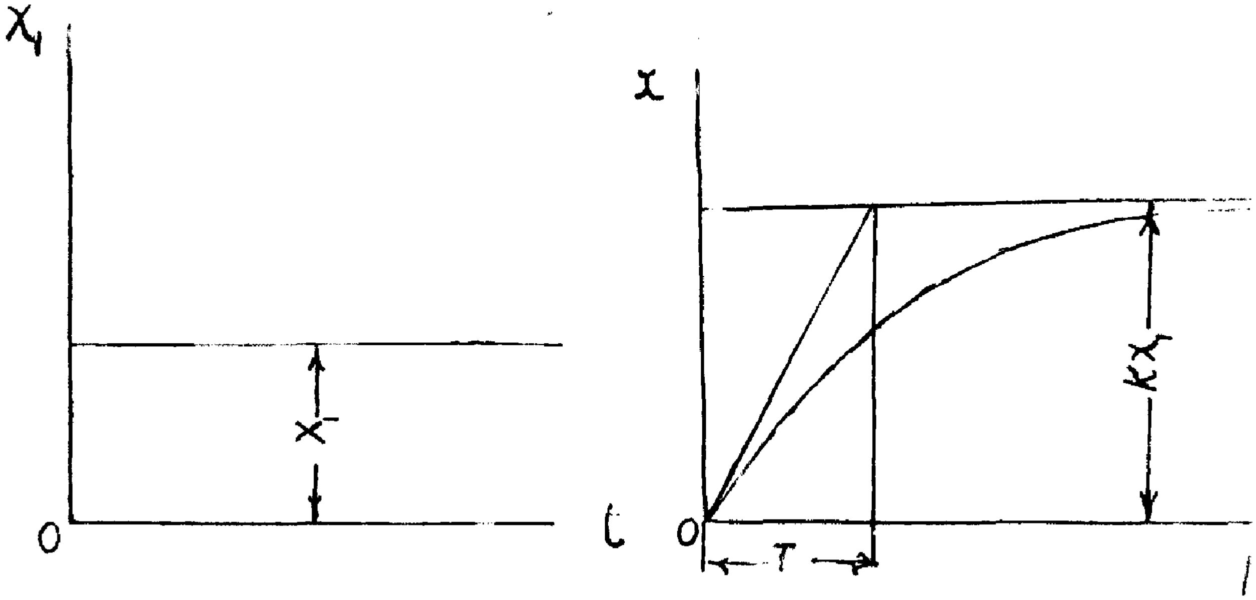


Fig (5b)

We can therefore express e in terms of a unit function, i.e.,

$$e = E\,[1] \qquad (4)$$

A unit function is an impulse function, which is equal to 0 when t is less than or equal to 0 and is equal to unity when t is greater than 0.

Equation 2 can also be expressed as follows:

$$T\,\frac{di}{dt} + i = \frac{1}{r}\,E\,[1] \qquad (5)$$

where, $T = L/_r$ — Time constant of the exciting winding.

Solution to the above equation may be expressed as :

$$i = i_y\,(1 - e^{-t/_T}) \qquad (6)$$

Here $i_y = E/_r$ is the final value of the current through the circuit, practically attainable after an interval approximately equal to 3 to 4 times T.

Let us now consider, the above exciting winding, as the object of a regulating system which has the usual, sensitive measuring element, differential element, controlling device and the regulating organ. Let us consider the voltage e, with an input value (x_1), and the exciting current, from the output terminals of the amplifier equal to (x). We therefore have:

$$T\,\frac{dx}{dt} + x = kx_1 \qquad (7)$$

where k = coefficient of amplification. Under steady state conditions, $\frac{dx}{dt} = 0$, in which case,

$$x_y = K x_1$$

$$\text{or} \quad k = \frac{x_Y}{X_1}$$

Equation 7, can be said to represent an inertia function.

If the disturbance on the input end is representable by a unit function, i.e.,

$$x_1 = X_1 [1]$$

The solution to equation 7 may be written as :

$$x = k X_1 (1 - e^{-t/T}) \qquad (8)$$

Fig. 5, graphically illustrates the results we arrived at by the above analytical methods. In addition to the above example, we may come across a similar case, with a D.C. motor separately excited and with negligible armature inductance. With the terminal voltage as the input and the speed of the motor as the output.

The above physical processes or properties, could as well be expressed by equavalent electric circuits. Inertia function; could be expressed by one of the two, equivalent circuits shown in Fig. 6. Consider the circuit with inductance L and resistance R connected as shown in Fig.6. The rectangular block k, represents the amplifier (ideal amplifier without inertia). If the input terminals are connected to a D.C. potential represented by a unit function, ($e = E [1]$),

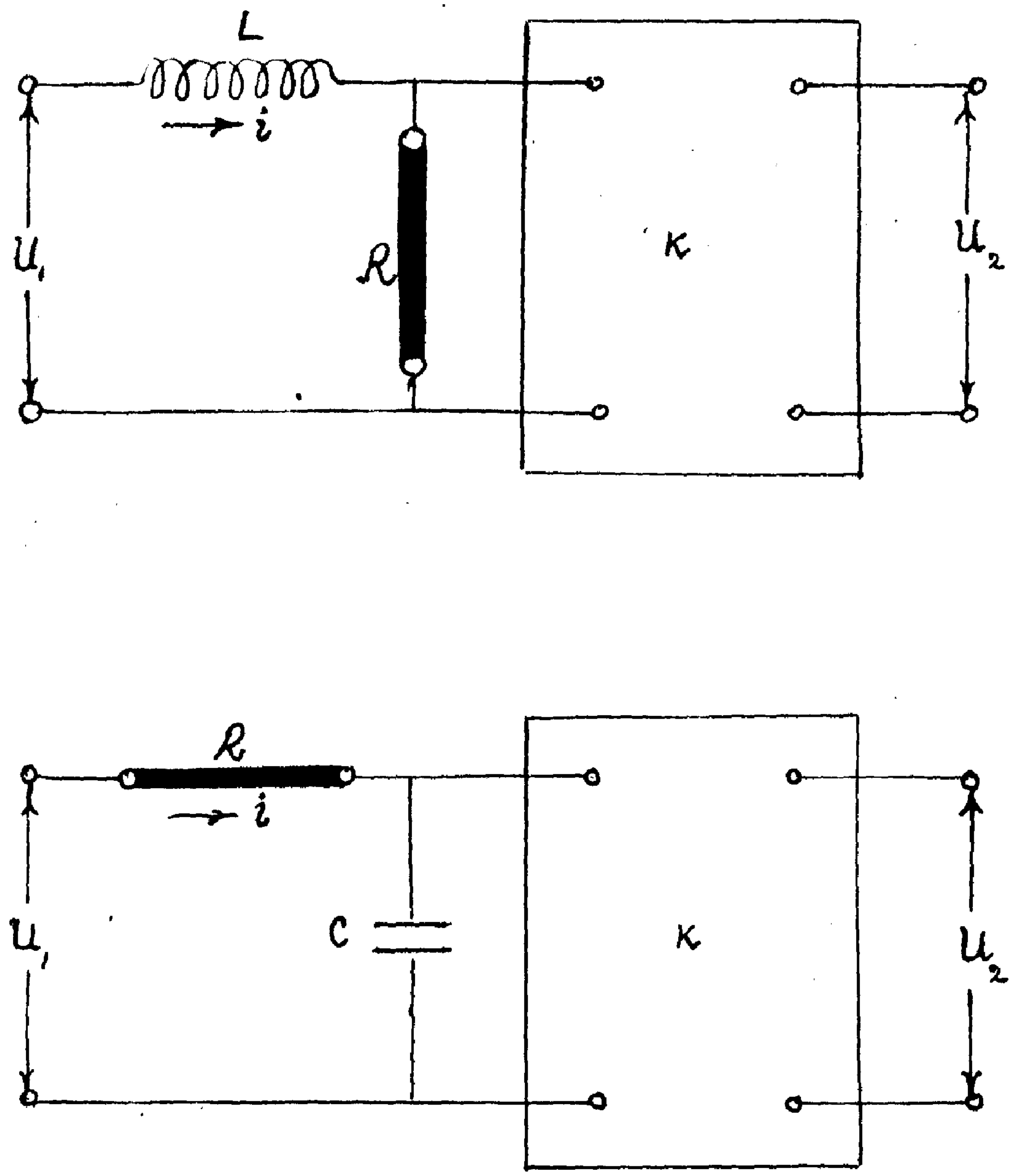


FIG (6)

- INPUT VOLTAGE
- OUTPUT VOLTAGE

the current on the input side will rise exponentially and so will the voltage rise on the output side. This exactly is what we arrived at by analytical methods. Similarly the other equivalent circuit with a resistance and capacitance is also representative of an inertia function, as here also currents & volta on the input and output ends follow and exponential law of variation.

(c) Oscillating function.

Consider the process of switching on a separately excited D.C. motor, with appreciable inductance in the armature circuit. Variation of current in the armature circuit at the time of switching in, is related to the change of the electro magnetic energy stored in the armature. Running or speeding of the motor is related to the kinetic energy and the moment of inertia of the armature. This system thus is a two capacity process, and it follows that the associated transient processes could be represented by a differential equation of second order. Depending upon the relative magnitudes of the armature circuit time constant and the electro mechanical time constant of the motor, the process of running may follow an oscillatory (damped)or a Non-Periodic pattern. Just when the supply to the motor is switched on, the armature current tends to increase very quickly. After a certain time delay, the motor correspondingly starts accelrating.

As the motor goes on running (i.e., picking up speed) the rate at which the current rises in the armature circuit is much more initially, but after some time the current starts decreasing and the rate of change becomes negative. If the armature circuit time constant is comparatively large, then the instant the motor attains its nominal or steady state speed the value of the armature current is still a little larger, than the nominal or steady state value with the result the motor speeds up. Now when the current starts decreasing and reaches the steady state value, motor speed is more than the steady state value, with the result the current again starts increasing. This way the system goes on oscillating. The oscillations are damped in course of time by the presence of armature resistance and frictional losses. To arrive at the law of variation of motor speed with respect to time, we utilise the following equation of the armature circuit, relating the applied voltage with circuit constants and the back e.m.f.

$$i\, r_a + L_a \frac{di}{dt} + e = U \qquad (9)$$

Equation of motion (rotation) of the motor will be :

$$I \frac{dw}{dt} = c\, i \qquad (10)$$

We assume for the sake of simplicity, that the static load torque is zero. In these equations :

e — e.m.f developed by the motor,

I — moment of inertia of the rotating masses about the motor shaft.

w — Angular speed,

$c = \frac{T_n}{i_n}$ — Coefficient of proportionality,

T_n — Nominal or rated torque of the motor,

i_n — Nominal current of the motor.

Assuming that there is no magnetic saturation;

$$e = \frac{E_n}{w_n} w,$$

where E_n — e.m.f. corresponding to a nominal speed of w_n.

From the above three equations we get:

$$\frac{d^2w}{dt^2} + \frac{1}{T_a}\frac{dw}{dt} + \frac{1}{T_a}\frac{1}{T_{EM}} w = c\,U \qquad (11)$$

Where,

$T_a = \frac{La}{r_a}$ — armature circuit time constant,

$T_{EM} = I \frac{w_n i_n r}{T_n E_n}$ — Electro mechanical time constant of the motor.

$c = \frac{1}{T_a T_{EM}} \frac{w_n}{E_n}$ — Coefficient of proportionality.

So as to find out the law of variation of the speed w.r.t. time, it is necessary to solve equation (11). The characteristic equation of this differential equation will be :

$$p^2 + \frac{1}{T_a} \cdot p + \frac{1}{T_a \cdot T_{EM}} = 0$$

which has two roots:

$$p_{1,2} = \frac{-1}{T_a} \pm \sqrt{\frac{T_{EM} - 4\,T_a}{4\,T_a^2\,T_{EM}}} \qquad (13)$$

i) If, $(T_{EM} - 4\,T_a) > 0$, roots (p_1 & p_2) are both real and negative, the general solution will be :

$$w = C_1\, e^{-p_1 \cdot t} + C_2\, e^{-p_2 \cdot t}$$

where C_1 and C_2 are arbitrary constants. We therefore infer that, when the roots to the auxilliary equation are real and negative the rise of speed takes place according to an irregular (non periodic) function—— sum of two decaying exponentials, with different coefficients.

ii) If, $(T_{EM} - 4\,T_a) < 0$, roots (p_1 & p_2) are imaginary (complex), the general solution will be :

$$w = e^{Ax} (C_1 \cos Bx + C_2 \sin Bx)$$

We have assumed, that $p_1 = A + i\,B$ and $p_2 = A - i\,B$.
It follows, that the rise of speed is associated with a decaying oscillation.

With increase in the resistance of the armature circuit, the oscillations will decay faster. This is obvious on account of the fact, that during each oscillation most of the energy will be dissipated in the form of heat, due to the presence of armature circuit resistance. With sufficient armature circuit resistance, the oscillatory processes may be completely annuled and thereafter may follow the irregular or the non periodic processes. In other words, with increase in armature circuit resistance, the armature circuit time constant is decreased and the real part of the roots increases which characterises the rate of decay. Simultaneously the imaginary part of the roots decreases, which characterises the frequency of oscillations. If the armature circuit resistance is such that:

$$T_{EM} = 4\, T_a \quad ,$$

the imaginary part of the roots vanishes and the oscillations completely die down.

With further increases in the armature circuit resistance, the nature of roots is real and negative, consequently rise of speed in the motor follows an irregular or non periodic pattern. It may be noted that the real part of the roots is always negative, because T_a is always greater than zero. This means that the speed of the motor always rises to the desired or the steady state ntly come across many other one discussed above. For the ht rewrite equation 11 as :

$$+ \quad b \frac{dx}{dt} + cx = d\, x_1 \qquad (1$$

ary equation will be,

$$p + c = 0 \qquad ($$

$$\frac{- b \pm \sqrt{b^2 - 4\,a\,c.}}{2a} \qquad ($$

both the roots are real and ten as:

$$- \frac{1}{T_1} \quad ; \quad p_2 = - \frac{1}{T_2}$$

ation may also be rewritten

$$1 \,)\, (\, p\, T_2 + 1 \,) = 0$$

$$= 0 \quad \text{or} \quad p\, T_2 + 1 = 0$$

may be considered as auxilliary

equations of a multistage inertia function:

$$\left.\begin{aligned} T_1 \frac{dx(1)}{dt} + x(1) &= K_1 x_{1(1)} , \\ T_2 \frac{dx_{(11)}}{dt} + x_{(11)} &= K_2 x_{1(11)} \end{aligned}\right\} \qquad (18)$$

The original, differential equation can be obtained if the output from the first stage is fed as input of the second stage. Input of the first stage and output from the second stage is equivalent to input and output of the system as a whole.

Therefore, let us quote :

$$x_{1(1)} = x_1; \quad x_{(1)} = x_{1(11)} ; \quad x_{(11)} = x$$

The combined differential equation may therefore be written as:

$$T_1 T_2 \frac{d^2x}{d\,t^2} + (T_1 + T_2) \frac{dx}{dt} + x = K x_1 \qquad (19)$$

where, $K = K_1 K_2$ —— resultant coefficient of amplification of a two stage inertia function.

It should be noted that the resulting coefficient of amplification or gain is a product of the individual gains per stage.

It follows that if a system of regulation can be written in the form of a second order differential equation, the auxilliary equation of which has real and negative roots, then the system can be considered to consist of two sub-systems connected in series. This is a very useful deduction and will be utilised in deducing the generalised equation of a system of regulation.

b) When $b^2 - 4ac < 0$, the roots are imaginary(complex).

$$p_{1,2} = r \pm j\,w; \; (j = \sqrt{-1}) \tag{20}$$

Transient processes in this case consist of a decaying sinusoidal oscillation. The real part of the roots is,

$$r = \frac{-b}{2a} = \frac{-1}{2\frac{a}{b}} = \frac{1}{2\eta} \tag{21}$$

which indicates the rate of decay. η is called the coefficient of decay. Imaginary parts of the roots is,

$$w = \frac{1}{2a}\sqrt{4ac - b^2}$$
$$\equiv \sqrt{\frac{c}{a}\left(1 - \frac{b^2}{4ac}\right)} \tag{22}$$

which indicates frequency of oscillation. Let us suppose that there is no decay, i.e.,

$$r = \frac{-b}{2a} = 0 \tag{23}$$

Under the above condition there will develop in the system a sinusoidal oscillation of constant magnitude and frequency,

$$w = w_0 = \sqrt{\frac{c}{a}} \qquad (24)$$

This frequency is known as natural frequency of oscillation. We may modify equation 22 and re-write the same as follows:

$$w = w_0 \cdot \sqrt{1 - \left(\frac{r}{2\,w_0 \cdot \eta} \right)^2} \qquad (25)$$

With the help of the above deduction the original differential equation (equation 14) can be re-written as follows:

$$\frac{1}{w_0^2} \cdot \frac{d^2x}{d\,t^2} + \frac{1}{w_0^2 \cdot \eta} \cdot \frac{d\,x}{d\,t} + 1 = k\,x_1 \qquad (26)$$

If the input to the system is of the nature of an single instantaneous impulse, i.e.

$$x_1 = X_1 \; [1]$$

The solution to the differential equation will be :

$$x = x_y + e^{-1/2\eta} \left(C_1 \operatorname{Sin} w\,t + C_2 \operatorname{Cos} w\,t \right) \qquad (27)$$

Here, $x_y = KX_1$ —— steady state output value,

C_1 and C_2 —— Arbitrary constants determined from initial conditions, i.e. when $t = 0$, $x = 0$ and $\frac{d\,x}{d\,t} = 0$

With the values of C_1 and C_2 calculated as indicated above the solution to the differential equation (26) will be :

$$x = K X_1 \left[1 - e^{-1/2n} \cdot \left(\operatorname{Cos} w t + \frac{1}{2 n w} \operatorname{Sin} w t \right) \right] \tag{28}$$

Fig. 7 shows the variation of x with respect to time, just after the system has been impressed with a single instantaneous impulse. Oscillatory function of a system of regulation, can be translated into an equivalent electrical circuit (Fig. 8). The input voltage and output voltage of this circuit, are related to each other by differential equation (26) , wherein the constants have the following particular values:

$$n = \frac{L}{r} , \quad w_0 = \frac{1}{LC} , \quad w = w_0 \quad 1 - \left(\frac{1}{2 w_0 n} \right)^2 \tag{29}$$

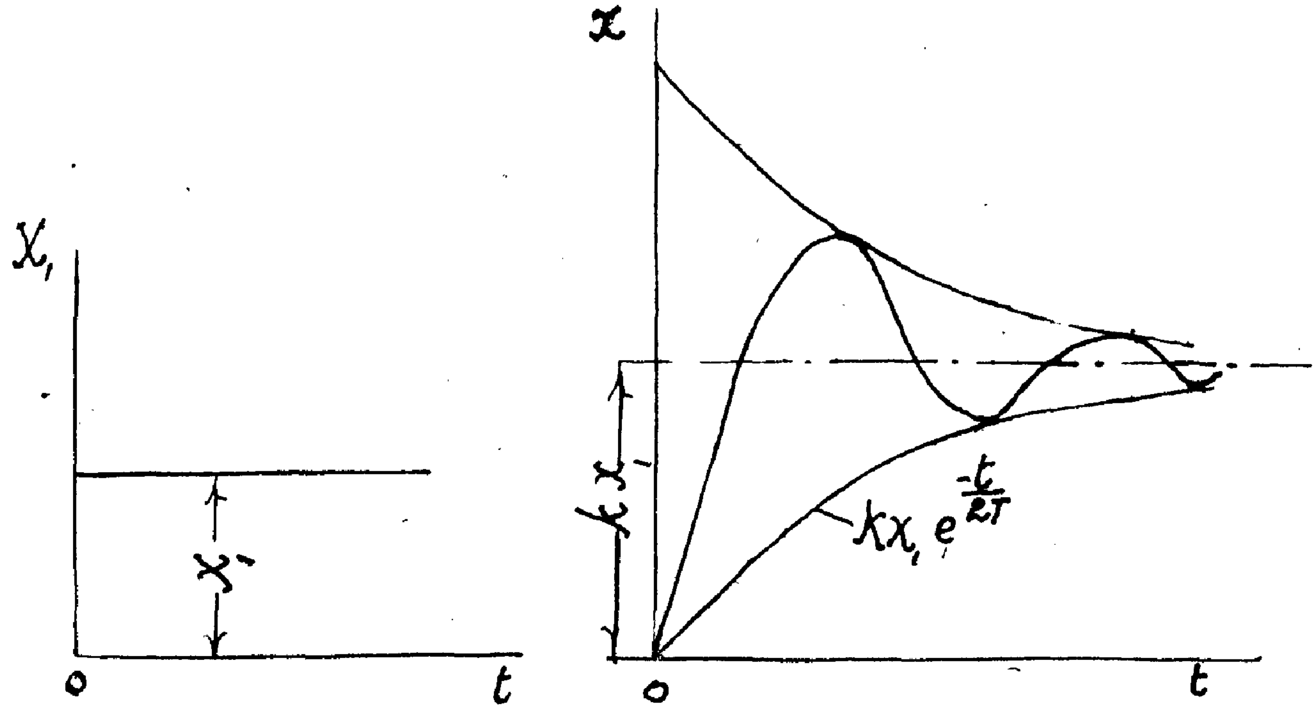
When $r = 0$, decrement in the amplitude of the oscillation stops. In which case ,

$$n = \text{infinity}, \text{ and } w = w_0$$

d) Integerating Function.

Integrating function of a system of regulation may be defined mathematically as :

$$x = K . \int^{t} x_1 . d t \tag{30}$$



FIG(7)

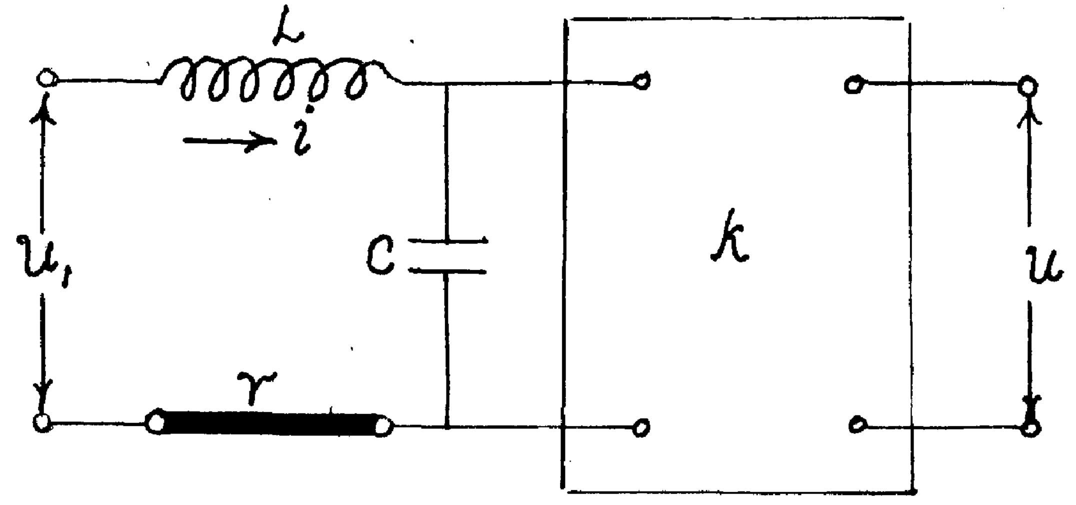


FIG (8)

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where x is the output value, and x_1 the input value. We may therefore say that the integerating function of a system of regulation is such that the output value equals the time integral of the input value. If we impress at the input terminal a disturbance of the nature of a unit impulse function of amplitude X_1 we will get a linear function at the output terminals:

$$x = K X_1 . t \qquad (31)$$

An example of an integerating function is offered by a separately excited D.C. motor, wherein the speed is the input value and the angle of rotation is the output value (see Figs. 9 & 10).

e) Differentiating function.

A differentiating function, of an element of system of regulation is such that,

$$x = k . \frac{d x1}{d t} \qquad (32)$$

i.e., the value at the output is proportional to the rate of change of the impressed disturbance with respect to time at the input terminals. Thus if we impress at the input terminals, a disturbance of the nature of a unit impulse function then at the output terminals we will have an infinite output.

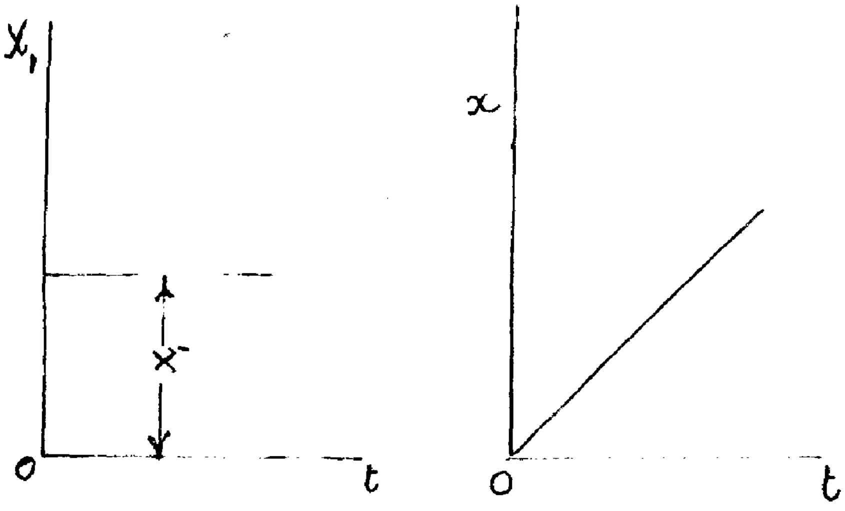


FIG (9)

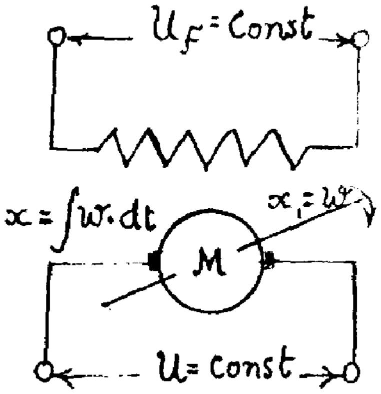
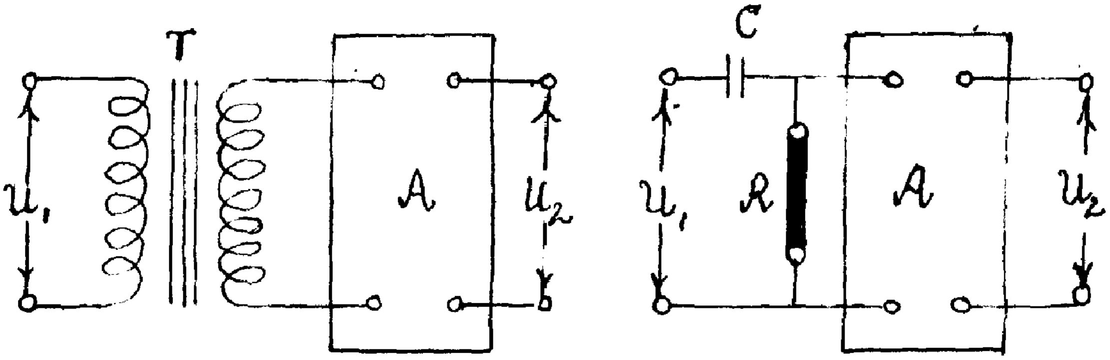


FIG (10)



(a) (b)

FIG (11)

In Fig. 11 are shown two possible diagrams of a differentiating function. In the first diagram the differential element is the transformer. The input voltage is impressed at the primary terminals of the transformer. Voltage at the secondary terminals (output) will be approximately, proportional to the rate of change of voltage in the primary winding. If the leakage fluxes of the transformer are small (i.e. with relatively small secondary loads) , the secondary voltage is more accurately proportional to the rate of change of the primary voltage. In the second diagram, the input voltage is impressed at the terminals of a series circuit consisting of a condenser and a resistance. The drop of voltage in the resistance is proportional to the current through the circuit, and is approximately proportional to the rate of change of voltage at the input terminals.

1.3 HOW A SYSTEM OF AUTOMATIC REGULATION, ENFORCES CONTROL.

If at any instant the existing steady state of a system of regulation is disturbed by some extraneous disturbances, the system is set in motion (a process of restoration) and depending upon its characteristics the system may or may not attain a new state of equilibrium.

If a system of regulation is such that after the occurrence of a disturbance within the system, the system again returns back to a desired steady state condition the system is said to be stable. If the above statement is reversed, we arrive at an unstable system.

In general stability is not characteristic to systems of regulation only but also to all the dynamic processes of the universe. The new state of equilibrium after the occurrence of a disturbance is different from the preceding state of equilibrium, in the sense that the various controlled parameters of the process have different values corresponding to a new desired set value. In such a condition the energy quantum that is stored in the various elements (depending upon the capacities of these elements), must change after the occurrence of the disturbance, reset with new values of these energy quantums. Thus with the increase in the voltage of a D.C. Generator, the field excitation of the generator must change (increase), and hence the electromagnetic energy stored in the field winding must also change (increase). The change in the total quantum of energy stored in the various elements of a system,such as in a magnetic system, cannot take place instantaneously as this would necessiate infinite motive force

Thus a change in an energy quantum can take place gradually and not instantaneously.

The enforcement of a desired control by a system of regulation , could be expressed with the help of a generalised differential equation. The following equation holds for a linear system of first order,

$$x = x_y + \sum_{i=1}^{n} C_i e^{p_i t} \qquad (33)$$

where,

x_y — particular solution of differential equation, g the steady state value of t deviation.

p_i — roots of the correspondin auxilliary equation, whic re generally complex.

C_i — Constants of integerati determined from the ini l conditions of the syste (initial energy quantu disturbing forces and s tem parameters.

Equation 33 shows, that at any instant of time th deviations from the original steady state, are a m of two deviations viz., the set value of the deviat (x_y) and the transient value of the deviation, x_{Tr}.

$$x_{Tr} = \sum_{i=1}^{n} C_i e^{p_i t^t} \qquad (34$$

The dynamic characteristics of a regulating s m is determined by the associated transient processes. The character of the transient deviations, are determined by the nature of the roots (p_i) of the auxilliary equation and the constants of integeration (C_i). If the roots of the auxilliary equation are real, the associated transient processes are non-periodic in pattern. The transient deviations, in such a case is a sum of functions, of the type $C. e^{p\,t}$. If the roots are negative too, the system is stable and the transient deviation goes on decreasing with the passage of time. Mathematically the same can be expressed as follows:

$$\left.\begin{array}{lll} & x_{Tr} \rightarrow & 0 \\ \text{when} & t \rightarrow & \text{infinity}\end{array}\right\} \qquad (35)$$

Fig. 12 illustrates graphically, the transient processes that are associated with a system of third order having real and negative roots, after the system has been disturbed by a disturbance of the nature of a unit impulse function. The resultant deviation in this example tends to set itself nearer to the steady state value x_y. If at least one of the roots were positive the system of regulation would become unstable, and the transient deviation would go on increasing to a maximum possible value for system under consideration.

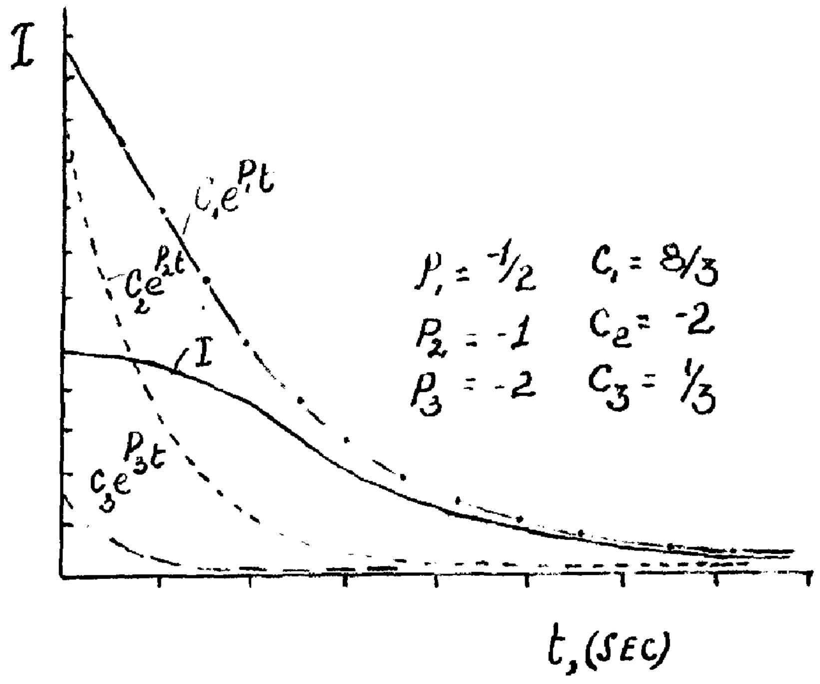

I
$C_1e^{P_1t}$
$C_2e^{P_2t}$
I
$C_3e^{P_3t}$
$P_1 = -1/2$ $C_1 = 8/3$
$P_2 = -1$ $C_2 = -2$
$P_3 = -2$ $C_3 = 1/3$
t, (SEC)

FIG (12)

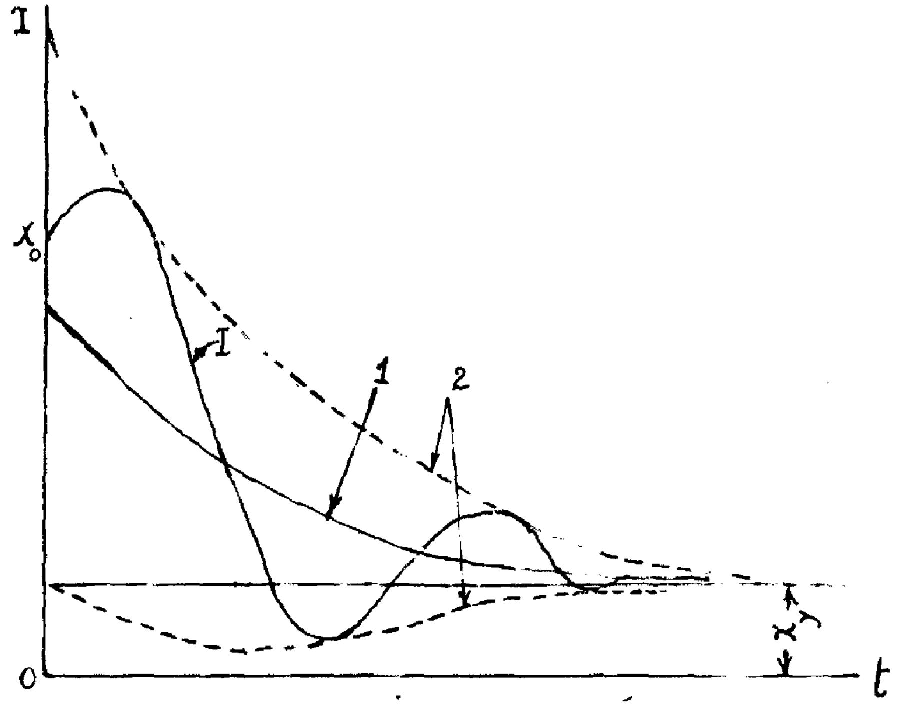

I
x_o
I
1
2
0
t
x_y

FIG (13)

If any one of the real roots (p_i), were equal to zero then in the system will develop a sustained deviation of constant magnitude. If in addition to the real roots the auxilliary equation has complex roots:

$$\left.\begin{array}{lll} & p_i & = r + j\,w \\ \text{and} & p_2 & = r - j\,w \end{array}\right\} \qquad (36)$$

then the transient deviation in addition to the exponential constituents (corresponding to real roots) will consist of the following; sinusoidal oscillations:

$$e^{rt}\ (C_1 \text{ Sin } wt + C_2 \text{ Cos } wt) \qquad (37)$$

If the real part of the complex roots (equation 36) is negative, the amplitude of these oscillations will go on diminishing with the passage of time and with t approaching infinity the amplitude will approach zero. (see Fig. 13) The resultant transient deviation in this case will tend to diminish so as to establish the steady state value (x_y) and the system will be stable. If the real part of the complex roots is positive the amplitude of the oscillation will continuously arise and the system will become unstable.

If the real part of the complex roots is zero, the transient deviation will consist of a sinusoidal oscillation of constant magnitude, which would be represented by the following equation:

$$C_1 \text{Sin } wt + C_2 \text{Cos } wt \qquad (37)$$

In such a case the system would have a sustained sinusoidal oscillation of constant magnitude.

In order to establish a stable control system, it is necessary that the roots of the characteristic equation possess negative real parts. Determination of roots, is rather simple in case of control systems, expressed by a second order differential equation. Solutions to third and fourth order differential equations, leads to elaborate mathematical analysis, making use of such tools as, Laplace transforms, Determinants and complex algebra.

Having thus, introduced ourselves with the basic theoretical features of control systems, we proceed to the more practical aspects, i.e. regarding the structural features of control systems. The following Chapters deal essentially with the latter.

CHAPTER 2

AMPLIDYNE CONTROL SYSTEMS

Amplidynes have been very successfully used in the Steel Industry for the control of mill drives. Why amplidynes have so successfully been used? Mainly, the high degree of amplification, high speed response and practically very little electrical and mechanical inertia go to explain the wide application of this invaluable machine.

The first and the most fundamental forerunner of the amplidyne generator was a conventional shunt wound D.C. generator. This machine has been with us for years and we know that generally it consists of an armature, with an armature winding and a commutator. It has a stator frame and a shunt field wound on its field poles. Finally it is usually driven at constant speed by some driving motor.

Another forerunner of the amplidyne generator was the three brush automobile battery charging generators. Until a few years ago, almost all automobile battery charging generators were of the three brush type and were driven by the car engine. The three brush generator had the characteristic of giving an almost constant battery charging current rate within a wide range of automobile engine speed. The setting of the current rate on the generator could be changed by shifting the third brush position.

A third type of direct current generator, was the Rosenberg rail road car lighting or battery charging generator. It had a pair of short circuited brushes and a pair of load brushes. It was driven by belting from the axle of a rail road car and gave a uniform current output for battery charging purposes.

The most recent predecessor of the amplidyne was the metadyne generator. It also was fitted with a pair of short circuited brushes and a pair of load brushes. The amplidyne is a metadyne generator fitted with an additional field winding a load current armature reaction compensating field.

3.1 PRINCIPLES OF OPERATION.

The amplidyne generator is an externally driven D.C. generator, similar to a conventional D.C. generator or motor. Even though it is a dynamo electric machine, it differs enough from the conventional D.C. motor or generator, in that it can stand alone on its unique characteristics alongwith the vacuum tube, the thyratron tube, the selsyn, the photo tube, the copper oxide rectifier, the saturable core reactor and the like. It owes its success to its inherently unique design utilizing a short circuit path between two brushes of a D.C. machine and to the use of a compensating winding on its stator.

Figure 14 shows a schematic diagram of the principle components of the amplidyne. The figure is meant for illustrative purposes rather than for accurately showing details of construction. If a small direct current is sent through the control winding on the left hand pole, a control flux will be produced on the horizental or direct axis. The direct axis flux produces a voltage between the short circuited brushes, and the short circuit current flows through the armature and back between the short circuited brushes. The ampere turns produced by the short circuited armature current creates a flux in the vertical or quadrature axis. Voltage will then appear at the load brushes and current will flow between the load brushes to the external load.

The load current in the armature will produce ampere turns on the direct axis, tending to oppose the ampere turns of the control winding. This unwanted condition is prevented by means of a load compensating winding on the direct axis as shown on the right hand pole.

The unit is thus a two stage D.C. amplifier, with first stage from the control field to the quadrature axis and second stage from quadrature axis to direct axis. Two major

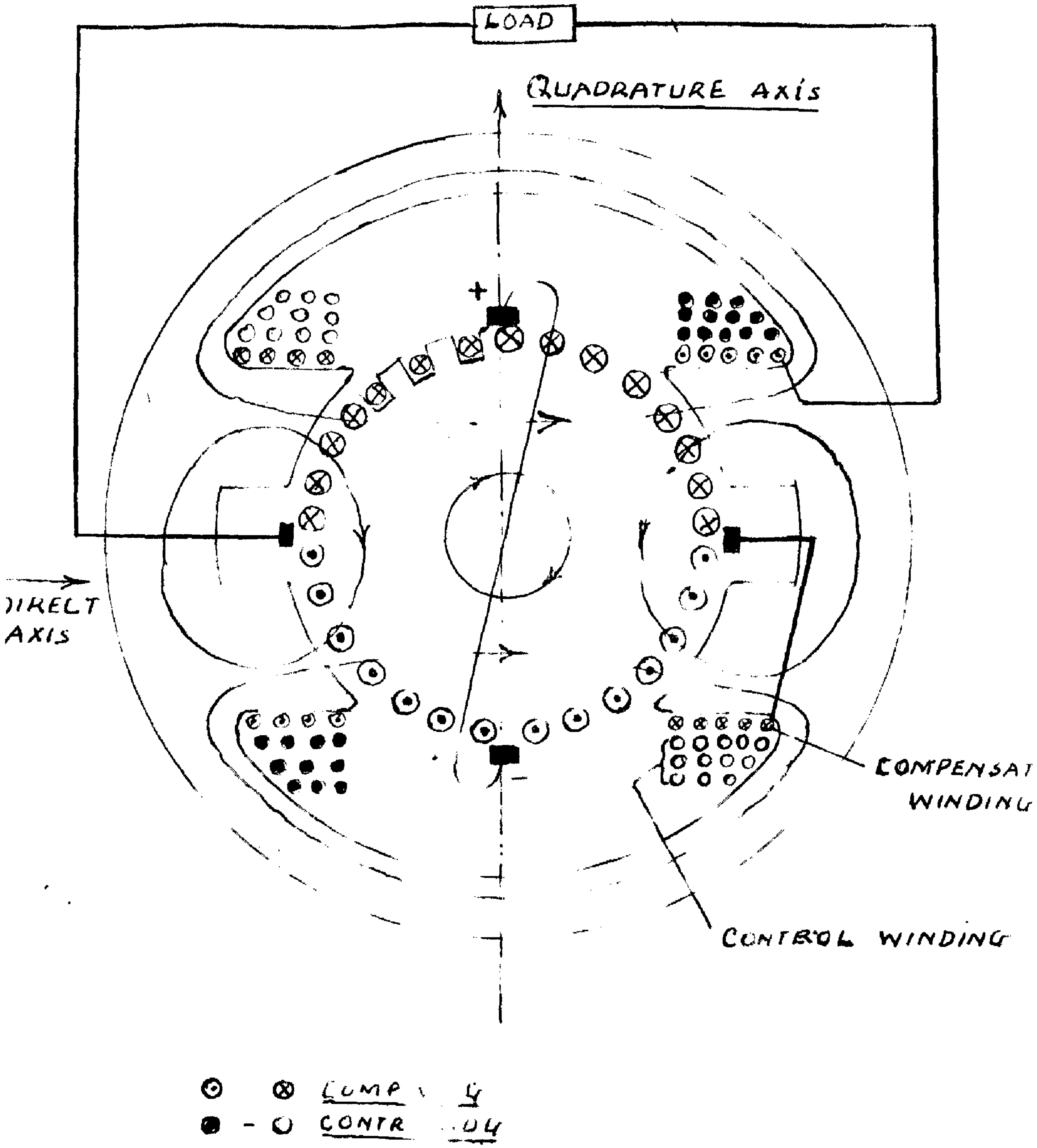

LOAD
QUADRATURE AXIS
+
-
IRECT AXIS
COMPENSAT WINDING
CONTROL WINDING
⊙ ⊗ COMP 4
● - ○ CONTR 04

Fig:14

benefits result from such a two stage amplifying machine. The first benefit is a high degree of amplification, and the second is a high speed of response to the control field signal.

Fig. 15 shows field of the amplidyne in schematic form. Other fields are used, but they need not be discussed here. Very often all the control fields shown are not provided for in all cases. An attempt is made to assign each control field number such as ($F_1 - F_2$) to a specific function. It should be noted that each control field is given a definite polarity; i.e., a current flowing into any odd numbered terminals will tend to produce a positive polarity at the C_2 terminal. Likewise the current flowing into any of the even numbered terminals will tend to produce a positive polarity on the A_1 terminal. Evidently, the polarity of the load brushes may be readily be reversed and the control fields, may be connected so as to aid or oppose each other. In all cases, the polarity at the load brushes will be determined by the algebric sum of ampere turns in all control field windings.

Ratings:

Amplidyne generators have been constructed ranging from 200 watts to 25 Kw capacity. A typical rating of a unit may be expressed as follows:

5 Kw, 1750 r.p.m. 250 V, 20 Amps & 40°C rise.

The field winding data will differ for different forms of applications. In almost all applications, we find the amplidyne used in one of the following functions:

i). As a generator, such as to furnish power to the armature terminals of a D.C. motor.

ii). As an exciter, such as to excite the shunt field of a motor or generator.

iii). As an amplifier, such as to amplify a small voltage indication to some larger and more useable voltage value.

iv). As a regulator, such as to regulate voltage on a generator or current in a generator or speed of a motor.

v). As a tachometer generator, where low excitation power and high response speed is required.

Specific examples of places where the functions are combined, is where the amplidyne:

a). can control armature current of a D.C. motor and at the same time hold speed and armature current of the motor within specified limits.

b). can hold the power input to a motor constant by controlling both the armature voltage and armature current of a D.C. motor.

c). can be made to hold the torque of a motor constant or within predetermined limits.

d). can control power input, power factor or armature voltage or combination of several quantities on synchronous alternating current machines.

e). can speed up operation of existing machine because of more uniform control of armature current and voltage during accelration and decelration of a motor.

f). can limit such quantities as torque, current, voltage excitation so as to protect other machines from damage.

g). can function as an exciter, as an amplifier, as a generator, or as a regulator in conjunction with electronic devices.

2.2. POWER AMPLIFICATION AS A FUNCTION OF MACHINE PARAMETERS.

Basically any D. C. generator with a

s

separately excited field, can be considered to be an amplifier. Amplidyne is only a special case, and those expressions for amplification that hold true for the farmer, do not alter for the latter except for some minor additional details.

Coefficient of power amplification/ of an amplifier is defined as the ratio of the power output to the power input, i.e. :

$$\mu = \frac{\text{Power output}}{\text{Power input}} = \frac{P}{p}$$

Let us consider, that the generator is feeding a load consisting of a resistance R, the resistance of the separate field winding is r, and the resistance of the armature is r_a.

We have;

$$P = UI = \frac{E^2}{(R + r_a)^2} \cdot R \qquad (51)$$

Where, E --- e.m.f.

The power input is given by :

$$p = i^2 \cdot r$$

where,

i --- Generator field current.

If we assume, that the no load characteristic of the generator is a straight line or in other words there is negligible saturation :

$$E = ciu$$

where,

u —— no. of turns in the field winding,

c —— coefficient of proportionality.

Coefficient of amplification,

$$\mu = \frac{P}{p} = \frac{E^2 R}{i^2 r (R+r_a)^2} = \frac{c^2 u^2 i^2 R}{i^2 r (R + r_a)^2}$$

$$= \frac{c^2 u^2}{r} \frac{R}{(R+ r_a)^2} \qquad (51)$$

From equation 51, we note that the coefficient of the amplification is a function of the parameters of the amplifier and the value of the external load.

It can be shown, that for the coefficient of amplification to be a maximum, the load resistance(R), must numerically be equal to the resistance of the armature(r_a). So that :

$$\mu_{max} = \frac{c^2 u^2}{r} \cdot \frac{1}{4 r_a} \qquad (52)$$

The above equation shows that the coefficient of amplification is directly proportional to the square of the field turns and inversely proportional to the field resistance. Increasing the number of turns of the control field winding, with comparably low field resistance, means that we are increasing the overall size of the machine. If Q represents the available cross sectional area for the field winding, the number of turns that can be accommodated in this space will be :

$$u = \frac{k\,Q}{q}$$

where, k —— copper space factor (less than unity),

q —— cross sectional area of the winding wire.

The resistance of the winding wire may be expressed as follows:

$$r = \frac{u\,l}{\lambda q}$$

where,

l = length of the mean turn of the winding,

λ = conductivity coefficient of copper.

Substituting the values of u and r obtained above in equation 51, we get;

$$\mu = \frac{c^2 k\,Q}{l} \cdot \lambda \cdot \frac{R}{(R+r_a)^2}$$

We infer, that the coefficient of amplification is not determined by the number of turns, and the resistance of the control winding, but by the size of the machine and the value of the external load.

As the armature current cannot increase, beyond a certain limit(from temperature rise consideration), consequently with the decrease in the load resistance, *it becomes necessary to decrease the operation voltage of the rotating amplifier.* In other words, for increasing the coefficient of amplification, the specified name plate power must be small.

Assume that the rated coefficient of amplification of the amplifier is u_H corresponding to a nominal load resistance R_H. Then with a variable load resistance, the coefficient of amplification will vary according to the following equation:

$$\mu = \mu_H \cdot \frac{R\,(R_H + r_a)}{(R + r_a)}$$

replacing,

$$R_H + r_a = R_H \quad (\text{ approximately})$$

we get,

$$\mu = \mu_H \cdot \frac{R\,R_H}{(R + R_a)^2} \qquad (53)$$

Fig. 16 shows a typical variation of the coefficient of amplification with a variable load resistance.

Equation (51), shows that coefficient of amplification is directly proportional to square of the coefficient'c', which was introduced as a constant of proportionality between field ampere turns and the developed e.m.f. This coefficient is directly proportional to the speed

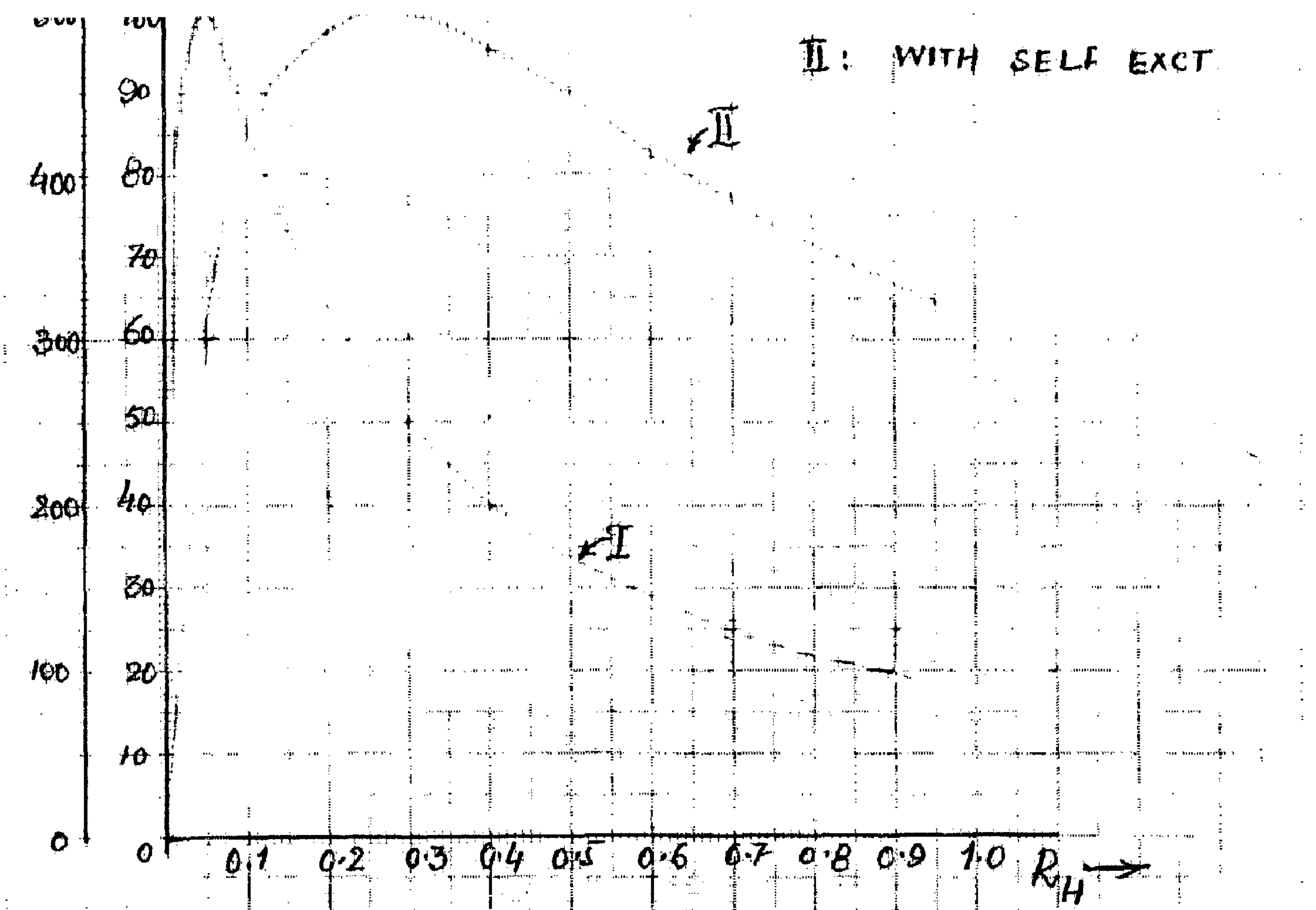


Fig 16

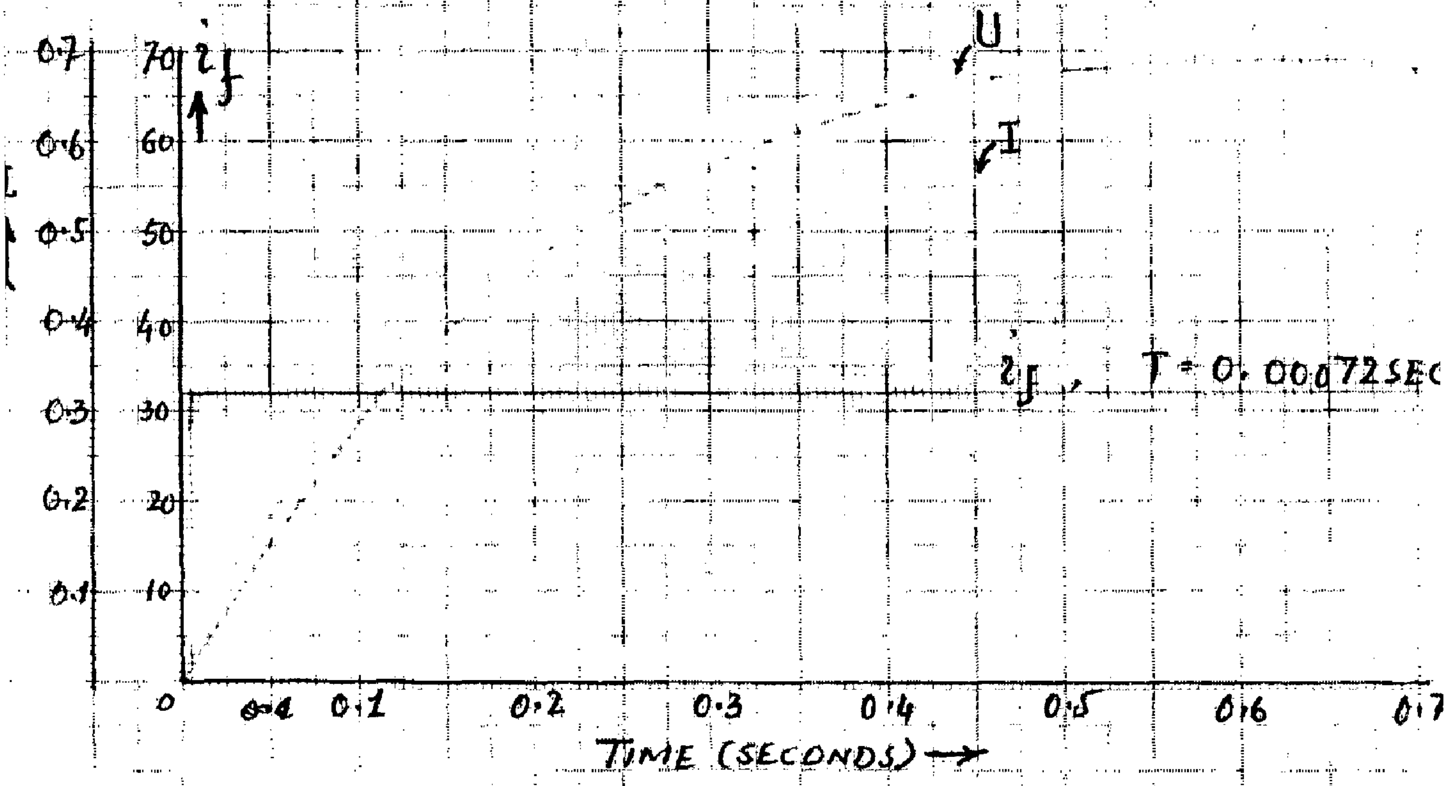


Fig 17

U = AMPLIDYNE VOLTAGE

I = CURRENT THROUGH SHORT CIRCUIT PATH

of rotation of the armature and inversely proportional to the magnetic reluctance of the machine. Reduction in the magnetic reluctance and increase in the speed of rotation of the armature increases the coefficient'c', and hence coefficient of amplification.

An amplidyne, as has been mentioned earlier is two stage amplifier. Input of the first stage consists of the control winding and the output is the armature, with short circuited brushes. Coefficient of amplification of this stage is very high, in view of the very small load resistance. If the rated coefficient of the amplification, with a nominal resistance (load) is 20, as in the case of an ordinary generator and the armature resistance is 0.05 of the nominal value, the coefficient of amplification will be:

$$\mu_1 = \mu_H \cdot \frac{r_a}{r_a 2} = 20 \cdot 1/0.05$$

$$= 400$$

Input of the second stage, is the short circuit path of the armature playing the same roll as the exciting winding of a generator and output consists of the armature winding with output brushes connected to the load. The value of the second stage coefficient of amplification is almost that of an ordinary generator, about 20 (μ_2).

Total coefficient of amplification is given by :

$$\mu = \mu_1 \cdot \mu_2 = 400 \times 20$$
$$= 8{,}000.$$

Normally the number of ampere turns in the control winding necessary for the excitation, of the amplidyne are small. This makes the size of the control winding very compact. So that we can accommodate, not one but a number of control windings.

Due to low losses in the control winding circuits of an amplidyne, these windings offer good overload capacity. This is a very important characteristic, as it determines the extent of forcing processes of excitation in control systems.

2.3. Transient response

One of the most important characteristics of an amplifier is its quick response. In electrical machines, the time taken for field excitation, is determined by the time constant of the field circuit and is proportional to the weight of field copper. The weight of copper is again determinable from the overall dimensions of the machine.

Amplidynes, as was discussed in Art 2.2, are essentially low capacity and low inertia machines. This, of course, limits their application to relatively lower power requirements. In the control system of Rolling mill main drives, amplidynes are used in the exciter field circuits where power requirements are lower.

In a two stage amplidyne, the short circuit path, has a relatively lower time constant, on account of the facts, that it connects elements of relatively lesser copper weight. In Fig. 17 is shown an oscillogram of field excitation process of an amplidyne rated at 2.5 KW. The control field winding is connected in series with a 'high resistance' of such value that the time constant of the control field winding circuit is 'almost' zero. The oscillogram shows that the duration of transient processes is determined, only by the time constant of the short circuit Path, which as per oscillogram is about 0.2 sec.

In a 'relay-contactor' control system, the time delays involved are of the order of 0.1 sec. In order to achieve lesser time delays with amplidyne control systems, one of the control field windings is used as a feed back winding and is connected across the output terminals of the amplidyne. The ampere turns of the feed back winding are directed in opposition to the ampere turns of the control field winding, which is supplied from an independent source. We will assume, that the time constant of the control field winding circuit is approximately zero, due to the high order of ohmic resistance connected in series with it.

In order to achieve a desired voltage at the output terminals of the amplidyne, the ampere turns of the control field winding must be larger than the ampere turns of the feed back winding, such that the resultant ampere turns are sufficient to develop the desired voltage. We could mathematically express the same thing, by the following equation:-

$$U_y = C_y \Sigma at$$

Here $\Sigma aT = at_c - at_{fb}$ - difference between ampere turns of control field winding and the feed back winding. Ampere turns, at_{fb} of feed back winding can be expressed as;

$$a.\, t_{fb} = \frac{U_y}{r_{fb}} .\, t_{fb}$$

where t_{fb} and r_{fb} are the number of turns and resistance of

Various important applications of amplidynes in the control system of steel mill drives have been enumerated under Art 2.1 of this Chapter.

CHAPTER 3

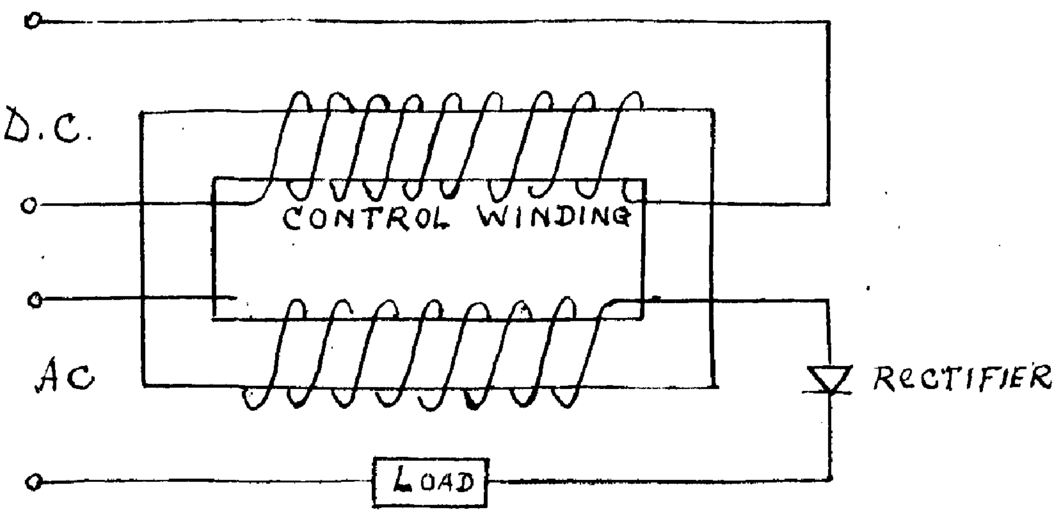
MAGNETIC AMPLIFIER CONTROL SYSTEMS

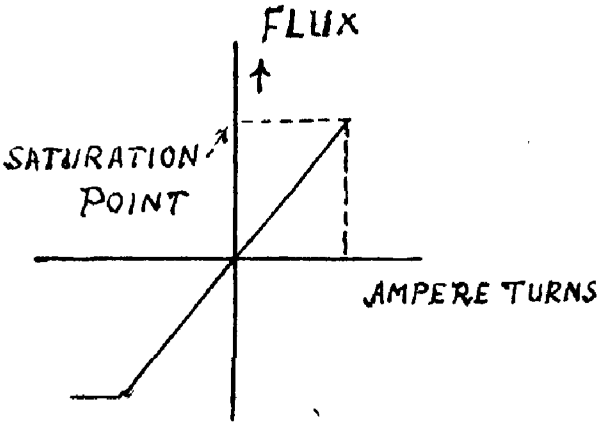
Magnetic amplifier is a more recent development in the control system field. The most significant developements in tandem mill control have been the introduction of IR drop compensation on common bus mills, the use of separate generator supply system with rotating regulator control and the more recent use of complete 400 c/s magnetic amplifier regulating control. The first tandem cold strip mill using complete 400 c/s magnetic amplifier regulating equipment went into operation in Pittsburg Steel Company's Allenport plant in 1954. In view of satisfactory performance, it has become necessary to further find out any more application of the magnetic amplifier.

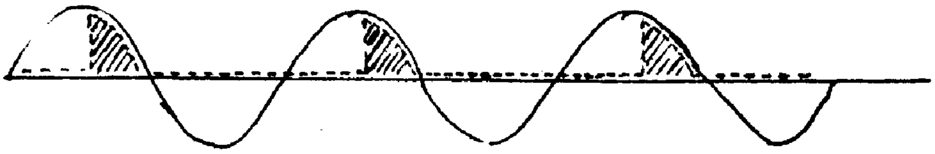
3.1 PRINCIPLE OF OPERATION.

What is the magnetic amplifier and how does it work? Basically it is a magnetic device for amplifying voltage and current. It provides a means of introducing a variable impedance into an A.C. circuit, through control of the saturation of its magnetic core. Various types of rectifiers (the dry type) added in series with load convert the A.C. output to D.C. for controlling a generator or motor field.

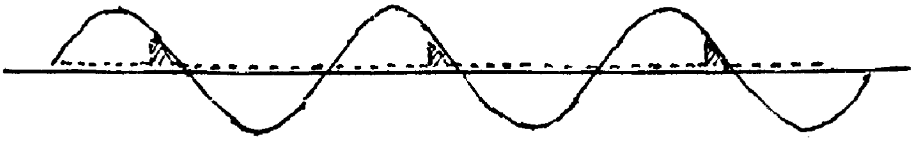
The operation of the magnetic amplifier can be understood by refering to Fig. 18 which shows a simple half wave amplifier. Also shown are the idealised magnetisation curve of its core material, and supply an output voltage conditions for different levels of control winding input. As the A.C. supply voltage wave increases from zero, load current is initially prevented from flowing through the load by the impedance of the magnetic amplifier, which is very high when the core is unsaturated. When the core becomes saturated the impedance of the magnetic amplifier drops rapidly and the load current rises sharply, to a level determined by the load resistance and the value of the supply voltage at that moment. As the voltage wave decreases, the current also decreases and becomes zero when the applied voltage wave reverses. During the negative half cycle of the voltage wave, current is prevented from flowing by the rectifier in series with the load. Because of the steep magnetisation curve, only a small D.C. control current is required to saturate the core and thus make a big change on the output. This high amplification makes the magnetic amplifier an unusually accurate and effective control device. The elementary circuit in the Figure referred to above is not practical for general use for two reasons. First the A.C. supply frequency introduces a high voltage in the control winding and for this objectionable circulating current,



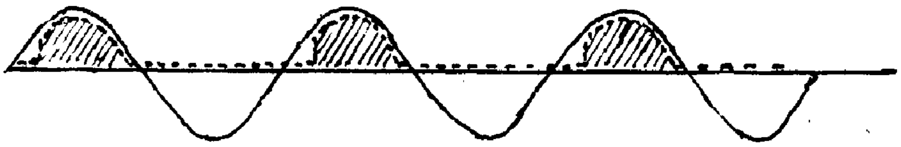




MEDIUM OUTPUT



LOW OUTPUT



HIGH OUTPUT

— SUPPLY VOLTAGE

----- OUTPUT VOLTAGE

Fig 18

to flow through this winding. Secondly since only a rectifier is used, the current through the load occurs only once during each cycle, and consequently has a relatively low average value.

A more practical form of magnetic amplifier is shown in Fig 19 . This is an elementary type of voltage regulator. The use of the two cores minimises the effect of induced voltages, since the two control windings are connected in opposition and any induced voltages tend to cancel each other. The generator field is connected in a rectifier bridge circuit, so that full wave rectification occurs and the average value of the current is considerably higher than with half wave rectifier shown in previous figure. Self saturating rectifiers in series with each output winding cause the load current to aid itself, in saturating the core and thus increase amplification by reducing ampere turns required from the control winding.

Like all other regulators, whether, mechanical, electronic or rotating, the magnetic amplifier in a regulating system first compares the regulating quantity, voltage, current, speed or tension against a fixed reference. It then amplifies the difference between the two and corrects the regulated quantity so as to reduce the error between it and the standard (steady state value).

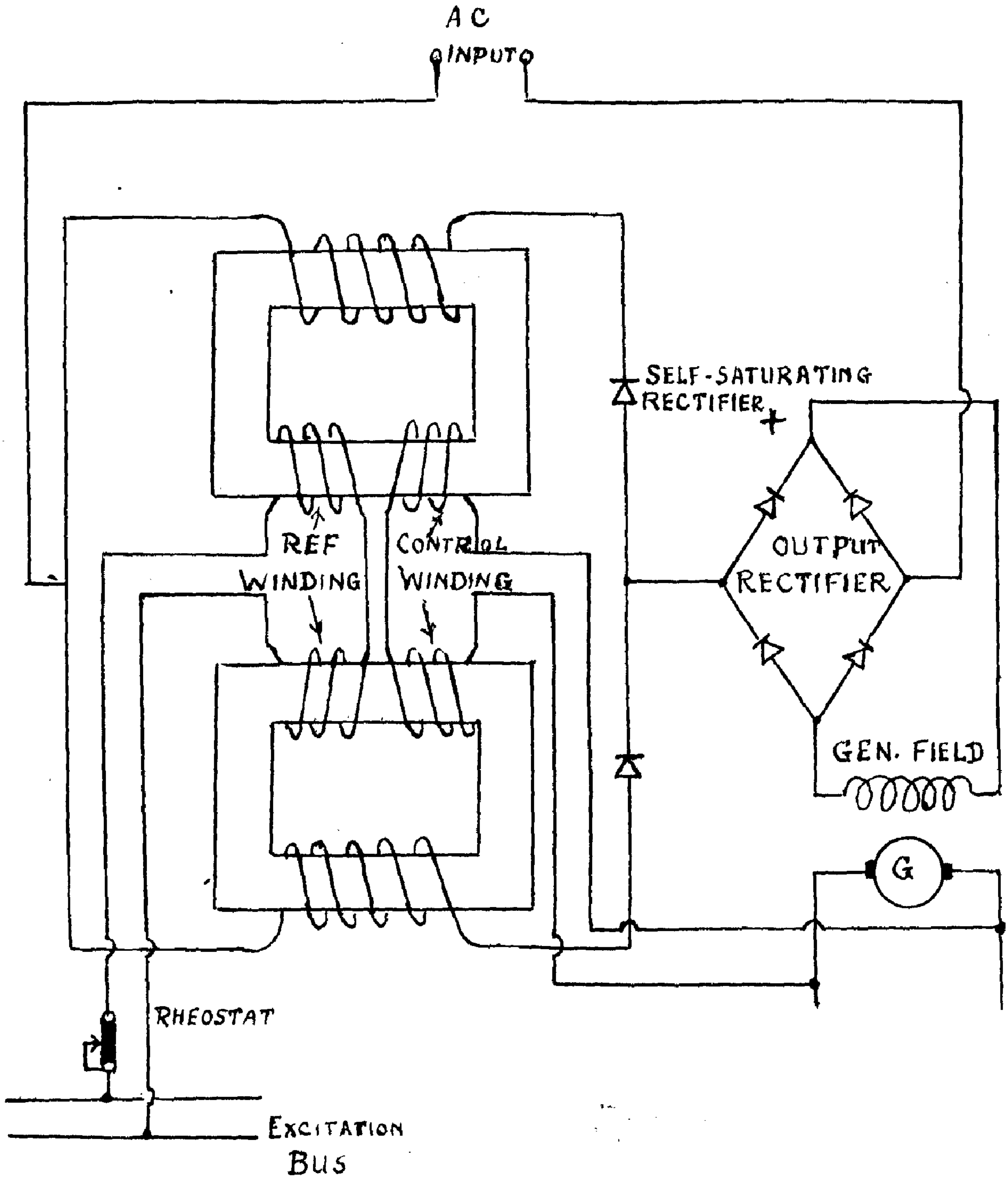

AC
INPUT
SELF-SATURATING
RECTIFIER
+
OUTPUT
RECTIFIER
REF
WINDING
CONTROL
WINDING
GEN. FIELD
G
RHEOSTAT
EXCITATION
BUS

Fig 19

In the voltage regulator, Fig. 19 the reference winding serves as a standard of comparison. The control winding measures the generator voltage and is connected so that its ampere turns oppose the reference ampere turns. A small difference in the strength of these windings will change the saturation of the magnetic cores and allow a proper corrective current to flow through the generator field, thereby causing its voltage to match the reference within close limits.

Certain regulator applications require greater amplification or higher power output, than can be obtained with a single magnetic amplifier. Where this requirement exists, two magnetic amplifier units may be connected so that the output current, from the first stage becomes, the control current of the second. Such an arrangement is therefore a two stage amplifier. The tandem mill voltage regulator is also a two stage unit. For applications requiring reversible regulator output, two magnetic amplifiers of opposite polarities may be used. Then the regulator will respond to positive or negative control signal, in the manner shown on the combined transfer curve in Fig. 20 .

Two types of magnetic amplifiers were constructed initially. One with a lower frequency (60 c/s) and the other

What about 50 Cycles!

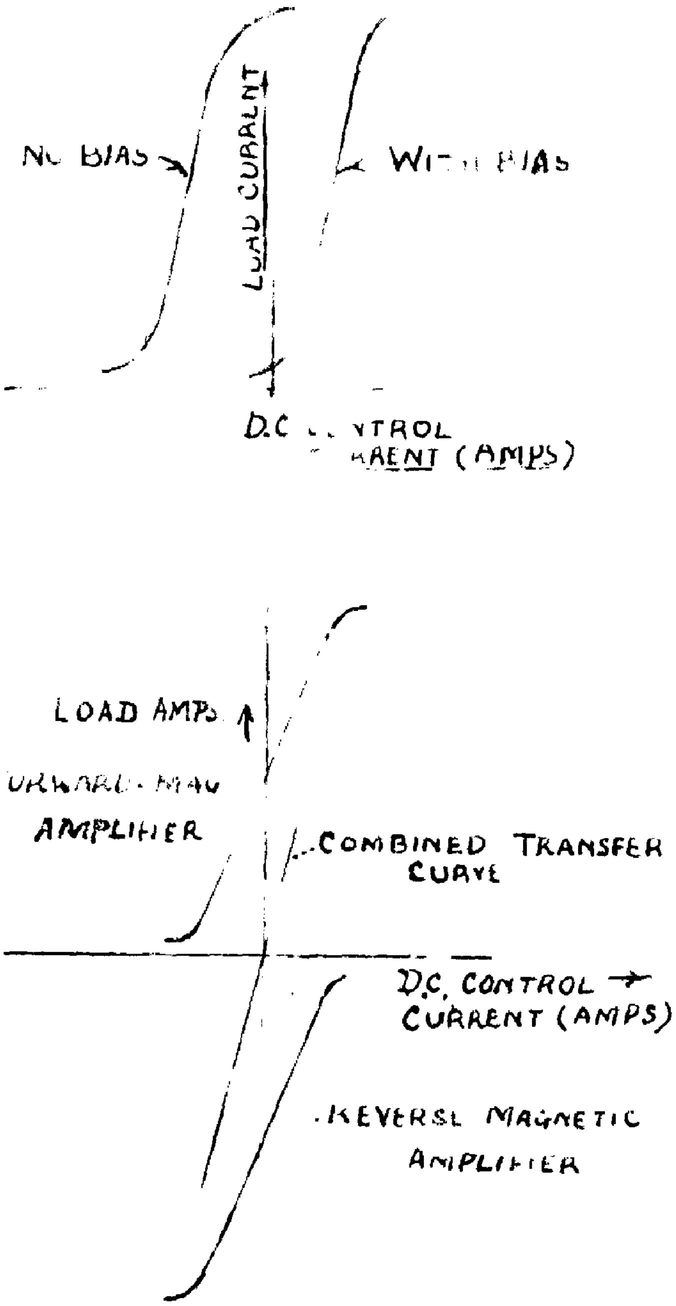

NO BIAS
LOAD CURRENT
WITH BIAS
D.C CONTROL CURRENT (AMPS)
LOAD AMPS
FORWARD MAG AMPLIFIER
COMBINED TRANSFER CURVE
D.C. CONTROL → CURRENT (AMPS)
REVERSE MAGNETIC AMPLIFIER

Fig 20

with a higher frequency (400 c/s). An anacom study of both the systems show that 400 c/s is close to ultimate performance, while the performance of 60 c/s magnetic amplifier is only slightly better than the existing rotating regulator systems.

3.2 SCOPE OF USE AND LIMITATIONS.

There has been considerable interest in the possibilities of application of static magnetic amplifier. Much of the literature written on this subject has only gone to show the applications of magnetic amplifier. Many of these papers have illustrated advantages of magnetic amplifier but however do not cover limitations of this device.

The question arises 'why it is not possible to use magnetic amplifier for all applications'? The two major advantages of the magnetic amplifier are that it is static and panel mounted. Since the magnetic amplifier is static no attention need be given to bearings or brushes, since the device is panel mounted by the electrical manufacturers. The user need not furnish conduit and wiring or a concrete base as for a motor generator set.

To go back to the question of using the magnetic amplifier for every application let us consider some of the characteristics of the device which often make it difficult to use them in regulating circuits. The most important of the characteristics is its unidirection output. That is the output polarity can not be reversed. This of course is different from a rotating amplifier, in which the output is reversed simply by reversing the field excitation.

Related to this characteristic is the fact that a magnetic amplifier will not block current in the normal direction of flow. If it could, the very convenient circuit of Fig. 21 could be used for supplying a reversing load. Here a simple box with a rectifier is used as the short hand symbol for a magnetic amplifier. This circuit shows a forward amplifier supplying plus voltage to the load and a reverse amplifier supplying negative voltage to the load. However, because of magnetic amplifiers' inability to block normal current flow, this circuit will not work. If the forward amplifier is turned on, the reverse amplifier short circuits the load and vice versa.

Other poor characteristics which make the magnetic amplifier difficult to apply are briefly:

i). Output voltage varies with the A.C. supply voltage.

? ii). A bias signal is required since, with no signal applied, the amplifier is turned on.

iii). The poor output wave shape of the device make limit circuits difficult to use.

iv). The poor wave shape makes the use of frequency sensitive feed backs, for stabilisation this is difficult.

Reversing circuits:

To get back to the point of ability to produce negative voltage, since it has been stated that this is the major disadvantage of a magnetic amplifier, the question should be considered further. When is a regulator required to produce negative voltage? A regulator for a reversing adjustable voltage drive must produce both polarities, since the excitation of the generator field must reverse to reverse the drive. A regulator for a non-reversing adjustable voltage drive must usually reverse to some extent. If the drive must decelrate rapidly, the generator field voltage must be forced negative to force the generator voltage down rapidly. Even to suicide the generator voltage, the regulator must produce a negative voltage to overcome the residual magnetism. Thus there are a large number of drives which require the regulator to produce negative voltage. For this reason let us consider the magnetic amplifier circuits which allow a reversing output.

If the reversing is to be done on one load the circuit of figure 22, may be used. Here two amplifiers are used, a forward and a reverse, which produce voltage on the

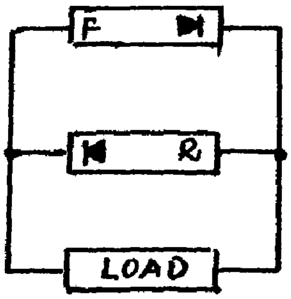


Fig 21

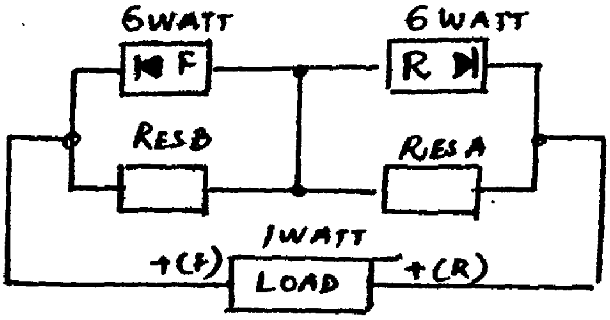


Fig 22

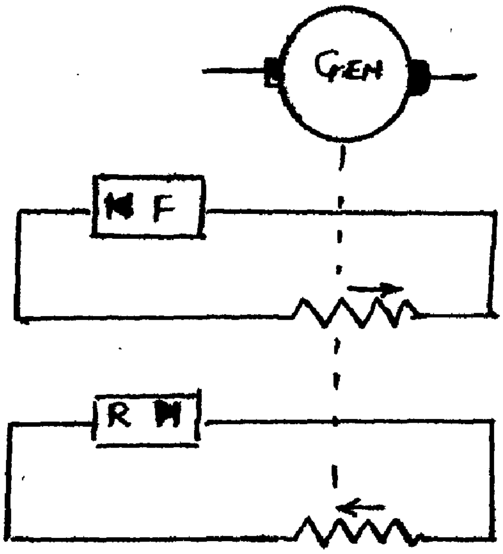


Fig 23

resistors A and B. If the two amplifiers are producing the same output, no net voltage appears at the load. However, if the forward amplifier is turned on and the reverse amplifier is turned off, a forward voltage appears at the load. It is important to note that the installed amplifier capacity is 12 times that required by the load, since considerable power is consumed in the resistors A and B. Thus with this circuit the magnetic amplifiers have 12 times the rating of an equivalent rotating amplifier.

If the load can be split into a buck and a boost field of a generator or exciter the circuit shown in the Fig. 23 can be used. Here again two amplifiers are used, one attempting to produce positive generator voltage and the other negative voltage. If the two amplifiers are producing equal outputs the generator voltage is zero. If the forward unit is turned on, and the reverse unit turned off, the net excitation will produce a positive generator voltage. This circuit requires, two magnetic amplifiers, each having a power output at least as great as the excitation requirements, of the generator. Thus with this circuit the installed capacity of the magnetic amplifier must be considerably greater than an equivalent rotating amplifier. An important point arises if the negative excitation requirements are small or of short duration, the two circuits just discussed can be unbalanced so that they become more efficient. This is the case with most non reversing adjustable voltage drives. To design these modified push-pull circuits, we must determine the amount of negative excitation required.

3.3. APPLICATIONS.

[illegible]

With this brief summary of the advantages and disadvantages of the magnetic amplifier, let us consider the field of application of the magnetic amplifier. The advantages of course make it desirable, to use the magnetic amplifier in place of other devices but at the same time truthful considerations must be given to the disadvantages or short comings of the magnetic amplifier. The importance of these short comings depends upon the application. For some applications, the disadvantage listed above may not apply. In like manner, other applications may require a considerable sacrifice of performance, economy and simplicity, that the advantages of using the magnetic amplifier are lost. In this section, the possible applications of magnetic amplifiers have been divided into four types. These applications are evaluated with regard to suitability of magnetic amplifier.

Preamplifiers

[illegible]

When the magnetic amplifier is used as a preamplifier there are many circuits which may be used since high efficiency is not important. A preamplifier is not always necessary but becomes desirable, when the gain of the regulator must be increased, when time constants must be decreased or when impedance must be better matched. The magnetic amplifier is relatively simple to apply, in a system when it is to be used as a preamplifier, since most of its limitations pose no problem. The major disadvantage of a magnetic amplifier (unidirectional characteristic) is overcome by using two units in a buck boost connection on two exciter fields. Since such preamplifier units are small, this is feasible. The use of two units does not represent a great cost.

There are so many applications in which the magnetic amplifier may be used as a preamplifier, that it is impossible to list them. However, some examples to illustrate its use are given below:

?

[illegible]

i). The magnetic amplifier - preamplifier may be used to provide gain and increase the input impedance of a voltage regulator. Such a system has been successfully been used in reversing planer drives which ~~have~~ to be controlled from a pendant station. To make it possible to use small potentiometers for control, a magnetic amplifier is necessary to preamplifier the signals.

ii). The magnetic amplifier has often been used, to amplify current limit signals, so that current may be more accurately limited. A magnetic amplifier was recently employed in this manner on a 12,000 H.P. blooming mill. It proved highly successful and allowed rapid top speed reversal since the feed back current was accurately controlled.

[illegible]

iii). Magnetic amplifiers have often been used to amplify an intertia compensation signal for the tension reel of a high speed cold strip mill. To obtain voltage proportional to accelration, a transformer is connected across a speed pilot; the output voltage of the transformer, which is proportional to the rate of change of speed, is amplified by means of the magnetic amplifior and applied so as to influence the regulator.

iv). Other uses of such a preamplifier are to amplify stablising signals, or to operate relays from a small signal.

Limited range regulators.

Some voltage regulators serve to maintain a constant voltage while compensating for disturbance of load and speed, but are not required to regulate the voltage over a wide range. If size permits the magnetic amplifier is easily utilised in a system of this type. That is the generator field current or field voltage need not reverse, since the generator operates over a limited range.

In this category falls the most frequent application of magnetic amplifiers; voltage regulators to regulate the A.C. voltage of engine driven alternatives, for air craft, railway equipment, etc.etc. Other applications of this nature are, the excitation of induction heating generators and the excitation of phase shifting net work for power rectifiers. In this same category is a D.C. motor field current regulator. Such applications are well suited to the characteristics of the magnetic amplifier, since here again the motor field excitation need not reverse. Thus only one magnetic amplifier need be used.

One example of this type of application, is a cold strip mill in which it is desired to have a means of quickly changing the motor field current at the operator's command. Here the magnetic amplifier provides, a convenient means to obtain speedy and accurate control of motor field current. There are many applications, in which the magnetic amplifier has been used to regulate the motor field current, as the reel builds up. Such drives are found in practically all continuous process industries, steel, paper, rubber, plastics and textiles etc.

Non reversing adjustable drives.

The magnetic amplifier may be used to supply the field of the generator for a non reversing drive. For this application the cost of overcoming the 'plugging' limitations of magnetic amplifiers must be weighed over the advantages brought about by their use. 'How fast must the drive stop?' is the important question to be answered.

For example consider, say a processing line using a 100 Kw, 1,200 r.p.m. generator. This machine has 1.5 second field time constant. If this drive is to be stopped in one time constant i.e. 1.5 seconds, the regulator must produce a negative excitation of more than 60 per cent. However, if the drive is required to stop in three time constants i.e. 4.5 seconds, the negative excitation requirements are not so severe. A 4.5 seconds stop requires only about 10 per cent negative excitation.

Continuous steel mill processing line achines are small and are usually not capable of stopping the heavy coil in less than 5 seconds. The generator time constant are usually 1.5 seconds, so magnetic amplifiers are reasonable for these applications. Moreover certain drives which have a high friction or work load so that dynamic braking may be used, for fast stopping. For such a drive, magnetic amplifier may be used since it would not need to produce negative excitation.

3.4 A COMPARISON BETWEEN THE APPLICATIONS OF ROTATING AMPLIFIERS VS STATIC MAGNETIC AMPLIFIERS.

For comparison purposes we will show a schematic circuit arrangement of rotating and magnetic amplifier regulator control for a tandem mill stand. The similarity is obvious (refer Fig. 24 & 25) in both cases. The voltage output of the main generator is bucked against a reference bus common to all stands, and any difference causes a corrective current in the control field.

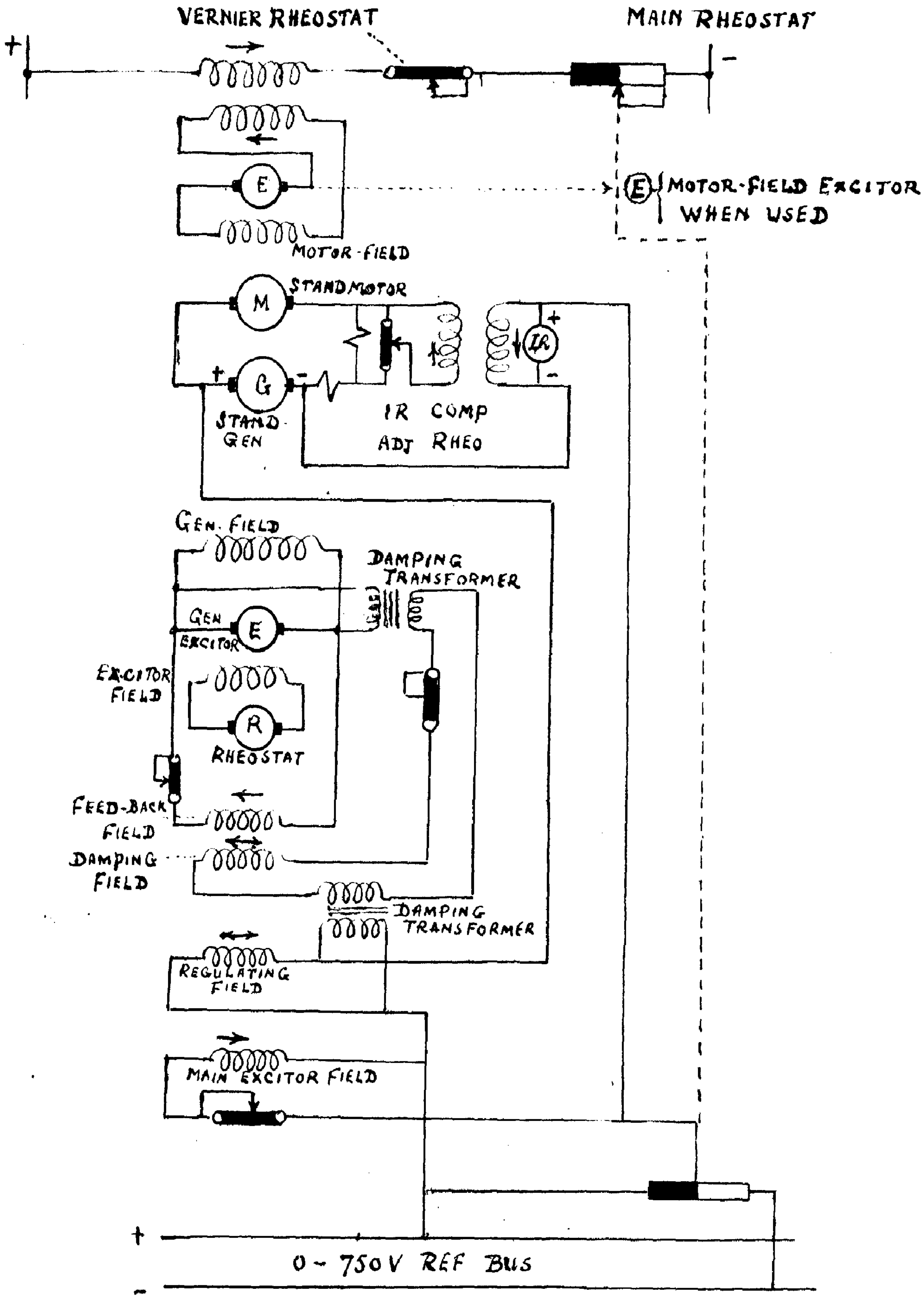

VERNIER RHEOSTAT
MAIN RHEOSTAT
+
-
E
MOTOR-FIELD EXCITOR WHEN USED
MOTOR-FIELD
M
STAND MOTOR
+
G
-
STAND-GEN
IR
IR COMP ADJ RHEO
GEN. FIELD
DAMPING TRANSFORMER
GEN EXCITOR
E
EXCITOR FIELD
R
RHEOSTAT
FEED-BACK FIELD
DAMPING FIELD
DAMPING TRANSFORMER
REGULATING FIELD
MAIN EXCITOR FIELD
+
0 - 750V REF BUS
-

Fig 24

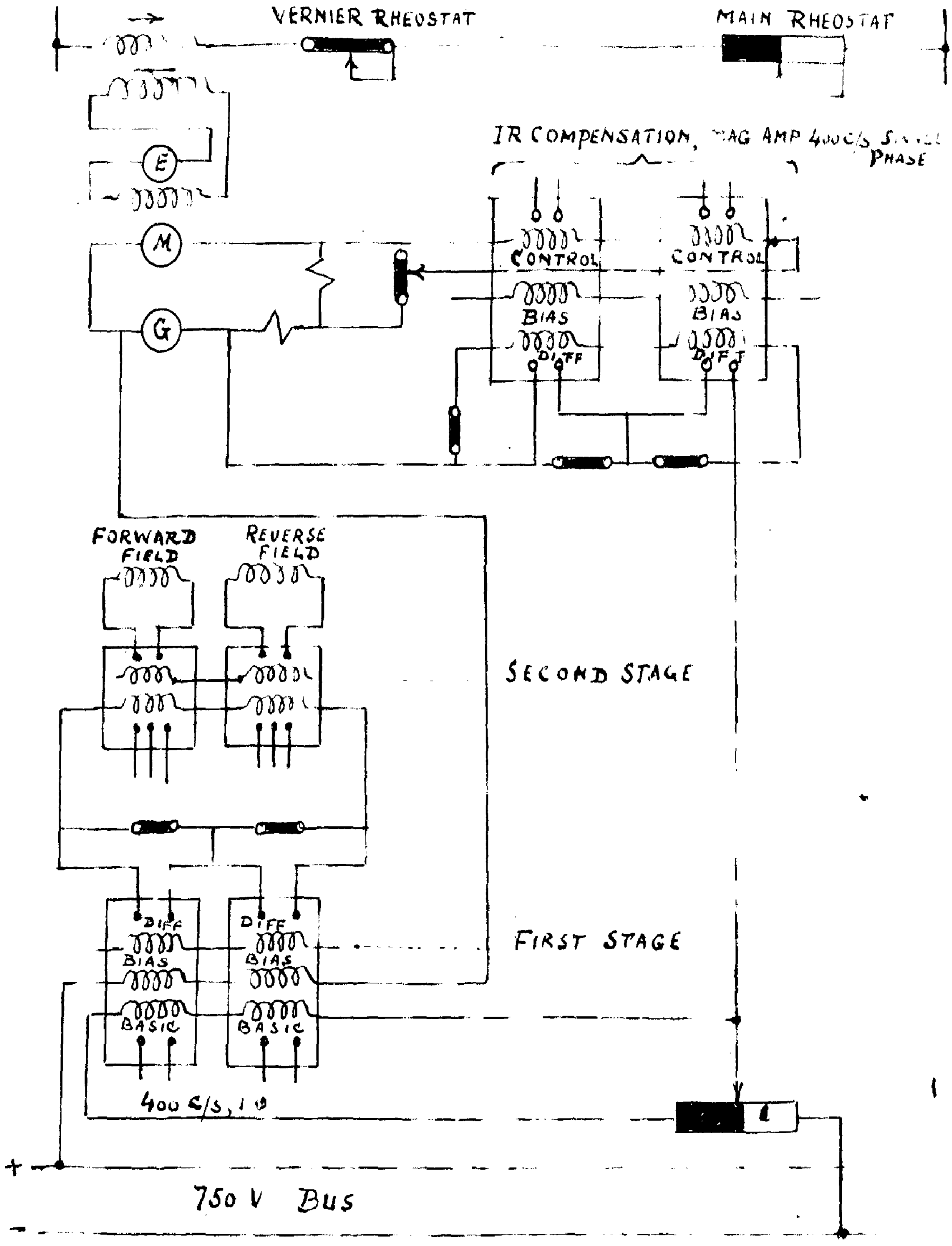

VERNIER RHEOSTAT
MAIN RHEOSTAT
IR COMPENSATION, MAG AMP 400c/s SINGLE PHASE
E
M
G
CONTROL
CONTROL
BIAS
BIAS
DIFF
DIFF
FORWARD FIELD
REVERSE FIELD
SECOND STAGE
FIRST STAGE
DIFF
DIFF
BIAS
BIAS
BASIC
BASIC
400 c/s, 1 φ
+
750 V Bus
-

Fig 25

Both regulators are two stage. Provision is made for operating the generator at a voltage lower than the reference by means of a voltage lowering section on the rheostat IR drop compensation is introduced directly in the circuit.

One important difference between the two systems is that the rotating regulator system is essentially a two delay system and damping circuits are used to stablise the regulator. As mentioned before the magnetic amplifier can be considered a single delay system which requires no damping.

Another obvious difference between the rotating regulator and magnetic amplifier circuits is that two generator fields -- one forward and one reverse are used in magnetic amplifier system. This of course stems from the fact that the magnetic amplifier has unidirectional characteristics. Forward and reverse channel are used, the forward channel controlling the forward field and the reverse channel controlling the reverse field. Then for any operating voltage the algebric sum~~n~~ of the ampere turns in the forward and the reverse fields is the same as if single field were used. The forward field is essentially the same design as would be used on rotating regulator controlled generator. The reverse field however needs only about 20 per cent of this continuous ampere turn capacity of the forward yield, as this satisfies the operating cycle requirements. For such condition as at the maximum rate or reverse jogging, the reverse field may be forced to several times its normal field current. A forward and reverse magnetic amplifier may feed its output into a single output circuit as shown for the first stage magnetic amplifier. Why not use such a circuit to feed a single full capacity generator field? There are two reasons:

a) The single output circuit, requires the use of mixing resistors to provide a return path of current flow. These resistors absorb considerable power reducing the efficiency to a maximum of 17 per cent as against an efficiency of 50 to 60 per cent in the case of independent forward and reverse output circuits. This extra resistor loss may run as high as 8 Kw for a generator of the size used on the mills. This extra power loss must be dissipated. But of more importance is the fact that a magnetic amplifier of considerably large size, would have to be used. The mixing resistor circuit is used on first stage output since the power level is only about 1/500th of that of the second stage. Hence efficiency is of little consequence in the first stage.

b) On generators for general application, there might be some problem in providing ample field winding space for the reverse field. But tandem cold strip mills are provided with machines of very liberal designs. There is ample field space to accommodate both forward and reverse field windings. The IR drop compensation is introduced in the control field circuit by means of small two channel magnetic amplifier. In addition to having faster response than a rotating machine, it also offers the advantage of having practically no residual voltage. This enables normal and emergency stopping, without any tendency to rock or creep.

CHAPTER 4

TYPICAL APPLICATIONS.

In this chapter we will consider some typical applications, with particular emphasis on the control of steel mill drives. We will concentrate our attnetion more on the well developed rotatory amplifier controls that have been very successfully and extensively used in the steel mills. In the following articles we have first dealt with elementary control circuits, scope of application and later the concepts from the former have been utilised in developing some typical schemes that are actually used in steel mill practice.

4.1. Elementary circuits using amplidynes.

While the amplidyne has served in a great variety of functions, some of its most general applications have been to regulate some characteristic of an electrical machine. Three common regulators are those concerned with voltage on a generator, armature current in a motor and speed of a motor. The circuits shown in Figs.16,17,18 are not only the ones which might be used, for different circuit arrangements but there are others also which might be used to meet specific applications. In addition these circuits have been simplified to the extent, that no protective or

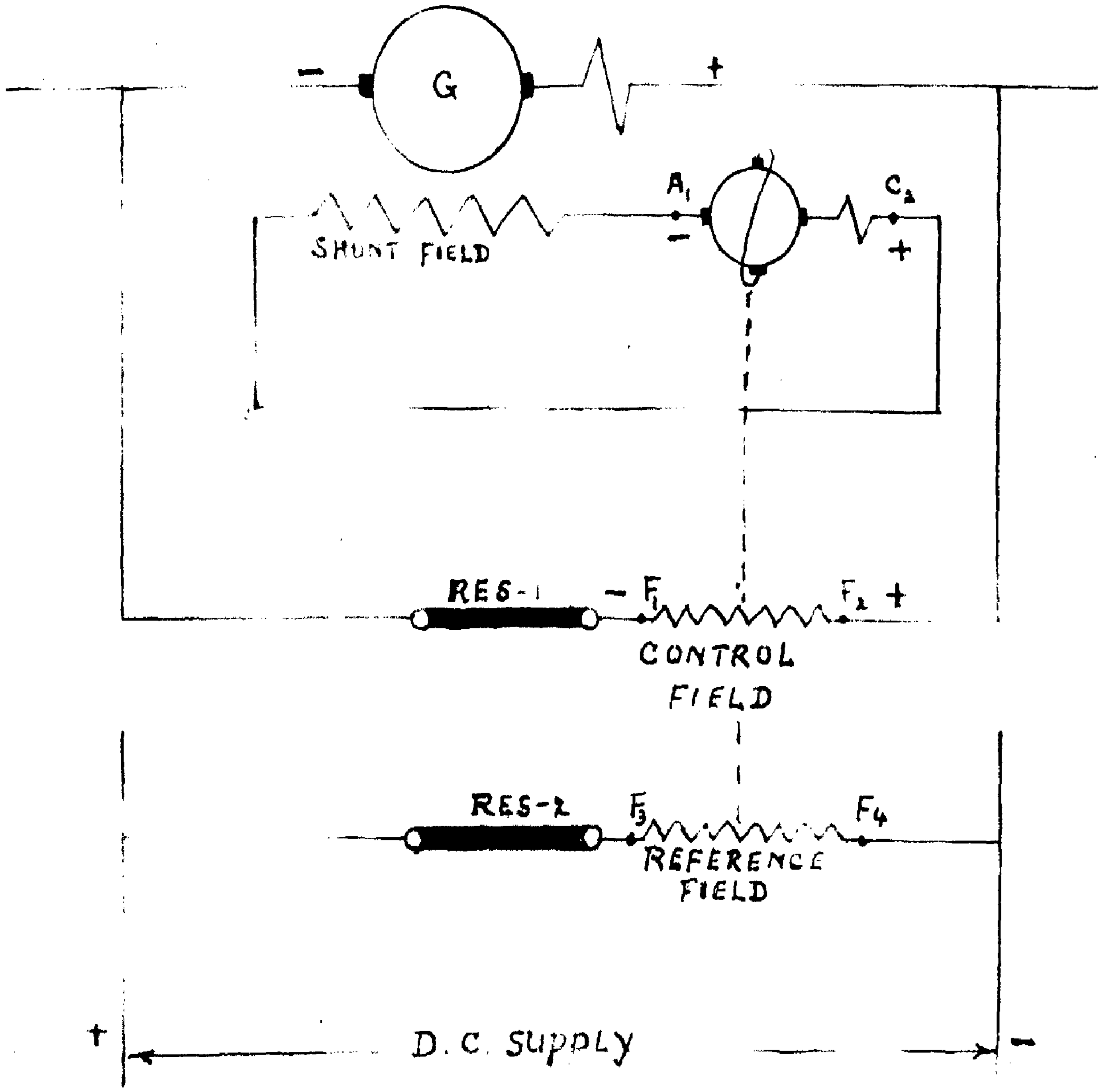


FIG 26

CONTROL DIAGRAM
OF
D.C. GENERATOR VOLTAGE REGULATOR

greater the ampere turns in field $F_3 - F_4$ the greater will be the regulator sensitivity. A slight different principle is illustrated in Fig. 17, where only one field controls armature current of the motor. Here a reference field is used across potentio-meter Res - 2, instead of using a reference field as shown in Fig. 16 . An armature current indication is obtained from the voltage appearing across Res - 1. This voltage is compared with the reference voltage obtained from potentio-meter Res - 2. The difference between the two voltages excites control field $F_1 - F_2$. If the load on the motor increases momentarily the strength of the field $F_1 - F_2$ will be decreased, lowering the counter E.M. F voltage on the amplidyne and hence increasing the motor field strength. The resulting increased motor torque will enable the armature current to be restored to its former value. A decreased load will have the opposite effect. Here again the value of current at which we regulate can readily be changed by altering the tap setting on Res - 2. In actual practice small rheostats are used for making changes in the regulator setting.

The reference voltage scheme of control, may also be applied to the motor speed regulator shown in Fig. 18, . A tachometer generator driven by the motor,

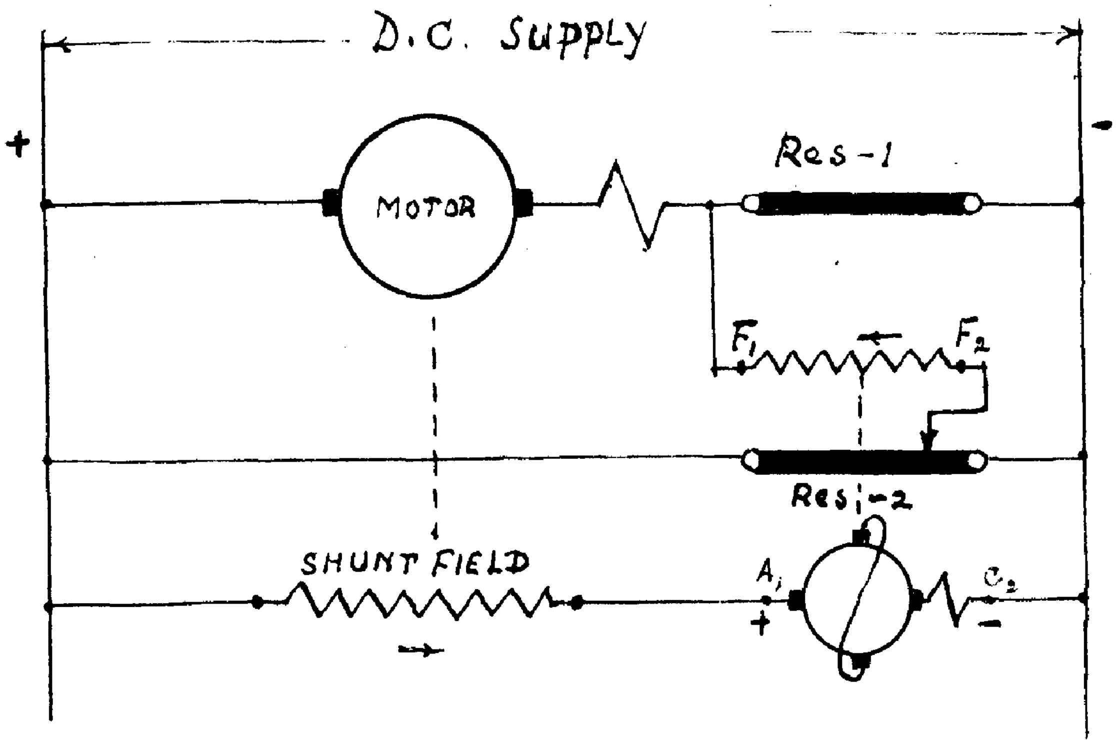

D.C. Supply
+
-
MOTOR
Res-1
F1
F2
Res-2
SHUNT FIELD
A1
+
C2
-

Fig 27

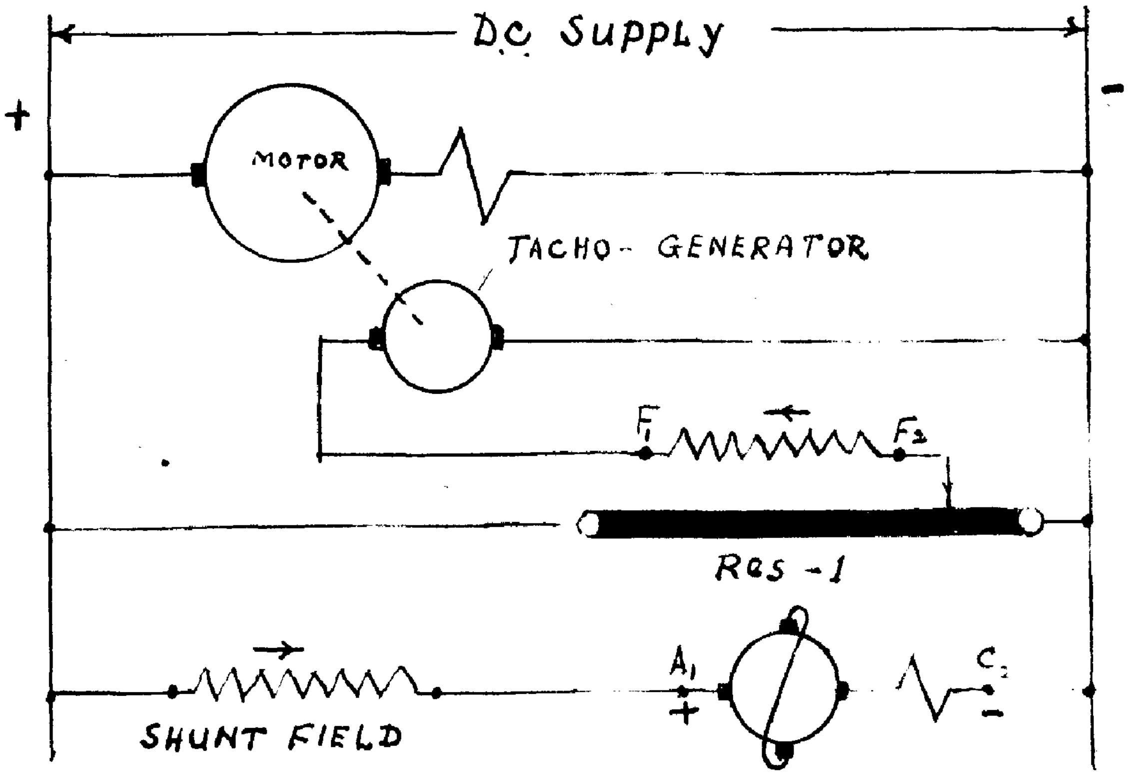

D.C Supply
+
-
MOTOR
TACHO- GENERATOR
F1
F2
Res-1
A1
+
C2
-
SHUNT FIELD

Fig 28

limiting features are shown. Once the principles involved are understood, the addition of protective elements can readily be made. Figure 26, shows a typical means for regulating the voltage of a D.C. generator where the amplidyne serves as a regulating exciter. Voltage on the regulator is regulated by the combined action of fields, $F_1 - F_2$ and $F_3 - F_4$. Control field, $F_1 - F_2$ tends to lower the voltage on the amplidyne which further tends to lower the voltage of the generator. Reference field $F_3 - F_4$ tends to raise the voltage on the amplidyne. The regulated generator voltage will be at that point where the algebric sum of the field ampere turns, gives just sufficient excitation to produce the required or the rated voltage. Any change in load or speed of the generator will tend to change the generator voltage accordingly. Even a slight change in voltage will change the field excitation $F_1 - F_2$ in such a manner, as to restore the generator voltage to its former value. Evidently the value of regulated voltage can be readily changed by altering the value of either resistances Res- 1, Res - 2. The sensitivity of the regulator at any voltage can be changed by altering the vlaues of Res - 1 or Res - 2. Generally speaking the greater the ampere turns in field F_3 - F_4 the greater will be the regulator sensitivity. A slight different principle is illustrated in Fig. 27, where only one field controls armature current of the motor. Here a reference field is used across potentio-meter Res - 2, instead of using a reference field as shown in Fig. 26 . An armature current indication is obtained from the voltage appearing across Res - 1. This voltage is compared with the reference voltage obtained from potentio-meter Res - 2. The difference between the two voltages excites control field F_1 - F_2. If the load on the motor increases momentarily the strength of the field $F_1 - F_2$ will be decreased, lowering the counter E.M. F voltage on the amplidyne and hence increasing the motor field strength. The resulting increased motor torque will enable the armature current to be restored to its former value. A decreased load will have the opposite effect. Here again the value of current at which we regulate can readily be changed by altering the tap setting on Res - 2. In actual practice small rheostats are used for making changes in the regulator setting.

The reference voltage scheme of control, may also be applied to the motor speed regulator shown in Fig. 28, . A tachometer generator driven by the motor, gives us a voltage indication proportional to the motor speed. This voltage is compared to the reference voltage across the potentiometer Res - 1. If the motor speed be decreased slightly the strength of the field $F_1 - F_2$ will be increased and the motor shunt field will be decreased in magnitude. The motor speed will be thus increased, untill the motor is brought very near to its former operating speed. An increased motor speed will tend to increase the motor field strength, so as to lower the motor speed to its former value.

4.2 SCOPE OF APPLICATION

Amplidynes have been applied to air craft devices, in mining industry, to machine tools etc. etc. In steel industry they have been applied all the way from iron ore operations, up to the operation of finished steel products. For example, they are in use on electric shovels used in open iron ore pits or surface coal mines. They are used on the blast furnace skip hoist control, finally at the finishing end they are applied to hot and cold strip mills and to processing lines, such as the electrolytic tin plate units. For typical example in steel industry we will examine the application in hot reversing mills, continuous hot strip mills, and cold strip mills. All the applications illustrated in Figs. 26, 27 & 28, are in actual use at present. These figures illustrate the wide range of actual uses in one phase of steel industry.

4.3: Typical control systems as applied to steel mill auxilliary drives.

Electric drives of reversible rolling mill auxilliaries, such as the roll tables, screw down devices, manipulators etc; are required to work under heavy intermittent duty, with frequent starting, braking and reversing. In order to increase the productivity of these units, on which depends the overall turn out of rolled steel products, it is very important to have efficient control systems which give a desired and a quick control. In order to attain quick response, the time of intermediatory Transient processes must be reduced to a minimum. A few typical applications are discussed in detail in the succeeding articles.

4.31. Control of a reversible auxilliary drive, with voltage cut off

Fig. 29 shows a typical control system of a reversible auxilliary drive with voltage feed back. Voltage feed back is accomplished with the help of a control field winding VW. We will henceforth name this winding as voltage winding for the sake of simplicity.

Let us suppose that, to build a voltage of 220 volts across the generator (G) terminals, it is required to impress a voltage of 60 volts across the generator field winding, GFW. Since this winding is connected across the amplidyne output

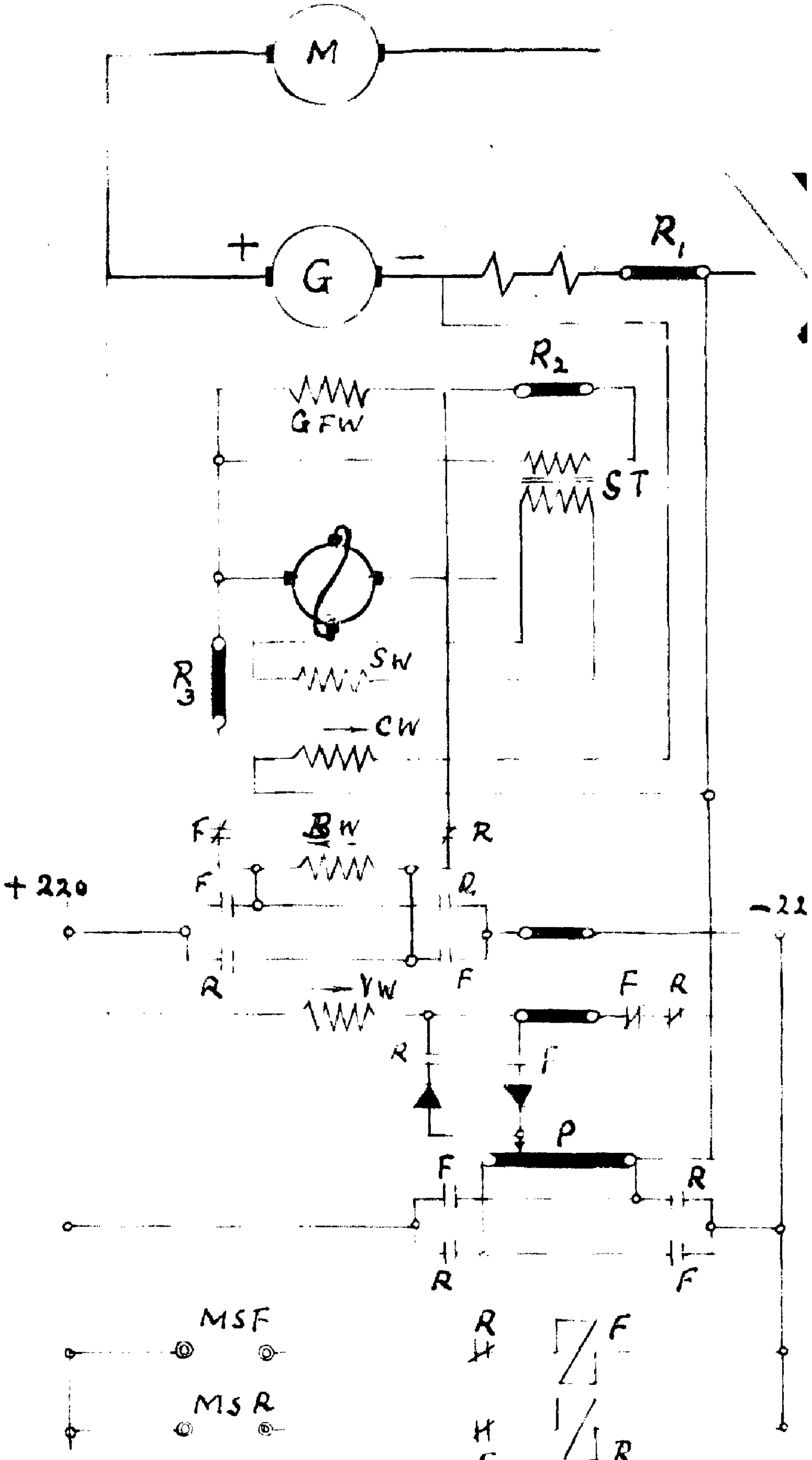

M
+
G
-
R1
R2
GFW
ST
SW
R3
CW
F
BW
R
+220
F
R
R
F
YW
-220
F
R
R
F
P
F
R
R
F
MSF
MSR
R
F
F
R

Fig. 29

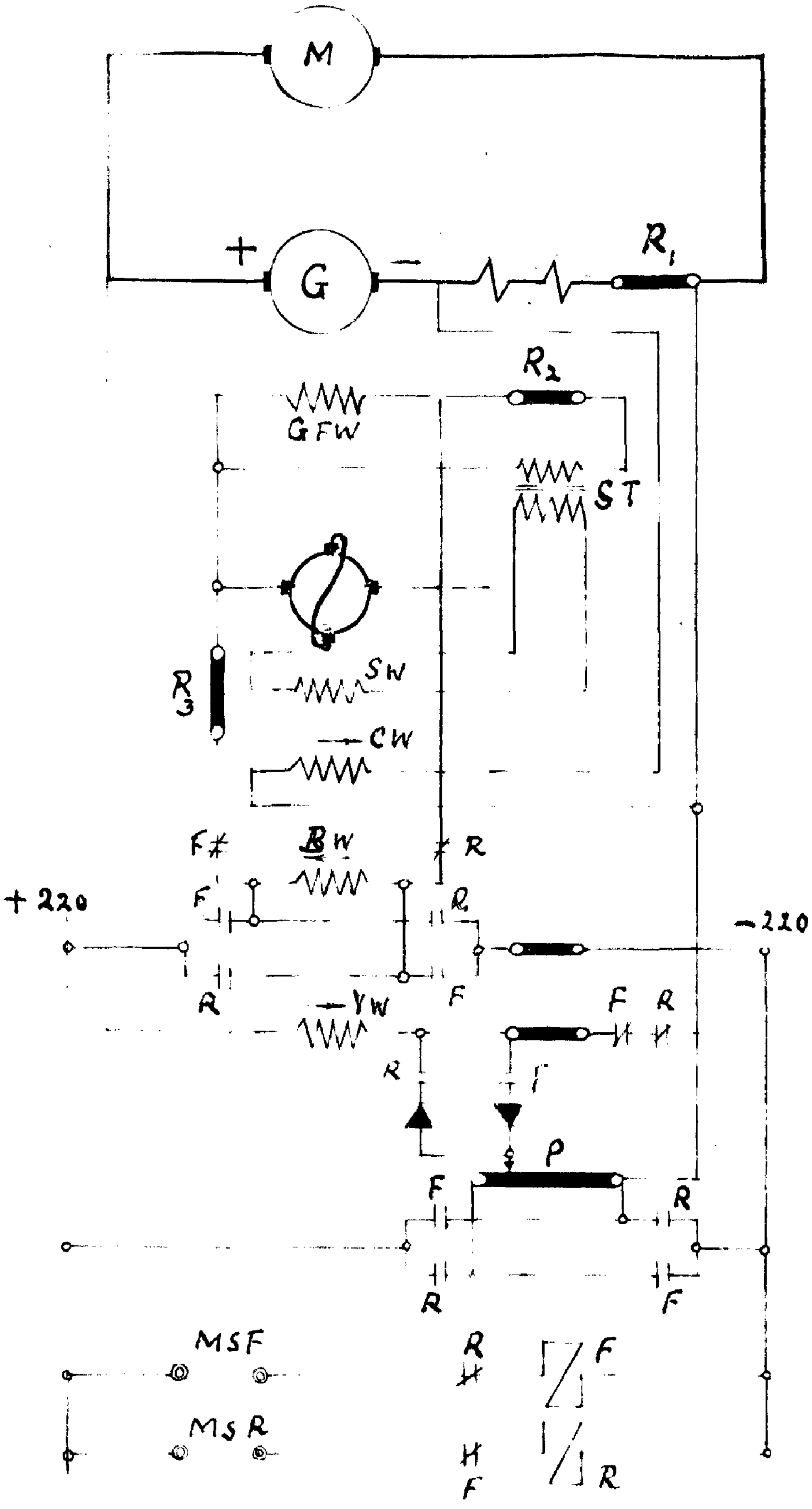


Fig. 29

terminals, it means that the amplidyne must build a voltage of 60 volts across its output terminals. Let us suppose that 20 ampereturns are required as excitation by the amplidyne to build 60 volts across its output terminals.

In order to attain quick acceleration of the motor to its nominal speed from its state of rest, the putput voltage of the amplidyne must be appreciably higher than 60 volts during the starting period. For this reason the ampere turns of the bias winding BW must be appreciably larger than 20 ampere turns . It is usual to have these AT as five times the nominal AT. If the bias winding has 330 turns and nominal current is 0.2 amps, then the bias must be of the order of $(5).(0.2).(330) = 330$ ampere turns.

During the starting period till the voltage winding VW comes into operation field forcing of the order of $\frac{330}{20} = 16.5$ times the nominal value is maintained. This helps quick build up of voltage across the generator terminals. However, the effectiveness of this forcing is less on account of saturation of the amplidyne magnetic circuit. If there were no saturation, the voltage across the amplidyne should have risen to $(16.5).60 = 990$ volts. If the maximum (or ceiling) voltage of the amplidyne is 420 volts, then the effective co-efficient of forcing during starting period is $\frac{420}{60} = 7$

As stated above, to build a nominal voltage of 220 V across the generator terminals, it is necessary, to have 20 ampere turns of amplidyne excitation. Consequently the voltage winding VW must reduce the total of 330 AT due to the bias winding BW by 310 AT. Supposing, that the voltage winding has 500 turns and a resistance of 38 ohms. In order to build an m.m.f of 310 AT, a current of $\frac{310}{500}$ = 0.62 ampere must pass through it, with an impressed voltage of 0.62 x 38= 23.5 volts across its terminals. This means that the voltage winding comes into action the moment the generator voltage starts rising above (220-23.5), or 196.5 volts. This is accomplished with the help of the potentio meter connection P. It may be pointed out the mmf of the amplidyne is maintained at 16.5 times its nominal value till the instant the generator voltage builds to 196.5 volts. Let us suppose that, the maximum, allowable starting current of the motor, is obtainable with a voltage of 180 volts impressed across the generator field winding. In our present example, we have said that, the amplidyne is excited so as to develop the maximum possible (ceiling) voltage, since the magnetic circuits of the amplidyne are saturated during the starting period. Naturally under this condition the generator field winding is impressed with appreciably higher voltage as compared to 180 volts, which will consequently mean higher starting current which the drive may not be able to withstand.

It is necessary, therefore, to limit to the extent of field forcing such that, the amplidyne voltage does not exceed 180 volts during the starting period. This as shown in the scheme (fig. 29) is achieved with the help of current winding CW of the amplidyne. This winding is directed in opposition to the bias winding, and is connected across the resistor R. In the foregoing example we noticed that to develop 60 V across the amplidyne, it requires a total magnetising mmf of 20 AT. Consequently, to limit the starting current the current winding should be able to generate sufficient ampere turns, such that the algebric sum of the bias winding AT and current winding AT, is just sufficient to generate 180 V across the amplidyne terminals. Ampere turns due to the current winding would be, 330-60 = 270 AT.

Let the allowable starting current of the motor be 200 amps, and the number of turns and resistance of the current winding be 330 turns and 18.5 ohms respectively. We can calculate the value of the resistor R_1. Current through the current winding during starting is, $\frac{270}{330}$ = 0.82 amps. Drop of voltage across the winding will be, 0.82 x 18.5 = 15.1 volts. This drop of voltage must equal the drop of voltage across the resistor R_1. Value of the resistor R_1 would be

$\frac{15.1}{200}$ = 0.075 ohms.

During, the course of initial starting period, as the armature current of the motor decreases, the demagnetising ampere turns due to the current winding are reduced, due to which the bias winding ampere turns become more predominant, raising the amplidyne voltage. With the help of current winding, we are able to keep the necessary forcing processes going, and as well put a limit to the starting current. Thus with this scheme we are able to regulate the generator voltage and as well as control the value of the starting current. During braking regime, the master switch (MS) is brought to the neutral position and the bias winding BW is disconnected from the supply source. The voltage winding VW is connected across the generator terminals through the normally closed contacts of the reversing contactors F and R. The amplidyne under the effect of demagnetising ampere turns due to the voltage winding changes output polarity. The generator field winding is thus impressed with a voltage of opposite polarity, due to which the generator field excitation and generator voltage are 'instantly' killed. During the process of braking the motor current changes direction, and the current winding ampere turns are directed in opposition to that of the voltage winding. This goes to show that, larger the braking current, smaller is the reverse voltage build up across the amplidyne. This further goes to show, that during braking, the current winding tends to maintain the braking current. As the voltage across the generator goes on reducing, the ampere turns of the voltage winding VW become smaller, and the intensity of braking processes is reduced. This is why, the initial braking current assumes a peaky character. In order that, the residual generator voltage is appreciably reduced, and at the same time the initial braking current is limited, the control scheme provides for the closure of bias winding across the armature terminal of the amplidyne through the normally closed auxilliary contacts of reversing contactors F & R and an additional resistance R_3 with such a scheme, the ampere turns of the bias winding BW, are directed in opposition to those of the voltage winding, and resistance R_3 is so selected that the resultant ampere turns due to VW and BW do not exceed the resultant ampere turns of BW & CW during starting. If this condition is satisfied the current peak at braking will not be more than the starting current. Peaky character of the braking current, is rather a defect of this control scheme.

The process of braking is, however, improved by shifting the master switch handle (not to the neutral position) to the opposite notch. In this case the voltage winding is isolated from operation, inspite of the fact that the corresponding reversible contactor has closed. This is because the generator is still maintaining the previous residual polarity and the metal rectifier blocks the passage of current. Voltage winding is switched into operation only when the generator voltage changes its previous residual polarity. Thus with this method, only the bias and the current windings are operating in opposition, during the braking regime. The Bias winding BW, develops ampere turns in the opposite direction (relative to the direction during starting) and changes the polarity of the amplidyne. The order of forcing is the same as that during the starting period, which in conjunction with current winding, maintains a constant braking current. As the generator voltage drops down to zero, the master switch handle must be put back in the neutral position, as otherwise the voltage will start rising in the opposite direction, which will reverse the drive.

Let us now examine the control scheme (Fig 29) under a variable load condition. We assume that the voltage at the generator terminals is at its nominal value and the motor is running under no load. If the motor is thereafter loaded, a load current starts flowing in the power circuit by virtue of which current winding builds some ampere turns directed in opposition to those of the bias winding.

This results in the gradual lowering of the generator voltage. The voltage winding VW will tend oppose this change, to an extent determined by the value of the tapping on the potentiometer P. In other words the voltage winding VW will be effective during the time when the generator voltage is above 196.5 V (example referred to earlier). When the generator voltage becomes less than 196.5 V, the voltage winding plays no part since the metal rectifier blocks the passage of current through it. Any further increase in load will demagnetise the generator and the motor will be stopped.

Taking the present example, we will calculate the value of the load current, necessary for reducing the generator voltage to 196.5 volts. The total effective ampere turns in the amplidyne control field circuit, for building generator voltage to 196.5 volts will be:

$$20 \times \frac{195.5}{220} = 17.8 \text{ ampere turns}$$

In order to have total of 17.8 ampere turns, the current winding must generate (330-17.8) or 312.2 ampere turns. The number of turns of current winding being 330, current through the current winding will be, $\frac{312.2}{330} = 0.945$ amps. The drop of voltage across the resistor R_1 , will be;

$$0.945 \;.\; 18.5 = 17.4 \text{ volts}$$

Consequently the current through the armature circuit must be

$$\frac{17.4}{0.075} = 232 \text{ amps.}$$

In order that the generator is completely demagnetised, current winding ampere turns must be equal to the bias winding ampere turns, in which case the load current will assume the following Value:-

$$\frac{330}{330} \cdot \frac{18.5}{.075} = 246 \text{ amps.}$$

Control schemes, which provide for stopping of the drive under a certain limiting load condition are also named as excavator type schemes. In our present example the limiting current exceeds the starting current by 46 amperes i.e.(about 23%). Such drives, which are subjected to frequent limiting load condition (such as manipulator drives) and in which limiting load current is appreciably higher than the starting current . This control scheme is not idealy suited.

In the scheme shown in (fig. 19) stabalising transformer ST, is used to stabalise the transient processes. The primary winding of the transformer is connected across the amplidyne armature, and the secondary winding is connected in parallel with the 4th control winding of the amplidyne, named as stabalising winding (SW). The polarity of the transformer is chosen such that, the ampere turns fed into the stabalising winding SW are so directed, that they prevent a change of voltage at the amplidyne armature terminals. Resistor R_2 regulates the intensity of stabalising influence.

4.32 Control of a reversible auxilliary drive, with current cut off.

Fig. 30 shows control scheme for a reversible d.c. motor drive. The amplidyne 'A' has four control windings: bias winding BW connected across a separate control supply source through the reversible contactors F & R, current winding CW connected across the resistor R_1 through the differentiating potentiometer, voltage winding VW connected across the generator terminal and stabalising winding SW.

When the contactor F is closed, by putting the master switch on the forward notch (Contact M.SF of the master switchis closed) , the bias winding BW gets excited. Due to the large ampere turns of the bias winding, the generator excitation builds up quickly at first and later, slows down on account of the opposing voltage winding ampere turns. In this scheme the current feed back is adjusted such that, when the drop of voltage across the resistor R_1 is higher than the voltage available between points I and II on the differentiating resistor R_5, only then should the current winding come into action. The number of ampere turns of the current winding are such, that the resultant ampere turns of the amplidyne, will increase the voltage at the generator terminals to such an extent, that will allow a current of the value of the starting current.

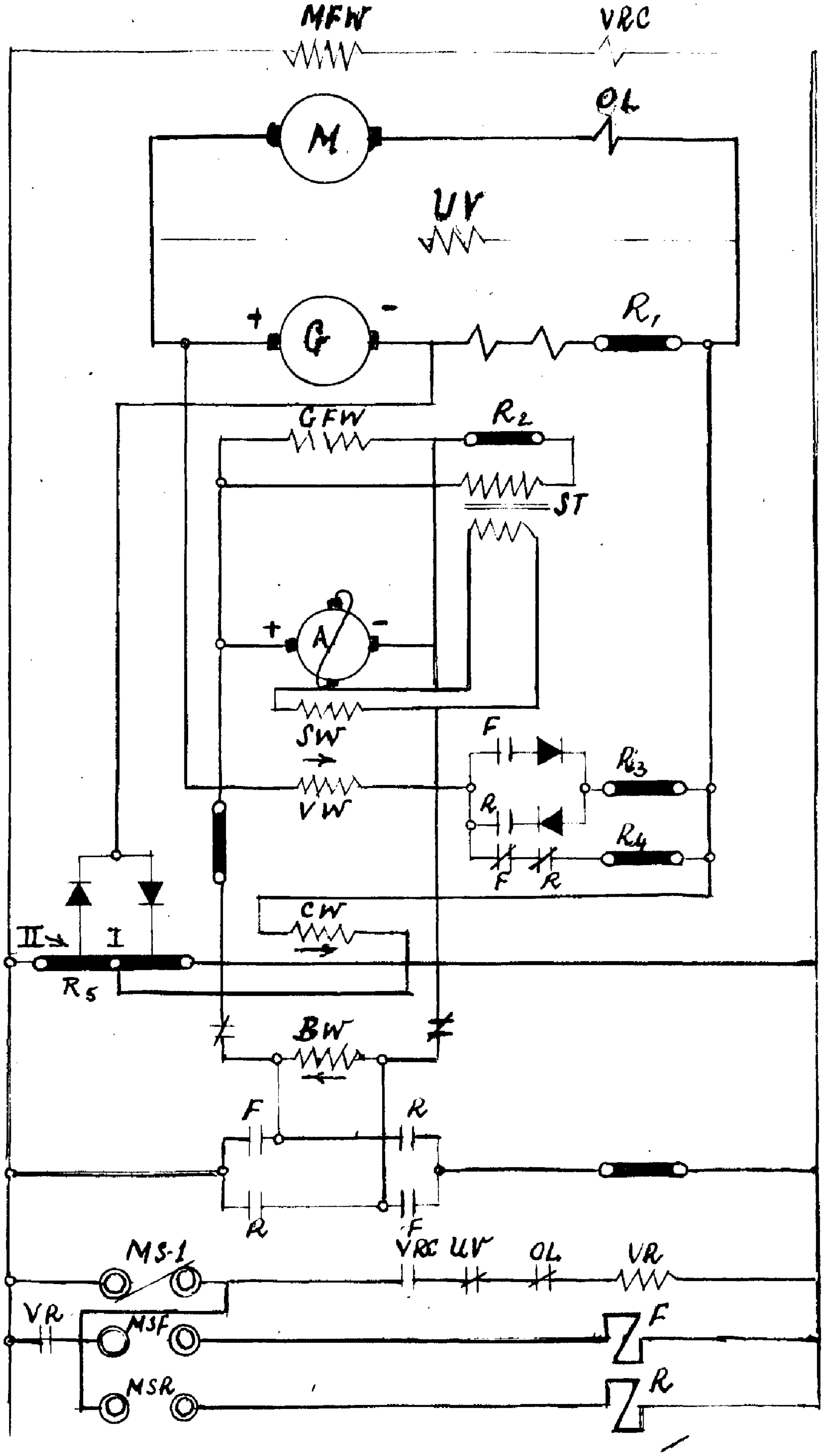

MFW
VRC
OL
M
UV
+
G
-
R1
GFW
R2
ST
+
A
-
SW
F
R3
VW
R
R4
F
R
II
I
R5
CW
BW
F
R
R
F
MS-1
VRC
UV
OL
VR
VR
MSF
F
MSR
R

Fig 30

We will assume that all the machine parameters are identical to that of the example given in Art 4.31. The bias winding ampere turns are 330, and voltage across the amplidyne armature terminals is 180 V. Since the ampereturns necessary to give a voltage of 180 V across the armature terminals are 60 AT, the current winding ampere turns will be, 330-60 = 270. As was shown in Art 4.31, to develope 270 ampere turns, the drop of voltage across the current winding must be 15.1 volts. The drop of voltage across the resistors R_1 must be 15.1 volts higher than the balancing voltage across the resistor R_5. It follows, that in thisscheme the resistor R_1 must have higher resistance than given in the scheme of Art 4.31. If R_1 is three times larger, than the value given in the previous article we have,

$$R_1 = 3.\ 0.075 = 0.225 \text{ ohms}$$

The voltage drop across resistor R_1 corresponding to a starting current of 200 amps will be 200 . 0.225 = 45 volts. Therefore the balancing voltage will be :

$$45 - 15.1 = 29.9 \text{ volts.}$$

This in other words means that no sooner the drop of voltage across R_1 exceeds 29.9 volts the current winding is brought into action . 29.9 volts across resistor R_1, corresponds to a load current of $\frac{29.9}{0.225} = 133$ amps. which value is appreciably lower than the allowable starting current.

If during the starting period the voltage winding VW, were not active, as in the case of the scheme shown in Fig (Art 4.31), the starting current would be maintained within limits, moreover with a better accuracy. Since the voltage winding is active from the very beginning, in our present scheme, it is not possible to maintain starting current to a set value. Starting characteristics are poorer than for the scheme discussed in Art 4.31. Starting current varies from a maximum limit of 200 amps to 133 amps depending upon the increase in voltage at the generator terminals.

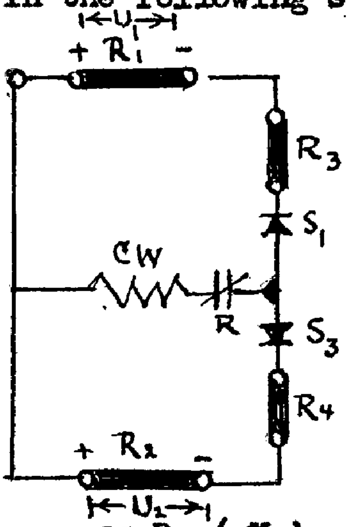
Our present scheme, also has what are known as excavator characteristics. The limiting current condition being that the total ampereturns due to the bias winding and current winding must be zero. In this example, the condition would be that, the current winding generates 330 ampereturns with a voltage drop of 18.5 volts across itself. In that case the drop of voltage across the resistor R_1 must be, $29.9 + 18.5 = 48.4$ volts. This gives an equivalent limiting current of $\frac{48.4}{0.225} = 215$ amp which is about 7.5% of the starting current.

One of the principal advantages of this scheme is that it reduces the difference between the limiting and starting current. For this reason, only such schemes are used for all electrical drives working under severe load conditions.

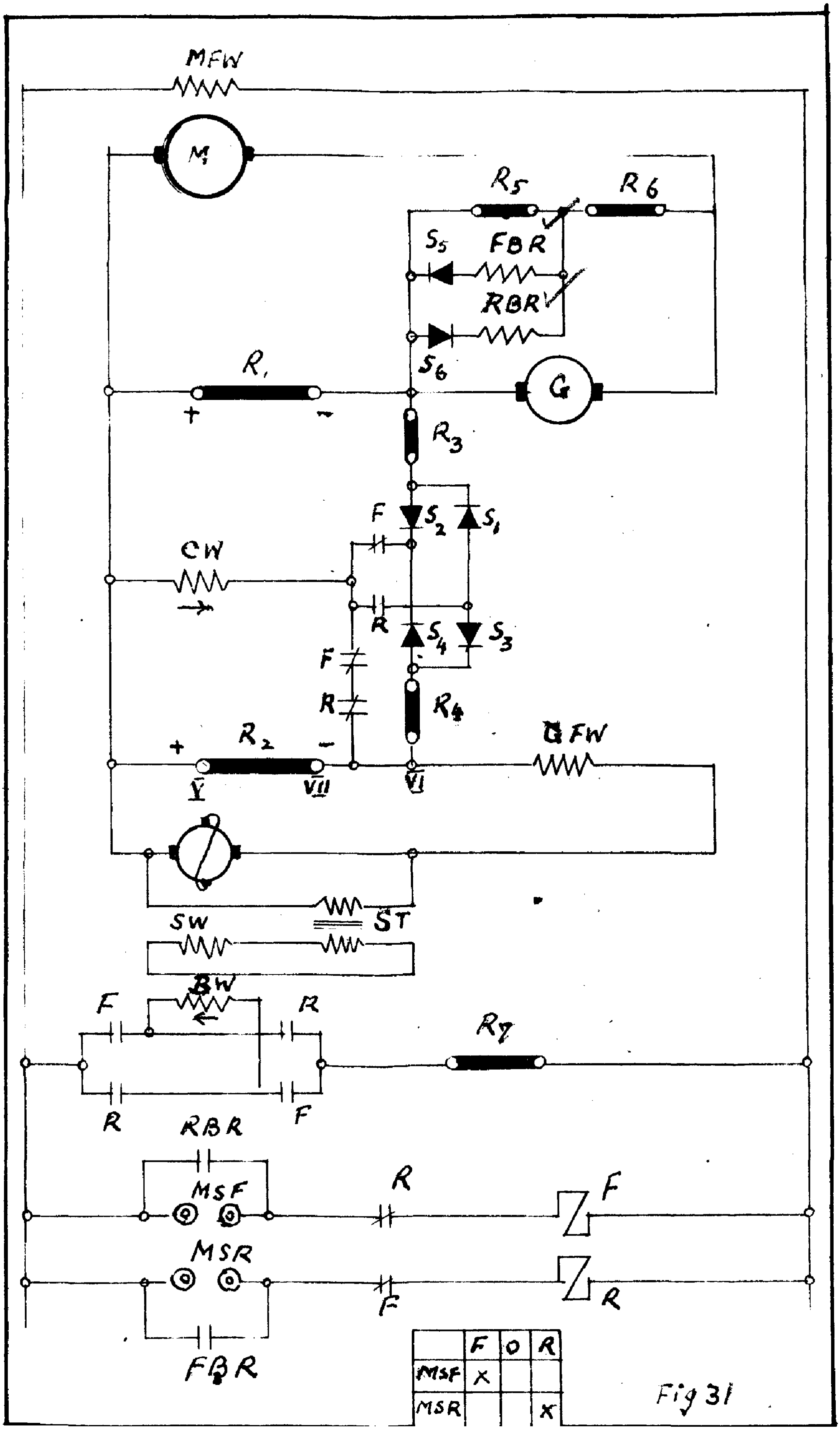
During braking the master switch is taken to the neutral position. Due to the stronger current winding, this control scheme is able to maintain a constant braking current.

4.33. Control scheme with combined current & voltage cut off.

With the master switch (MS) on the forward or the reverse notch, one of the reversible contactor, say F is closed (see fig. 31) . The control winding CW is connected as shown in the following simplified sketch.-



Drop of the voltage across R_1 (U_1) is determined by the value of the current in the motor armature circuit. Drop of voltage across R_2 (U_2) is similarly determined by the value of the generator field excitation. The reference or the bias winding BW is also switched into operation through the contacts of the forward contactor F. The bias winding quickly excites the amplidyne on account of its large number of ampere turns. During the initial stages of starting the generator field excitation is relatively smaller and so is the drop of voltage, U_2 across the resistor R_2. But, however, the current, through the motor armature rises sharply, thus creating a higher voltage drop, U_1 across the resistor R_1. Consequently during the initial period of starting the demagnetising



	F	O	R
MSF	X		
MSR			X

Fig 31

ampere turns due to the control winding are proportional to the motor armature current just the same way as with the voltage cut off circuit explained in Art 4.31. The resistor R_1, is so chosen, that the control winding CW develops sufficient opposing ampereturns, such that the starting current of the motor does not exceed the allowable limit.

By the end of the starting period, the generator field excitation rises to near about its nominal value. Due to this increased field excitation, the drop of voltage across the resistor R_2 (U_2) becomes larger than the drop of voltage across the resistor R_1 (U_1). This results in, having the control winding ampere turns proportional to the generator field excitation and not to motor armature current as during the initial starting period. The value of the resistor R_2 is so calculated, that the demagnetising ampere turns generated by the control winding CW at the end of the starting period cancel the additional ampere turns due to the bias winding BW, to develop the nominal voltage across the generator terminals.

After the starting period is over, the control winding provides sufficient and constant excitation of the generator field winding GFW, if the motor is loaded to its rated capacity. If however, the motor is overloaded beyond a limit, the drop of voltage across resistor R_1 will become greater than the drop across resistor R_2. The amplidyne will work now, on the current cut off regime. The control winding CW will generate sufficient demagnetising ampere turns, such as to bring down the generator field excitation. The motor speed decreases and is brought gradually to a complete stoppage. The limiting current in this case is appreciably higher than the starting current, as in case of the voltage cut off scheme discussed in Art. 4.31.

That is how, the control winding CW, plays the role of a generator voltage regulator, and also provides current limiting characteristics for the drive.

Braking of the drive is achieved with the help of relays FBR & RBR, which are connected across the generator terminals through metal rectifiers S_5 & S_6. When the motor is running in the forward direction, with the master switch MS in the forward notch, the contact MSF of the master switch is closed, through which is energised the forward contactor F. During the forward running, the relay FBR is closed. Normally open contact of FBR shunts the reverse contact MSR of the master switch. So long the forward contactor F is closed the reverse contactor R cannot be energised. No sooner the master switch is put in the neutral notch, the contactor R is closed, which changes the direction of current through the bias winding BW. This change of direction provides large demagnetising ampere turns, which are responsible for quick killing of the generator voltage. When the voltage at the generator terminals, is almost zero, the relay FBR is de-energised, which further de-energises the reverse contactor R. The bias winding is thus cut off. The control winding CW is now connected across the resistor R_2 through the normally closed contacts F and R, which acts as a discharge resistor.

Enumerated below are some of the defects of this scheme;

(a) Regulation of voltage is a function of the generator field excitation, and not the generator voltage.

(b) The control winding is connected to a number voltage sources, and these are no differentiating elements. This results in lesser accuracy in control.

(c) It has a number of rectifying elements. These, as is experienced in practice change their resistance with the passage of time which may again lead to inaccurate control.

(d) It is not possible, with this control scheme, to have a "speed control range". To lower the speed, it must not be necessary to completely stop the drive as is the case with this control scheme.

The last of these defects is, however, improved upon by using a scheme with two control windings, as shown in fig. 32. Each of the control windings CW_1 and CW_2 work only in forward and backward running respectively. When introducing braking in the direction" forward"

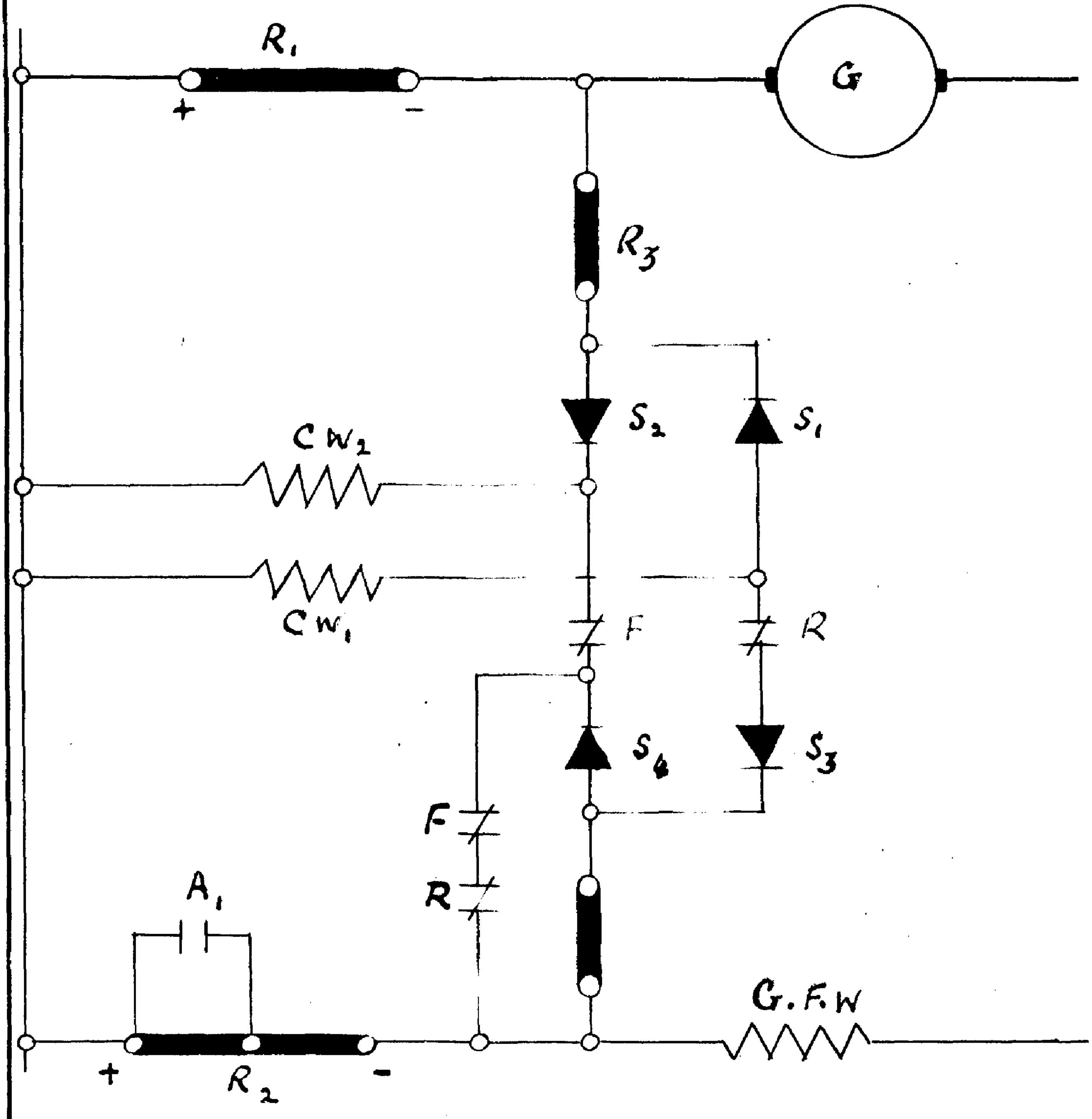
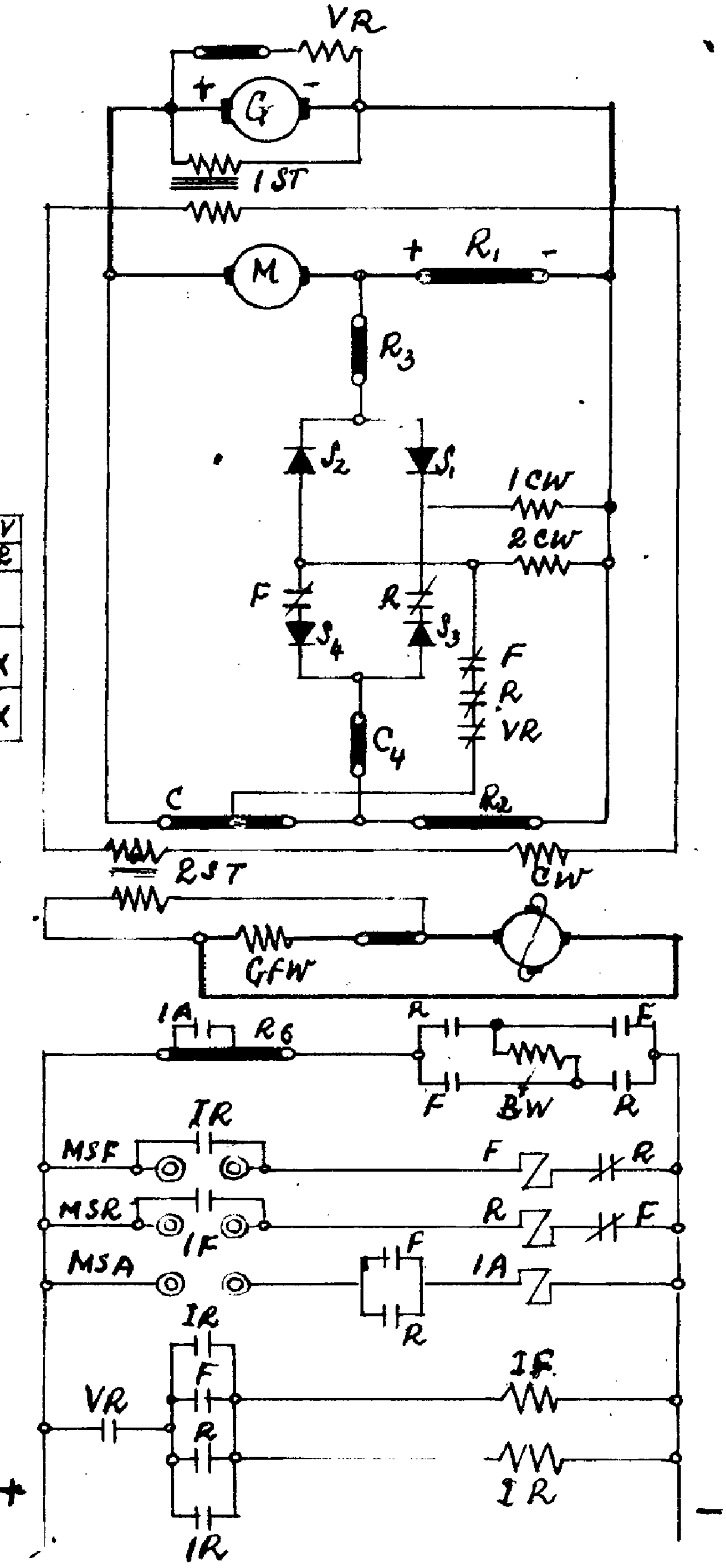


Fig 32



	FWD		0	REV	
	2	1		1	2
MSF	X	X			
MSR				X	X
MSA	X				X

Fig 33

(from a higher speed to a lower speed), the accelrating contactor A_1 is de-energised introducing more resistance in the generator field winding (GFW) circuit. This instantly changes the polarity across the resistor R_1 with the result that the control winding CW_2 is brought into play . The control winding CW_2, is connected such that the direction of current passing through it (depending upon the polarity of voltage drop across R_1 and the rectifier S_2) is in opposition to that of the control windings CW_1. Control winding CW_2, remagnetises the amplidyne and retards the rate of lowering of the generator voltage, and as well as limits the braking current.

This control scheme does still retain various other defects enumerated under (a),(b) and (c) above. Fig 33 shows a more modern scheme, which gives a better control. The scheme is described in detail below:

When the master switch is put on the Ist "forward" notch (see fig. 33) contactor F is closed, which further connects the bias winding across the control voltage mains. This results in quick rise of voltage across the generator terminals due to the large number of ampere turns of the bias winding. However, the starting current is maintained within limits with the help of the demagnetising ampere turns provided by the control winding 1CW, which during the initial starting period is connected across the resistor R_1 through the metal rectifier S_1. When the generator voltage has just risen to about 10% of the nominal value, the voltage relay VR is closed, which further closes the interlocking relay IF. At the end of the starting period when the voltage has risen, corresponding to the " Ist forward notch speed", the voltage drop across the resistor R_2 is more than that across R_1. The control winding, is therefore activated by drop of voltage across R_2 and is connected to it through the normally closed contact R and metal rectifier S_3. The drop of voltage across resistor R_2 is a function of the generator voltage, by virtue of which, control winding 1 CW develops sufficient demagnetising ampere turns for establishing the generator voltage at the desired value.

When the master switch is put in the Second forward notch, accelrating contactor A is closed which shunts part of the resistor R_6, thereby increasing the current through the bias winding voltage of the generator increases thereby increasing the speed of the motor M. During the interval when the speed of the motor is still increasing, the control winding 1 CW comes into action, just the same way as at starting.

When the master switch handle is taken back to the Ist forward notch the generator voltage starts decreasing quickly. The motor M is subject to dynamic braking. The current direction in the main power circuit changes and so does the drop of voltage across the resistor R_1. Under such conditions the winding 1 CW can no longer, effect current control in the main power circuit. But however, control winding 2CW is activated through which current is allowed to pass by the metal rectifier S_2.

Control winding 2CW, remagnetises the amplidyne generator and retards, lowering of voltage across the generator terminals and further limits the load current. When the speed of the motor drops to the first notch speed, the current direction in the power circuit is again changed and the control winding 1CWcomes back to operation as discussed earlier.

Again when the master switch handle is brought back from "Ist forward notch" to the "neutral notch", the contactor F is de-energised. Contactor R is immediately closed through the normally open contacts of the interlocking relay IF (which is shunting the MSR contact of the master switch). This results in the change of current direction through the bias winding, which immediately changes the polarity of the amplidyne generator. The generator voltage falls steeply and the motor undergoes dynamic braking. The braking current is limited with the help of the winding 2CW.

When the generator voltage has sufficiently dropped down, (say a few percent of the nominal voltage) the relay VR opens. Due to this relay IF and contactor R are de-energised. The control winding 2CW is now connected across the generator terminals through the normally closed contacts F, R and VR and the voltage divider, $R_2 - R_5$. This results in self extinction of the generator voltage, as the direction of current through 2CW is in opposition.

(un stabilising windings)

For minimising the effect of transient disturbances, stabalising transformer, IST and 2ST are used. The primary windings of transformers IST and 2ST are connected across generator and amplidyne terminals respectively. The secondary windings of these transformers are connected in series which feed the control winding CW of the amplidyne.

4.34 Control scheme with independent current and voltage cut off

Control schemes with independent current and voltage cut off exhibit better performance in respect, to the regulation of generator voltage, smaller starting periods, and accurate control of limiting load conditions. Such a scheme is shown in a simplified form in fig 34.

In this scheme the current and voltage windings are connected independently to the differentiating or balancing ciruits which are set for definite current and voltage cut offs.

It is apparent then that, the current winding is activated only when the load current rises above a particular set value, and so also does the voltage winding.

Braking of the motor is achieved by reversing the direction of current through the bias winding. Voltage winding VW is used for the self extinction of the generator voltage.

The disadvantages of the above control scheme are that, it involves complicated balancing circuits which require absolutely constant D. C. voltage. Secondly, with the passage of time the metal rectifier change their characteristics and this requires recalibration.

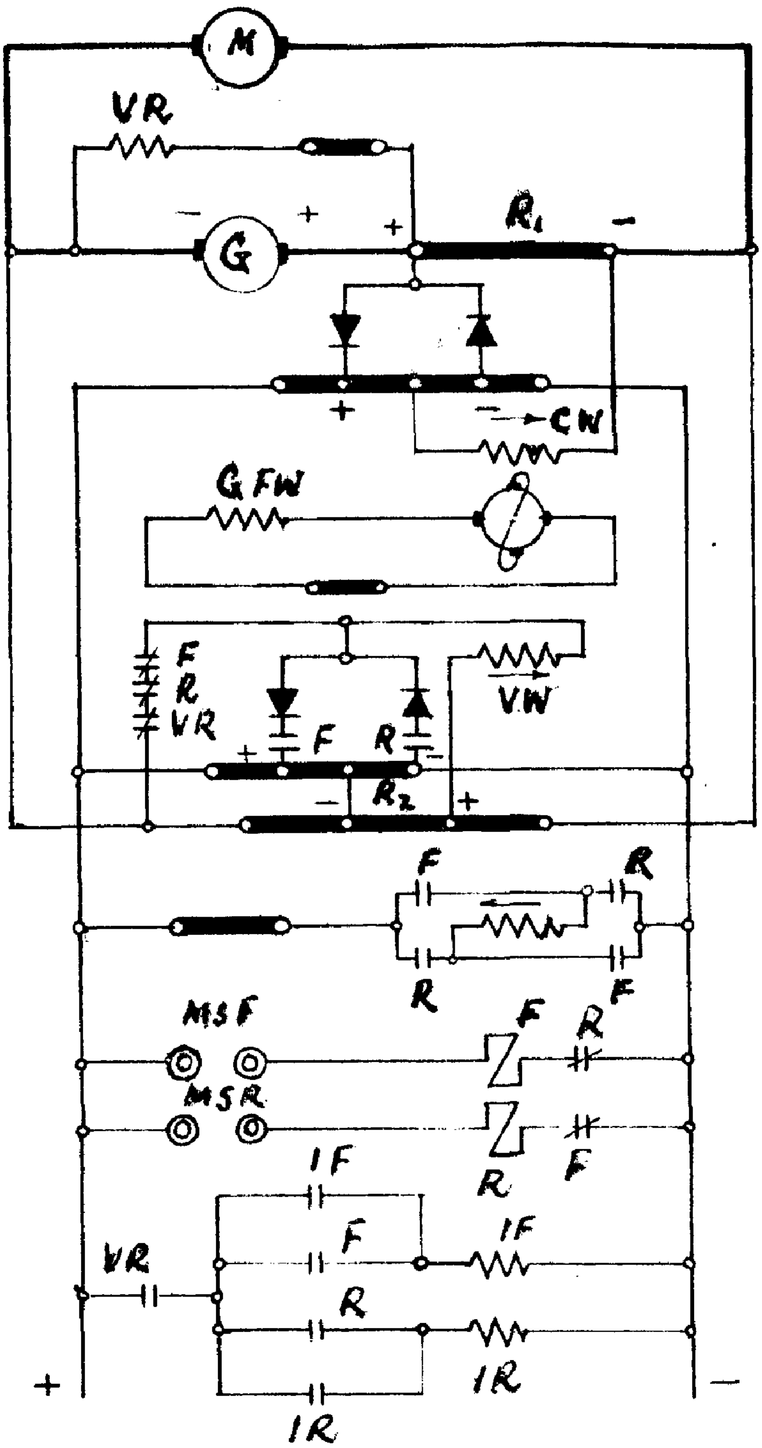


Fig 34

4.4 CONTROL SYSTEMS OF REVERSIBLE MAIN DRIVES

A general arrangement of control for a hot reversing mill such as the blooming mill is shown diagramatically in fig 35. A modern blooming mill stand mainly consists of the following electrical equipment;

1) Reversible main mill motor

2) Fly wheel motor generator set, providing supply to the main mill motor.

3) Exciter sets for supplying, field excitation to the generator of the main M.G set, field excitation to the main mill motor & field excitation to all control generators and amplidynes. In addition, the exciter sets have additional generator for providing control supply to all panels and dynamic braking for the main M.G set.

4) Amplidyne generator sets
Complete, automatic control of a modern blooming mill stand is effected with the help of amplidyne generators, as indicated in fig 35. In order to simplify the description of the control system employed for the main mill motor; the complete control scheme is divided into several sections. These are:

   a) Power circuits
   b) Generator voltage control circuits
   c) Motor field excitation circuits.
   d) Constant potential generator circuits.
   e) Control circuits of main circuit breakers
   f) Relay contactor circuits

In the succeeding articles we will only discuss important sections, mentioned under (a),(b) & (c) above.

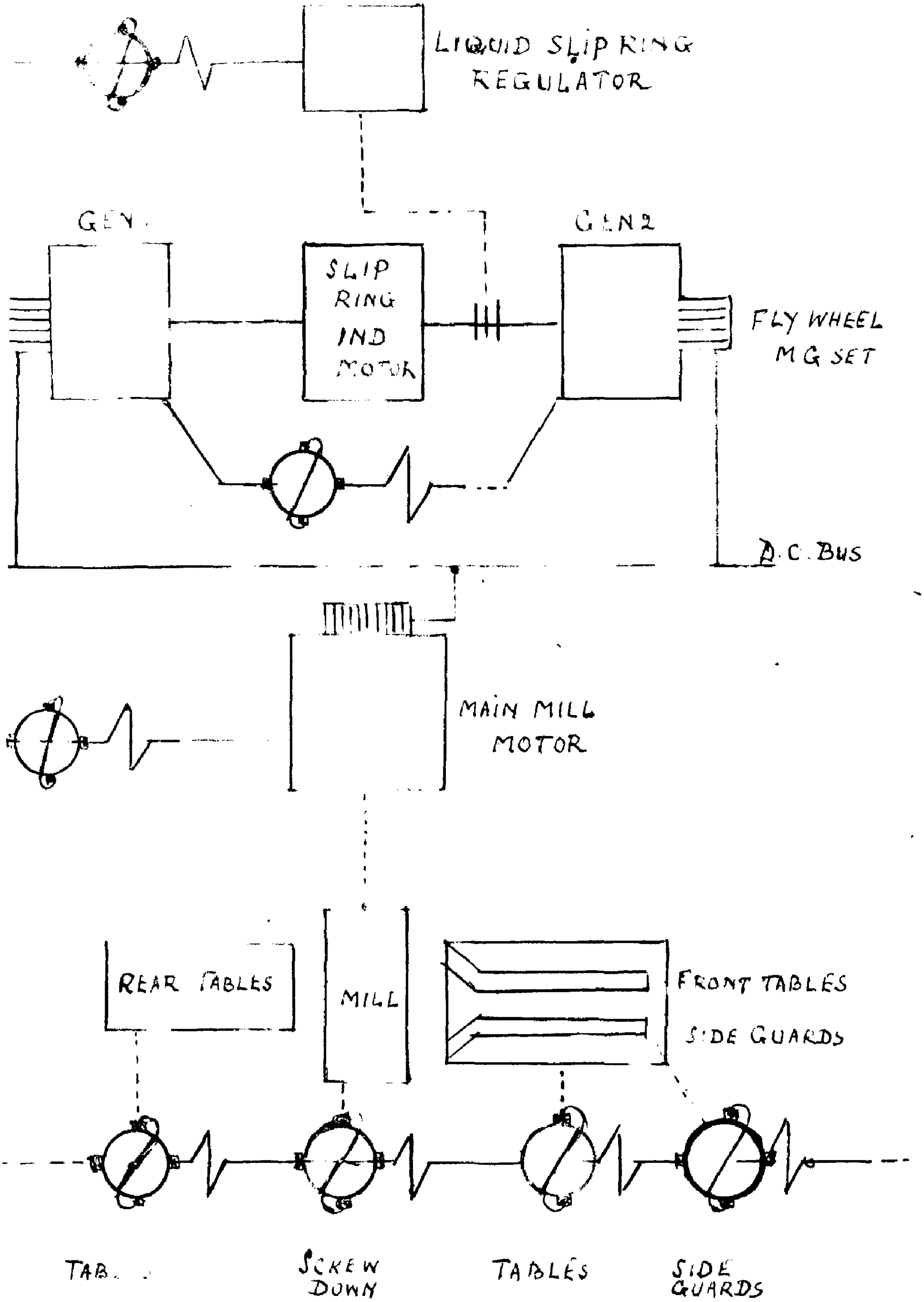

LIQUID SLIP RING REGULATOR
GEN
SLIP RING IND MOTOR
GEN 2
FLY WHEEL MG SET
D.C. BUS
MAIN MILL MOTOR
REAR TABLES
MILL
FRONT TABLES
SIDE GUARDS
TAB.
SCREW DOWN
TABLES
SIDE GUARDS

Fig 35

4.41 Power circuits

The flywheel motor generator set comprises of a number of generators, a flywheel and a driving motor. The driving motor is generally an A.C slipring induction motor. It will be realised, that as the M.G set is required to supply power to the mill motor, which is generally rated as high as 7000 h.p, due attention must be paid to the operating speed of the M.G.set. It is apparent, that in order to reduce the "floor area size" of the driving motor, the operating speed must be higher as otherwise it would become unwieldy. At the same time there is a limit to raising the operating speed. With 500 rpm the optimum output from a generator is 3500 kw. That is why for a mill motor rated at 6000-7000 H.P., the MG.set is comprised of two generators each rated at 3500 kw.

The diagram of power circuit shows (fig 36) each generator connected to the common bus through individual air circuit brakers with over current protection, for equidistribution of load between generator equiliser windings EG-1, and EG-2 are connected in series across the armatures of the two generators. The equiliser windings are so connected that, when one of the generators takes a larger share of the total load, a current flows through these windings such that the over loaded generator is under exciter due to the demagnetising influence of its equiliser winding.

differential
[illegible]

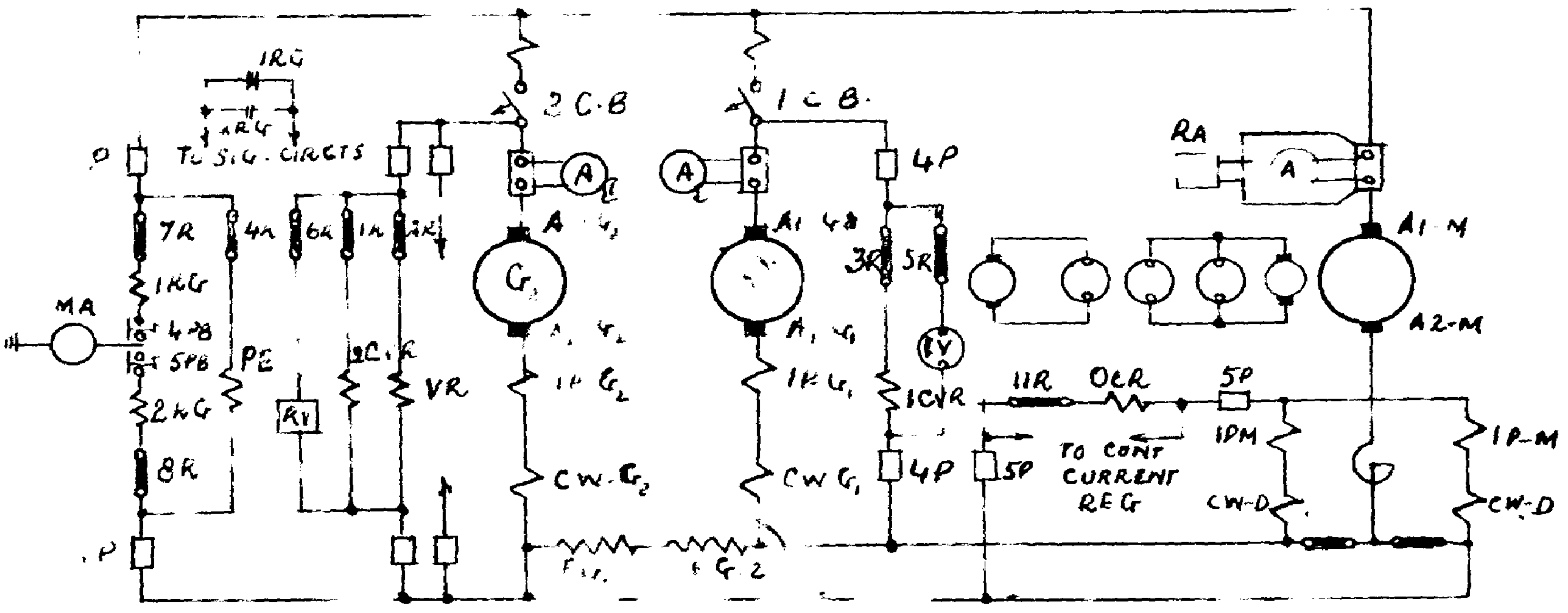

IRG
4RG
TO SIG. CIRCTS
2 C.B
1 C B.
RA
A
4P
P
7R
1RG
4PB
5PB
2RG
8R
P
MA
PE
4R
6R
1R
2R
RV
2C.R
VR
G1
A
A1
1P G2
CW. G2
F.F.
G 2
1PG1
CW G1
3R
5R
V
1CVR
4P
11R
OCR
5P
1PM
5P
TO CONT CURRENT REG
CW-D
A1-M
A2-M
1P-M
CW-D

Fig 36

Similarly the underloaded generator is overexcited due to the magnetising influence of its equiliser winding. Over voltage protection, for the generator is provided with the help of relays 2OVR and 2OVR. Voltage relay VR, sets the normal working voltage which is about 70% of the generator nominal voltage. Additional speed regulation is obtained by weakening the motor field. As is seen from fig 36 to one of the generator armatures are connected the control circuits for voltage regulation of generator. Drop of voltage across the compensating winding and inter pole windings is utilised for controlling the load current.

4.42 Voltage control circuit

This control circuit (see fig 37b) provides four stepped voltage control. Voltage at each step being proportional to the total number of steps. Corresponding operational sequence is obtained with the help of reversible contactors 1F or 1R, relay 1GCR, relay 2GCR & relay 3GCR respectively. Each voltage step corresponds to a fixed motor speed.

In addition the scheme provides for an idling speed of 5 to 7 rpm necessary for cooling the rolls during idling period of the mill. This is achieved with the

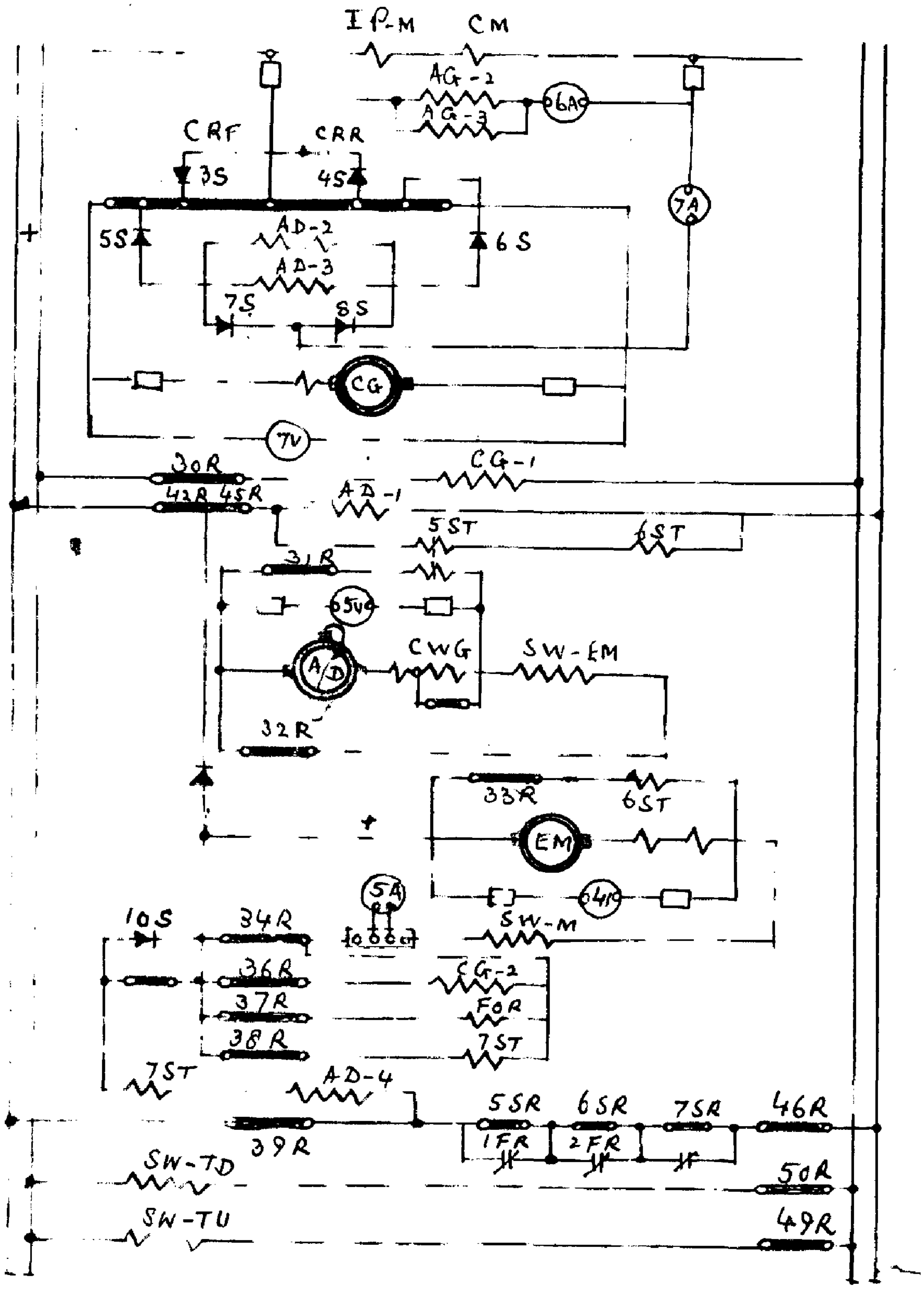

IP-M
CM
AG-2
AG-3
6AC
CRF
CRR
3S
4S
7A
5S
6S
AD-2
AD-3
+
7S
8S
CG
7V
30R
CG-1
42R 45R
AD-1
5ST
6ST
31R
5VG
A/D
CWG
SW-EM
32R
33R
6ST
EM
+
5A
41C
10S
34R
SW-M
36R
CG-2
37R
FOR
38R
7ST
7ST
AD-4
5SR
6SR
7SR
46R
39R
1FR
2FR
SW-TD
50R
SW-TU
49R

Fig 37a

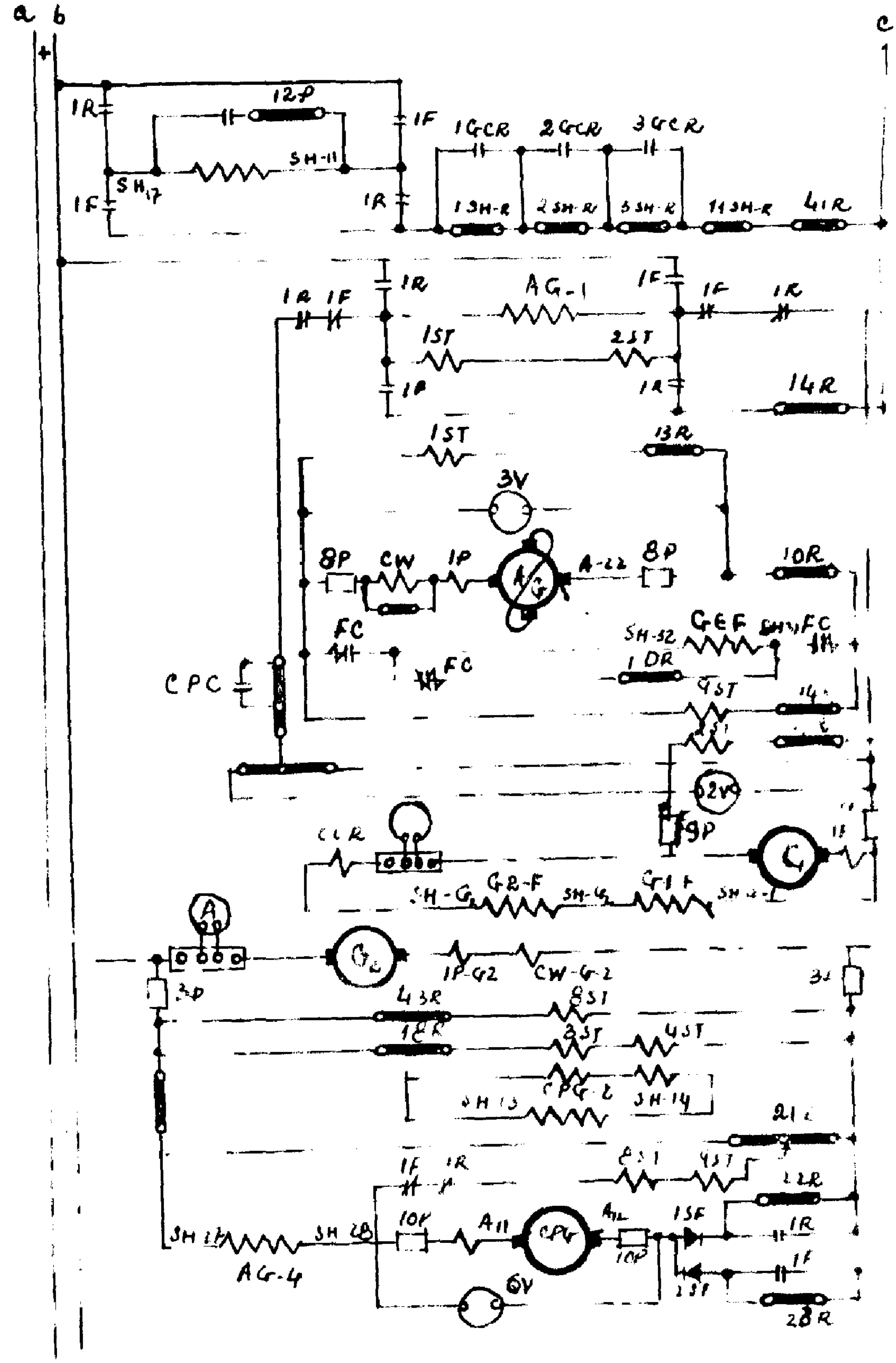

a
b
c
+
1R
1F
12P
SH-11
SH17
1GCR
2GCR
3GCR
1SH-R
2SH-R
3SH-R
11SH-R
4IR
AG-1
1ST
2ST
14R
13R
3V
8P
CW
1P
AG
A-22
10R
FC
GEF
SH-32
1DR
4ST
CPC
52V
9P
G
CCR
SH-G
G2-F
G1F
A
Gz
IP-G2
CW-G-2
3P
43R
8ST
1ER
3ST
SH-13
CPG-2
SH-14
21R
22R
AG-4
SH 28
10P
A11
A12
CPG
6V
1SF
2SF
28R

Fig 376

help of relays ISR and reversible contactor 1F and 2F. The relay coil of ISR is energised as shown in the relay contactor circuit (fig. 37b) . For stabalisation of transient disturbances the control scheme provides for three stabalising transformers, 1ST, 2ST& 3ST. The primary windings of these transformers is connected at the following situations; (a) armature circuit of the amplidyne generator,(b) armature circuit of the exciter (c) generator armature circuit. The secondary windings of 1ST and 2ST are connected in series across the amplidyne output terminals. Secondary winding of 3ST is connected across the exciting winding, GVR-2 of the voltage regulator.

During braking, two additional stabalising transformers (8ST and 9ST)are used, which react on the amplidyne through one of its control windings. These transformers come into operation only during braking, through the normally closed contacts 1F and 1R.

The exciting winding of the exciter is connected to the amplidyne generator through a contactor FC, with the help of which the winding is connected across the discharge resistor 1DR and is at the same time disconnected from the amplidyne.

In addition to the over-voltage protection provided by the relays 1OVR and 2OVR (see fig 36), an over load relay, OLR introduced in the generator field circuit as a further protection against over-voltage.

In this control scheme, during the starting period, the motor is controlled as a function of generator voltage. During braking control is effected, as function of load current. This is obtained with the help of windings AG-3 and AG-4 which are connected across the compensating and interpole windings of the generator. As stated before these windings are activated only during the braking regime, with the help of normally open contacts of reversible contactors, CRF and CRR and metal rectifiers 3S and 4S. The value of braking current can be adjusted with the help of potentiometer connected across the current generator CG (see fig 37a).

4.43. Motor field excitation circuits.

Motor field excitation, as mentioned earlier, is called for variance in case speeds above the nominal value are desired. This again is achieved with four stepped control, of the motor field excitation. This gives four distinct speeds above the normal speed.

Initial starting of the mill motor is effected with the rated motor field current, when all the field weakening contactors (1FR, 2FR,3FR, 4FR) are closed. (See fig 37a

In order the motor runs on any of the overspeed steps, corresponding field weakening contactors open reducing the Voltage drop tapped from the potentiometer, which reduces the current through the control winding AD1.

For stabalising the transient disturbances involve during changes in the motor field excitation, stabalising transformers are used as shown in fig 37a.

The control scheme provides for controlling the motor field excitation as a function of load current. When the armature current through the motor exceeds the allowable limit for a particular speed through control windings AD-3 and AD4 passes a proportional current which increases the resultant excitation of the amplidyne generator. This increases the amplidyne voltage which increases the motor C.E.M.F and brings down the armature current.

4.5 CONTROL OF WINDING REEL MOTORS IN COLD ROLLING MILLS.

At each end of a reversible cold rolling mill stand, are located the winding reels, that alternately serve as feeding in and winding reels, depending upon the number of passes. Each of these reels aredriven by individual driving motors. For achieving, uniform quality of these cold rolled sheets, it is necessary to maintain constant tension along the sheet while it is undergoing rolling under the stand.

If the linear speed of rolling is constant, as is usually the case, then little the increase of the winding reel diameter, the speed of the 'reel driving motor' must change correspondingly. A little consideration would show, for obtaining constant reel tension, under a constant speed of rolling, it is sufficient to run the reel motor under a correspondingly constant load condition. Fig. 38 shows a control scheme, designed to obtain this constant load condition.

Reel motor M is supplied by a separate generator G. Motor field is separately excited with a constant excitation. The generator field winding GFW is connected across the output terminals of the amplidyne A. The amplidyne A, is excited, with the help of the reference or the bias winding BW. The control winding CW, assumes control of the net excitation of the amplidyne and hence that of its output. Excitation current through the bias winding, determines the desired reel tension and is set with the help of the regulating rheostat RR. The control winding excitation is a function of the voltage difference across the terminals of the tachogenerator TG and the control generator CG. The tachogenerator voltage is a function of the

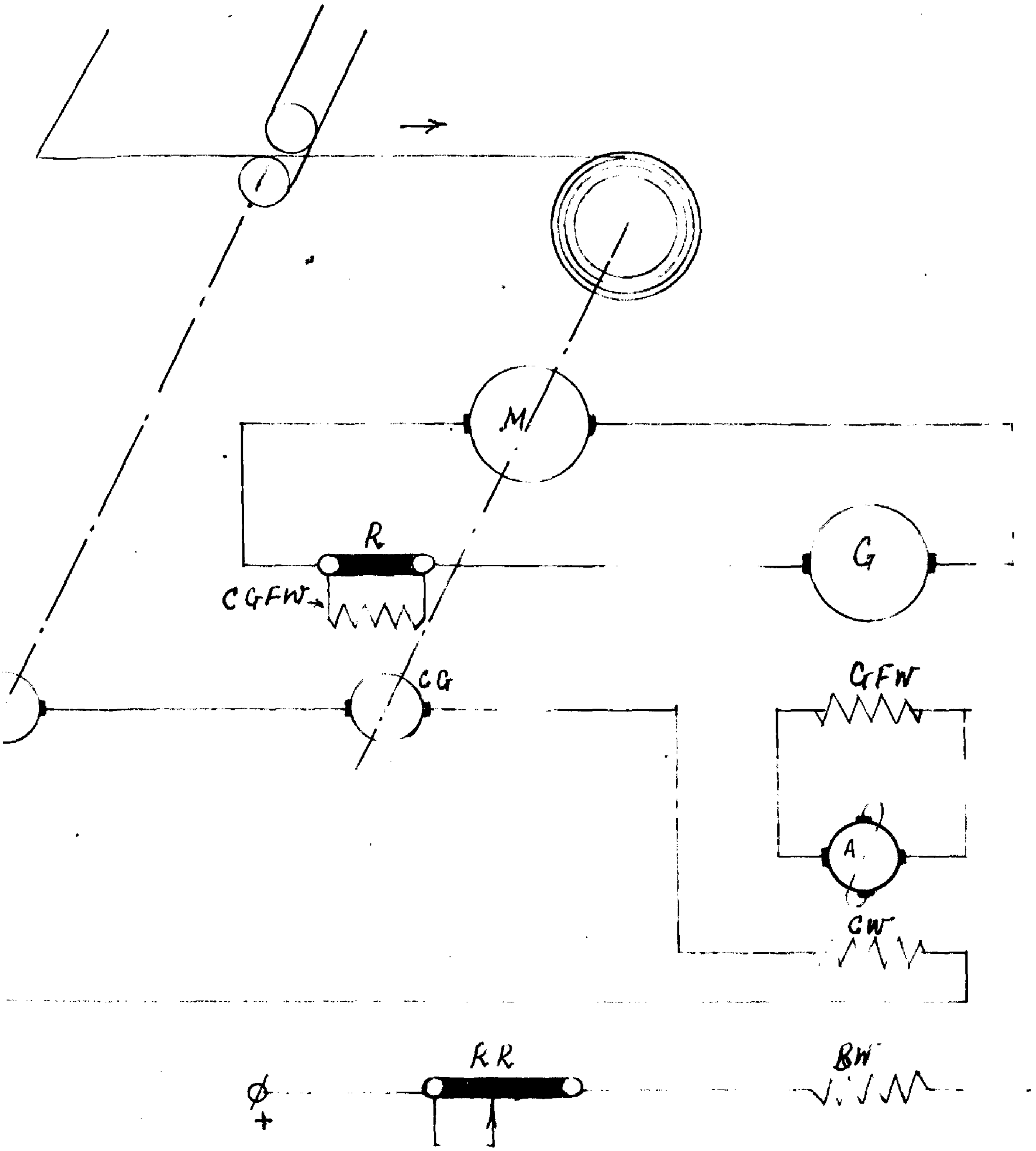


Fig 38

rolling speed of the stand, while control generator is driven on the motor shaft. The field winding CGFW$_R$ of the control generator is connected across the resister R, voltage drop across which is a function of the motor armature current. As stated above the motor field excitation is constant, and hence the armature current is a function of the motor torque. It follows, therefore, that the control generator field excitation is a function of the motor torque. The speed of the control generator and the reel motor being the same, since each is driven on a common shaft) the control generator voltage is proportional to a product of the motor torque and the motor speed. In other words, the control generator voltage is proportional to the motor horsepower. With a constant rolling speed, the tacho-generator voltage is a constant, and the control generator voltage starts rising. Current through the control winding CW, is determined by the voltage difference between TG and CG.

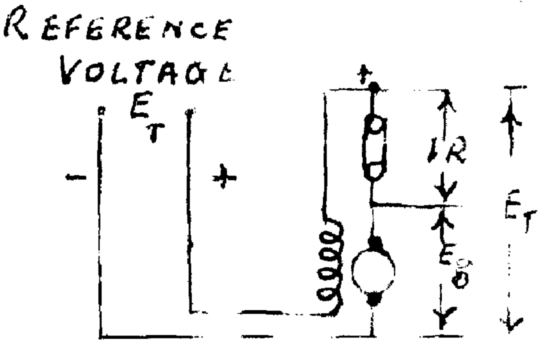
In an idling stand, the generator voltage, motor current, and consequently the reel tension are determined by the set bias of the reference winding BW. In a working stand, the generator voltage should be higher to have the same reel tension. A proportionate rise in the generator voltage is obtained with the help of the control winding as explained above.

CHAPTER 8

CONCLUSION

This concluding discussion includes a brief and interesting review of practical studies made on control systems wi the help of anacom-computors. These studies practically demonstrate the effect of such variables, as system gain, exciter size, ceiling voltage, rotating machine time constants and saturation, on the overall performance of a control system regulator. We have discussed some of these effects at various places in the main text of this dissertation. It will be interesting to see how our theoretical conclusions agree with these practical measurements. We will see, how important it is to carefully co-ordinate each component of a drive system, including the regulating element, exciters, main drive generators and motors to meet requirements of the driven machine.

Fig. 39 illustrates the effect of gain on the steady state performance of regulating system. The connections are for a simple single delay system where the field of a D.C. generator is connected between its own terminals and the reference voltage. The generator is then its own regulator. The system voltage gain 'A' is defined as follows: if one volt on the generator field produces 50 volts on the generator terminals, the system gain would be 50:1. In the tabulation, the full load resistance drop



$$E_T = E_g - IR$$

$$E_T = \frac{A}{A+1} E_s - \frac{IR}{1+A}$$ — STEADY STATE

A : SYSTEM GAIN

A	E_T	E_T (NO LOAD)	E_T FULL LOAD	% ERROR
0	—	100	90	10
1	200	100	95.00	5.00
2	150	100	96.67	3.33
5	120	100	98.33	1.67
10	110	100	99.08	0.92
25	104	100	99.62	0.38
50	102	100	99.80	0.20
100	101	100	99.91	0.09

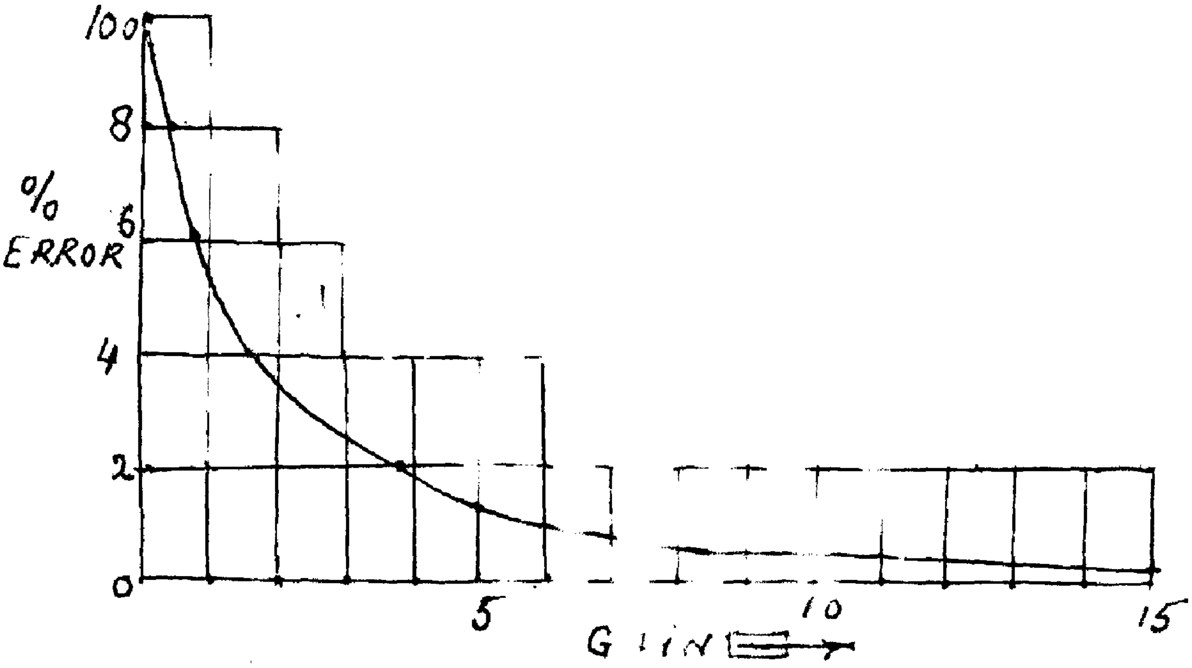


Fig 39

in the generator has been taken as 10 volts for a generator rated at 100 volts output, and the voltage under full load condition is shown for various values of gain.

Such a single time delay system is ideal from the simplicity standpoint, but it is not practical because of low gain and high power drain on the reference circuit. For instance, assume that a 3000 Kw generator rated 600 volt requires 3 Kw of excitation. For a gain of 50, field voltage would be 12 volts and field current 250 Amps. Since the reference bus must be at 600 volts, the drain from this source is 150 Kw (250 A x 600 V.). An amplifier or separate regulating device is normally required to reduce this drain to reasonable limit.

Fig. 40, shows a two delay system with a rotating regulator operating in the field of the D.C. generator. With this system, the drain from the reference voltage source will be only a few watts compared with 150 watts cited above. In general the better the regulating element as to power amplification, the smaller the drain from reference voltage which is an important consideration, in the size of pilot generators, exciters and other reference and measuring circuits. An anacom study was made on two delay system as shown in Fig. 41 to demonstrate the effect of system parameters on regulating system performance. For this study, the time

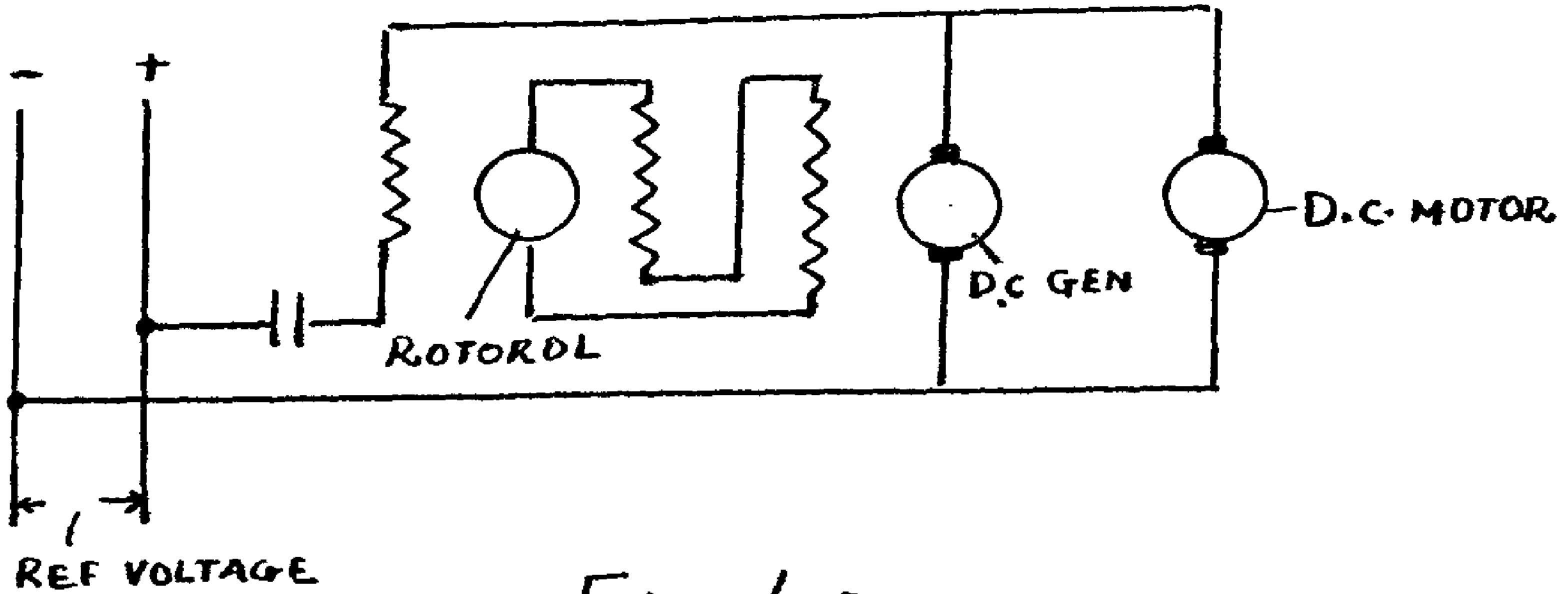


Fig 40

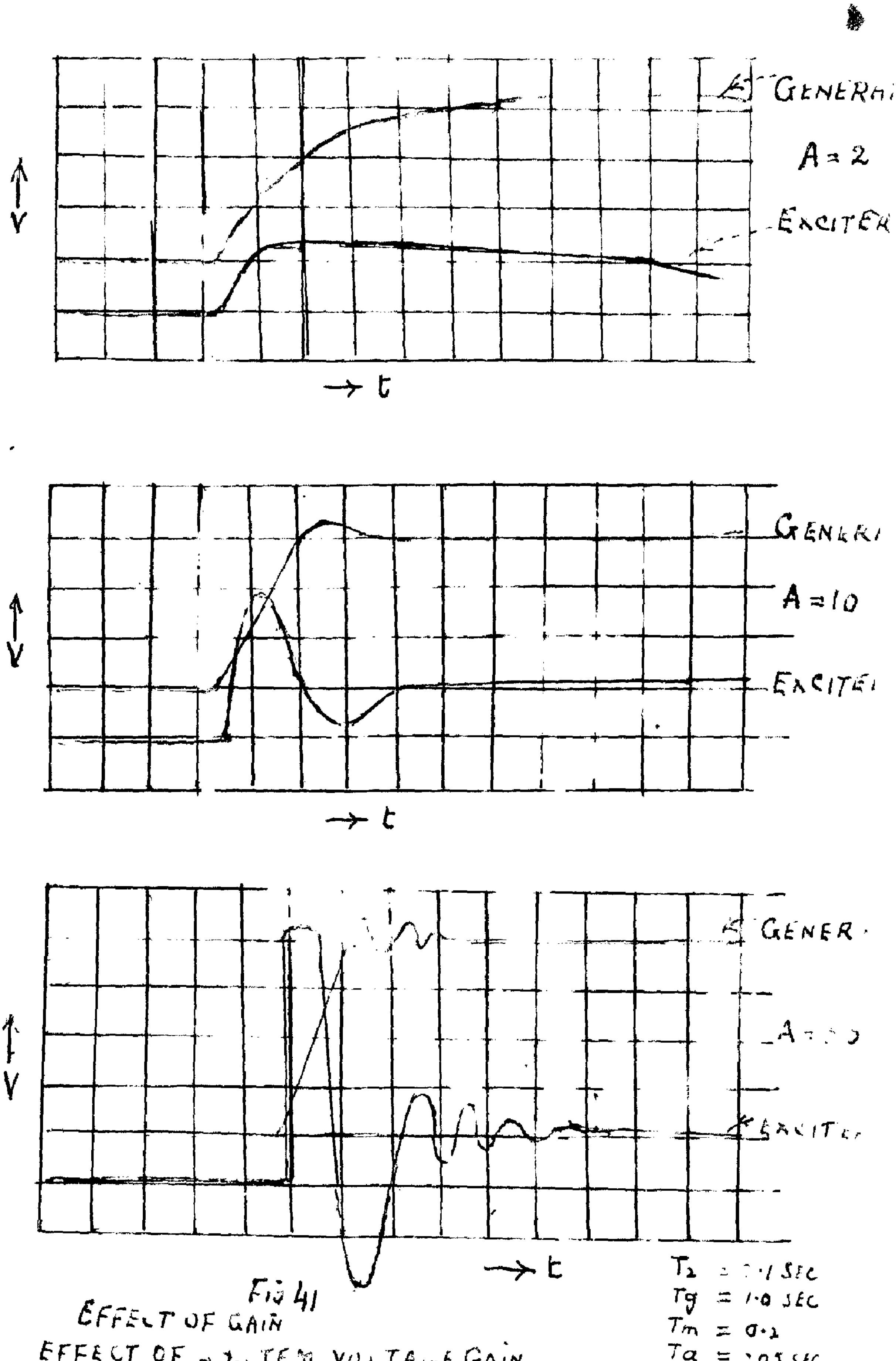


Fig 41

EFFECT OF GAIN

EFFECT OF SYSTEM VOLTAGE GAIN
ON TRANSIENT RESPONSE

T_2 = 0.1 SEC
Tg = 1.0 SEC
Tm = 0.2
Ta = .05 SEC
NO DAMPING
CEILING = 8PU
4 DIV = 1PU

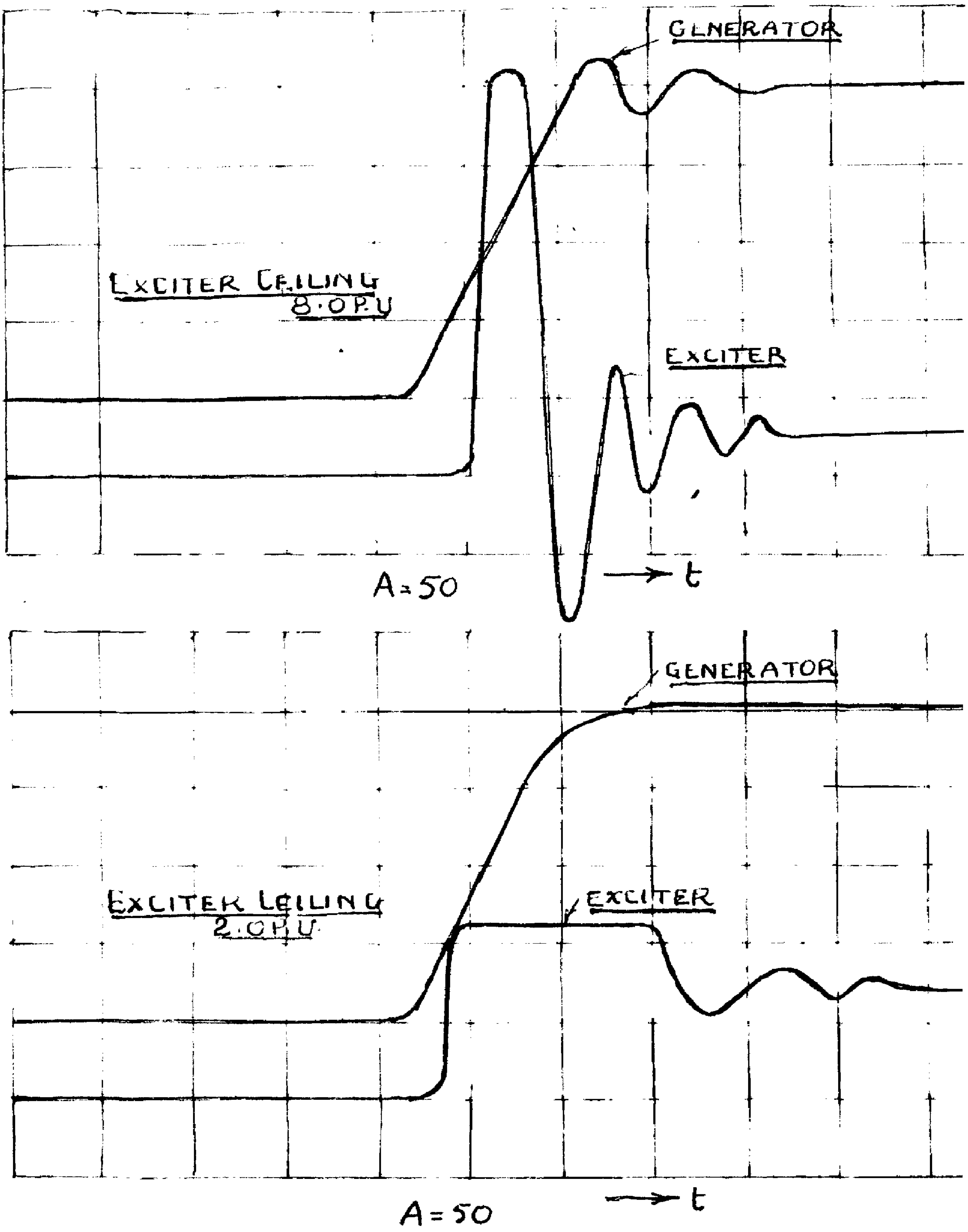
constant of regulator was taken as 0.1 second, the time constant of the generator as 1 second, the motor armature time constant 0.05 seconds, and the mechanical time constant of the motor and connected load 0.2 seconds. It should be again stressed that the regulator is merely one component of the system. To obtain the best performance, good regulator design must be coupled with good motor and generator characteristics and good control as will be shown.

Fig. 41 shows the effect of system gain on transient response of regulating system. In this case, the contact applying the regulating field was closed, which takes the generator voltage from 0 to full rated value. No damping is used. With various gains the generator voltage response and exciter ceiling voltages in per unit values are as follows:

Gain A	Transient response	Per unit exciter voltage.
2	2.50	1.5
10	0.25	5.2
50	0.10	8.0

System gain has a marked effect on transient response. Also note how the sealing voltage of the exciter is affected by system gain. The sluggish generator field has electrical inertia much the same way as a heavy flywheel has mechanical inertia. It takes time to get electrical current in motion just as it takes time to accelrate an automobile. To obtain fast response, high degree of forcing must be applied to sluggish fields. The sealing voltage of the computer used for this study was a maximum of 8 P.U; otherwise with a system gain of 50, the exciter voltage would have been somewhat higher than 8 times rating and response would have been somewhat faster. Fig. 42 shows the effect of a limited exciter ceiling voltage on regulating system performance. On this figure and as well as on Fig. 41 no damping is applied and it will be noted, that the regulator is somewhat unstable. It is interesting to note that as the exciter ceiling is limited to 200 per cent with the gain and other constants remaining the same, the response changes from 0.1 to 0.6 seconds. Thus high peak exciter voltage as well as high gain is necessary to get fast transient response.

Table I shows the steady state Kw require? by various machine fields an equivalent exciter rating actually applied to force fast response for the blooming mill generator voltage regulator, the exciter rating is in excess of 10 times



EFFECT OF EXCITER CEILING

Fig. 42

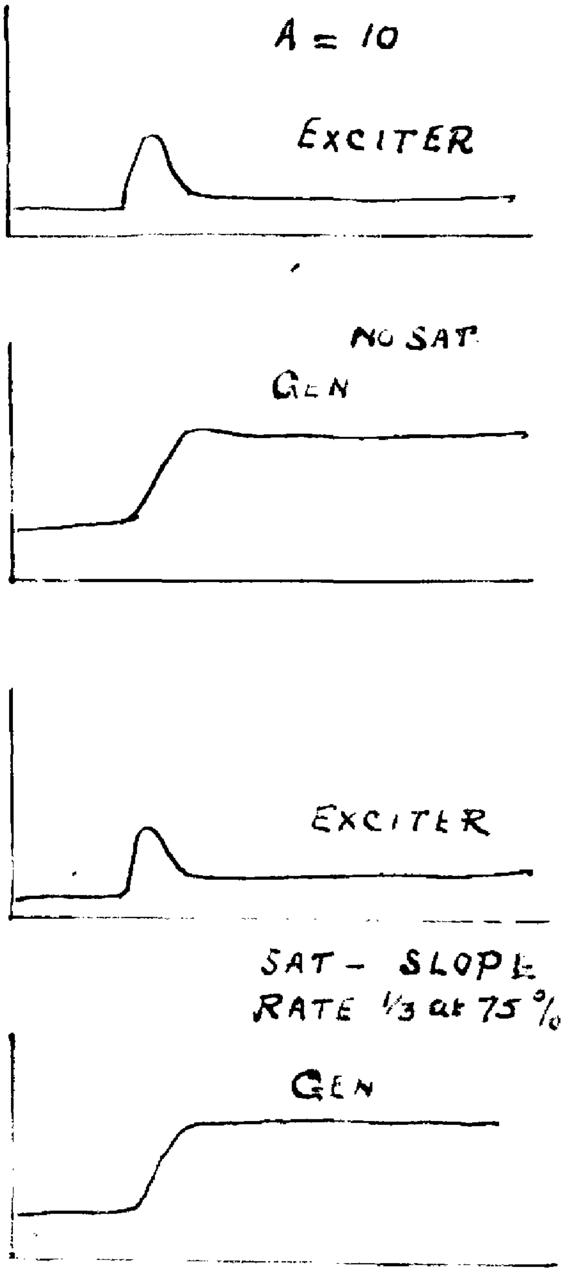
the steady state field requirements. These values have been taken from 10,000 H.P. twin drive using four 2500 Kw generators. The overall performance on reversal from base Speed in the opposite direction was one second. The fastest that has been obtained upto date is also near about 1 second.

TABLE I.

No.	Mill	Regulated function	Steady state field-Kw.	Exciter rating
1.	Blooming	Generator voltage	10	104
2.	Blooming	Motor field amperes	45	280
3.	Tandem cold	Generator voltage	1.8	7.5
4.	Screw down	Generator voltage	0.7	10

On blooming mill motor fields, it is also necessary to apply high forcing values in order to obtain fast response. The values in the chart are for the same as cited previously— the exciter size 280 Kw for a steady state field Kw of 45. The values for the tandem cold mill voltage regulator and the variable voltage screw down also reflect increased size to provide the necessary forcing values. Fast response can be only obtained at the expense of large exciter sizes. In fact some of these exciters are so big that they are in class with main generating equipment.

The generator saturation has to be carefully watched on regulating system requiring a close match with other systems, for example, the individual generator for tandem cold reduction mills. Fig. 43 indicates that difference in response: first with no saturation and second with the saturation slope ratio of 1/3 beginning at 75 per cent voltage. Close examination of these two curves will show, that they are essentially the same upto 75 per cent voltage. Beyond this value the saturation, in the generator cuts the total gain of system to 1/3 of its former value and the response is correspondingly slower. If an unsaturated and saturated system were side by side as in a tandem cold reduction mill drive, the difference would be enough to cause a major change in strip tension as the mill is accelrated. The difference cannot be reconciled by an increase in the regulator gain. The performance at either the start or the end of accelration could be matched, but it is impossible to match both conditions. On such drives it is necessary to match generator saturations with narrow limits to get the best mill performance. Generally low values of saturation are used which increase the size and cost. For systems where regulator operates in the motor field (reel drives and rod mill speed regulators), saturation must be carefully watched, in order to get good performance over the entire speed range.



EFFECT OF GEN: SATURATION ON TRANSIENT RESPONSE

Fig 43

NOTE HIGHER STEADY STATE EXCITER VOLTAGE ON THE LOWER CHART WITH GEN: SATURATION.

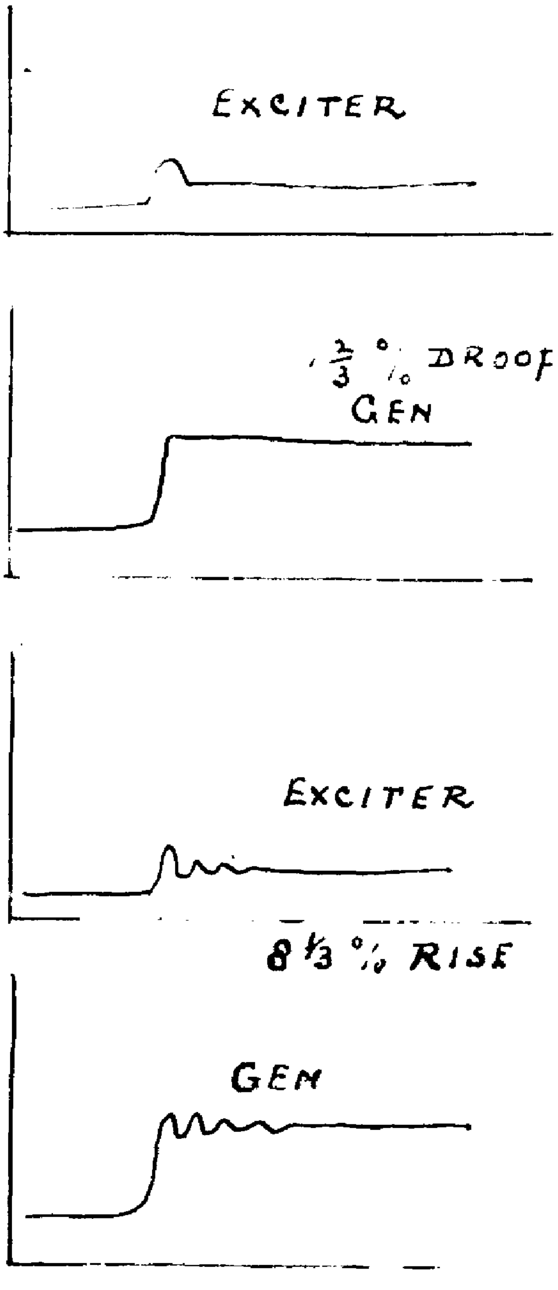


Fig 44

EFFECT OF RISING VOLTAGE LOAD CHARACTERISTIC WITH CLOSE SYSTEM TIME DELAY.

For the above cases a generator voltage regulating system with normal drooping voltage load characteristics on the generator has been discussed. A rising characteristic on the regulated machine can frequently cause serious difficulty, particularly if the system time delays are close to one another. For instance with 0.1 and 1.0 second time delays no instability was encountered even with rise in the generator voltage because of wide separation of time constants.

Fig. 44 shows the effect of lowering time constant to 0.2 second which approaches the motor mechanical time constant of 0.2 second and the regulator time constant of 0.1 second. With 1$\frac{5}{8}$ per cent droop the damping was adjusted to give essentially no overshoot. However, more oscillation will be noticed than on the previous figures because the generator field time delay of 0.2 seconds is fairly close to regulator time delay of 0.1 seconds. With a rising voltage load characteristic on the generator and all other system constants remaining the same, the performance begins to become critical and several oscillations are introduced. In general the best performance is obtained when there is no rise in the speed, load or voltage- load characteristics of any of the motors or generators involved.

The trend of industry has been towards faster operation, more continuous processes, and better drive and mill performance in order to improve tonnage and quality of product. These factors have led to the use of a large number of regulating systems for main and auxilliary drives. As much as 27 regulating systems are used to control some of the main drive auxilliaries and associated equipment of a modern glooming mill. Present day regulators are wonderful devices, but to obtain optimum results other components must be carefully selected and co-ordinated into the drive system. Exciter size and ceiling voltage, damping devices for stability, time constants of all components, generator and motor saturation, speed-load and voltage-load characteristics and overall system gain, are all important and meritful considerations in the design of a regulated drive system.

BIBLIOGRAPHY

1. Beadle R.G.	Application of Control Regulators to Steel operations — "Iron & Steel Engineer" August 1955, vol. XXXII, No. VIII.
2. Campbell J.D.	The Amplidyne Generator from an application stand point — A.I.S.E. Year Book 1945.
*3. Cheluistkin A.B. & Rosenman E.A.	Automaticheskoi Upprauleniye Prakatnimi Stannami. (Automatic Control of Rolling Mill Stands).
*4. Fegin V.I.	Electro-mashini Oosiliteli va Prakatnikh Chekhakh. (D.C. Cross field machines as applied in Rolling Mills).
5. Harris W.R.	Effect of Regulator Systems on Associated Apparatus— "Iron & Steel Engineer" August 1955, vol. XXXII No. VIII.
6. Lajoy Millard H.	Industrial Automatic Controls — Prentice Hall Inc. N.J.
*7. Levitanski B.A.	Electro - Obrudovaniye pridprayati Chorni Metallurgy. (Electrical Equipment in Iron & Steel Industry).
8. Peth J.C.	Operation of Magnetic Amplifier Controlled Tandem Mills — ' Iron & Steel Engineer' June 1955.
9. Piaggio H.T.H.	An elementary Treatise on Differential Equations and their applications— G.Bell and Sons Ltd., London.)
*10. Veshenevuski C.H.	Raschot Kharakhteristicyi Spratiuleniye Dilya Electro-Dwigatilye. (Calculation of characteristics and resistances for electric motors.)

---

* All these are Russian Publications.

BIBLIOGRAPHY

*11. Privalski B.A. Automatic Chas Koyi Upprauleniye Electro Privada'mi Prakatnik Stanuov (Automatic control of Rolling Mill Drives) Metallurgi Publishers Edn. 1954.

---

*All these are Russian Publications.