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Paper Machine Drives

The historical development of the paper machine drive is reviewed, from the early steam-engine-driven line shaft drive up to the latest thyristor drives. Then follows a summary of the drive requirements, and an attempt is made to specify the limits of steady state and transient performance. The paper ends by considering the effects of the mechanical parts of a drive and gives general recommendations on the subject.

1. Historical review

It is assumed that the reader has some knowledge of the papermaking process and of the terms peculiar to this industry. A useful and concise description of the principles involved is given by Hamman[1].

The earliest drives, quite naturally, used steam engines driving lineshafts. It is interesting to have a brief look at this type of drive, the basic features of which are shown in Figure 1. A steam engine supplies the motive power to the lineshaft, which runs the whole length of the paper machine; at the indrive point to each section, power is taken from the lineshaft via a belt and cone pulleys, then through a clutch and right-angle gearbox, to the section slow-speed shaft. The relative speed between sections ('draw') is adjusted by moving the belt sideways along the cone pulleys, and the clutch enables a section to be individually started and stopped, while other sections are running.

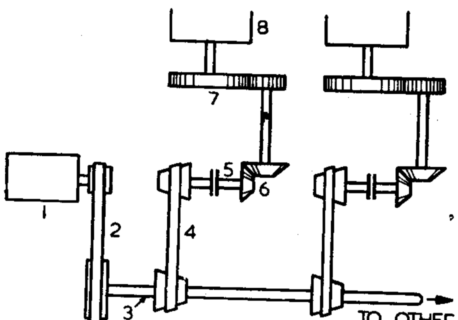

Fig. I. Simple Mechanical Drive

1. **Steam Engine.**
2. **Lineshaft belt transmission,**
3. **Lineshaft.**
4. **Belt and cone pulley drive to each section.**
5. **Clutch.**
6. **Bevel gears.**
7. **Paper machine gears.**
8. **Paper machine section.**

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This type of drive fulfilled the basic requirements for a drive, but it had many limitations. The accuracy of speed holding was affected by belt-slip on the cone pulleys and this limited the power that could be trasmitted; also, the mechanical layout of the lineshaft drive occupied a great deal of space and restricted the design of the paper machine. The original lineshaft drive underwent numerous modifications and improvements; the belts and cone pulleys were replaced by PIV gears and power differential gearboxes (see Figure 3), the steam engine by an accurately-controlled electric motor, while electric helper motors were added to various sections. The result is that the modern lineshaft drive is capable of good performance even on large paper machines.

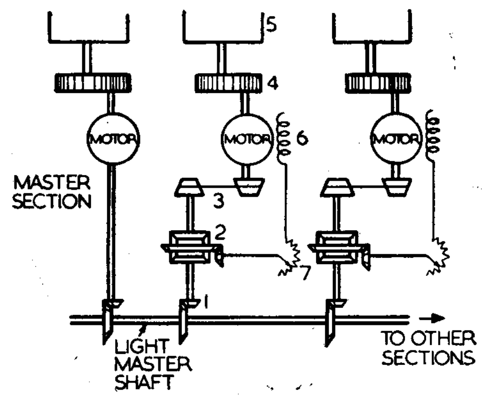


Fig. 2. Early Sectional Electric Drive.

1. **Bevel gears.**
2. **Differential gears.**
3. **Cone pulleys and belt.**
4. **Gear box.**
5. **Paper machine section.**
6. **Motor field.**
7. **Field rheostat.**

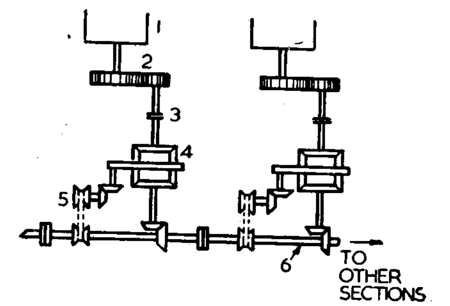


Fig 3 Power Differential Mechanical drive

1. **Paper machine section.**
2. **Paper machine Gears.**
3. **Clutch.**
4. **Power Differential.**
5. **PIV gear.**
6. **Power linesthaft.**

A different type of drive is the sectional electric drive in which the various sections of a paper machine are driven by individual motors. Early attempts at this type of drive had been largely defeated by the inability to control the speed to the required accuracy but about 1920 a breakthrough was achieved with the differential regulator.

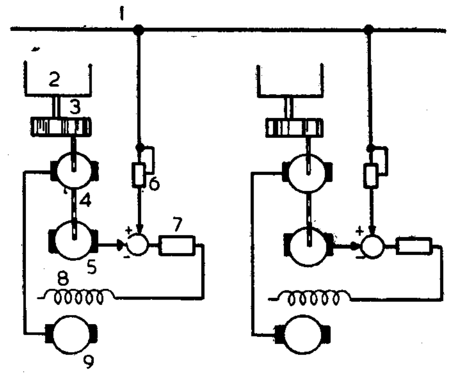
A typical arrangement is shown on Figure 2. The master shaft of low power and light construction is driven by a section of the paper machine, usually the first dryer, and this forms a reference for control of the other sections. Figure 2 shows that each of the controlled sections constitutes a position–controlled servo system, in which the master shaft is the reference quantity denoting the required value, while the motor shaft rotation denotes the actual value; these two rotations are fed into opposite sides of the differential gearbox and the differential output shaft operates the motor field rheostat. The motor field is varied in such a way as to correct the position error between the master shaft and the motor; theoretically, therefore there can be no speed error between them.

The differential regulator type of drive achieved great success and enabled paper machine speeds to be increased. But while its steady state performance was more than adequate for the machine speeds of the time, its transient performance was less satisfactory; the response was rather slow and poorly damped and the only means of stabilising was to reduce the overall system gain.

This situation persisted until the theory of closed loop systems was better understood, and this led to the introduction of velocity feedback. The performance of the control against load changes was then good and was comparable to the most modern electronic regulators; when draw changes were called for the response was still slow, mainly because of the belt–shifting mechanism which by its very nature is sluggish.

In addition, other improvements were made to the differential regulator type of drive; the master shaft was replaced by an electrical shaft consisting of an a.c. generator driven by the master section of the paper machine, and a.c. motors driven by the controlled sections. In place of the rotating field rheostat a carbon pile resistance was used, and several variants of both electrical and mechanical differential were produced.

Following the developments made in electronics during the last war, these techniques found their way into the paper industry and an electronic paper machine drive was produced. The basic features of the drive are shown in Figure 4. The master reference voltage provides the speed reference quantity to all paper machine sections, indicating the required value; the reference is modified by the draw adjustment rheostat to give the required draw between paper machine sections. The section motor speed is measured by a tachogenerator, it is compared with the reference, and the resulting difference (or error) signal is fed into an electronic amplifier. The performance of the early electronic drives was poor compared to the



1. **Master reference voltage.**
2. **Paper machine section.**
3. **Gear box**
4. **Section driving motor.**
5. **Tachogenerator.**
6. **Draw adjustment potentiometer.**
7. **Electronic speed regulator.**
8. **Generator field.**
9. **Generator**

Fig. 4. Early sectionnal Ward-Leonerd drive with electronic control

then well–developed and well–established differential regulator; the tachogenerator, amplifier and other electronic components all suffered from drift and had poor reliability. Nevertheless, it was established that the principle of the electronic drive was sound and it had a number of attractive features including greatly simplified contactor circuits and elimination of belt–shifters and other mechanical items; in addition, the description of the drive as 'electronic' made it attractive to many people.

By about 1950 sufficient improvements in the equipment had been made for the drive to obtain general recognition. A rivalry began to develop between those designers and users who favoured position control, and the suporters of the electronic speed-controlled drive; without openly admitting it, both sides recognised that there were favourable features in each scheme of control.

Position control was found to be superior in those sections of a paper machine where the paper must be transferred between sections as a free loop without tension; by its very nature, position control maintains the exact relative positions of the paper machine sections so that although there is a small position error the long-term speed error is zero and a free loop of paper can be maintained indefinitely. In contrast, with a speed-controlled system there will always be speed error; it can be reduced by using highgain amplifiers to some 0.03 per cent but cannot be held below this for any length of time. Consequently it is impossible to run with a free loop of paper between two sections; if an attempt is made to do so, the loop will be always increasing or decreasing at a small rate, and in a typical paper machine running at 1500 feet minute (460 metres/min) with the above error of 0.03 per cent the loop will change at 0.45 feet per minute (0.14 metres/min) and this slow rate is still enough to upset the papermaking process.

At the same time it was found that speed control gave faster response than position control when load disturbances occurred on the paper machine. This is because speed is a derivative of position and gives an earlier signal when a change occurs; any speed error may be detected and the necessary correction applied before a position error has developed.

In the end, the speed control system achieved complete victory. Its steady state accuracy was adequate in the wet-end sections of a paper machine and it performed well enough in the dry-end sections; its superior transient performance proved of the greatest value because most paper breaks occur during some transient disturbance.

There has been a steady improvement in the design of the electronic drive. The thermionic valve amplifier has been displaced by a transistorised amplifier; the final power stage has had several forms, including cross-field machine and thyristor. None of these alternatives offered any spectacular improvement in performance but the increase in reliability has been significant.

From its earliest days one of the disadvantages of the speed-controlled individual generator drive, as shown in Figure 4. had been the excessive number of rotating machines. Consequently many attempts were made to replace the generator with a static convertor. Initially the mercury arc rectifier was tried with a good degree of success but it never reached any great popularity in the paper industry. In the late 1950's the power magnetic amplifier was developed and it soon proved a resounding success; many paper machine drives were built using this principle. At the present time the thyristor has taken over this role and is in the position of unchallenged and almost universal use.

The comments made on amplifier development apply equally well here; the mercury arc rectifier, power magnetic amplifier, and thyristor are simply different devices whose performance is nearly identical. The improvements have been made mainly in the reduction of physical size and, more important, in the reduction of the convertor costs.

Any doubts as to thyristor reliability have now been largely dispelled and it is true to say that when the thyristor is used in well-designed and well-protected circuits it is the most efficient and the most versatile of all power convertor devices.

2. General requirements

The performance required of a paper machine drive is considered in this section. Because many different types of paper are manufactured, using various types of paper machines, the requirements set out below can be taken as typical only.

2.1 Overall speed

The overall paper machine speed must be accurately controlled to maintain a constant basis weight of the paper. This means that the master reference voltage source must be very stable, and with modern electronic techniques there is no problem in achieving stability of 1 part in 10,000.

It is also necessary to make overall speed adjustments while papermaking, and these must not affect the percentage speed relationship between paper machine sections; this is ensured, in the face of widely differing inertias and loads between the various sections, by limiting the rate of change of overall speed to a low value. Normally a rate of some 3 parts per thousand per second (0.3 per cent per second) is acceptable, but this rate may well be higher where automatic process control is used, and paper machine speed is adjusted continuously by a process computer.

2.2 Individual sections

Individual sections of the paper machine must be capable of being started, crawled, accelerated, decelerated and stopped without affecting the speeds of other sections. This requirement is imposed by the operating conditions, when a section is stopped for cleaning, while the other sections continue running undisturbed; for example, it is quit common to stop the calender, while the rest of the machine makes paper which is dropped into the broke pit directly from the last dryer section.

The rating of motors and thyristor convertors is fixed as much by acceleration requirements as by the running load; for instance, to accelerate a dryer section to top speed in 100-150 seconds requires an acceleration power greater than the steady running load; and the convertor must, therefore, be over twice the size demanded by steady running conditions. Acceleration is normally under current limit control, providing constant motor armature current, and therefore constant torque, during acceleration; this gives the most efficient use of both motor and convertor.

Heavy sections of high-speed paper machines require some form of electrical braking to stop them in a reasonably short time; this is most easily provided by reversing the motor field and then using the thyristors in the inversion mode to feed the motor regenerative power back into the ac supply.

2.3 Inching

Certain sections, particularly the wire and sometimes the *dryers*, require an inching facility for maintenance, cleaning and inspection.

2.4 Master reference

The required stability of the master reference has already been mentioned. Additionally, there must be a high resolution of the master references so that small changes of speed can be made rather than large steps; typically this is about 0.03 per cent, and in an analogue speed control system this means that the master reference potentiometer must have at least 3,300 turns.

2.5 Draw between sections

The *draw* (or speed difference) between sections is dictated by the type of paper machine. A typical speed relationship is given below, taking the reel speed as 100 per cent :

Wire	93 per cent
1st Press	97 per cent
2nd Press	99 per cent
1st Dryer	100 per eent
2nd Dryer	100 per cent
3rd Dryer	100 per cent
4th Dryer	100 per cent
Calender	100 per cent
Reel	100 per cent

The resolution of draw setting should be as high as possible, certainly better than 1 part in 10,000 (0.01 per cent) of top speed. A progressive draw system is a useful feature. in which a draw adjustment to a section will also alter the following sections: for instance, if a loop of paper has developed between sections, a progressive draw adjustment will remove the loop right out to the final section of the paper machine.

2.6 Slack take-up

Slack take-up is a temporary increase of draw to remove a loop, but with the orignal and rather critical, draw settings still set up on the control..

The percentage increase of speed is related to the length of paper in the loop and to the machine speed; typical values are 0.5 per cent for a 1500 feet/minute (457 m/min) paper machine, and 0.25 per cent for a 3,000 feet/minute (915 m/min) machine. This means that the loop disappears at the rate of 7.5 ft (2.3 m) per minute.

2.7 Negative torque

Negative (i.e. braking) torque should be provided for paper machines making heavy grades of paper. At the dry-end, the sheet is under heavy tension and this tension power may exceed the friction power of a section; this tends to pull the section round, make it over-run, and transfer the tension to earlier section of the machine where the sheet is weaker. Quite clearly this is an undesirable condition and the sheet tension must be arrested by each section drive.

While the rotating generator drive could accept braking power from a motor, special measures have to be taken with static convertors. In marginal cases a simple method of power absorption, such as a load resistance across the motor armature terminals or an electric brake on the motor shaft, offers an acceptable solution.

In other cases, anti-parallel connection of two convertors is required. The motor torque should ideally be under smooth control from positive, through zero, to negative torque; it should include stable operation around zero motor armature current, which normally calls for convertor circuits with circulating current.

2.8 Steady-state accuracy

The required steady-state accuracy of speed control of a paper machine is a diffcult quantity to define.

There exist a great variety of papers ranging from heavy multilayer board to fine tissue papers, while the same basic grade of paper can be made from different materials under different operating conditions. Some paper mills are fortunate enough to have high quality modern plant, experienced papermakers, and good basic materials; here the accuracy of control is naturally less critical than under less favourable conditions. Indeed, there are situations where, however perfect the drive, it can never be good enough because of adverse conditions elsewhere.

Broadly speaking, the paper web at the wet-end is very weak, non-elastic, but can accept a fair amount of permanent stretch. At the dry-end the paper web has a true elastic limit of about 0.1 per cent, but it can be stretched well above 0.1 per cent without damage, provided a long time is allowed for it to return to its original conditions; it will break when stretched to about 1.5 per cent.

2.9 Wire—Ist press

The draw between wire and 1st press can be anywhere between 1 per cent and 8 per cent. Taking a typical figure of 4 per cent, and assuming that a 10 per cent variation of the set draw is acceptable, this indicates that a stability of draw of 0.4 per cent is required. Taking the worst case, where adjacent section speeds are changing in opposite directions, we arrive at the requirement of steady-state accuracy of 0.2 per cent.

2.10 Ist-2nd press

The 1st to 2nd press draw may be from 1 per cent to 3 per cent. Taking the average figure of 2 per cent, and using similar reasoning to that used when considering the wire section the steady state accuracy of a press section should be 0.1 per cent.

2 11 Dryers

For the dryer sections, the control should be such that the paper strain is within the true elastic limit of about 0.1 per cent; there is a weight of evidence and opinion that the paper should be completely unstressed, which implies that there is a free loop of paper between dryer section and as described before, this can only be achieved by a position-control servo. If this were disregarded and a paper strain of half of the maximum strain is accepted, then the accuracy of speed control of each dryer must be :

$\frac{1}{2} \times \frac{1}{2} \times 0.1 = 0.025$ percent

2.12 Calender

The calender section is a difficult one to control, because it has to meet various operating conditions. When feeding the paper web through, no tension at all can be applied and it is usual to keep a free loop of paper; once threading has been achieved, the paper tail is rapidly widened to the full machine width and this gives a sharp increase of load to the calender, possibly 50 per cent of full load. The sudden load thus applied tends to increase the loop further and the loop must now be taken up at a fast rate, but not so fast as to cause snatching.

When the full paper width has been reached, the calender is accelerated slightly to tighten the sheet and apply tension; correct and steady tension avoids creasing.

The preferred mode of control of the calender is, therefore, position control while threading and tension control while running with a full width sheet; the transition between these two conditions should be smooth, taking up to 2 seconds, according to the length of material contained in the loop and the operating speed. Generally speaking, it is not possible to control tension by motor current control because the tension power is small compared to the total load; also the seat on each side of the calender is under tension, so absolute sheet tension is not controlled. Tension must be measured directly, using load cells.

The breaker stack section is controlled similarly to the calender.

2.13 **Reel**

In a well designed reel section, the friction load is small, so that almost all the load on the reel is due to sheet tension. Tension control is then easily achieved by controlling motor current. This arrangement is preferable to tension control, using a tension-measuring device, because paper reels are often slightly eccentric and out-of-balance, giving a rapidly varying tension signal which must then be smoothed; the motor current control is much steadier and ignores these rapid fluctuations.

2 14 **Summary**

The required steady-state accuracy and the recommended type of drive for each section are summarised below :

Table I Steady-state accuracy

Section	Steady-state Accuracy	Type of Drive
Wire	0.2%	Tachogenerator
Presses	0.1%	Tachogenerator
Dryers	0.025%	Tachogenerator with over-riding digital control or position control
Calenders Breaker Stack	0.025%	Tachogenerator with over-riding digital control or position control for feeding. Tension control for running
Reel		Torque Control

2 15 **Transient performance**

The transient performance requirement for a paper machine can be defined quite simply—it must be as good as possible.

Modern speed regulators are unaffected by supply voltage variations, because they incorporate subsidiary feedback control circuits of voltage or current; these circuits act so quickly that the speed is virtually unaffected and the main speed control does not need to take corrective action.

However, the speed regulator must also deal with sudden load changes on the section. Ideally, it should allow only the smallest possible paper web strain after a load disturbance. in other words the time integral of the speed deviation (the shaded area of Figure 21) should be a minimum.

A few years ago, the time constants in amplifiers and generator fields were limiting the performance but now these have virtually disappeared with the advent of transistor amplifiers and thyristor convertors. The transient performance of the drive—shafts, couplings, gearboxes—and their characteristics are of great importance. A fuller treatment of this subject is given in section 4.

3. **Thyristor drive system**

The drive system for a paper machine in the form of a single line diagram is shown in Figure 5. Basic components and connections for overall drive control and the operation of a single section are numbered.

3.1 **Drive transformer**

The drive transformer (rated to suit the drive power requirements) supplies power to all sections of the drive. The tranformer is specially designed for rectifier operation and has a star-connected secondary winding with the neutral point connected to earth through a high ohmic value discharge resistor. The thyristor power circuits are therefore not tied directly to earth and this permits the drive to continue running even when there is an earth fault in the system.

As a safety feature, the drive transformer has an earthed screen between primary and secondary, which ensures that the high voltage on the transformer primary can never reach the thyristor power circuits. The drive transformer feeds the a.c. power busbars (6), and an auxiliary transformer (2) supplies the excitation and master reference source for the drive.

3.2 **Drive excitation**

The excitation supply (4) for drive motor fields and contactor circuits is obtained from a three-phase bridge rectifier and saturable reactor circuits, regulated to deliver a constant output voltage.

3.3 **Drive master speed reference supply**

The drive master speed reference voltage, which represents the desired value of motor speed, is in the form of a highly stabilised d.c. voltage, and is produced by a transistor regulator. The value of reference voltage is varied by the speed setting rheostat (5) which is connected in the control circuit of the reference supply. Normally the master speed reference is 50 volts at maximum paper machine speed, and proportionately less at lower speeds.

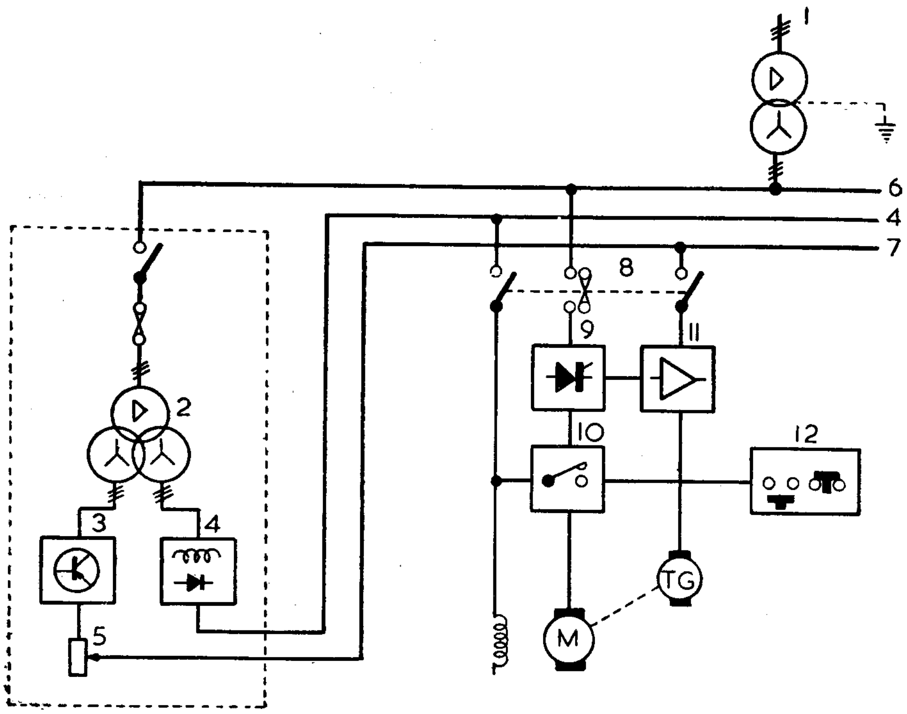


Fig 5. The PTA drive system

1 Drive Transformer
2 Auxiliary Transformer
3 Master Referencc Supply
4 Excitation supply and busbars
5 Speed setting Rheostat
6 A.C. Power Busbars
7 Master Reference Busbars
8 Sections Isolator
9 Convertor
10 Contactors
11 Electronic Modules
12 Operator's Control Station
M Section d.c. Motor
TG Tachogenerator

The master speed reference voltage supplies the reference buswire system (7) which runs to all sections of the paper machine drive.

3.4 Individual sections

Each individual section is supplied from the busbar system described above.

(a) The main a.c. supply is taken through a three phase isolator from the a.c. busbars (6). This isolator contains fuses to protect the cubicle internal circuits in case of short-circuits or earth faults. Isolation is also provided for the reference and excitation supplies.

(b) The power thyristor convertor gives controlled power conversion from a.c. to d.c. Normal maximum d.c. volts corresponding to maximum paper speed is 600 volts d.c. at the motor M.

(c) The stopping and starting operations on the section are performed under remote control from the operator's front-of machine control station by a d.c. contactor circuit.

(d) The electronic module units for the closed-loop speed control system include the section feedback circuits, amplifier and currents, limit circuits and also pulse units for control of thyristors. Each section contains its own electronic power supply unit, (4) in Figure 6, so that it is as self contained as possible.

The tachogenerator *(TG)* giving a d.c. output proportional to section motor speed, delivers a speed signal to the electronic circuits, to provide a feedback signal for the closed loop speed control. Normally the tachogenerator output is approximately 120 volts at maximum speed.

(e) The section control station carries operator's controls as required, including 'Stop/Crawl/Run' pushbuttons or control switch, draw control rheostat and section motor ammeter. Additional controls can be provided to give progressive draw control or for sections having a multi-motor drive.

3.5 Control diagram for a single section.

The control diagram of the PTA drive for a single paper machine section is shown in Figure 6.

The various items in the control are as follows: Master reference (1) is the voltage representing the desired-value of paper machine speed; it is derived from a highly stable reference source. Draw rheostat (2) is an adjustable rheostat connected in the reference supply to the section; it is used to

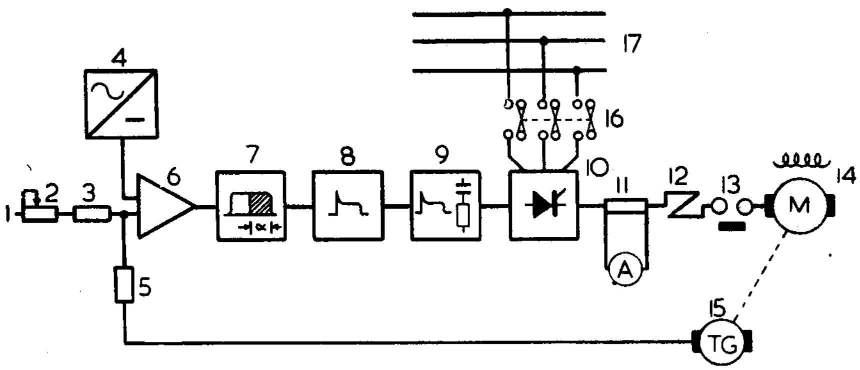


Fig. 6. Control diagram for a single section

1 Master Reference
2 Draw Rheostat
3 Input Resistor
4 Power Unit
5 Input Resistor
6 Amplifier
7 Phase Shifter
8 Pulse Generator
9 Pulse Amplifier
10 Power Thyristor Assembly
11 Ammeter Shunt
12 Magnetic Overcurrent Relay
13 Main Contactor
14 Section Motor
15 Tachogenerator
16 Section Isolator
17 AC Power Busbars

make small adjustments to the section motor speed, and is normally mounted on the operator's control desk. Resistors (3) and (5) are the input resistors for the reference and tachogenerator signals; these signals are of opposite polarity, so that the input to the amplifier (6) represents the difference between them. They are fitted in the feedback unit.

(6) is the amplifier unit. It is a precision, high sensitivity transistor amplifier.

(7) is the phase shifter, actually comprising three separate phase-shifter units. It is regulated by the amplifier and provides sets of pulses of variable phase angle, which are applied to the pulse generator. (4) is the power unit, which provides a number of d.c. supplies for the various electronic modules.

(8) is the pulse generator, actually comprising two separate pulse generator units. It accepts the pulse signals from the phase-shifter, and produces powerful pulses of fast rise-time suitable for controlling power thyristors.

(9) is the pulse amplifier, one unit being provided for each power thyristor. Each one contains a pulse transformer to give electrical isolation between the power thyristor and the electornic units. It also con'ains surge suppression components.

(10) is the power thyristor assembly, which comprises the power thyristors, with associated chokes and high speed fuses. The thyristors are connected as a three phase, full-wave bridge, using six thyristors. The complete assembly is supplied with high-power a.c. and is controlled by pulses on the thyristor gate electrodes to give a variable voltage d.c. output.

(14) is the section motor, driving a section of the paper machine. It is a d.c. motor, its speed being varied over the speed range by varying the armature voltage supplied from the power thyristor assembly. Normally the motor has a constant field excitation.

(15) is the tachogenerator, coupled to the section motor. (14). It is a permanent magnet d.c. type and gives a d.c. voltage output strictly proportional to section motor speed.

3.6 Power circuit

The a.c. power for a complete paper machine drive normally comes through a trasformer, with a high voltage delta-connected primary winding, and a star-connected secondary winding with an output voltage to suit the requirements of the cubicle. A transformer is not necessary for a single-motor drives or low-power machine drives, the a.c. supply being taken direct from the paper mill low voltage distribution supply.

The a.c. supply enters the cubicle through busbars (17) and is isolated by the section isolator (16). The busbar system and the isolator are rated to withstand a fault current of 46 kiloamps, and the section isolator contains high rupturing capacity fuses.

The thyristors have individual high-speed fuses, carefully rated to protect the thyristors against overloads and faults.

The d.c. output from the power thyristor assembly flows through an ammeter shunt (11), a mganetic overcurrent relay (12) and a single pole main contactor (13), and then to the section motor armature. In addition, there are control relays to select crawl or run speed, and for other duties as required.

3.7 Description of electronic modules and power thyristor assembly

The arrangement of the electronic modules has already been outlined in the control diagram for a single section; the modules and the power thyristor assembly are now described in greater detail. The module titles and reference letters are the same in Figure 6.

3.7.1 Feedback unit

This unit contains the precision resistors (3) and (5) for comparing the master reference and tachogenerator voltages, and also contains resistor–capacitor circuits for stabilising the control system. Potentiomoter adjustments are provided for stabilising, and also for setting the crawl speed to the required value.

In addition, a testing circuit is fitted, including a test-run switch and a test potentiometer, which ensures rapid testing of performance and assists in fault finding. To use the testing circuit, the test–run swich is set to *test*; this disconnects the speed reference and tachogenerator inputs from amplifier, and connects instead an adjustable signal from the test potentiometer. Under this condition, the convertor is controlled by rotation of the test potentiometer, which enables the performance to be rapidly checked.

The feedback unit contains all the variable components and adjustments which must be selected to suit the particular motor speed and machine inertia: 'this means that all the other electronic modules are identical for all ratings of the cubicle.

3.7.2 Amplifier unit

This unit has two separate circuits :

(a) Speed control amplifier

(b) Current control amplifier

The speed control amplifier uses a high–gain integrated–circuit d.c. amplifier for the first amplifying stages, ensuring predictable gain with negligible offset voltage and temperature drift. The last two amplifying stages are of higher power, and use discrete transistors and other components. To standardise the overall gain of the amplifier, two dc feedback circuits are used, one across the complete amplifier, and the other across the early amplifying stages only. The current control amplifier accepts the output from the current transformer circuit, which is proportional to the actual value of power thyristor amplifier d.c. output current and compares it against the current reference voltage. It develops an output signal which is passed to the phase–shifter units for control purposes.

3.7.3 Phase shifter

There are three phase–shifter modules in each cubicle, one for each phase; the description that follows applies to a single module.

The principle of operation of the phase–shifter is that of controlling the magnetic saturation of a saturable reactor, which incorporates a magnetic core of highremanence nickel–iron alloy.

The phase–shifter comprises two main sections :

(i) Square wave generator

(ii) Reactor circuit

The square wave generator accepts a d.c. input at 24 volts, and this is switched by two transistors. The transistors have their base–emitter circuits connected in series opposition, and their bases are supplied by a common a.c. supply; this makes the transistors conduct (emitter-collector) for alternate half-cycles, and they switch the 24 volt d.c. supply alternately to the two ends of the winding of a transformer. This gives the effect to the transformer of a 24 volt square wave, locked in phase to the a.c. input.

The reactor circuit incorporates two saturable reactors, together with associated components; the reaetors operate as flux–resetting magnetic amplifiers, delivering two output voltages, suitable to operate pulse generator units. These output voltages take the form of pulses 22 volts in height, with, a leading edge variable in position, according to the controlling input from the amplifier unit. See Figure 6 (a).

This method of producing a pulse of adjustable phase angle has the advantage that it is fuudamentally

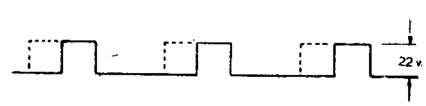


Fig. 6 (a) Output pulses from phase shifter

not affected by stray voltage spikes, often present in thyristor equipments; the phase angle is determined by the magnetic–flux–change of the reactor core, and this means that a definite voltage–time integral is required to operate the circuit. Short–duration voltage spikes picked up by the unit wiring, even if they are of relatively high voltage, will have negligible effect on the phase shift because the voltage-time integral will be insignificant.

Because the phase–shifter output pulses are of constant voltage (approximately 22 volts), the actual phase–shift of the output can be measured using a standard moving coil voltmeter, making a cathode ray oscilloscope unnecessary. In a complete cubicle, using three phase-shifters, the six output voltages can be measured in this way, giving a check on the correctness of the value and on the similarity between the phases.

To help with this test, the built–in cubicle test voltmeter can be used, and two test sockets are provided on each phase–shifter to measure the two output voltages.

3.7.4 Power unit

The power unit accepts three-phase inputs at low voltage and from them produces several d.c. supplies suitable for driving the various electronic modules.

Two of the outputs, of plus and minus 12 volts, are used to drive the transistor stages in the amplifier unit. These outputs are stabilised by low–temperature–coefficient Zener diodes, so that the output voltage is virtually free of ripple and is unaffected by ambient temperature or load current changes. The outputs are protected against overload and short–circuit by a series resistor in each circuit.

A separate stabilised output of higher power, giving 24 volts, is used to supply the phase–shifter units. This output is stabilised by a high–power Zener diode mounted on a cooling fin of generous dimensions and is also protected against overloads and short–circuit faults.

For use with test voltmeter fitted in the cubicle, the power unit carries five test sockets, enabling the five output voltages of the power unit to be measured. Reservoir capacitors are fitted to each of the two rectifier outputs to make sure that the power unit can provide output current pulses of fast rise-time without attenuation.

The power unit accepts a.c. supply voltage variations of plus or minus 10 per cent of nominal without loss of performance. The stabilised output voltages will be maintained substantially constant with an a.c. supply voltage as low as 80 per cent of nominal.

The circuits of the power unit are of simple design, and yet provide outputs of adequate power and excellent stability. The use of complicated transistor regulating circuits has been avoided, and this ensures the economical use of a minimum number of components.

3.7.5 Pulse generator

There are two pulse generator units in each cubicle. One controls the three upper thyristor arms of the thyristor bridge and the other controls the three lower thyristor arms. Each pulse generator accepts three input signals, one from each of the three phase-shifters and from them produces three sets of firing pulses suitable for firing power thyristors.

The firing pulses used in the thyristor control are of a specially designed character and incorporate two features :

(a) Spike of high current and fast rise-time to give hard firing of the power thyristors. The hard firing ensures that the thyristor conduction spreads rapidly over the initial area (preventing local overloading and damage) and also gives better current-sharing when thyristor bridges are operated in parallel. Typically the spike gives 1 ampere in 1 microsecond, 2 amperes in 2 microseconds, to each thyristor gate electrode.

(b) Holding pulse of lower power, to ensure that the power thyristor conduction is maintained for its correct duration of 120 degrees (i.e. for $6\frac{2}{3}$ millisecond on a 50 Hertz supply). Typically the holding pulse is 0.18 amperes in to each thyristor gate and the gate–cathode voltage is normally 1.5 volts.

Precautions are taken against false operation of the pulse generator due to interference from stray signals in the cubicle. These precautions include high–frequency capacitors at each input, which conduct unwanted spikes of voltage harmlessly to earth. In addition a negative bias voltage is applied to the circuit at six different points to provide a threshold which must be overcome before the circuit can operate. The normal operating signals are strong enough to overcome this threshold reliably but any stray pick-up voltages are of lower magnitude and cannot affect the circuit.

3.7.6 Pulse amplifier

There is one pulse amplifier for each power thyristor. It is mounted close to the thyristor, with short, direct leads, so that there is a minimum of exposed high voltage wiring.

The pulse amplifier contains resistors and capacitors for the firing pulse circuits, and also a pulse transformer to give electrical isolation between the electronic circuits and the power thyristor. In addition, resistors and a capacitor are connected between the power thyristor anode-cathode to give protection against voltage surges.

The pulse circuits include components to provide a negative bias on the thyristor gate, when the thyristor is not conducting. This prevents the thyristor being accidentally fired by stray pick-up voltages. The negative bias circuit provides approximately 20 milliamperes negative gate current to each thyristor; this large value indicates the safety-factor provided, because the thyristor cannot be fired accidentally unless the pick-up signal on the gate exceeds 20 milliamps, and the circuit design prevents this.

Further, the negative gate bias also improves the thyristor capability of withstanding high rate of change of anode voltage (dv/dt).

3.7.7 Power thyristor assembly

The power thyristors are connected as a three-phase full wave bridge, comprising six thyristors, six high speed fuses, six air cored reactors, and six pulse amplifier units. The complete thyristor assembly is mounted in an enclosure suitable for forced air cooling at an air velocity of approximately 1300 feet/minute (400 metres/minute).

The output of the bridge is regulated by phase-shift control of the firing pulse applied to the thyristor gate electrodes. The firing pulses are of special characteristics, designed for controlling high-power thyristors, and incorporate a high-power spike for hard-firing of the thyristor, followed by a low-power holding pulse of 120 degrees duration.

The power thyristors have a reverse voltage rating sufficiently high to withstand all expected voltage surges. Protection against random thyristor firing due to high rate-of-rise of anode voltage (dv/dt) is provided by an aircored reactor in series with each thyristor and a capacitor connected between thyristor anode-cathode. In addition, the thyristor gate electrode receives a negative bias voltage when not firing.

Protection of the thyristor against damage by excessive rate-of-rise of current (di/dt) is provided by the air cored reactor, which softens the build-up of anode current. Because the thyristor is hard-fired by a powerful firing pulse of fast rise-time, as described above, this ensures that conduction spreads rapidly over the initial conducting area, so that thyristor can safely accept high rates of (di/dt).

The output available from a single thyristor bridge using six thyristors can be up to 600 volts and 800 amperes d.c. Where greater output is required, two or more thyristor bridges can be operated in parallel. An air pressure switch is connected to the cooling air system, to shut down the equipment if the air supply falls to a dangerously low level.

4. Speed control—general aspects

A typical modern speed regulator may be represented by the block diagram Figure 7. To a first approximation, the amplifier and thyristor convertor time delays may be neglected, while the d.c. motor and its load can be represented by the inductive (L/R) time constant of the armature circuit, together with the electro-mechanical time constant. This latter may be defined as the time constant of the change of motor speed, following a step change of armature voltage, (see Appendix 1) and it varies from 0.05 seconds on a small couch section to over 5 seconds on a large dryer.

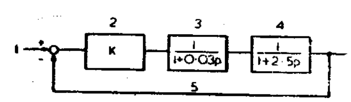


Fig. 7

1. **Reference**
2. **Amplifier and converter**
3. **Motor L/R time constant**
4. **Motor electromechanical time constant**
5. **Speed feedback loop**

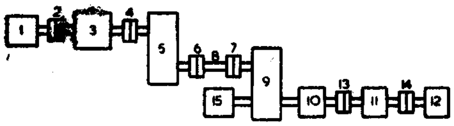


Fig. 8

1 Speed transducer (Tacho Generator
2 Speed transducer coupling
3 Driving motor
4 High speed coupling between motor and gearbox
5 Gearbox
6, 7 Low speed couplings
8 Cardan shaft
9 Additional gearbox on paper machine
10, 11, 12 Inertia of paper machine rolls. (There may be many more rolls than shown.)
13, 14 Imaginary coupling representing flexibility and backlash between various paper machine rolls
15 Preferred position of speed sensing transducers

Considering the regulator of Figure 7, and taking typical values of the L/R armature time constant of 0.03 seconds, and the electro-mechnical time constant of 2.5 seconds, we can see from servo theory (see Appendix 2) that the regulator can have a steady state gain of 20.8 and be critically-damped.

Indeed, if such a regulator is built in the laboratory, with the load inertia solidly coupled to the motor shaft, the transient performance is excellent. However, if the same regulator is tested on a section of paper machine with identical time constants, the operation is completely unstable; there is a vicious hunting at a frequency of several Hertz, which is clearly due to the flexibility of the mechanical transmission (shafts, couplings, etc).

Figure 8 shows diagrammatically the drive components which can intorduce flexibility; of all the items shown, the cardan shaft and low speed couplings contribute the greater part, and so the mechanical arrangement can be represented by Figure 9. This arrangement has a natural resonant frequency which is a function of the shaft stiffness,

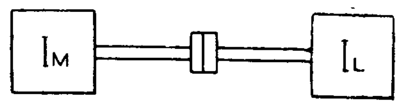


Fig. 9

the inertias and the backlash, according to the well-known principles (summarised in Appendix 3) at a common frequency which is directly proportional to the square root of stiffness (or square of the shaft diameter) and inversely proportional to the square root of inertia.

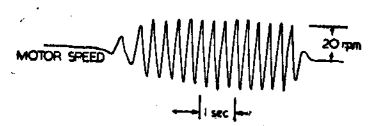


Fig 10 Dryer motor with manual excitation

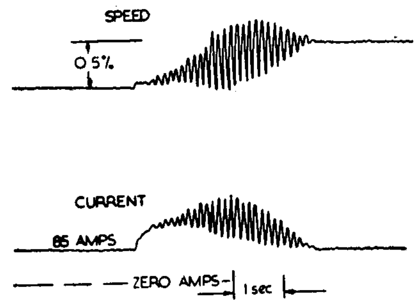


Fig. 11 Response of dryer section to step reference

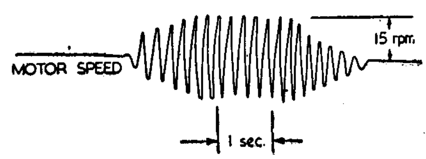


Fig. 12 Size press motor with manual excitation

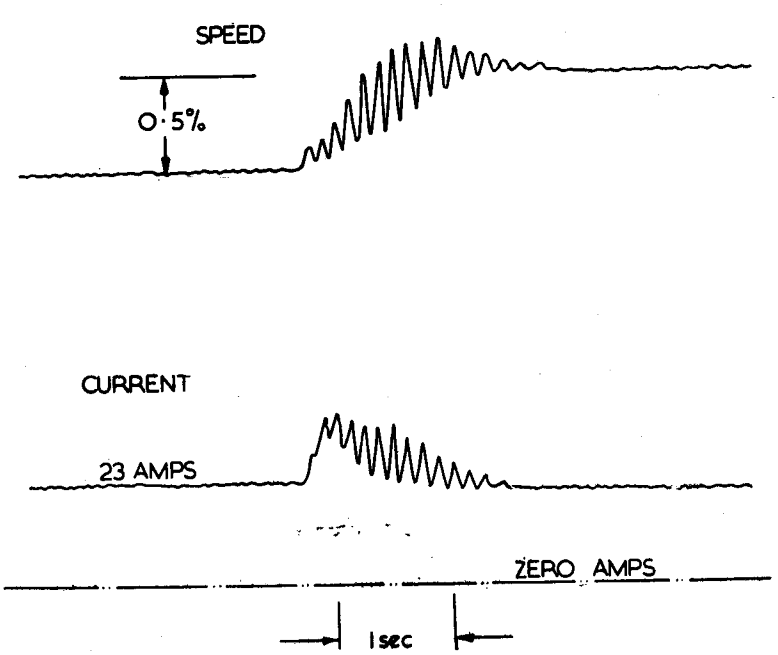


Fig. 13 Response of size press section to step reference

The recorder charts, Figures 10 to 13, taken on an inverform board machine, illustrate some of the statements made. Figure 10 was obtained on a dryer section with an operator rocking the motor coupling backwards and forwards, trying to fall in with the natural frequency; Figure 12 shows a similar test on a size press. These two charts show oscillations of considerable amplitude, at frequencies of 3 and 5 Hertz for the dryer and size press respectively. Apart from the difference in the two frequencies, it is interesting to note that the size press recording shows lower damping; it will be shown later that the natural frequency and the damping both have a great influence on the performance of the speed regulator.

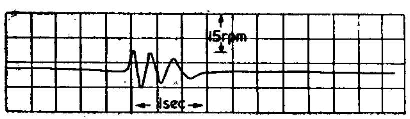


Fig. 14 Jogging test on press section

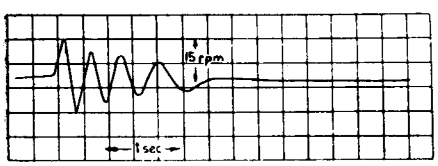


Fig. 15 Jogging test on dryer section

Figures 14 and 15, taken on a medium size fine paper machine, show further examples of shaft oscillations; to obtain these charts the motor was jogged for an instant, care being taken not to move the rolls of the paper machine. Figures 16 and 17 correspond to Figures 14 and 15, but this time the rolls were accelerated to crawl speed; in this case, the initial acceleration is of the motor alone within the backlash and flexibility of the transmission, followed by well-damped oscillations, and finally by acceleration of the paper machine rolls.

Figures 11 and 13 show the servo response of the dryer and size press section of the inverform machine, when a step reference change is applied; the servo stablilising had been specially adjusted so that the speed regulators were just stable as regards the torsional oscillations, which were excited by the reference change, but died out afterwards. Although the response is critically damped in the region of the natural frequency of the servo, this type of response is quite unsuitable, because a small change in the parameters could easily produce continuous torsional oscillations; these in turn could lead to stress fatigue and eventual failure of a mechanical component.

By comparing Figure 10 to Figure 11, and Figure 12 to Figure 13, it is seen that the frequency of torsional oscillations is higher with closed-loop control than with manual excitation. This is a normal feature and is due to the following causes:

(a) With manually excited oscillations, the paper machine rolls were stationary; referring to Figure 7 and to Appendix 3, exprsssion 4, it is evident that in this condition the natural freqency is lower than when the load inertia is free to move.

(b) Under closed-loop control the backlash is not fully traversed, because the load torque is unidirectional and tends to close up the clearances.

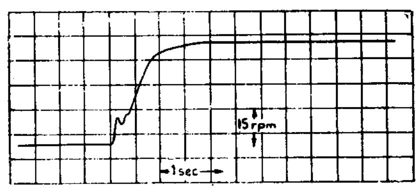


Fig. 16 Acceleration test on press section

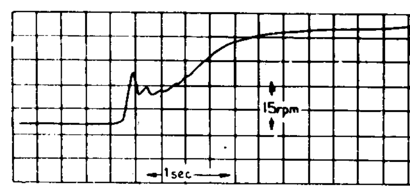


Fig. 17 Acceleration to crawl speed of dryer section

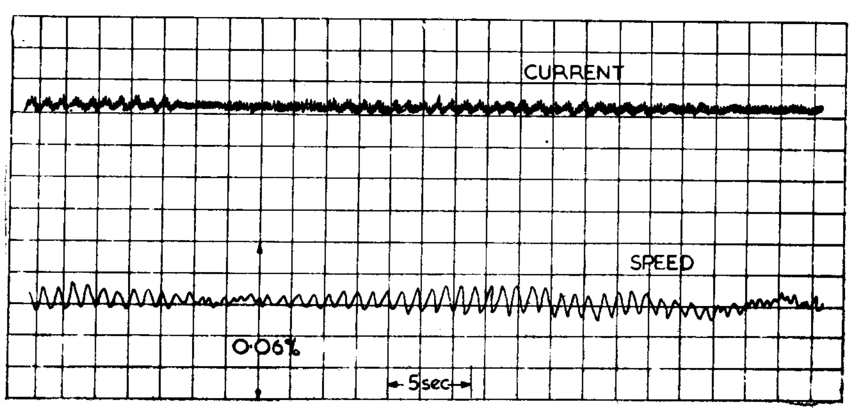


Fig. 18 Illustrating beat effect on dryer section

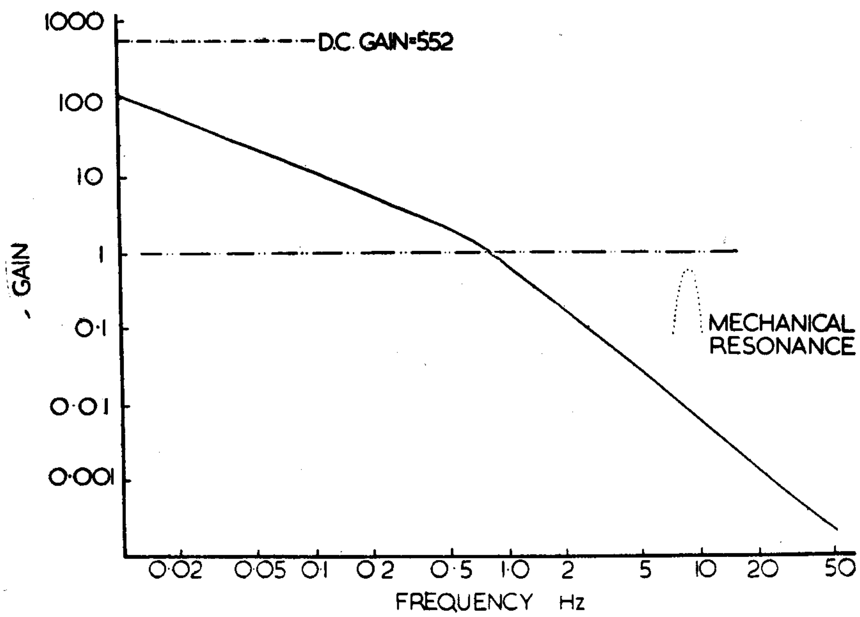


Fig. 19 Gain frequency plot for dryer section

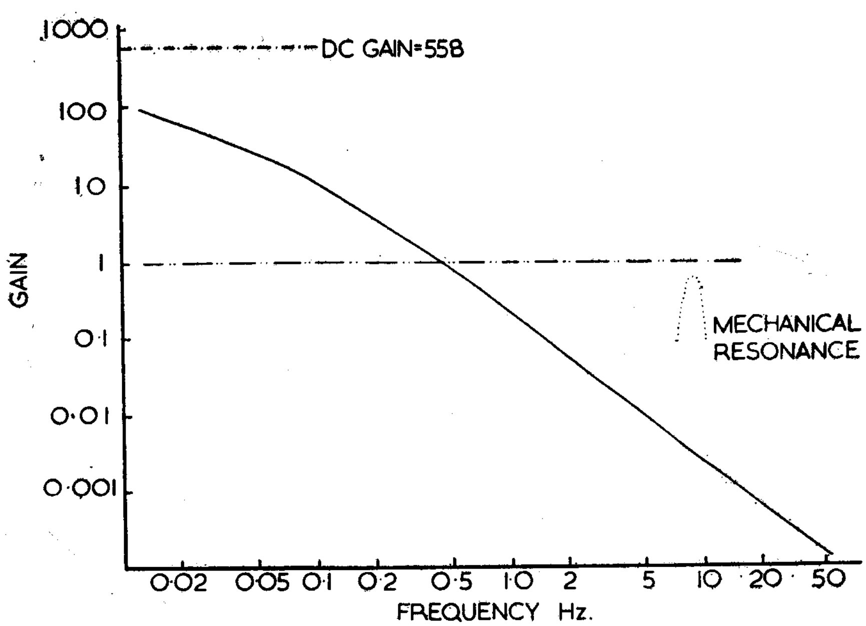


Fig. 20 Gain frequency plot for size press section

(c) The closed-loop system forces an increase in frequency due to its own dynamic properties.

Contrary to some opinions, it must be stated quite firmly that the shaft oscillation *is not purely mechanical in nature,* and that it cannot, in practice be eliminated merely by the redesign of shafts and couplings. It is, in fact, a *system oscillation* which includes the electrical and mechanical components of the closed loop. On modern drives the mechanical components have little friction loss and therefore poor damping; however, the oscillation could not occur without assistance from the electrical closed-loop control. Conversely, some degree of mechanical damping is necessary, otherwise the mechanical oscillation would be difficult to eliminate.

Another way to explain the principles involved is by considering the gain-frequency curves for the speed control systems. Figure 19 shows the curve for the speed regulator of the dryer section described earlier; Figure 20 shows the one for the size press.

The solid line is the graph of the open-loop transfer function, assuming the shafts and couplings have no deflection. It is seen that the control has a large margin of stability because :

a) At the cross-over frequency (i.e. where the gain is unity) the rate of change of gain with frequency is less than 40 dB per decade.

(b) This rate of change of gain is maintained into the higher frequency range, giving a safe value at high frequencies.

The dotted line in Figure 19 and Figure 20 is the gain-frequency curve of the complete system in the region of mechanical resonance, with the actual flexibility being taken into account. The curves show that the gain recovers sharply, and that it peaks at the resonant frequency; the large stability margin, as indicated by the solid line, is now greatly reduced. For the dryer section, the gain at the resonant frequency (8.5Hz) is 0.6, compared with 0.009 without mechanical flexibility, which indicates that the additional gain introduced by shaft and coupling flexibility backlash is aoproximately 70. The corresponding value for the size press is over 100, which could well have been expected from the difference in damping. (See Figures 10 and 18.)

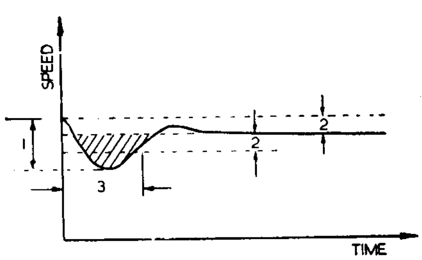
The additional gain due to resonance, and the frequency at which it occurs, are both of considerable importance since they limit the transient performance of the regulator. To obtain the best performance the shafts and couplings should be stiff, giving a high resonant frequency, and should have good damping, leading to a low gain at resonance. With these characteristics, the gain-frequency curves of Figures 19 and 20 could be moved to the right, and the regulator would have a higher speed of response.

Some improvement in response can also be made by special electrical circuits, in particular by using filters with a large rate of gain reduction above the cross-over frequency. In this way, it is possible to speed up the response, but the adjustments become more critical, during the running life of a paper machine there are continuous changes in the mechanical characteristics of the drive, as gearboxes and bearings are run-in, and backlash increases in gears and couplings. The gain due to mechanical resonance will almost certainly increase and the natural frequency will fall so that if critical electrical circuits are used there is a danger of instability and severe torsional oscillations developing during the life of the drive.

5. Transient performance

As mentioned earlier, the modern regulator deals very quickly and effectively with supply voltage changes; these are no longer a problem and will not be discussed here.

Good response against sudden load changes is of the utmost importance, and is less easy to obtain. Ideally, the response time as defined in Figure 21 should be less than the paper time constant (see Appendix 4) but owing to limitations from the mechanical components of the drive, it is not always possible to achieve the required response time on high-speed machines. At the wet end of a paper machine, the requirements are less critical and it is relatively easy to maintain the maximum transient error well within the tolerance defined in Table 1; hence, the speed of response is of no consequence because the paper strain never exceeds the stipulated limits (e.g. 0.1 per cent for press sections.)



Typical Response Of Regulator To Step Reference Change

1. **Max. Transient Error**
2. **Steady State Error**
3. **Response Time**

Fig. 21

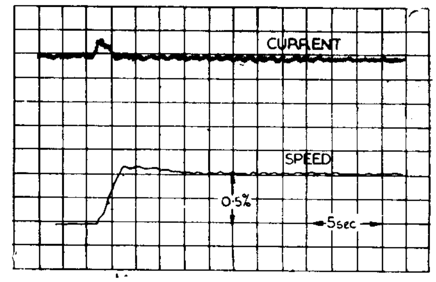


Fig. 22 Typical response to a unit step function of a dryer section

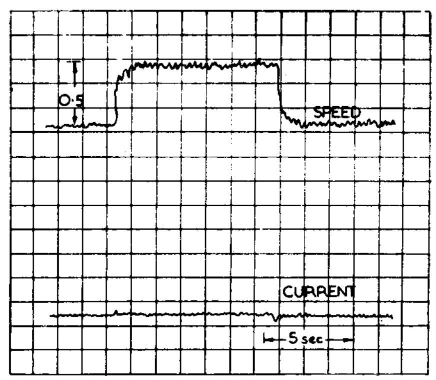


Fig. 23 Response to unit step function of a light section (a one roll press)

Control of the dryers is more serious problem, and at the present time, or in the foreseeable future, it is unlikely that it will be possible to design a drive with sufficiently fast response. Hence a reasonable solution is to run with a free loop of paper between sections, storing enough in the loop to cope with transients. A modern drive incorporating a reasonably good mechanical system can limit the maximum transient speed deviation to 0.06 per cent for a 10 per cent load change, while a typical loop between sections can store up to 0.5 inch (13 mm) of paper; thus, the response time must be such that no more than 0.5 inches of paper is taken out from the loop. Clearly, the faster the paper machine, the shorter must be the response time as shown below.

Machine speed			
FPM	1200	2400	3600
M/M	366	732	1098
Response Time of Dryer in Seconds	7	3.5	2.3

In recent years, the accepted standards for the mechanical parts of drives have been scrutinised and their suitability for fast and accurate control have been questioned. There is no doubt that they constitute a limiting factor and that for higher performance some improvements are necessary.

The progress in this direction is relatively slow mainly because of the time lag between design of a new plant and collection of the experimental data from site.

Additionally, there are difficulties of communication between mechanical and electrical engineers because in most cases the mechanical work is done by a separate company. Quite clearly without an authority to co-ordinate the whole project including the electrical and the mechanical work, no rapid progress can be expected. The features described below may serve as an indication of the areas which can be usefully explored.

5.1 Increasing the stiffness of the cardan shaft

This is one of the most obvious courses to take but the penalty is an additional cost and weight. The natural frequency varies as the square of the shaft diameter, so that 70 per cent increase in the diameter would treble the frequency. However, in many designs the shaft deflection is only a small portion of the total, so that one can expect only a moderate improvement by using heavier shafts.

An interesting development has recently been tried out on dryer sections of a new paper machine. It consists of a gearbox with two output shafts of conventional design, driving two points of a dryer section through stiff couplings; a dryer section commonly consists of 8 or 10 cylinders geared together, and by driving at two points instead of at a single point, the effect of backlash is greatly reduced. The tighter control given by this arrangement makes it possible to increase the high fiequency gain of the system about 4 times that of the conventional system.

5.2 Increasing the stiffness of other mechanical components

In this category are all the items of Figure 8, but attention should be focussed on the low speed couplings, which normally provide the greatest deflection. Unavoidably, the mechanical system will have some misalignment, and there will be some play in couplings but these should be kept to a minimum.

5.3 Avoiding cyclical disturbance

Every section of the paper machine has disturbances which repeat themselves once or several times per roll revolution. Often one part of a paper machine interacts with another part which runs at a slightly different speed and in this case there is a possibility of beating caused by the disturbances at times adding together and at other times subtracting. An example of this is shown in Figure 18. The beat effect here is caused by close-ratio machine indrive gears of 74 and 76 teeth. The cardan shaft cyclical load is at a frequency corresponding to 74 teeth, and the dryer cylinder load corresponds to 76 teeth; there will, therefore, be a beat repeating itself every 37 revolutions of the cardan shaft.

Frequently several sections may interact on one another through the paper tension, which leads to multiplication of the disturbances. While complete elimination of the cyclical loads may be impractical, it is believed that certain simple precautions, such as staggering of dryers manholes and scoops, would be helpful.

Of more serious nature are the cyclic load frequencies which can fall closely to the natural resonant frequency of the indrive system. For example, a breaker stack roll of 32 inches (0.81 m) diameter, designed to run at a maximum speed of 3,500 feet per minute (1,070 m/min) would have the highest frequency cyclical disturbance at 7 Hertz; the indrive shaft system should therefore be designed to have a natural frequency well above 7 Hertz.

5.4 Damping

Developments in the direction of increasing the damping of the mechanical system are the most promising. With continual improvements in bearings and lubrication, both friction loads and damping decrease; while in a general sense a deliberate introduction of a friction loss element is a retrograde step, this course of action can be justified in some cases. A friction load of a few kilowatts can increase the damping by one order of magnitude, and this in turn may lead to a greatly improved transient performance.

5.5 Position of speed transducer (tachogenerator)

It has been shown in theory and practice that the best position for mounting the speed transducer is at the load end, near the paper machine rolls. In the majority of cases the roll inertia is much greater than that of the motor armature and so the amplitude of torsional oscillations is less at the load end of the cardan shaft. The transducer therefore generates a smaller output at the shaft-resonant frequency and hence it is easier to eliminate this oscillation; also, it gives a more accurate measure of the paper machine section speed when transient variations occur, which enables quicker correction of speed errors, than when the transducer is mounted on the motor shaft.

If the transducer is mounted on the motor shaft, clearly the regulator will try to maintain the speed or position *at this point;* so even with an ideal regulator, which does not permit any error at the motor shaft, there can be a substantial error at the paper machine. To illustrate this point, Figure 17 shows the acceleration of a dryer section caused by a step reference change; the trace indicates motor speed, and the first peak of speed (18 rpm) is reached while the dryer rolls are still stationary. The motor has moved through backlash and flexibility of the mechanical system—the position error at the motor shaft is well over 20 degrees.

For elimination of torsional oscillations, the best position for the speed transducer is at the nodal point, which usally lies near the paper machine roll. Although this could lead to a substantial improvement, the nodal point is seldom accessible. Further, the speed of the cardan shaft is usually much less than the motor so that when the transducer is moved from the motor to the load end it is necessary to speed it up again to regain the loss in output; this requires backlash-free precision gearing well above normal commercial standards. Also, because of steam, water and high temperature, the environment near the paper machine is hostile to the speed transducer.

5.6 Electrical components

There are three electrical components of the drive which can be altered to give improved drive performance : servo stabilising circuits, motor and thyristor convertor.

The servo stabilising circuits can be varied to obtain the most suitable system response; some of the problems have been described earlier in this paper.

The other two items, the motor and the thyristor convertor, offer much less scope for improvement, but are worth further consideration.

Taking first the motor, it is seen from Figure 9 and Appendix 3 that the resonant frequency of the mechanical indrive system can be increased by reducing the motor armature inertia; this would permit faster control response. However, low inertia motors are non-standard and, therefore, expensive, and standard motors are normally used.

Considering the thyristor convertor, improvement can be obtained by providing electrical damping for the motor. During torsional oscillations, the motor generates a voltage at the oscillation frequency, and the currents produced can have a powerful damping effect; its effectiveness depends on the inductive time-constant (L/R) of the armature circuit including the power supply.

Control circuits having an armature current feedback loop, which have gained much popularity in recent years have an adverse effect on damping because by attempting to maintain the armature current constant at the shaft resonant frequency, they destroy the natural damping of the motor. In this respect, an armature voltage feedback loop is superior because the output impedance of the power supply (i.e. thyristor convertor) is lower, thus allowing more damping current to flow.

6. Conclusions

A paper of this type would appear incomplete without some sort of recommendation as to the best type of drive for a given application. Paper machines differ in their characteristics, and each case should be judged on its own merits, but it is the author's belief that one should use the simplest and most straightforward drive that is sufficient to perform the required duty.

It is convenient to divide paper machines into two broad categories :

low-speed—up to 2000 feet per minute (610 m/min), and high-speed-above 2000 fpm. There will naturally be a band of speeds around 2000 fpm where machines could fall in either category depending on the type of product, raw materials and, above all, the mechanical condition of the machine.

For low-speed machines, the normal speed control type of drive is quite suitable; the limit of accuracy is imposed by the tachogenerator, whose design is at present being reviewed in order to improve its stability. If this is successful, we may look forward to the performance of the speed controlled drive being substantially upgraded.

For high-speed machines, the drive requires a mixture of controls : speed control at the wet end, position control at the dryers, position and/or tension control at the calender and breaker stack, current control at the reel. A well-designed drive for a high speed paper machine should have the same basic speed contol on all sections: the overriding controls of position, tension and current are then added to the sections as required. These overriding controls are made in the form of electronic module units which are added to the basic speed control circuits; in this way, the principle of simplicity stated earlier is satisfied, and all sections have a high proportion of common components and circuits.

For the best possible performance, the author prefers a more rigorous approach, which starts with the specification of the physical properties of the product, including the permissible stress and strain at all sections of the paper machine. Using these data, one can design both electrical and mechanical components of the control system so as to meet the original specification without over-designing.

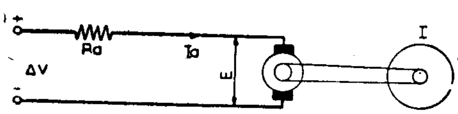
Reference:

1. Hamman, J. N. The use of electricity in the manufacture of newsprint, *Trans. SA Institute of Electrical Engineers*, Vol. 54, July 1963.

Appendix 1

ELECTROMECHANICAL TIME CONSTANT–DERIVATION AND MEASUREMENTS

The d.c. motor armature circuit is shown below :



Where :

$\triangle V$—is the step change of voltage across motor armature terminals.

I_a —is the motor armature current.

I —is mechanical inertia of the armature together with inertia of the driven mass.

E —is the back EMF of the d.c. motor.

K_e—is the motor constant representing back EMF per unit speed.

K_t—is the motor torque per unit of armature current.

Also: $\dot{\theta}$ —is the motor speed.

p —Laplace operator.

Motor equation is $\triangle V = I_a R_a + E$

but $E = K_e \dot{\theta}$

and torque $= K_t I_a = I p \dot{\theta}$

Hence $\triangle V = \dfrac{I R_a p \dot{\theta}}{K_t} + K_e \dot{\theta}$

$$\therefore \dot{\theta} = \frac{\triangle V}{K_e}\left[\frac{1}{1+\dfrac{I R_a p}{K_t K_e}}\right]$$

$$= \frac{\triangle V}{K_e}\left[\frac{1}{1+p T_m}\right]$$

$\therefore$ Electromechanical time constant T_m is given by

$$T_m = \frac{I R_a}{K_t K_e} \quad \cdots \quad \cdots \quad \cdots \quad (1)$$

The above expression for T_m neglects the armature reaction and the effect of the series field which, when taken into account, make the mathematical expression for T_m very complex. For this reason it is recommended that T_m is measured by the following method :

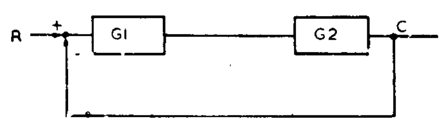
(a) By means of a stop watch, measure the accelerating time t_a from back EMF E_1 to E_2. (It is assumed that current limit acceleration is available.)

(b) Measure the mean accelerating current i. e. the current limit value of current less the mean friction current. Let mean accelerating current be I_a.

$$\text{Then } T_m = t_a \frac{I_a R_a}{E_2 - E_1} \quad \cdots \quad \cdots\cdots \quad (2)$$

Appendix 2

CONDITION OF CRITICAL DAMPING IN A TWO DELAY CLOSED LOOP SYSTEM



Let :

(i) $G1$—be the transfer function of the amplifier, the converter and the motor armature.

$$G1 = \frac{K}{1+pT}$$

Where —K is the d.c. loop gain.

T is the L/R time constant of the armature circuit.

p is Laplace operator.

(ii) $G2$ —be the electromechanical time delay.

$$G2 = \frac{1}{1+p T_m}$$

Where T_m is the electromechanical time contsant.

(iii) R —be the reference.

(iv) C —be the controlled variable (speed in this case).

Then the closed loop equation is :

$$\frac{C}{R} = \frac{G1\, G2}{1+G1\, G2}$$

$$= \frac{K}{K+(1+pT)\ (1+pT_m)}$$

$$= \frac{K}{TT_m p^2 + (T+T_m)p + (K+1)}$$

For critical damping :

$$(T+T_m)^2 - 4\ TT_m\ (K+1) = 0$$

$$\therefore\ T^2 + T_m^2 - 2TT_m - 4TT_m K = 0$$

$$\therefore\ \frac{T}{T_m} + \frac{T_m}{T} = 2 + 4K$$

$= 4K$ if $4K \gg 1$ which is usual

Also if $T_m \gg T$ then $\dfrac{T}{T_m}$ —0

$$\text{And } \frac{T_m}{T} = 4K \quad .\ .\ .\ .\ .\ . \quad (3)$$

Or in words : Approximately, the condition for critical damping is when the ratio of the longer time constant to the smaller one is equal to four times the d.c. loop gain.

Appendix 3

SUMMARY OF MECHANICAL FORMULAE RELATING TO TORSIONAL VIBRATIONS

Resonant frequency of the system shown in Figure 7 is:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{S}{I_e}} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

Where : S —is shaft stiffness.

Ie—is equivalent inertia

$$= \frac{I_L + I_m}{I_L \quad I_m}$$

I_L —is load inertia.

I_m—is motor inertia.

The stiffness of the shaft of diameter D and length L is given by :

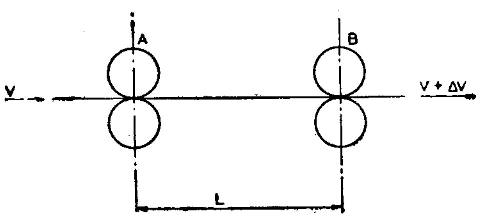
$$S = k\frac{D^4}{L} \quad \text{......................} \quad (5)$$

Where K—is a constant.

From equations (4) and (5) it can be seen that f_r is proportional to D^2. The rigorous treatment of backlash is complex; it's overall effect is to decrease the resonant frequency in the ratio of deflection without backlash to the total deflection with backlash.

Appendix 4

PAPER TIME CONSTANT



Assume that speeds of the two paper machine sections shown above are : The linear speed of the paper web entering Section A is V.

The linear speed of the web leaving Section A is $V + \triangle V$.

During time dt the paper extension is the difference of the above two speeds multiplied by dt.

Extension $= (V + \triangle V - V)dt = \triangle V\ dt$.

The extension acts on the length of the web L plus the length of the web that has passed during the time dt, i.e. $V\ dt$.

Thus the strain is:

$$S = \frac{\triangle V\ dt}{L + V\ dt}$$

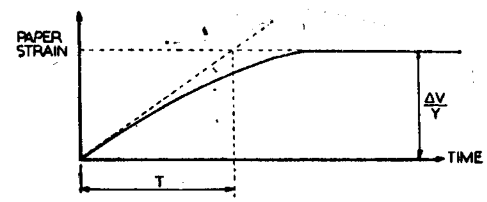
$$= \frac{\frac{\triangle V}{V}}{1 + \frac{L}{V}\ \frac{I}{dt}}$$

$$= \frac{\frac{\triangle V}{V}}{1 + p\frac{L}{V}}$$

$$= \frac{\frac{\triangle V}{V}}{1 + pT} \quad \text{. . . . . . .} \quad (6)$$

Where : p is Laplace operator.

$T = L/V$ is the paper time constant which can be defined graphically as below.



Following a step change in draw between two sections A and B of $\triangle V$ the web strain increases exponentially at the initial rate $T = L/V$ and it's final value is $\triangle V/V$.

Some typical values of the paper time constant are given in the table below.

Draw	Time Constant (Secs) 3.000 FPM Newsprint Machine	2.000 FPM Fine Paper Machine
1st Press to 2nd Press	0.11	0.25
2nd Press to 1st Dryer	0.12	0.30
1st Dryer to 2nd Dryer	0.11	0.25
2nd Dryer to 3rd Dryer	0.11	0.30
3rd Dryer to Breaker stack	0.19	—
3rd Dryer to size Press	—	0.45
Breaker Stack to 4th Dryer	0.19	—
Size Press to 4th Dryer	—	0.45
4th Dryer to Calender	0.31	0.75
Calender to Reel	0 27	0.65