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Paper 11

Research for AC Traction

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1 Introduction

The term 'research' is used in British industry to cover a diversity of activity ranging from fundamental studies intended to advance the frontiers of knowledge through development to test work of a routine character. For our present purposes, two categories are important, firstly the advancement of basic knowledge likely to assist in the conception of radically new solutions to technical problems and secondly, the application of the appropriate scientific methods to the study of the performance of systems and equipment. The distinction is more clearly expressed in the German language where research (inquiry, exploration) is translated 'Forschung' and the word ' Versuch ' denotes trial or experiment.

An outstanding feature of Railway electrification is the large amount of capital involved. This presents a two-fold challenge to the research worker, firstly to devise means which will assist the fullest possible utilisation of the asset created by electrification, and secondly to do what he can to reduce the capital cost of further electrifications, thereby making it possible to electrify a greater proportion of secondary lines so that, by elimination of dual working, the utilisation of the electrical equipment on the main lines may be still further improved.

The selection of the 25 kV commercial frequency system represents a revolutionary advance in electric traction technology but, in spite of the achievements to date, there is a continuing and even increasing need for research effort.

Comprehensive testing of a complicated system in order to ensure that designers' intentions have been realised and to provide design data for use in the future, as exemplified by the System Tests described in this Conference, is not regarded as research in this present context but does embrace certain aspects of a research character and is an essential prerequisite for a research programme.

Research in our field may also be said to take two forms:—

(1) that aimed at the detailed improvement of basic designs which have already reached a high state of development, e.g., the improvement of commutation of D.C. motors; or

(2) the search for radically new means for achieving the desired objective, e.g., the elimination of the commutator by such means as the use of A.C. induction motors.

Research may also embrace the application of modern devices or theories to improve the utilisation of existing equipment; for example, the provision of means for rapid inspection of the catenary system. Rapid detection of local variations in wear, tension or lateral alignments may considerably reduce the occupation of the line for inspection and afford firmer assurance against mal-functioning leading to delays in traffic.

Considering the influence of capital charges on operating expenses, these are roughly equally divided between motive power and fixed equipment, although it would appear from the relative technical complexity of the former that the greater benefits likely to accrue from a research effort will lie in this field. Morover, with the elimination of the steam locomotive and its substitution either by direct electrical machinery or by diesel locomotives having electrical transmissions or electrical control, the possibility of refinements in control are greatly extended.

2 Adhesion

It is obvious that adhesion between wheel and rail constitutes the overriding limiting factor to the tractive force exerted by a locomotive of given weight. This is a topic of considerable complexity and has been the subject of much investigation which is being continued by the Chief Electrical

Engineer's Research Section. The basic causes of friction are not yet beyond the range of controversy so that a solution of the problem presupposes an advance in knowledge of a fundamental kind. We can assume that clean oxydised steel rubbing against itself will give a coefficient of friction of 0·6; why, therefore, in railway operation are much lower values recorded and why do they fluctuate so much to the embarrassment of those responsible for operating the Railway? The effect of weather is well known but not completely understood. Nevertheless, sufficient progress has been made to enable tentative theories to be advanced to explain the observed behaviour and for remedies to be suggested which show promise in preliminary trials.

Closely bound up with the adhesion coefficient available between wheel and rail is the design of motive power capable of utilising this to the full. In certain circumstances, though not in others, the coefficient of friction falls off rapidly as the relative speed of the rubbing surfaces increases. This obviously represents a very unstable situation if the characteristics of the motive power are such that torque does not fall off rapidly with increasing speed. Considerable advances in locomotive design are noted from the point of view of minimising weight transfer between axles due to torque reaction, and the ease with which motors may be connected in parallel rather than in series, which the A.C. system permits, has enabled a notable advance to be made.

The consequences of an uncontrolled slip may be so serious, even resulting in the bursting of armatures by centrifugal force, that anti-slip relays have been used for a number of years. These are usually arranged to indicate the situation as a basis for remedial action by the driver or to remove current completely from the motor. Evidence exists that the catastrophic falling off in coefficient of friction occurring when slip takes place is preceded by a region in which friction increases with relative sliding. If torque could be so regulated that the critical value of relative sliding were not exceeded, better use could be made of the adhesion potential of locomotives. This presupposes firstly more detailed knowledge than we now possess of the way in which friction varies with relative sliding, and secondly a system of control of torque which could be influenced in a continuous manner by the output of sensitive slip measuring devices. Work on these subjects is proceeding.

Locomotives have been shown to be capable of exerting safely tractive efforts of a high order where sand is used to ensure good adhesion but the storage, preparation and supply of sand for locomotives complicates the operation of motive power depots and the necessity to return to depot for sanding militates against the high availability otherwise attainable by electric locomotives. Moreover, there is doubt during high winds for example, whether existing designs of sanding gear are successful in causing sand to be deposited where it is required.

A recent British development goes a long way to counter these objections. As a result of chemical research, a formulation has been derived which enables sand to be kept in a moist consistency indefinitely so that it may be readily handled even under conditions of extreme cold. The mixture is packed and stored in metal containers ready for use and the reservoirs on the locomotive may be charged by hand at any time. The mixture, which has to be kept away from direct contact with air, is applied by a special apparatus developed by Messrs. Gresham and Craven as a high velocity jet pressurised by compressed air through a diaphragm. The exit nozzle is closed when not in use by rubber flaps. Tests in the laboratory indicate that the sand mixtures applied by this method enable a high coefficient of adhesion to be attained, and a locomotive has been fitted for service trials.

Further, a continual effort will be made by British Railways to improve knowledge of adhesion phenomena so as to obtain desirable adhesion characteristics without the use of sand. For most of the time in most places, a reasonable coefficient of friction may be expected to exist between the wheels and the rails of locomotives. At certain times and in certain places, however, low values are recorded which may have serious operational consequences. It would appear, therefore, that the most rational approach to the problem is that of designing locomotives and their controls so as to make the maximum use of the adhesion occurring at any one time and of providing supplementary apparatus which would be rarely used but available in an emergency. This safeguard would be reinforced by conditioning those sections of the track which, for one reason or another, yield persistently low values of adhesion. A wider effort under U.I.C. auspices is envisaged.

3 Transmission

The next item of moment is the means used to transmit torque from motors to the axle. Several excellent designs have been evolved which appear to be effective but much controversy exists:—

(*a*) as to the relative merits of the designs, and

(*b*) whether in fact they are necessary at all.

Whilst in its technical aspects the question may be considered to be one of development rather than research, the factors involved are somewhat complex and considerable study of a research character is desirable. This is closely connected with the question of individual axle drives. In most countries it is now taken for granted that this method should be employed but some advantage may be obtained from the adhesion point of view by connecting axles together and it is possible that improved performance and the cost of a few large motors may be sufficiently lower than that of more numerous small motors to pay for the additional components involved. It is not inconceivable that a single motor may be used driving through cardon shafts in the manner analogous to that used on the Western Region diesel hydraulics. These questions also discussed in Paper 23 are essentially for the

development engineer rather than the research worker but the latter must be prepared to provide the fundamental data required for the successful introduction of such basic innovations.

Considerable work has been carried out in British Railways' Research Department on the effect of electrically propelled vehicles on the track and a collaborative effort is now envisaged in which accelerometers will be fitted to motor cases and other important components to assess the effect of the method of suspension on the electrical equipment itself.

4 Motors

The series motor, which is used almost without exception on electrification schemes, dates back some 70 years and has evolved continuously to provide greater powers with reduced weight and space requirements. Totally enclosed motors which were bulky and heavy have been replaced by ventilated motors with considerable savings. However, there is still room for improvement in them by removing such present limitations as commutation, lack of stability or proneness to flashover and the effects of natural ventilation. These are now major factors limiting the duty that can be performed by a motor of given size and weight.

These features are predominantly matters of design but attention by research workers to the basic physics of such matters should be of considerable value.

An investigation of commutation is in progress jointly between the Commission and the Electrical Manufacturing Industry. One aspect of the Commission's contribution has been the development of a low temperature radiation pyrometer to enable commutator surface temperatures to be measured in normal service.

The advantage of the substitution of ventilated for totally enclosed motors arises from the ease with which heat may be transmitted away from the conducting and magnetic circuits. Clearly some advantage may result from enabling the windings to reach a higher temperature without damage and the introduction of modern materials such as glass fibres bonded with silicone resins is useful in this connection, but is subject to certain limitations which afford a useful opportunity for research.

The simplest type of motor extensively used in industry is the squirrel-cage motor. This is not immediately applicable to single-phase traction because it normally requires three-phase current and only operates efficiently at a set speed. However, the complete absence of any need to provide a conducting path to the armature indicates that a very robust, reliable and maintenance-free motor could be constructed on this principle. To operate satisfactorily, however, it would require to be fed with poly-phase current of variable frequency. This can be achieved simply by providing an auxiliary rotary machine to transform single-phase current to poly-phase but it is considered that the cost and weight of such a device is prohibitive. Locomotives based on this principle have been employed but it does not appear that experience has been such as to justify continuing this design. However, new devices are coming forward, such as semi-conductor inverters, which may well enable the power supply to the locomotive to be converted into a form assimilable by squirrel-cage motors without too heavy a penalty in cost, weight and factors including reliability (fig.1). The circuit shown is grossly oversimplified. In practice provision has to be made for switching off (commutating) the units and for conservation of reactive power. Of the various circuits which can be designed on the assumption that controlled semi-conductor rectifiers will become available in sufficient powers, several envisage the interposing of a D.C. link between the main single-phase supply and the secondary poly-phase variable frequency current fed to the motors. This offers promise to end the 'tyranny of the systems' and would make it possible to design locomotives without additional complexity which would operate on any supply system that may be imposed for historical or geographical reasons.

5 Braking

One of the factors limiting the availability of electric rolling stock at present is the necessity to return to the depot for replacement of brake blocks. This somewhat laborious operation has to be carried out at intervals of the order of 15 days. Elimination of mechanical braking carries with it a danger of reduced adhesion between wheel and rail and the building up of contamination on the tyre which will inhibit the operation of track circuits. Regenerative braking can most easily be achieved at high speeds as control becomes difficult at very low speeds because the voltage generated is low in relation to the internal resistance of the machines. Brake block wear, however, which may be expected to be sensibly proportional to distance travelled during the retarding period, would be reduced to a comparatively minor factor if mechanical brakes were only used to bring a train to a standstill after it had reached comparatively low speeds by regenerative braking. Such applications would serve to retain higher adhesion values and to ensure that mechanical braking was always available for use in an emergency such as the interruption of power supplied to the locomotive.

Because braking is essentially a process of dissipating energy, it should not be necessary to supply power to a coach or wagon for this purpose. In the air brake system the train-pipe fulfils two functions, one command and control and the other the provision of energy for application of the brakes. The command and control function can best be carried out electrically as is demonstrated by the successful use of the E.P. brake. The work which has to be done to apply the brakes bears no relation to the energy required to be dissipated, and it does not appear to be beyond the range of mechanical ingenuity to provide some system whereby sufficient energy to actuate the energy dissipating device can be stored electrically, pneumatically or hydraulically in the vehicle itself. If this can be achieved, the only connection required between vehicles will be electrical so that the train-

pipe may be abolished, greatly simplifying the problem of the provision of automatic couplings.

6 Control Gear

Because present methods of control all involve to a greater or lesser degree the operation of contactors to interrupt flow of current in the main power circuits, they are particularly vulnerable from the utilisation point of view. A desirable solution would be to avoid the mechanical interruption in the main power circuits and to control the current therein without the necessity for opening mechanical switches. Semi-conductor devices offer considerable promise in this connection as well as devices wherein flux intensity can be varied in a continuous way without opening the circuits.

If a system is employed wherein the magnitude of the main motor currents is continuously varied by means of very weak signals, a more sophisticated system of control becomes possible which might enable the power and the high short-term rating of locomotive equipment to be utilised very fully irrespective of the skill of the driver. For example, the provision of anti-slip control would be very much simplified so that the locomotive could fully utilise the adhesion available at any given time and, by embedment of temperature-sensitive device at some critical points in the equipment, a control system could be devised whereby very heavy overloads could be applied for short periods, being automatically controlled by the conditions of the equipment.

7 Current Collection

The continuous contact between the pantograph running strips and wire is obviously of importance from several aspects. Frequent interruptions to the supply have obvious repercussions on the functioning of equipment within the locomotive and would lead to arcing which might damage both wire and contact strip as well as introducing high frequency interference. This very important situation, being as it is the meeting point of the rolling stock and fixed equipment, is of interest and concern to all traction engineers. Very considerable progress has been made in recent years in the detailed design of both pantographs and overhead equipment. The situation is not entirely unaffected by the mechanical design of the vehicle in so far as its riding implies consequent movements of the pantograph, and also by any track condition which contributes to this movement. The situation is a complex one, therefore, in which both the engineer and the research worker may expect to find much to challenge their ingenuity.

Most electrified railways have vehicles which are specially instrumentated for measurement of the position of the contact wire. The riding characteristics of these vehicles are not, however, necessarily identical with the service vehicles which normally use the track. A convenient arrangement for studying the behaviour of the pantograph and overhead equipment from a service vehicle is shown in fig.2. The camera is mounted on the vehicle itself and the necessary illumination provided by lamps mounted on the roof. The most convenient speed for subsequent frame by frame analysis has been found to lie between 100 and 200 frames per second. Slower speeds or single shot programmes could be used if the method were required as an inspection tool.

The results of analysis of some of these photographic records indicate that when a well designed pantograph is used, there is little difficulty in obtaining good current collection in open sections. Whilst there is still scope for effecting economy in such situations, the most difficult problems remaining are associated with special work at stations, junctions and sectioning points. This matter also discussed in Paper 21.

8 Overhead Contact Line

There has been a general improvement in the design of the supports system for the contact wires over the last decade brought on largely by the need for increased speeds. However, it is only recently that serious attention has been given to the dynamics of the overhead system, and the design of section insulators and neutral sections for high speed operation still leaves something to be desired. Researches of this character are reported in Paper 33A and it may be expected that considerable further research will be needed resulting in modifications mainly of a quantitative character which will result in more economical and still more reliable means of construction.

Essential tools for full scale research into these matters are transducers to measure movement and acceleration of the contact wire. In order that experiments may be carried out with the line live, these instruments and their associated leads must be insulated from the supply voltage.

The problem of insulation has been overcome by transmitting motion from the point under study on the equipment to the measuring instrument through resin bonded glass fibre reinforced tubes 0·562 inches in diameter, five feet long and weighing approximately 1 oz. per foot. The tubes were lightly smeared with a silicone grease. Two types of instrument were used to convert the movement into an electrical signal. One type consisted of a weatherproof rotary potentiometer fixed in space and rotated by a steel wire which was permanently subject to tension. The arrangement is illustrated in fig.3.

The other type consisted of a linear potentiometer having a travel of nine inches. A stainless steel piston rod actuated a slider within the housing and the instrument was rendered waterproof by a silicone rubber gland. Fig.4 shows both types in use adjacent to a bridge structure.

Where fixed points at earth potential for mounting the transducers were not available as at cantilever structures, pulleys were mounted on energised equipment above the wire under study and were driven by tensioned steel wire in the same manner as on the type illustrated in fig.1 but the insulated rod, instead of being placed between the contact wire and the pulley, was used as a torsion member to transmit rotary motion between the pulley and the transducer.

The transducers were of low resistance (100 to 200 ohms) and had fixed tappings at one-third and two-thirds of the

winding to provide a calibration voltage. Results were recorded on high speed multi-channel galvanometer recorders. Galvanometers having a frequency response of 250 c.p.s. have been found satisfactory.

Fig.5 shows a section of an installation in which vertical movements of both catenary and contact wire may be made as well as lateral movements. It will be noted that it has been necessary to incline the rod attached to the contact wire in order to provide adequate clearance from the catenary.

The insulating rods, although comparatively light, must add something to the mass of the wire adversely affecting the precision of the results. A system of measurement of acceleration has now been devised whereby the instruments are allowed to reach line potential and the readings transmitted by a short telemetric link.

Satisfactory insulators have been, of course, available for a number of years but troubles may still be experienced occasionally due to contamination by industrial conditions or salt in sea areas. Difficulties, for example television interference occasioned by this contamination, may be overcome by periodic cleaning. Nevertheless, it is to be expected that a study of the problem from the point of view of surface physics will enable greatly extended periods between cleaning to be attained. Much useful information has been obtained at the test gantry installed at Bishopsgate which is referred to in Paper 34 and which is now being reconstituted on an even larger scale at Finchley Road.

9 Signalling

Probably the most important aspect of Railway modernisation, both from the point of view of achieving maximum utilisation of the investment in tracks and motive power and for achieving a maximum reduction in manpower, is signalling. However, modern signalling can be expensive.

The basic requirements of a train control system are as follows:—

(1) Detection of an obstruction.
(2) Route setting and elimination of conflicting movements.
(3) Communication of information to the locomotive.
(4) Control of the train.

These functions are all catered for by existing systems with a varying degree of employment of human agencies at different stages in the cycle of train control. If the system is reconsidered from first principles, stages (1) and (4) appear to offer the greatest scope for innovation.

10 Conclusion

In deciding the scale of the research effort, it is necessary to appreciate that we are living in an age where basic scientific knowledge and applied technology are advancing extremely rapidly and, unless active steps are taken by Railway authorities to keep abreast with this general advance and to ensure that all relevant applications are made in Railway business, we may eventually find ourselves with heavy commitments for obsolescence. It is necessary, indeed, to exert some influence to direct advances in the desired directions. For example, the recent inventions concerned with variable speed induction machines have all been concerned with poly-phase supply. Railways are the only users of large single-phase powers and so have a responsibility for ensuring that corresponding developments, if feasible, should take place in single-phase machines.

A strong but small central laboratory for basic research is being set up at the office of the Chief Electrical Engineer so that the leading members of the Research staff may be closely associated with the Officers responsible for Development. This central research organisation will be complementary to research in the manufacturing industry, universities or specially sited out-stations. These will include the test gantry at Finchley Road for the study of Insulators under Contaminated Conditions and the Adhesion Laboratory at Willesden where some of the factors discussed in (2) are being studied. In addition, the Rugby Locomotive Testing Station will be developed for research on heavy electrical machinery and a section of track is proposed for trials in association therewith.

It is hoped, by these means, that Electric Traction will benefit from the noteworthy developments in electrical technology of which British workers in both the industrial and academic fields are justly proud.

SUMMARY

Research may take two forms (1) that aimed at the detached improvement of basic designs which have already reached a high state of development, e.g. the improvement of commutation of D.C. motors, or (2) the search for radically new means for achieving the desired objective, e.g. the elimination of the commutator by such means as the use of A.C. induction motors.

Regarding adhesion, a recent British development which should overcome most of the objections to the use of sand, is based on a formulation which enables sand to be packed and stored in metal containers and in a moist condition indefinitely so that it may be readily handled, even under conditions of extreme cold. The mixture is applied in the form of a high velocity jet pneumatically actuated.

The ideal of substituting induction for commutating motors may be brought nearer to reality by the development of controlled semiconductor rectifiers. This solution offers the promise of providing locomotives which can operate on any power supply.

The use of medium speed photography (100 – 200 frames per second) has been shown to be a useful means for studying the behaviour of pantographs mounted on service as distinct from test vehicles.

Study of the dynamics of overhead equipment has been facilitated by the use of potentiometric transducers. The problem of isolating these from the supply voltage has been solved by the use of resin bonded-glass fibre reinforced tubes. Whilst the mass of the apparatus attached to the wire will affect its movement, the effect has been reduced to negligible proportions by the extreme lightness of the tubes (1 oz. per foot).

RÉSUMÉ

Les recherches peuvent affecter deux formes: 1) celle qui vise exclusivement l'amélioration des constructions fondamentales qui ont déjà atteint un haut niveau de développement, et 2) la recherche de moyens radicalement neufs pour parvenir à l'objectif voulu, par exemple l'élimination du collecteur qui est inhérent aux moteurs à courant continu par des moyens tels que l'emploi de moteurs asynchrones à courant alternatif.

Quant à l'adhérence un récent développement britannique qui devrait surmonter la plupart des objections à l'emploi du sable, est basé sur une formule qui permet d'empaqueter et d'emmagasiner indéfiniment le sable dans des récipients métalliques et dans un état humide de telle sorte qu'il peut être utilisé facilement même sous les conditions d'extrême froid. Le mélange est appliqué sous forme de jet actionné pneumatiquement à haute vitesse.

La réalisation de l'idéal de substituer les moteurs asynchrones aux moteurs à collecteur peut être approché par le développement de redresseurs réglables à semi-conducteurs. Par cette solution on entrevoit la possibilité de construire des locomotives capables de fonctionner avec n'importe quelle forme d'énergie électrique.

L'emploi de la photographie à moyenne vitesse (100 – 200 prises par seconde) s'est montré utile pour l'étude du comportement des pantographes en service par distinction avec ceux qui sont montés sur des voitures d'essais.

L'étude de la dynamique de l'équipement caténaire a été facilitée par l'emploi des transducteurs potentiométriques. Le problème de leur isolation de la tension d'alimentation a été résolu par l'emploi de tubes renforcés en fibres de verre imprégnées de résines. Bien que la masse de l'appareillage attaché au fil de contact affecte son mouvement, l'effet a été réduit à une valeur négligeable par l'extrême légèreté des tubes (une once par pied).

ZÚSAMMENFASSUNG

Forschung kann zwei Formen annehmen, nämlich 1) die Suche nach einer speziellen Verbesserung einer grundsätzlichen Konstruktion, die an sich schon einen hohen Entwicklungsstand erreicht hat, z.B. Verbesserung der Kommutation von Gleichstrommotoren, oder 2) die Suche nach vollständig neuen Wegen ein erwünschtes Ziel zu erreichen, z.B. Vermeidung des Kommutators, indem ein Induktionsmotor benutzt wird.

Eine neue britische Entwicklung auf dem Gebiete der Haftreibung, die die Mehrzahl der Einwände gegen die Benutzung von Sand entkräften sollte, gründet sich auf eine Formel, die es gestattet, Sand in feuchtem Zustande in Metallbehälter zu packen und beliebig lange zu lagern; der Sand kann selbst bei grosser Kälte ohne Schwierigkeiten benutzt werden. Die Mischung wird als ein von Druckluft getriebener Strahl hoher Geschwindigkeit angewendet.

Das Ideal, Kommutator- durch Induktionsmotoren zu ersetzen, kann durch die Entwicklung gesteuerter Halbleiter-Gleichrichter der Verwirklichung näher gebracht werden. Diese Lösung ist ein vielversprechender Schritt auf dem Wege zu Lokomotiven, die an Stromversorgungssystemen jeder Art arbeiten können.

Die Benutzung von Filmaufnahmen mittlerer Geschwindigkeit (100 bis 200 Bilder je Sekunde) hat sich als ein nützliches Mittel zum Studium des Verhaltens von Stromabnehmern unter Betriebsbedingungen, im Gegensatz zu der Verwendung von Messwagen, erwiesen.

Die Untersuchung des dynamischen Verhaltens der Fahrleitungen ist durch Benutzung von Spannungsteilern als Umsetzer wesentlich erleichtert worden. Das Problem, die Spannungsteiler gegen die Fahrleitungsspannung zu isolieren, konnte durch Verwendung von Harz gebundenen Glasfaser verstärkten Röhren gelöst werden. Die Masse des mit dem Fahrdraht verbundenen Gerätes wird zwar die Fahrdrahtbewegung beeinflussen; dank des sehr geringen Gewichts der Röhren (1 Unze je Fuss) ist dieser Effekt jedoch zu vernachlässigen.

RESÚMEN

Toda labor de investigación puede revestir dos formas: 1) la que se destina a perfeccionar, objetivamente, los diseños básicos que ya han alcanzado un alto nivel de desarrollo, como por ejemplo, el mejoramiento de la conmutación de los motores de corriente continua, o 2) la búsqueda de medios radicalmente nuevos para conseguir el objetivo deseado, como por ejemplo, la eliminación del conmutador mediante el empleo de motores de inducción de corriente alterna.

Con respecto a la adherencia, merece citarse un invento británico con el que se eliminarán las objeciones que se anteponen al uso de arena. Este descubrimiento se basa en una fórmula que permite acumular arena en recipientes metálicos y en estado húmedo indefinidamente para poderla utilizar fácilmente incluso en condiciones de intenso frío. La mezcla se aplica por medio de un chorro a presión de alta velocidad y accionamiento neumático.

La introducción de rectificadores semiconductores controlados hace cada vez más posible la idea de reemplazar los motores de inducción por motores de conmutación. De esta manera se podrían utilizar locomotoras que funcionasen con cualquier suministro de energía.

El empleo de la fotografía de velocidad media (100 – 200 imágenes por segundo) ha demostrado ser un ventajoso medio de estudiar el comportamiento de los pantógrafos montados en vehículos en servicio en lugar de vehículos de prueba.

El uso de transductores potenciómetricos ha facilitado el estudio de la dinámica de las líneas de contacto aéreo. El problema de aislar estos transductores del voltaje de la corriente se ha resuelto usando tubos reforzados con fibra de vidrio impregnada de resina. Aunque la masa del aparato acoplado al cable afectará su movimiento, este efecto ha sido reducido a proporciones imperceptibles a causa del peso extremadamente reducido de los tubos (1 oz. por pie).

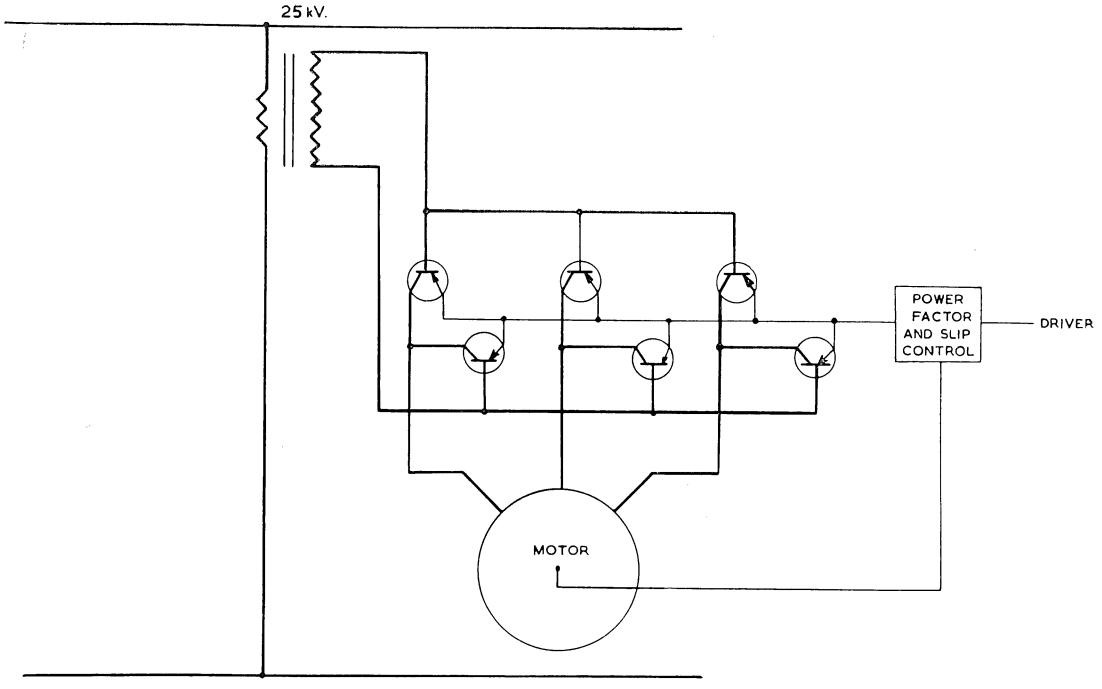

Fig.1 Three-phase system using controlled rectifiers

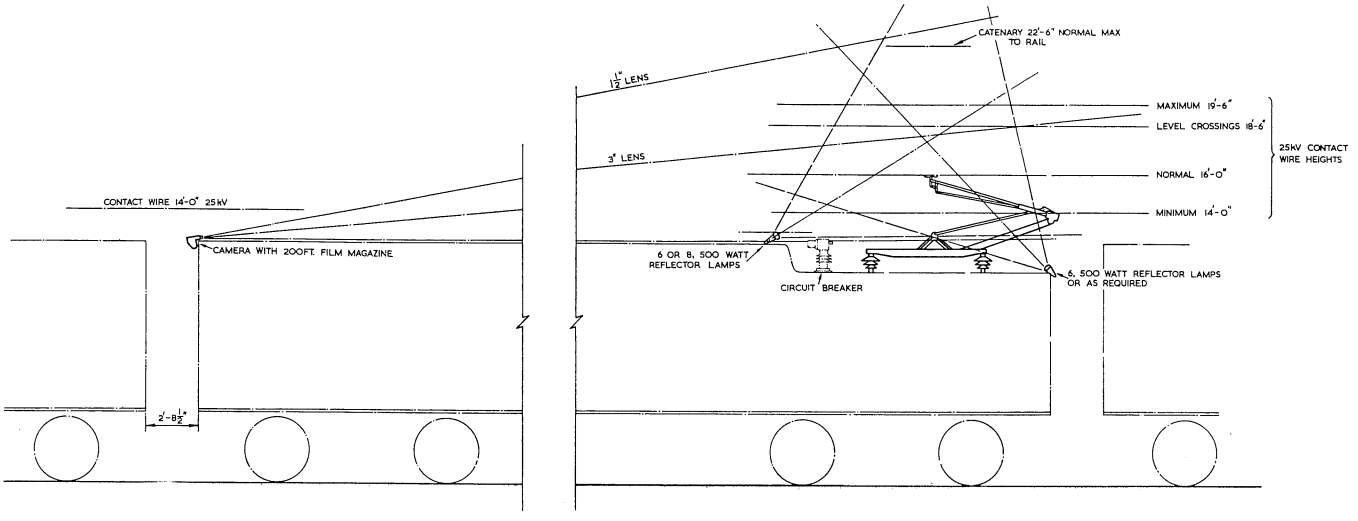

Fig.2 Arrangement of camera recording apparatus on coach roof

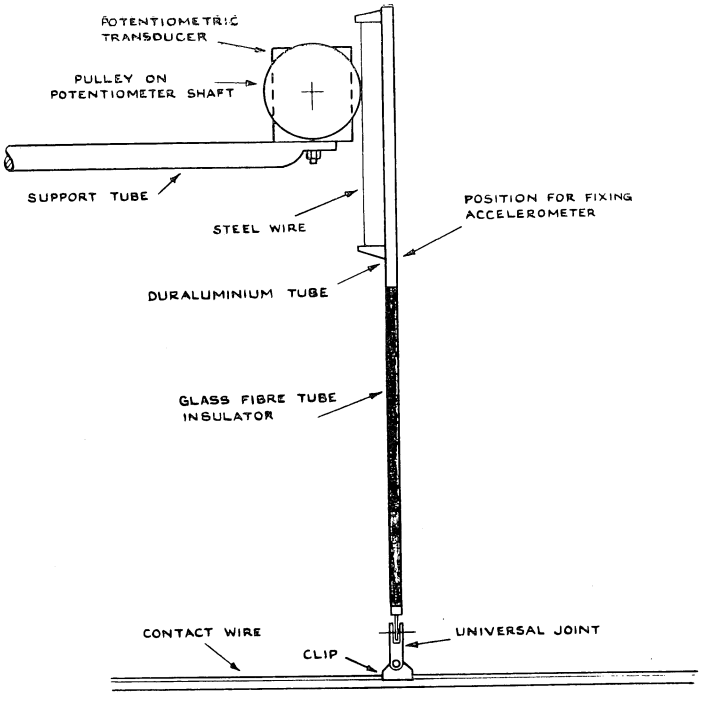

Fig.3 Potentiometric displacement transducer for use on portal structures

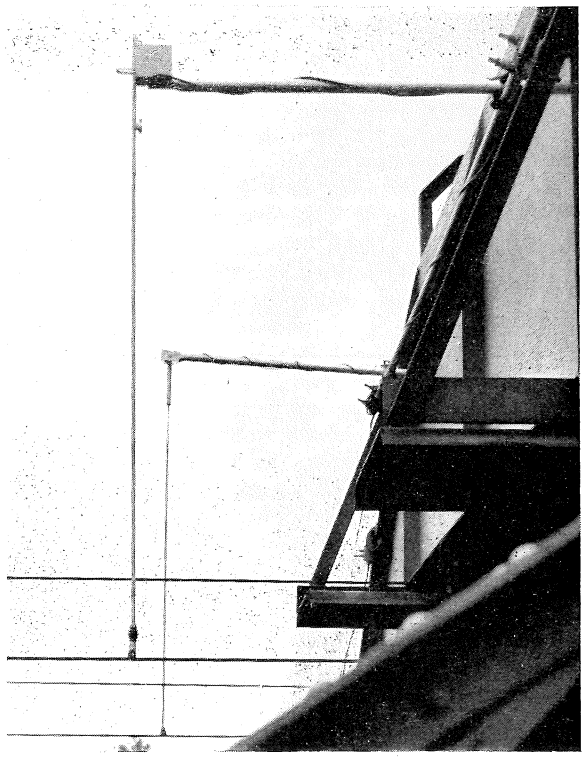

Fig.4 Rotary and linear potentiometers fitted to bridge structure

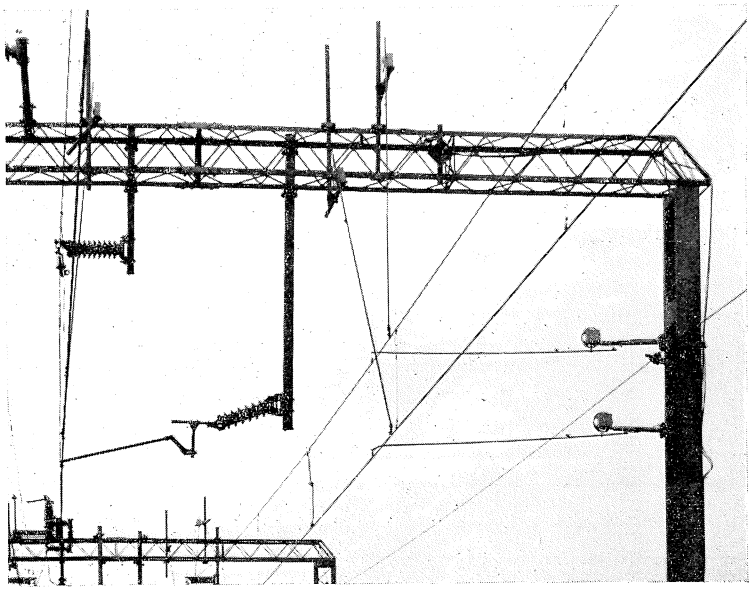

Fig.5 Rotary potentiometers for measuring uplift and lateral flow off of catenary and contact wire

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