THE DISTRIBUTION OF ELECTRICITY

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Before proceeding with the business of the day, the meeting stood in silence as a mark of respect to H.R.H. the late Duke of Kent, brother of His Majesty the King, Patron of the Society, and of the late Captain Colin Bain-Marais.

Consideration was given to the papers to be read during the forthcoming Session.

Mr. William Will was appointed Honorary Adviser in matters concerning the *Journal*.

A Committee was set up to examine further the motion of Mr. A. C. Bossom on the part to be played by the Society in relation to Government Departments concerned with post-war design.

A quantity of formal and financial business was transacted.

RECONSTRUCTION

The pamphlet containing the series of twelve lectures on "The Post-War Home" is now on sale at 2*s.* per copy to Fellows (2*s.* 6*d.* to non-Fellows) and may be obtained from the Acting Secretary.

PROCEEDINGS OF THE SOCIETY

CANTOR LECTURES

THE DISTRIBUTION OF ELECTRICITY

By E. Ambrose, M.I.E.E.

Lecture I—*Delivered on April 20th*, 1942.

Introduction

This year may be said to mark the 60th anniversary of the first public supply of electricity,—1882—although experimental installations in which the electric arc was the only form of light giving apparatus, had been in existence for many years prior to that date. In these early installations there were required the electric generator (with some form of engine to drive it), the arc lamps and the necessary connecting wires to convey the current from one to the other, that is, from the generator to the consuming apparatus. In the public distribution of electricity to-day, the fundamental principles remain unchanged, but the details have been considerably expanded. The consuming apparatus, instead of being but a few yards from the generator is, in many instances, a hundred or more miles away.

The use of electricity for lighting and power purposes was a novelty sixty years ago, but now it is considered almost a necessity. The early pioneers of the art were no doubt familiar with the whole subject of electrical science as it was then understood, including generation, transmission and distiibution, but the rapid progress which was soon made towards the present complex nature of the industry made specialisation necessary, and engineers were soon tending to devote their energies to one of the three main groups: generation, transmission and distribution.

In these lectures I propose to devote myself to the third group, that of distribution, but it will be of interest briefly to refer to some of the milestones along the road of progress with a glance at the fundamental principles governing development. Perhaps by far the most important event was the epoch-making discovery of Faraday which made possible the generation and distribution of electricity as we understand it to-day. Before examining this work, I propose to go back to the time when electricity was known only as an interesting but useless natural phenomenon.

Frictional Electricity

About 2,500 years ago (600 B.C.), Thales, the Greek philosopher, is said to have observed that amber, when rubbed with woollen substances acquired the peculiar property of attracting light bodies. Amber was known to the Greeks as "electron," and from this the English word, "electricity" is derived.

The attractive force possessed by amber when subjected to friction, remained an isolated fact for about 2,000 years.

In the year 1600 A.D. Dr. Gilbert, physician to Queen Elizabeth, discovered that many other substances besides amber (glass, sulphur, sealing wax, resins, etc.), when suitably rubbed, became similarly endowed with the power of attracting light bodies. A body which has been rubbed and acquires this property of attracting other bodies is said to be electrically charged, or is electrified.

Electrical charges are for convenience divided into two kinds, positive and negative. If a glass rod is rubbed with silk, the glass becomes positively charged, and the silk becomes negatively charged. If sealing wax is rubbed with flannel the sealing wax acquires a negative charge and the flannel becomes positively charged. Electricity produced in this way is known as frictional or static electricity. The terms "positive" and "negative" are conventional.

Much work has been done by many investigators on the behaviour of electrical charges, on conductors and insulators, on quantitative measurements, and on frictional machines for producing greater quantities of electricity than is obtainable with glass rods or sealing wax.

The Primary Cell

The next important discovery was due to the experimental work of Galvani and Volta. About the year 1780, Galvani, a professor of anatomy in Italy, whilst experimenting in his laboratory, found by accident that if two different metals are held in contact, and one metal touches the nerves of a frog's leg while the other metal touches the leg itself, the leg kicks out violently as if a shock had been

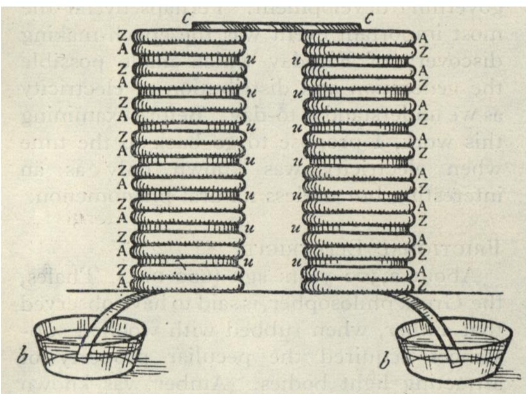

Fig. 1.—*Drawing of a Volta pile.*

administered. It is interesting to note that having broken or mislaid his forceps, he used an improvisation consisting of different metals. Poverty and illness prevented Galvani from following up his discoveries, but these effects were investigated more thoroughly by Volta, a professor of physics in Italy; and a scientific battle took place between these two men.

Galvani held that the electricity originated in the frog. Volta, on the other hand, believed the electricity to be generated by the contact of dissimilar metals, and as a result of much experimental work on the contact of different metals, he announced in the year 1800 that he had constructed an electric "pile." (Fig. 1.) It consisted of a number of circular discs of two metals, silver and zinc. These discs were placed, alternately silver and zinc, one on top of the other, like a stack of coins, and between each pair of discs was inserted a similar disc of cloth or blotting paper which had been moistened with brine. Volta found that if he put one hand in a vessel containing brine, which was connected to the bottom of the pile, and touched successive discs with a moistened finger of the other hand, he could feel a shock which increased in intensity as he touched higher up the pile. Moreover, he found that he could repeat Galvani's experiments with greater effect.

Volta varied the construction by substituting glass jars containing weak sulphuric acid for the moistened pads, and copper in place of silver. Into each jar he placed one copper rod and one zinc rod, and so formed an electric cell. By arranging a number of these cells in a row and connecting the copper of the first cell to the zinc of the second, and so on, he formed what is called the first primary battery. The end of the zinc rod outside the liquid was found to possess properties similar to that of sealing wax after it has been rubbed with flannel, that is, negatively electrified. The copper, on the other hand, had an electrical state similar to a glass rod after it has been rubbed with silk, that is, positively electrified.

The experiments of Galvani and Volta are therefore very important as they led to a means of creating a continuous electrical current by the action of liquids upon metals.

It was soon found by experimenters that the Volta pile and the simple primary cell, when at work, were not able to maintain the current at a constant value; the current gradually became weaker and weaker. This defect was caused by the formation of hydrogen gas at the surface of the negative electrode. The effect increased so long as the cell remained in circuit and, in the end, the flow of current ceased. In this condition the cell was said to be "polarised." Numerous investigators set to work to overcome this defect and, as a result, the Daniell, Grove, Bunsen, Leclanché and other constant current cells were invented.

The Storage Battery

The storage battery of to-day is sometimes referred to as the secondary battery. Gautherot, in 1801, observed that during his experiments on the decomposition of salt water, the platinum or silver wires which served as electrodes became polarised, and that by the absorption of oxygen and hydrogen they became electrically different. By disconnecting his battery and then connecting the two electrodes he obtained a secondary current.

Two years later, Ritter obtained the same effects with gold wires and noticed the formation of metallic films and peroxides by electrolytic action. He embodied the results of his observations in his secondary pile which consisted of discs of copper separated by discs of pasteboard moistened with saline solutions and arranged in the manner of Volta's pile. By means of connecting wires, current was allowed to pass for some time from Volta's pile through his secondary pile. After this process of charging, the secondary pile could give out transitory currents. Ritter was well aware of the importance of his experiments, but did not follow them up at the time. Some say the cause was lack of means.

It was not until after Planté's extensive investigations that the construction of secondary cells was completely achieved. He investigated the phenomena of polarisation with a view to their utilisation instead of their elimination. He carefully examined the polarisation of all the ordinary metals, and found that all gave secondary currents, although, in some instances, this was very small; those obtained with lead electrodes in dilute sulphuric acid far exceeded the others, both in duration and intensity.

Planté constructed the first practical secondary cell. He placed lead plate electrodes in a 10 to 30 per cent. solution of sulphuric acid, and passed a current through the cell; the direction of the current was frequently reversed. The hydrogen liberated at the negative, bubbled away, but the oxygen liberated at the positive oxidised the lead to form a thin layer of lead peroxide (P_bO_2). On reversing the current, the negative electrode became superficially oxidised, the lead peroxide on the other electrode being reduced to spongy lead. This process, many times repeated, finally resulted in the formation on one plate of a layer of lead peroxide, on the other a layer of spongy lead. The active material formed in this way was very strong mechanically, but the process had two great disadvantages. The storage capacity of the finished plate was very low, compared with its weight and volume, and the time and electrical energy needed for the formation was excessive. Later improvements in the process resulted in more rapid formation.

Although Planté showed how a practical storage cell could be constructed, the time was not ripe for its commercial application, and further development was held up for some years. Interest in the subject was renewed when the development of the dynamo reached a commercial stage enabling large currents to be furnished at comparatively high voltages.

In 1881 Camille Faure took out a patent for preparing the active material for the plates of lead storage cells. The material was mechanically applied to the plates and thereby obviated Planté's long process of formation from the material of the plates themselves. Faure coated the plates with a paste of red oxide of lead mixed with dilute sulphuric acid, but in the more modern cells the pastes are lead oxide for the negative plate and red lead for the positive plate. When the cell is charged the positive plate takes the chocolate colour of lead peroxide and the spongy lead of the negative plate a light grey colour. In order to increase the volume of active material the modern plate is made in the form of a lead grid of which a large number of types exist. The voltage of this type of cell when fully charged, is 2. To avoid using very large plates, cells of large capacity are provided with a number of plates. For portable cells, the containers are usually made of celluloid or glass, but for large batteries, such as those for emergency lighting in hospitals, for telephone exchanges or for generating stations stand-by use, the containers are large open-topped glass jars or lead-lined wooden boxes.

ELECTRO-MAGNETISM

With the availability of cells, such as Volta described, for producing electric currents, scientific investigators in many countries set to work and reference has already been made to the experiments of Gautherot and Ritter. In 1819, Oersted of Copenhagen University, whilst demonstrating the work of Galvani and Volta, placed a magnetic compass needle near the current-carrying wire and observed that the needle was affected. Oersted had discovered that electricity in motion is capable of exercising a magnetic effect. An account of the direction in which the needle turns in obedience to the magnetic force evoked by the current flowing in the wire, was described by him in July, 1820.

Ampère, in France, showed that a wire coiled in the form of a solenoid and carrying current behaves like a magnet, and he demonstrated that mutual action exists between two wires carrying current. His name is perpetuated by its use to denote the unit of current.

Michael Faraday believed that somehow a wire carrying a current ought to be able to produce a current in another wire placed alongside it. His experiments in this direction led to his epoch-making discovery in 1831, of the fundamental principles of electromagnetic induction. He wound two coils of wire on the opposite sides of an iron ring, one coil being connected to a battery and the other to a wire passing over a pivoted magnetic needle. Faraday found that whenever he started the current by connecting the battery, the needle was deflected in one direction, and whenever the current was stopped by disconnecting the battery, the needle was deflected in the opposite direction. This experiment showed that an electromotive force, as it is called, was induced in the second coil by the magnetism set up by

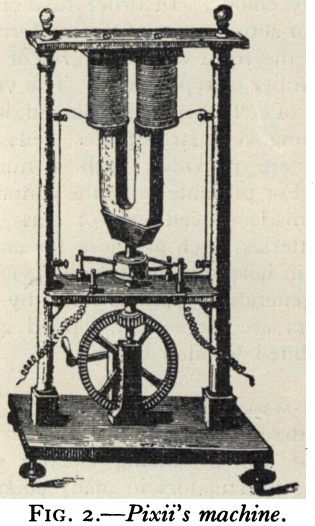

FIG. 2.—*Pixii's machine.*

the current in the first coil. A few weeks later he discovered that whenever he moved a magnet close to a coil of wire, he again produced momentary currents in the coil, and so solved the problem of generating electricity from magnetism.

THE DYNAMO

By rotating a circular disc of brass between the poles of a horse-shoe shaped electromagnet, Faraday obtained a steady current of electricity, and so started the evolution of the dynamo. Collecting brushes rubbed against the edge of the disc and the axle.

The early machines based on Faraday's experiments were, naturally, of the laboratory type. Possibly the first machine to be constructed was Pixii's in 1832. (Fig. 2.) The fixed portion consisted of two soft iron cores on which were wound several turns of wire. The rotating portion consisted of a powerful permanent magnet shaped like a horse shoe which was made to rotate under the fixed iron cores. The changing condition of the magnetic circuit induced currents in the wires, and the direction of the current was reversed as first one and then the other pole of the magnet passed an individual core.

Pixii thought that the continued alteration of the current direction might be inconvenient for many purposes, so he therefore added a commutator to this machine, which caused the currents in the external circuit to flow in one direction. Although the current obtained from such machines was unidirectional, it was rather intermittent owing to the relatively large interval of time, in one complete revolution, during which the coil was outside the influence of the magnet.

Other machines based on the same principle were produced by different workers, and in some instances the permanent magnet formed the fixed portion, the coils being made to rotate.

An important advance in construction was due to Siemens in 1857. He devised the cylindrical armature for the rotating portion. In its simplest form, it consisted of an iron cylinder which was cut away so that its cross section was of an " H " form. Covered copper wire was wound longitudinally round the cylinder and the two ends of the wire were connected to a two-part commutator. For the magnet system, some eight or nine horse-shoe magnets, made of rectangular section steel, were placed parallel to each other, and cut out at their poles to form a hollow cylindrical space in which the armature could be made to revolve. With this arrangement the coils moved in a much more concentrated magnetic field, but there still remained a relatively large interval of time when the coils were inactive.

The use of electromagnets for the field system had been suggested by Wheatstone and Cook in 1845, and a machine of this type, in which the exciting current for the electromagnets was obtained from a separate small generator provided with permanent magnets, was constructed by Wilde in 1863. A further advance was made in 1867 when Siemens described a machine in which the whole of the current induced in the armature was passed through the coils of the electromagnets in order to maintain and increase the magnetic strength. The magnet cores were initially magnetised feebly by sending through a current from a battery. In the same year

Wheatstone suggested that a part of the induced current of the armature should be passed through the field coils. Such are called dynamo-electric machines, to distinguish them from magneto-electric machines.

These two methods of connection exist to this day in what are known as "series" and "shunt" wound dynamos. Each has its purpose—the series wound machine being used for constant current operation, and the shunt wound machine for constant voltage operation.

There remained the problem of producing currents with less intermittency. This was solved by substituting for the "H" armature, with its one coil of many turns, an armature in the form of a ring, on which the wire is wound continuously round the core; a large number of tappings, equally spaced, led to a multiple part commutator. The first armature on this principle was constructed by Pacinotti, about 1860, but little progress was made until the improvements by Gramme in 1870.

From the foregoing it will be realised that the essential parts of a dynamo are an electromagnetic field system, a continuously wound armature and multipart commutator with brushes for collecting the current, and, with all these essentials, the Gramme machine provided the starting point for the generation of electricity on a practical scale. Since 1870, there have been many improvements in the construction of the armature, the method of winding and the introduction of the multipolar machine, but the principles remain the same.

Alternating Current Machines

It will be remembered that Pixii, when constructing his dynamo, thought that the alterations in the direction of the current which his machine produced, might be inconvenient for many purposes. This was true, because, without a direct, or a uni-directional current, it would not be possible to carry out electrodeposition or to charge batteries except, of course, by using the small currents which could be obtained from primary cells.

Between 1857 and 1863 permanent magnet machines, without commutators, were constructed and installed in lighthouses for supplying current to electric arc lamps. In place of a commutator two separate rings were fitted on the spindle, and from these the current was collected by brushes and conveyed to the lamp. The current increased and decreased in strength and changed in direction as the armature coil passed successively the opposite poles of the magnets. This complete set of changes is called a cycle, and the number of cycles per second is defined as the frequency. In some of these early machines the frequency was about 50. A current which repeats itself in this manner is called an alternating current, and the type of machine which generates it is called an alternator.

In or about the year 1876 when there was a considerable demand for alternators, the Gramme alternating current machine was perhaps the most popular. This machine was of the radial revolving field type with a fixed armature, the field coils being excited from a separately driven dynamo. (Incidentally, Wilde in 1863 anticipated the use of separate machines for exciting modern alternators.)

In the early eighties, alternators were being constructed by various makers to the designs of Siemens, Gordon, Ferranti and others. In 1895 an alternator, known as the Copper Alternator, was designed by Ferranti for use at the Deptford power station of the London Electric Supply Corporation. The armature, which was the rotating part, consisted of flat coils of copper strip mounted in pairs and supported by insulated clamps to the rim of a flywheel. The armature ran between the fixed electromagnet field coils which were arranged around each side of the circumference of the wheel and projected horizontally inwards, adjacent poles being alternately N and S, and the poles immediately facing each other also of opposite sign. As the armature discs or coils moved from one pole position to another, and so cut across opposite magnetic fields, the induced electromotive force generated changed direction simultaneously in each coil. The voltage measured at the terminals of the machine would be found to vary in the same manner as would that of a single coil rotating uniformly between the magnets of a two-pole machine. Fig. 3 illustrates a copper type alternator built by Crompton & Co., Ltd.

All of the machines mentioned so far produced currents of the so-called "single phase" nature. There were no difficulties about using this sort of current for lighting or heating, but it could not be utilised satisfactorily for operating motors. In 1891, however, the problem of using alternating currents for power purposes was solved at the Frankfurt Exhibition by the use of currents differing somewhat in character from the ordinary, or single phase, current.

Consider the simple Gramme ring, with its continuously wound conductor and arranged to revolve between the two poles of a magnet. If, for example, two tappings be taken off the continuously wound conductor at the opposite ends of a diameter a single-phase alternating current will be obtained. Now suppose that two more tappings are made at the opposite ends of a second diameter at right angles to the first, then another single-phase current will be obtained. One of these two currents, however, will reach its maximum value after the other at an interval of time represented by a quarter of a revolution of the armature. The machine would therefore be generating two

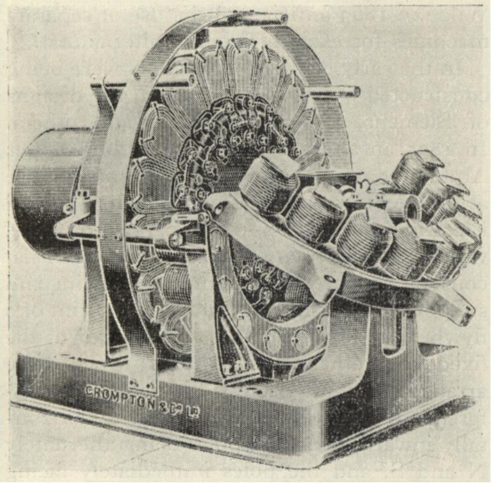

FIG. 3.—*Copper type alternator.*

currents differing in phase by 90°; in other words, a two-phase alternator.

Consider now an identical Gramme ring, revolving between two poles as before. If three tappings only be made, each spaced 120° apart, between any two of the tappings a single phase supply could be taken. The three currents, however, would each reach their maximum values one-third of a revolution apart. The machine would be generating three currents differing in phase by 120°. This is called a three-phase alternator with a mesh connected armature.

If now the armature coil be cut into three equal portions, and the corresponding end of each of the three coils so produced be joined together at a common junction and the other free ends taken to separate collecting rings on the spindle, the armature is said to be star connected.

The modern alternator, though modified very much in details of construction, works on these principles, and although single-phase, two-phase and three-phase machines have been built, the majority of present-day alternators are built for three-phase working.

The very early small machines for laboratory purposes were hand-driven, but as machines became larger mechanical motive power was necessary. For this purpose gas, oil or steam engines, and where it is available, water turbines are used.

THE TRANSFORMER

The transformer is a piece of apparatus capable of changing an alternating current at one voltage into an alternating current at another voltage. The principle of the transformer was established by Faraday in 1831, when he made his famous experiment with an iron ring on which he had wound two coils of wire.

In his original transformer, Faraday used a welded ring of soft round bar iron, 7/8 inch thick, the diameter of the ring being 6 inches. Round one part of this ring he wound about 72 feet of copper wire, 1/20 inch in diameter, in three layers, about one-half of the ring being covered in this way. On the other half of the ring a length of 60 feet of copper wire was wound in two layers. The three-layer or primary coil was connected to a battery, and the other coil, the secondary, was connected to a simple galvanometer. Mention has already been made of the way in which Faraday conducted his experiment. Had he supplied the primary circuit with a rapidly alternating current, he might have obtained an alternating current in the secondary circuit; but his galvanometer would not have indicated the presence of this current if the reversals were too rapid to give the needle time enough to move with each pulsation. Furthermore, there might have been considerable heating of the iron ring due to the eddy currents set up by the rapid changes in magnetisation. The circulation of eddy currents in the iron represents a loss, and this can be reduced by building up the core with small diameter iron wire or thin sheets of iron. Early illustrations of these methods are recorded in the transformers of Varley and Ferranti.

About 1852, Varley constructed a transformer with iron wires forming the core. He took a bundle of wire of approximately equal lengths, and over this bundle wound the primary and the secondary coils. These coils were placed in the middle of the bundle, and extended along it for a distance of about one-third of its length; the iron wires therefore protruded from each end a distance equal to the length of the coils. The two ends of the iron wires were then turned over the outside of the coils and made to overlap each other. In this way the coils were completely encased with iron. Space was made, however, for leading through the connecting wires. Varley was perhaps a little ahead of requirements, because, at that time, the need for anything except small transformers did not exist, but some thirty years later transformers were built by Ferranti which were a further development of the type.

Ferranti took a quantity of thin strips of iron, divided into six bundles and placed side by side. Over the middle of this he wound a layer of thick insulated wire or strip, to form the secondary coil. Finer wire to form the primary coil was wound on a convenient frame in sections, and slipped over the secondary. The ends of the iron strips were then turned over the coils, one half over the top and the remaining half at the bottom, their ends meeting and overlapping in a similar manner to the iron wires in Varley's transformer. The whole arrangement of core and coils was then placed in a cast-iron framework, made in two halves, and securely bolted together.

When a transformer is at work a certain amount of heating takes place owing to the eddy current losses in the iron of the core and resistances losses due to the flow of current in the copper of the primary and secondary coils. In the comparatively small transformers, such as those already described, the heat generated was carried away by radiation into the atmosphere. Subsequently, when transformers were required for considerably higher voltages, it became necessary to immerse the core and coils in insulating oil, thus diminishing the risk of electrical discharge between the high voltage coil and the frame or the low voltage coil; it also greatly reduced the risk of personal shock due to accidental contact with the coils.

The transformer, then, is a comparatively simple structure. There are no rotating parts, and the chief elements of its construction are, a magnetic circuit comprising the core, two electric circuits comprising the primary and secondary windings, and auxiliaries comprising tanks, oil and cooling plant.

THE ELECTRIC ARC

In 1800, the year Volta announced the construction of the voltaic pile, Sir Humphrey Davy mentions experiments in which electric sparks were obtained between two carbon points caused by a voltaic pile, and in 1810 he showed to a distinguished audience, assembled in the theatre of the Royal Institution in London, the brilliant light that was produced by passing a current of electricity through two pencils of charcoal about an inch long and one-sixth of an inch in diameter, the points being placed end to end and slightly separated from each other. The only available source of electricity in those days was the voltaic cell and a battery consisting of 2,000 of these cells was used for the demonstration. Foucault, in 1844, instead of using charcoal, as Davy did, made use of carbon from the retorts of gasworks, which is much harder and did not burn away so quickly. Foucault constructed a hand-regulated arc lamp which Deleuil is said to have made use of in showing the first electric light in the Place de la Concorde, Paris. The next step was to devise some means for automatic adjustment of the carbons, and the first apparatus of this kind was devised by Thomas Wright of London in 1845. This was carried a step further by Staite in 1848, when he made use of the current of the arc for the regulation of the carbon.

A phenomenon of the direct-current arc is that the positive carbon burns away at approximately twice the rate of the negative carbon, and the end of the positive carbon becomes cup-shaped whereas the negative carbon becomes pointed. This is thought to be due to bombardment of the positive carbon by particles flying off the negative.

In 1876, Paul Jablochkoff invented the famous "Jablochkoff Candle." This consisted of two parallel carbon rods separated by a layer of plaster of paris. A thin plate of graphite laid across the carbon tips and held in position by a paper band serves to light the candle. The arc thus formed maintained itself between the carbon rods, volatilising the intervening partition. Owing to the unequal burning away of the carbons with direct current, these lamps were found to operate best with alternating current.

The pioneers of electricity supply started by experimenting with arc lamps for lighthouse work. Experimental installations were tried at Blackwall in 1857, then in 1858 at South Foreland and 1862 at Dungeness.

The arc lamp was only suitable for the lighting of large areas, and one of its first installations of this kind was at the Gare du Nord, Paris, in 1875. Within the next three years a number of Jablochkoff candles were installed in the same city; some at the Grands Magasins du Louvre, and others for street lighting in one or two of the important avenues. In December, 1878, Jablochkoff candles were installed along the walls of the Thames Embankment, London, between the Waterloo and Westminster bridges. Other installations using the same type of lamp were tried, but they all failed subsequently because of the high cost when compared with gas lighting.

The Incandescent Lamp

When a current of electricity flows through a solid conductor, heat is developed and the amount of heat so developed is proportional to the total energy expended in the conductor. This energy is proportional to the product of two factors, the strength of the current and the difference of potential, or the voltage, between the extremities of the conductor, necessary to maintain the current. So, the heat developed is proportional to amperes multiplied by volts (1 ampere multiplied by 1 volt = 1 watt). It was not very long before men conceived the idea of using the heating effect of a current upon a conductor foi illuminating purposes, and patents based upon this principle were taken out. In 1858 Jobart proposed to make use of a small carbon rod in a vacuum. Moleyns of Cheltenham, took out a patent for a lamp which had a glowing platinum spiral upon which coal-dust was allowed to fall. In 1859 Du Moncel obtained very good results by experimenting with carbon filaments of cork, sheepskin, etc. Between the years 1877 and 1880 the incandescent glow lamp began to take practical form, and Edison in America and Swan in this country were independently working on similar lines. The first glow lamp constructed by Edison had platinum wire for the filament. Edison examined the properties of many organic and inorganic substances, with a view to finding the best substance for the filament. He fixed finally upon bamboo fibre.

Edison held the view that to give the carbon the highest possible resistance and the smallest tendency to disintegration, it should retain its structural character. Swan, on the other hand, maintained that the structure of the material should be entirely destroyed, and the carbon filament made as dense as possible. Long before Edison he tried to obtain more durable carbon filaments.

The filament of the Swan type lamp was made either direct from cotton thread, or from thread formed by squirting a solution of cellulose through a fine nozzle at high pressure, cellulose being the chief constituent of such vegetable substances as cotton, linen, paper, etc.

Early in 1900 experiments were renewed to obtain a satisfactory metal filament lamp in place of the carbon filament. About the year 1911, lamps were made with filaments of the metal tantalum. This metal was found unsatisfactory, mainly because it was not possible, owing to its low specific resistance, to make a lamp satisfactory for voltages in excess of about 125. In 1914 tantalum was superseded by tungsten. With this metal lamps for voltages of 230 to 250 could be made, and as the filament could be run at a temperature some 300 C. above that of the carbon filament, there resulted a great improvement in the efficiency, the consumption of the new lamp being just under one-half that of the carbon lamp. Of recent years the efficiency has been further improved by operating the filament in an inert gas (argon or nitrogen) instead of in vacuo. This enables the filament to be worked at even higher temperatures with a saving of about 15 per cent. in the consumption.

The Electric Motor

As early as 1830, that is before the results of the Faraday experiments on electromagnetic induction became known, various experimenters constructed apparatus which translated electricity from primary cells into mechanical work. In general, the apparatus consisted of a long straight bar of metal supported rather like the beam of a pair of scales. Attached to the beam on one side of the fulcrum was a fixed piece of iron, called the armature, which was influenced by an electromagnet fixed immediately underneath. At the end of the beam, on the other side of the fulcrum, was fitted a rod which acted as a pawl to a toothed wheel. The electromagnet in being energised from a battery attracted the armature which tilted the beam and so moved the wheel to the extent of one tooth. This movement actuated a switch in the battery circuit and the current being cut off, the lever reverted to its original position. This sequence then repeated itself, and so the axle, on which the toothed wheel was fixed, rotated. Other similar devices were constructed. In 1845 Froment constructed a machine which showed a great improvement. It consisted of two wheels mounted a short distance apart on the same axle, and at intervals around the periphery, soft iron bars were fastened, in line with the axle, the bars rigidly connecting the two wheels. Mounted on a framework which carried the axle were four pairs of electro-magnets so arranged that they would attract the soft iron bars on the wheel and bring about a continuous rotation. Current for energising the electromagnets was supplied from a battery and was periodically interiupted by a

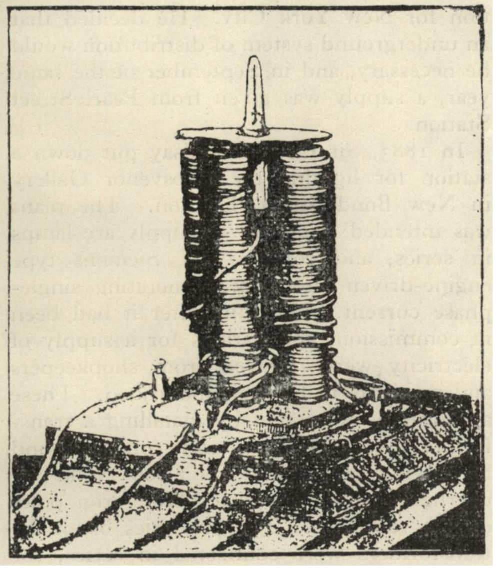

FIG. 4.—*Walter Bailey's machine.*

commutator attached to the axle of the wheel, the whole being so arranged that the two electromagnets which were being approached by the iron bars on the wheel, were energised in turn.

Various motors were constructed in which the reciprocating motion of an iron plunger inside a solenoid was made to transmit motion, in much the same way that the motion of a piston in the cylinder of a steam engine is utilised.

A great advance was made in 1860 when Pacinotti invented the ring armature which, it will be remembered, was improved and used by Gramme in the construction of his dynamo. Notwithstanding, Pacinotti built a small model machine in 1860 which he called an electromagnetic machine. He failed, however, to bring it to such perfection as to enable its adoption for practical use.

In 1867 Siemens observed the reversibility of the dynamo. If the armature of a dynamo electric machine be made to rotate, as does the ring of a Gramme machine, currents are produced in the coils of the ring which may be utilised for the excitation of the electromagnets, and for giving a supply to the external circuit. If the process be reversed, i.e. if the terminals of the machine are connected to a source of electricity supply, the electromagnets will be excited and current will also flow in the armature. The magnetism produced by the armature coils will be affected by the fixed electromagnets, the armature will revolve, and continue to do so as long as current flows through the coils of the machine.

A public experiment in the transmission of power by electricity and its conversion into mechanical power was made during the Exhibition at Vienna in 1873. A Gramme machine, with permanent horse-shoe magnets, driven by a steam engine was used as a generator, and current was conveyed to a similar machine about 500 yards distant. The second machine operated as a motor and worked a pump.

When considering the alternating-current motor, the solution is not quite so simple, particularly with regard to single phase currents, because with the rapid reversals of the current the armature conductors would be pulled alternately in one direction and then in the other, with the result that no movement would take place.

As early as 1824, Arago observed that when a copper disc is made to rotate in its own plane, and a magnetic needle is placed over it, the needle turns round in the same direction as the disc. A part of the field from the magnetic needle passed through the copper disc, which, on being rotated cut the magnetic lines and thereby induced currents in the copper.

In 1879, Walter Bailey showed how Arago's rotation could be produced by a number of electromagnets acting on a copper disc. Below a pivoted disc he arranged four electromagnets with their vertical axes equidistant from the centre. The magnets were excited by currents from a battery, and a commutator was used for alternately reversing the polarity. By causing the current to be reversed rapidly, the effect of a rotating field was produced. (Fig. 4.)

On this principle the modern alternating-current induction motor is constructed. A rotating field is produced by winding on the fixed part of the machine coils displaced at 90° or 120° apart, to which either a two-phase or three-phase supply is connected. The rotating magnetic field so produced induces currents in the winding on the rotating part or rotor.

LECTURE II—*Delivered on April 27th*, 1942

EARLY ELECTRIC SUPPLY INSTALLATIONS

In the first lecture reference was made to some of the early installations of arc lamps for lighthouse work and for street lighting. As these lamps were not suitable for interior use, progress in the field of electric lighting generally was hampered; and so, investigators then sought to "divide the electric light." This problem was solved in 1878 by making use of incandescent glow lamps, connected in parallel. This made possible the electric lighting of domestic premises and the interiors of public buildings.

Many installations using Swan lamps were soon in being; among them was the lighting of the Savoy Theatre, London, in 1881. The current was obtained from Siemens alternating current generators. In the same year a small generating station was installed and operated by Siemens Bros. & Co. at Godalming in Surrey. The power was developed by making use of a waterfall on the River Wey. Certain streets were lit by both arc and incandescent lamps, which were connected to cables laid along the street gutters. As there seemed to be no prospect of a demand for electric lighting by the householders in the district, the supply was discontinued in 1884.

At the end of the year 1881, Mr. Robert Hammond went to Brighton to stage an exhibition of the Brush arc lighting system in the town; this proved a success and resulted in the formation of the Hammond Electric Light Co., which, in February 1882, was giving supply to 16 arc lamps for illuminating the premises of certain shopkeepers. At the same time, the Company were offering to supply current to any prospective consumers.

In January, 1882, Edison's agent in London obtained the permission of the City authorities to undertake the lighting of Holborn Viaduct and some of the neighbouring streets by means of Edison incandescent lamps. Steam driven dynamos generating at 110 volts were installed in a building near the east end of the Viaduct, and the main cables were laid along the existing subways. From these cables, services were taken to most of the premises on either side of the street. Soon afterwards the supply was extended to the General Post Office in Newgate Street. It was provided in the agreement between the two parties that the Viaduct and the streets were to be lighted, free of cost to the City, for a period of three months. The supply was commenced in April and, at the end of the three months' trial, fresh agreements were made and the service continued until 1886, when the station was shut down.

In 1882, Edison planned his first installation for New York City. He decided that an underground system of distribution would be necessary, and in September of the same year, a supply was given from Pearl Street Station.

In 1883, Sir Coutts Lindsay put down a station for lighting the Grosvenor Gallery in New Bond Street, London. The plant was intended originally to supply arc lamps in series, and consisted of Siemens type engine-driven alternators generating single-phase current. Not long after it had been in commission, applications for a supply of electricity were received from shopkeepers and residents in the neighbourhood. These applications were met by installing a transformer in the house of each consumer and by giving a supply at 2,000 volts by overhead cables, supported from iron poles on the roof tops. The primaries of all the transformers were connected in series, the consumers' lamps being connected to the secondary. The demand from outside consumers continued to grow, and so a larger station was constructed and further overhead cables and transformers were installed, as before, with their primaries in series, an arrangement suggested by Gaulard and Gibbs. Trouble was soon experienced with this arrangement, and S. Z. de Ferranti, then a young man, was called in to advise. He entered the service of the Grosvenor Gallery Co. and one of the first things that he did was to replace the series transformers by others designed to operate in parallel across the mains and so introduced a method which remains to this day. He replaced the Siemens alternators by others of his own type. Later, a new company, called the London Electric Supply Co., was formed to take over the Grosvenor Gallery station, and progress was made. Subsequently, a power station was built at Deptford for the purpose of sending current at high voltage to London. Ferranti, who was responsible for the installation, chose 10,000 volts for the transmission. He designed and built the cable and the transformer for stepping up the voltage for transmission and for stepping down again at the receiving end. By laying the cables underground along the railway track between London and Deptford, he was able to avoid certain provisions of the Electric Lighting Acts.

Electric Lighting Act

In August, 1882, the first Electric Lighting Act was passed by the House of Commons. This Act conferred powers on municipal

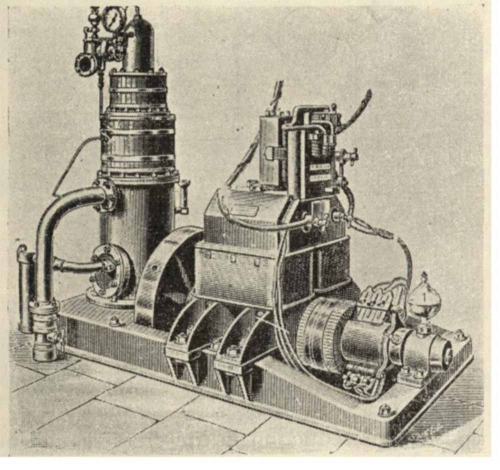

Fig. 5.—50-*kilowatt steam-generating set.*

and other undertakers to break open streets for the purpose of laying mains, and gave powers to local authorities to raise loans in connection with the supply of electricity. The Act provided that application for the necessary Provisional Orders or Licences to supply were to be made to the Board of Trade. It also empowered the local authority, at the end of 21 years, to purchase the undertakings of the enterprising supply company, or so much of it as lay within the jurisdiction of the authority, without having to pay anything for the goodwill or increase in the value of the undertaking. The onerous character of the purchase clause produced universal dissatisfaction and this was reflected in the very few applications that were made to the Board of Trade.

The development in the supply of electricity, however, was not altogether held up, because wherever a company could obtain permission of the local authority to erect mains overhead, it could carry on its business without reference to the Act. This was done by the Hammond Electric Light Co. at Brighton in 1882, the Grosvenor Gallery Co., London in 1883, and at other places. At Hastings and Eastbourne, cables were laid in the streets with the assent of the local authorities, without reference to the Act. The Kensington Court Electric Light Co. started by Colonel R. E. Crompton, was able to carry on without regard to the conditions of the Act by obtaining permission of the Kensington Court Co. to lay mains in the subways that existed under the roadways. Fig. 5 illustrates a 50-kilowatt steam-generating set of the type installed by Colonel Crompton.

In the meantime, efforts were being made by influential people to obtain the repeal of the 21 years' purchase clause. Ultimately, and due mainly to the efforts of Lord Thurlow, an Act was passed in 1888 which, amongst other provisions, extended the period of security to the companies from 21 to 42 years. The effect of this concession was immediate and manifested itself in the promotion of new companies and applications for the necessary powers to supply electricity in various areas.

Public Supply

Godalming may claim to be the first place in which a public supply was given, although Holborn Viaduct was the first place in which a supply was given for both public lighting and for private houses. Both of these installations, however, existed for only a few years.

If consideration be given only to those undertakings which have had a continuous existence, then priority should be given to Brighton. At first, the supply, which was provided by a special type of dynamo capable of delivering direct current at a high voltage, was used for arc lighting only. All the arc lamps supplied by any one machine were connected in series so that the same current flowed through each lamp. Soon, however, Mr. Wright, the station engineer, devised a scheme for supplying incandescent lamps from the arc circuits. The supply was given by overhead conductors and the system continued until 1887, when it was changed over to single-phase alternating current, generated at 1,800 volts, and reduced to 100 volts for the consumers by means of local transformers.

Subsequently, a further change was made, in 1891, when the Municipal Authority started a system of direct current supply at 115 volts. Following the completion of arrangements for the purchase of the original undertaking, the consumers were transferred to the mains of the Corporation.

D.C. Systems

In most of the earlier methods of distribution a direct current supply was given and, because the incandescent lamps then available were constructed for a pressure not exceeding 100 volts, the operating voltage of the system was limited to that pressure. The initial step was to run one or more pairs of main cables, radiating from the generating station, and to tap-off from these wires two conductors to form a branch at the point where the supply was needed. Across these branch wires were connected the lamps or other consuming devices. With this arrangement, the supply to each branch was independent of the rest, but, with a common main and separate branches a fluctuation of voltage was introduced, owing to alterations of current flowing in the main cables. In addition, a voltage drop would occur proportional to the current density and the length of mains. One way to reduce this drop would be to increase the cross-sectional area of the conductors, but this would mean increased capital expenditure, apart from the difficulties involved in making the change. A less expensive method would be to instal, in the first instance, mains tapered in section. In other words, the section of the conductor which, at the generating station end would be the maximum, would be reduced by joining on mains of a somewhat less cross section, and, as the distance from the station end increased, conductors of a still smaller section would be joined. This method had the disadvantage that the conductor at its smallest section would form a path of high resistance were it ever necessary to connect the ends of two pairs of radial mains for the purpose of feeding back, in the event of a fault on a main near the station.

The introduction of incandescent lamps capable of operating at 200 to 220 volts was a useful step forward, because it enabled distribution on the two-wire principle to be carried out at double the pressure, and with half the current for the same power required.

Three-Wire Distribution

In 1882, long before the advent of the 200 volts incandescent lamp, Dr. John Hopkinson invented a three-wire method of working ,and in the same year this method was invented, independently, by Edison in America. In its original application, the use of the third wire was obtained by coupling together two similar dynamos in series, the positive and the negative cables being connected to the outer terminals of the set, while the third or middle wire was connected to the junction of the two inner terminals (see Fig. 6). If each dynamo were capable of generating current at 100 volts, then the pressure between each outer and the middle wire would be 100 volts, and there would be 200 volts between the two outer wires. With this arrangement there are the advantages of working at an increased voltage, with the

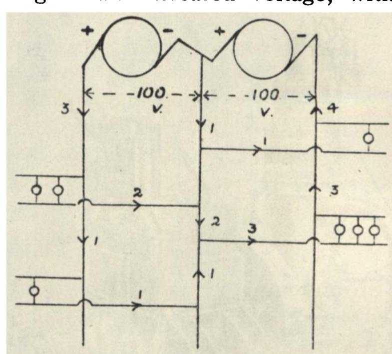

Fig. 6.—*Diagram of direct-current three-wire method.*

consequent reduction in the cross section of the cables, and still retaining the low voltage lamps. If an equal number of 100 volt lamps, all of the same rating, are connected between each of the outers and the middle wire, then no current flows back through the middle wire to the generators ; but there is certain to be some condition of loading when there are more on one side than the other. If the load on the positive side is greater than that on the negative side, the difference between the two currents will flow along the middle wire back to the dynamo on the positive side ; a similar effect would take place if the greater load was connected to the negative side. Since there is current flowing through the middle wire only when there is an inequality or unbalance of load, it is usual in practice to make its cross sectional area not more than one-half of what either of the two outers may be, although in some instances a cross section equal to one-quarter of that of an outer main has been used. The connection of consumers is carried out in such a manner as to secure as perfect a balance or equality of load on the two sides of the middle wire as possible. Ordinarily, consecutive consumers would be connected alternately across the positive and the negative sides, two-wire service being used. But for large consumers a three-wire service would be used, the consumers' wiring would be divided into two independent circuits, as nearly equal as possible, one of the circuits being connected between the positive and the middle wire, and the other between the negative and the middle wire.

Five-wire Distribution

The next development was the introduction at Manchester, in 1893, of the five-wire distribution network with 400 volts between the outers. The distributors would consist of five wires, one of them being the equivalent of the middle wire in the three-wire system. Service connections could be made on either side of the middle wire to give 100 or 200 volts. A connection across the extreme outers would give the full 400 volts. This system operated for some years in Paris, and for perhaps a lesser period in Manchester. It was a system which gave great flexibility of distribution, but it was also complicated and great care was necessary for its operation and maintenance.

A.C. Systems

Whilst many of the supply engineers had been developing the direct-current system of distribution, others were putting in networks for alternating-current working. The pioneer system of alternating supply consisted in running several independent alternators, each driven by its own engine, the distribution being usually effected by a number of high-pressure mains, from which branches, or services, were tapped off to feed small transformers fixed on consumers premises. This system was adopted in 1889 by the House-to-House Electric Light Co., Ltd., later to become the Brompton & Kensington Electricity Supply Co., Ltd. Single-phase current was supplied at 2,000 volts and transformed down at the consumers premises to 100 volts. A similar system was used at other places where the primary voltage was 1,000. As the system involved a large capital outlay in small and inefficient transformers, it soon gave way to one in which a low-pressure network was fed by larger transformers installed in substations scattered about the district.

Three-wire A.C. Distribution

A three-wire alternating-current supply can be given from two similar transformers, if their primaries are both fed from the same source and their secondaries are connected in series. The third or middle wire would be connected to the junction between the two secondaries whilst the outer conductors would be connected to the two remaining terminals of the combination. The same remarks with regard to balancing the load applies as to the direct-current system. About the year 1899 a few 2-phase systems were being installed. In general the method was to instal two groups of single-phase transformers in a substation, and to feed the primaries of one group from one phase of a high-voltage two-phase supply, and to feed the primaries of the other group from the second phase.

The low voltage mains, consisting of two conductors, were connected to the secondary of the transformers and formed separate single-phase circuits to which the consumers' wires were connected. To maintain, as nearly as possible, a balanced load on the complete two-phase system it was usual to connect successive houses to alternate phases. The introduction of the two-phase system provided means for the development of a more satisfactory motor. If, therefore, in a district in which a single-phase supply had been originally installed, there arose a considerable demand for motive power, the change from single-phase to two-phase could be effected without replacing any of the original mains. A saving in conductor material can be effected by suitably interconnecting the two primaries and/or the two secondaries of the transformers and so require three instead of four wires for the distribution. As the third or common wire need only be about one and a half times the cross section of either of the outers, the total weight of conductor material is reduced to 85 per cent. of the original amount.

Three-phase four-wire Distribution

Early in 1900 the three-phase four-wire method of distribution was being installed for new supply areas and in many instances it has replaced existing networks originally put down to operate with three wires direct current. In this method the three line wires are connected to one end of the three secondary windings of a three-phase transformer, the opposite ends of the same three windings being connected together; this forms what is called the star connection. The fourth wire is connected to the star point, and, together with the three line wires, forms a four-wire circuit from which a supply is given to the consumers (see Fig. 7). The voltage between any one of the three-phase wires and the fourth, or neutral wire, is arranged to correspond with the normal lamp voltage, usually 230 volts, whilst the voltage between any two of the phase wires would be $\sqrt{3}$ times this value, namely 400. (This can be verified by drawing two lines of equal length with an angle of 120° between them and measuring the length of a line which would form the third side of the triangle.)

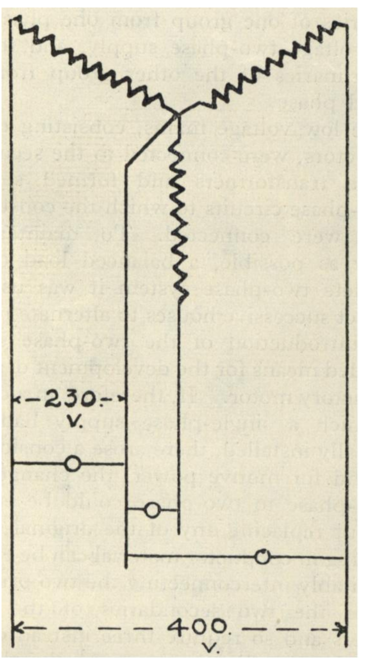

FIG. 7.—*Diagram of 3-phase four-wire method.*

All service wires to domestic premises for lighting would be connected between one of the phase wires and the neutral wire, but for three-phase motors the three phase wires only are required. For large premises with a good deal of lighting installed, all four wires are taken into the building and the lighting circuits are divided into three so that the total load may be balanced over the three phases.

THE BATTLE OF THE SYSTEMS

By the time electricity was being used for distribution to the public both the direct-current and the alternating-current systems had been demonstrated, at least so far as the single-phase current was concerned, and naturally there were strong advocates for each system. Pioneers like Ferranti, Gordon and Mordey ranged themselves on the side of the alternating-current system, while men of equal importance such as Crompton, Hopkinson and Kennedy, supported the claims of the direct-current system. And so for many years this difference of opinion existed as to the merits of the rival forms of current. Alternating and direct current gave equally good results for incandescent lighting; for arc lighting the direct current formed a crater in the positive carbon which had the effect of directing most of the light downwards, but where arc lamps were used for lighting railway goods yards or docksides, the alternating-current arc was no doubt better suited, because with both carbons pointed most of the light was directed out horizontally and so gave general illumination over a wider area.

Direct current was more suitable for driving motors as at that time no satisfactory single-phase motor was available. The possibility of using storage batteries to supply the night load and so save running the generators throughout the 24 hours of the day, was a point in favour of the direct current.

The transmission pressures adopted for the Oxford system in 1896-7, when direct current at 2,000 volts was transmitted to substations where it was reduced by motor-dynamo sets to a lower voltage for the consumers, showed the possibility of developing high voltage direct current. Another drawback to the alternating current was the difficulty of running alternators in parallel ; a difficulty which, however, was soon to be overcome. By 1903, there were large generating stations situated outside the centre of cities, from which three-phase current at high voltages was being transmitted to substations for transformation and distribution at lower voltage. The advantages of static transformers as compared with the rotating machines necessary for giving a direct-current supply was being recognised. To meet the objection to rotating machinery in substations, the mercury arc rectifier was developed and quite a number of direct-current networks were kept in service by the installation of rectifiers fed by high voltage alternating-current feeders from remote generating stations. Although it cannot be said definitely that the battle of the systems has been won, there is every evidence of an increasing use of alternating current for distributing networks.

Conductors

In selecting a material for an electrical conductor, consideration should be given to its resistance to the flow of current in order that as little energy as possible would be lost in transmitting from the source to the point of utilisation. Of the metals, silver and copper offer the lower resistances, there being about 7 per cent. difference between them, which is in favour of silver. Copper being the more commercial metal was adopted as the most satisfactory material for the purpose.

For the insulation of the conductors, the electric lighting engineers were able to make use of the experience of the telegraph engineers, who for many years before, had put cables both underground and undersea. Materials such as cotton, jute, rubber and gutta-percha were available. Rubber and gutta-percha seemed the most promising, but both are to some extent unstable, particularly gutta-percha which is readily oxidised and had to be protected from the air. For underwater telegraph cables it proved satisfactory, but it was not considered to any extent for electric light conductors. The early overhead cables used by the Grosvenor Gallery Co. consisted of 19/15 stranded copper cable insulated with rubber and braid suspended by leather thongs from 7/16 steel cables which were supported by iron poles mounted on the house tops. A similar arrangement was adopted by the Hampstead Electric Supply Co., the largest cable supported in this way being a 37/12 rubber covered and braided. Later, when supply undertakings were empowered to break open streets for the purpose of laying mains, the practice of supporting cables over the house tops was discontinued.

In recent years, aluminium wires, in combination with steel wires to form a compound conductor, have been used extensively for overhead lines erected on poles of wood, concrete or steel, to give a supply of electricity in rural areas. The steel wires which form the core of the conductor adds materially to the strength and permits the use of longer spans between supports.

Underground Cables

Aluminium has also been used to a small extent for underground cables, but its resistance is so much greater than that of copper that for equal conductivity an aluminium conductor would be approximately one-quarter greater in diameter than a copper conductor. There is also the problem of jointing which is made difficult by the material being so readily oxidised.

The forms taken by the cable, its insulation and the methods of laying underground are so varied and numerous, that it may be of interest to refer to some of them. In the early days of distribution Edison worked out a very complete scheme in which the conductors were copper rods of segmental cross section. These rods were placed in wrought-iron tubes filled with insulating material, and having on the outside tarred ribbons wrapped round them to prevent the oxidation of the iron. To hold the copper rods in position perforated paste-boards were arranged at intervals. These conducting tubes were manufactured in lengths of 20 feet. The copper rods protruded about 2 inches from the ends of the tube, and were connected by means of a U-shaped piece, so as to allow for expansion and contraction of the metals; the whole joint was then covered by a cast-iron split box filled with insulating material. The tubes were made in seven sizes from 1 inch to $3\frac{1}{8}$ inches dia., and the cross section of the copper ranged from ·0248 to 1·287 square inches. (See Fig. 8.)

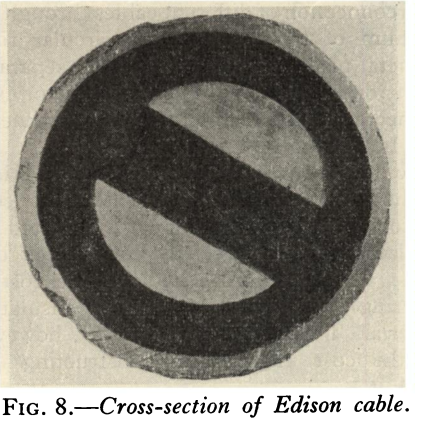

FIG. 8.—*Cross-section of Edison cable.*

Edison made use of the tapered main in distribution; he arranged for the cross section of the conductor to diminish with the distance from the generator.

To make a T joint or service connection, a few inches of the tube and conductors would be cut out and specially T shaped connectors would be inserted to make the connection to the conductors of a similar tube. The completed joint would then be protected by a split T cover and afterwards filled with insulating matter.

For a three-wire system, the D shaped conductor was replaced by copper rods of circular cross section. Three rods were both kept apart and also bound into a bundle by long spirals of jute rope. The bundle of rods was placed in an iron tube, and insulating material run in, which was liquid whilst hot, but solidified in cooling. The tubes were made in convenient lengths, and the conductors in successive lengths were joined together by short pieces of flexible copper cable inside special junction boxes.

For feeding points Edison devised a large cast-iron junction box which permitted the interconnection of different cables through the medium of three substantial circular rings of metal placed vertically over, but separated from one another. Each conductor was connected to one of the three rings by means of a bolted lug.

For low pressure distribution various methods were devised in which the conductors were of bare copper supported on insulators laid in specially constructed culverts. These methods avoided the cost of covering the conductor with insulating material. This expense was offset, however, by the cost incurred in constructing the conduit.

A culvert specially constructed by the Compagnie Edison of Paris, in connection with the lighting of the boulevards, was built of concrete and covered with slabs of the same material; it was 30 inches wide, 14½ inches high and placed under the pavement at a depth which gave 6 inches from the top of the cover to the surface of the footwalk. Stranded conductors, which were of silicium bronze rested on porcelain insulators secured to the floor of the culvert and placed about 6 feet apart.

Crompton devised a culvert system, but in place of stranded conductors, he used flat strips of copper laid on top of one another until the required cross section was obtained. These strips were pulled up taut and supported on glass insulators. This system was used in Kensington and Notting Hill, London, and at many places in the provinces, on direct current systems. Until quite recently, the installation at Notting Hill was in service.

The St. James's and Pall Mall Electric Light Co. used cast-iron culverts in place of concrete. Each length of culvert, 3 ft. 6 in. long, consisted of two parts, a lower part or trough, and a cover which is bolted to the former, the joint being packed with yarn and red lead. The trough was 10 inches wide and 6 inches deep, and the separate lengths were connected by binding pieces 5 inches wide, the joint being run with lead for the trough, but packed with red lead and yarn for the covers. The joint boxes were built of brick with cast-iron frames and covers. The conductors, which consisted of copper strip on edge, were supported on glazed earthenware insulators. Services consisted of vulcanised rubber cable drawn into gas piping.

About the same time that the Crompton strip method was invented, Callenders introduced a method of laying underground insulated cables in troughing, and then filling up with bitumen. The nature of the troughing varied from time to time. At first, it was of cast-iron, and later installations using wood, and in some instances, sheet-iron, were put down. The cables rested on bridges so that the compound could flow completely round them.

Ferranti Cable

An event of historic importance was the production of a paper insulated cable for 10,000 volts working made by Ferranti at Deptford in 1890. It was made in lengths of 10 to 16 feet. The insulation was of brown paper rolled on (not taped) and impregnated. The inner conductor consisted of a copper tube on which was rolled the paper. This was then inserted in another copper tube as an easy fit and the tube drawn down until it was tight on the paper and all air excluded. This also was insulated, inserted in an iron tube which was drawn down in similar manner.

The joints were made by cutting back the outer iron pipe and the outer copper tube and tapering the insulation with a special tool. The inside of the inner conductor tube was reamed out to correct size for a solid copper rod or plug that was forced into the two ends to be joined by a hydraulic press which drew the two together. Insulation was then applied and a short length of copper tube previously slipped along the outer conductor from which a portion of the insulation had been removed, was slid into position bridging the gap between the two ends to be joined. This tube was then squeezed down at several points on to the conductor by means of a rotary wheel press similar to a pipe cutter but with rollers in place of cutters.

The outer insulation was then added and the joint in the iron pipe made in a manner similar to that for the outer copper tube. The joint was completed by filling up any space there may have been under the iron by pouring in melted compound through a small hole and sealing up.

A cable made in this way was very rigid, and until some other way of putting on the paper and the outer protective coating was devised, a flexible paper-insulated cable could not be made.

Shortly after Ferranti's experiment at Deptford, cables insulated with narrow strips of paper, saturated in a resin compound and covered with a lead sheath, were being made in America. These were probably the first flexible paper insulated cables. The system was adopted and further developed in this country. In 1890–91, lead-covered cables insulated with jute, rubber, bitumen or paper were being used.

In his Cantor Lectures given to the Society of Arts in 1892, Professor George Forbes, F.R.S., referred to a system of mains, which he had described at the meeting of the British Association in Manchester in 1877—" It consisted of cast iron pipes through which are run bare copper tubes. The copper tubes, which are supported on porcelain insulators may be first used as the conductors alone, and when the demand increases, bare wires can be drawn through the tubes. In the figure which is more or less diagrammatic, the method of making a house connection is shown, iron tubes being tapped into the side of the pipe, through which the house mains are led and soldered to the outside of the copper tubes only, the inner wire conductors being left untouched."

In 1898, Mr. J. S. Highfield invented a cable which was intended to enable service connections to be made whilst the cable was alive, in anticipation of electric cooking.

For use on a three-wire system, the cable would consist of two conductors of segmental cross section having a dovetail groove running along the crown of the segment, and a third conductor in the form of a deep double-headed rail with a dovetail groove running along one of the heads. The conductors are bedded in prepared wood, within a steel pipe. Each length of pipe has three holes drilled opposite the grooves in the conductors; these holes are plugged. In making a connection, two plugs are removed for a two-wire service, and in the holes is screwed a short tube containing within it a connecting piece which is split at its end and has a wedge inserted in the split. This end is driven into the dovetail groove of the conductor, the wedge expanding it so that it takes firm hold in the dovetail. The service connections may be made to the piece in any suitable way. About two miles of this main was laid at St. Helens about 1898.

About the year 1894, lead covered cables were being made with the steel armouring put on over the lead. This permitted the cables to be laid direct in the ground and so dispense with the use of pipes or conduits. Cables were soon made in various forms to suit the needs of the different systems of supply. The triple concentric, and the three-core cables were used for three-wire systems and the four-core cable suited the requirements of the three-phase four-wire system.

LECTURE III.—*Delivered on May 4th*, 1942

DISTRIBUTION AT CONSTANT CURRENT

Electricity may be distributed either at constant current or at constant voltage. With constant current all the consuming apparatus are in series with one another and with the generators; the breakdown of any one of the consuming devices results in the interruption of the service. Special arrangements must be provided for by-passing the faulty device so as to maintain continuity of supply. As the current remains constant, an increase of power at any point is possible only by raising the voltage. The system has been used for the lighting of street lamps in series, in which direction it found its greatest, and perhaps only, development on the side of distribution. A constant-current high-voltage series system for transmission, as devised by Thury, has been in operation for some years in France and Switzerland. One installation was put down in this county by Mr. J. S. Highfield for the Metropolitan Electric Supply Co., Ltd., in 1910. The cable was designed to work at 100 amperes, with increasing voltages up to 100,000. An electrostatic machine was specially constructed for testing the cable at 100,000 volts after it had been installed. The machine, together with the small motor for driving it, was enclosed in a steel casing in which the air was maintained at a pressure of 100 pounds per square inch.

This pioneer system was in operation until 1924, when it was replaced by an extra high voltage three-phase system.

Distribution at Constant Voltage

In general, the distribution of electricity is carried out at constant voltage. In this system all consuming devices are connected in parallel across the supply mains. Thus each device is independent of the other, and the failure of one piece of apparatus does not interfere with the supply to its neighbour, since each device—such as lamps, motors, heating apparatus and cooking appliances, etc.—is designed to be operated at a definite voltage. The supply engineer is required to maintain, as nearly as possible, a constant voltage at the consumer's terminals, the current being the variable quantity.

Regulations Affecting Distribution

The principal provisions regarding the mains and distribution networks of undertakings supplying electrical energy to the public are contained in the Regulations of the Board of Trade and the Electricity Commissioners under the Electricity (Supply) Acts of 1882 to 1926. They provide for the means to be taken to secure the safety of the public, and an efficient supply of electrical energy.

Before commencing to supply, the standard pressure on the distributing mains must be fixed by the undertaking and public notice given of the figure decided upon. The limiting condition affecting the design of the distributing system is that the variation of pressure at the consumer's terminals may not exceed 4 per cent. from the declared constant pressure at which the undertaking has stated the supply would be given. With alternating current systems, the frequency of supply must also be declared and the variation of frequency may not exceed 2½ per cent. from that figure.

Principles of Distribution

One of the important principles of distribution which has to be considered is the location of the generating station or main source of supply, relative to the distributing network.

For preference the station would be placed in the centre of the demand for supply, thereby keeping all the mains as short as possible; in this way the losses would be reduced to a minimum. Unfortunately, as a rule, stations cannot be located in this way owing to commercial considerations which are of the first importance. Another essential matter is the efficiency of the system. This necessitates the utmost use being made of the copper in the distributing network. Continuity of supply is also of great importance, and this requires that the maximum current densities be kept low enough to prevent overheating of the cables and connections. Pressure regulation must also be borne in mind, and the system must be designed so that the pressure at any consumer's terminals should not vary beyond the limits fixed by the regulations.

The Distributing Network

A main is any electric line laid down in any street or other place, through which electrical energy is supplied. A distributor is a main which is used to give origin to the services of the consumer. The distributing network consists of mains arranged in the form of a network from which services can be taken to give supply to premises in a number of adjoining streets. In the past, many of the smaller generating stations fed directly into the network through feeders, or cables, which conveyed current from the station to selected points in the network. Without this arrangement of feeders the consumers nearest the station would be getting the generated voltage, whilst consumers remote from the station would be receiving a much lower voltage due to the loss in mains. Networks of this type were usually supplied with direct current by the three-wire method with voltages not exceeding 460 across the outers for motors, and 230 between outer and middle for the ordinary domestic lighting and heating circuits. Naturally the first networks to be put down were for the purpose of supplying electricity to cities or urban towns as offering the best chance of making the greatest use of the network, and thereby obtaining a good return for the capital invested.

The engineers who put down the original low-voltage networks were faced with the problem of estimating the consumer loads, the growth of the demand, and the possible change in character of the district itself. To instal insufficient copper would result in the necessity of opening the streets in a short time in order to replace the distributor cables with others of a larger cross section, and to remake all the service connections. Apart from this there would be an interruption of supply to several consumers whilst the work was in progress. On the other hand, to put in an excess of copper was considered by some to be the right course to adopt so as to provide for unseen development.

Although the problem is readily amenable to mathematical treatment, little can be gained by such investigation, as the engineer has to meet the conditions he finds in practice and cannot create such as would enable him to utilise his theoretical deductions.

In addition to the uniformly distributed load assumed for shop and domestic lighting, allowance had to be made for heavier concentrated demands, such as hotels, factories, office blocks, etc. In order that a fault, which might occur on a distributor, or on a consumer's service, should cause as little dislocation of supply as possible, a number of network fused disconnecting boxes provided with light fuses were inserted at selected points. Should a fault develop at any one point, the fuses would blow in the network boxes on either side of the faulty section. Careful consideration had to be given in selecting the points at which to insert these boxes. The best positions were those at which normally no current would flow—called nodal points. In a network in which the load demand shifted, due possibly to the connection of a large hotel, the nodal points also shifted with the result that in some of the network boxes current was normally flowing through the fuses, and not in others. In this way, fuses were often blown, on the occasion of a fault, in boxes which should not have been affected.

In cities and large towns, the cables for the three-wire direct-current networks were usually of the concentric and triple concentric type, although later, three-core cables were used. They were drawn into earthenware ducts, fibre conduit, or iron pipes laid just beneath the footway with draw pits for pulling in the cables at suitable intervals. In some instances a small brick chamber with a surface cover was provided in the run of the pipes or ducts, opposite the dividing line between each pair of houses or shops, in readiness for making the service connections. In this way little obstruction was caused in the streets when service connections were being made, or when it became necessary to change a length of distributor for one of a larger section. Fig. 9 shows a method of making a two-wire service from a three-core cable.

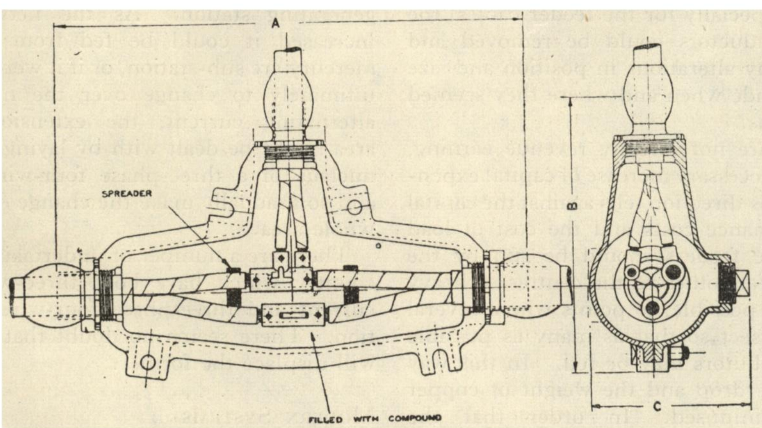

FIG. 9.—*Method of making a two-wire service from a three-core cable.*

In urban and country towns the cables were laid generally on the solid system devised by Callender. When properly laid, this method affords to the conductor perfect protection against mechanical damage, chemical action and other troubles, including those caused by vermin. It is also free from one of the great drawbacks of the culvert and the draw-in system, namely, the danger of accumulations of an explosive mixture of gasses, or water in the spaces surrounding the conductors. Compared with the draw-in system, it has the disadvantage that should it become necessary to remove the conductor, this would involve the opening up of the street and the breaking up of the mass of bitumen protecting material around the cables. Further, with this system it is not possible to lay down additional cables without breaking up the street.

In rural districts where the growth of the load develops more slowly, and the opening of the ground causes little or no obstruction, the armoured cable originally introduced by Siemens, is very much used. Over the lead covering of the cable, an armouring of steel tape or steel wires is provided which gives mechanical protection, and this permits of the cable being laid direct in the ground without any other form of protection except, perhaps, a warning board or tile laid above it to draw the attention of any workman who may be engaged in opening he street in the vicinity of the cable.

Feeding Points

When a distributing system is first projected, it is usually possible to fix upon likely feeding points to which the feeders might be connected. As the load demand increased, other feeders could be installed and put into use, and, if necessary, the first selected feeding points discarded and others substituted to meet the new requirements. Of course, with a system of mains laid either solid in bitumen or direct in the ground changes of this sort were more or less out of the question. With a draw-in system, however, especially for the feeder cables, the original conductors could be removed and relaid, or any alterations in position and size of cables made when and where they seemed advantageous.

Feeders are not directly revenue earning, and any unnecessary increase of capital expenditure in this direction tells against the capital and maintenance costs and the cost of load losses. The feeders should be run by the shortest street routes to the centres of heavy load and, if possible, to points where several streets intersect so that as many as possible of the distributors may be fed. In this way the pressure drop and the weight of copper can be minimised. In order that the engineer in charge of the system might know the pressure at the feeding points, it was usual to run underground with the feeder a pair of small wires called pilots. These wires were connected at the feeding point and gave indications on a voltmeter at the generating station.

As the load increased and the area of supply extended, necessitating the laying of additional feeder cables from the station, engineers began to find it difficult in some of the older direct current systems, fed directly by radial feeders from the station, to find space in the ground for the cables. The crowding together of a large number of cables at one point reduced their current-carrying capacity owing to the heating effect of adjacent conductors. As the area of supply continued to expand the current density of the cables had to be reduced in order to keep the pressure within the permissible limits. The whole network had to be interconnected either through fuse or link boxes, in order to make use of all available copper, with the result that the development of a fault on any portion sometimes caused network fuses to be blown at points far removed from the fault.

Where a supply of alternating current could be obtained in bulk in place of the small local generating station, an existing three-wire direct current network might be improved in efficiency and regulation by installing mercury arc rectifiers at selected points of the network. The rectifiers might be placed in small sub-station buildings to which a supply could be taken at high voltage three-phase alternating current. After rectification, the supply could be delivered to the network by short radial feeders, the copper for which could be recovered from the original feeders that gave supply from the generating station. As the network area increased it could be fed from a further mercury arc sub-station, or if it were intended ultimately to change over the network to alternating current, the extension of the area might be dealt with by laying down the nucleus of a three-phase four-wire system, and so gradually make the change over of the whole area.

There are a number of undertakings in this country which have both three-wire direct current and three-phase four-wire distribution. There seems no doubt that the latter will displace the former.

Modern Systems

Although in the past there have been many different voltages and frequencies in the various undertakings of this country, there is now, followng the passing of the Electricity (Supply) Act, 1926, a standardisation of voltage and frequency for new systems. The standard declared voltages measured at consumer's terminals are: (*a*) For direct current, 230 volts, with 460 volts across the outer conductors of a three-wire system; (*b*) for alternating current three-phase systems, 400 volts between phases, and for a four-wire system, 230 volts between the neutral wire and each of the principal conductors.

The standard of frequency is 50 cycles per second. (It is interesting to note that in America, the frequency adopted is 60 cycles per second, and the voltage most favoured is 110, both for A.C. and D.C.)

For the three-phase four-wire network, the four-core cable is universally adopted, and, although in theory the fourth, or neutral, wire would only be required to carry the unbalanced current and, therefore, could be of a smaller cross section than the principal conductors, it is usually made of equal section, that is, all four conductors are of the same size. This makes a more symmetrical cable ; moreover, as it helps to reduce the voltage drop due to unbalanced load, the small additional cost is justified. The outer layer of paper on the individual cores of three- and four-core cables are usually of a different colour to act as a distinguishing mark for the jointer when he opens up the distributor cable for the purpose of making a service connection.

The three-phase four-wire system has the most advantages for the distribution network. It provides in one and the same cable for domestic lighting and heating at 230 volts, and for three-phase motors for industrial purposes. It is as economical in copper as any other method of supply and further, alternating current is more flexible due to the ease of transformation from one voltage to another. It seems, therefore, that this method will be adopted for all new networks.

In urban districts and small provincial towns where the character of the streets and premises does not change so rapidly as in large cities or industrial towns, the network could be designed to operate from comparatively small transformers in kiosks placed in selected parts of the network. To prevent radical changes in the sizes of the distributors or the disturbance of the streets as the character of the demand alters, it would be advisable to put down initially distributors all of one cross section, and as the load centres shift, additional transformers could be installed in new positions. The size of conductor to be put down in the first instance could be determined only from an estimate of the kilowatt demand per yard of street, or in terms of a given area. For the distribution in large cities the problem of providing the necessary amount of copper in densely loaded streets was becoming very acute. To lay down a low voltage network, capable of meeting the demands of such large business premises as are to be found in Oxford Street, London, and similar streets in provincial cities, and which would at the same time serve the much smaller business and residential houses in the immediate surroundings, would be enormously expensive, if not impossible.

The problem is solved by providing transformers in the basement of the large stores premises, and by feeding them from a high voltage main. The voltage is reduced by these transformers to give a supply to the stores and to feed on to a low voltage network outside for supplying the smaller premises. An extension of this system would be to lay down over the whole area of the city a low voltage network, and to feed into this from either grouped or distributed transformers situated at the more densely loaded points. An additional network of high voltage cables would give supply to the transformers from one or more high voltage sub-stations.

In order to make the most economical use of the copper in the mains, advantage must be taken of the diversity of load requirements at different times by the relative consumers. To do this, the low voltage network should be coupled up either solid through links, or semi-solid through network fuses. The coupling of a very large network as a whole, however, would be unwise and even dangerous, because, in the event of a serious cable fault, the whole of the transformer capacity would be available for feeding into it. This would mean that a large amount of power would have to be interrupted by switches incapable of performing this operation, and the dislocation of supply to the whole area.

SOLID NETWORK

The basis of the solid network system is to divide the area into a number of smaller areas, and to feed each of these through one or more transformers supplied from a high voltage

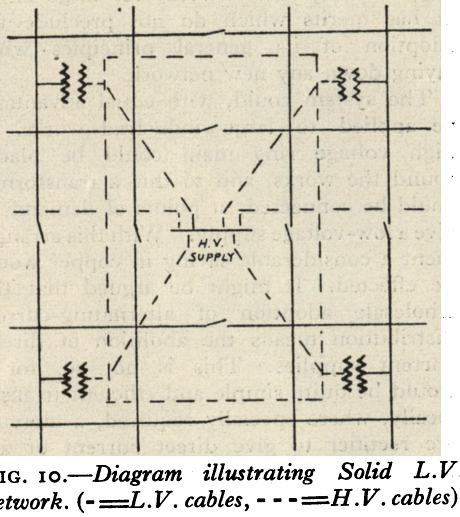

FIG. 10.—*Diagram illustrating Solid L.V. network.* (-=*L.V. cables*, - - -=*H.V. cables*).

network (shown diagrammatically in Fig. 10). The transformers may be grouped in one place or they may be distributed. With the latter arrangement a better regulation of pressure is obtained and some saving effected in copper.

Almost every large city has already a network of mains so that, in preparing a scheme of the solid network type, it would be possible to make some use of the existing material, such as cable ducts, draw pits, service pipes and the like. In general, the low voltage cables would be laid direct in the ground as they need not be disturbed except for making new services. The same remarks would, at least for some considerable time, apply to the high voltage feeders, because increased demand would be met by running new high voltage feeders to a new point.

A reasonable size of low-voltage cable for a city area would be 0·25 square inches cross section. For the high-voltage cables, which might operate at 6,600 volts in the first instance, a cross section of 0·15 square inches might be used.

If ducts were provided for the feeder cables it would be a simple matter to change an existing cable for one of larger section, or even to run cables for a higher voltage; this, of course, would mean also the changing of the transformers.

Developments on these lines have been made in this country, America and Germany. The method is receiving a good deal of attention just now by distribution engineers, particularly with reference to the standardisation of design of networks for large cities. It has merits which do not preclude the adoption of its general principles when laying down any new network.

The system could, with equal advantage, be applied to large industrial works. A high voltage ring main could be placed round the works, and to this a transformer could be connected, at points of demand, to give a low-voltage supply. With this arrangement a considerable saving in copper would be effected. It might be argued that this wholesale adoption of alternating-current distribution means the abolition of direct-current supplies. This is not so, for it would be quite simple and efficient to instal locally, where specially required, a mercury arc rectifier to give direct current of any convenient voltage and power.

RURAL SUPPLY

For rural supplies, current is conveyed by conductors of copper, aluminium or by compound conductors of steel and aluminium wires (Fig. 11). These lines are supported for span lengths up to about 450 feet by wood, steel or concrete poles; for larger spans lattice steel structures are used. The overhead lines, unlike underground cables, are not restricted to highways; they are more often than not taken across country. In this way distribution to isolated villages is given without the heavy capital expenditure of underground systems.

Depending on the amount of the load demand and the extent of the district over which supply is to be given, the voltage of these overhead lines varies from 3,300 to 33,000. The lines are operated at three-phase alternating current. Near the point

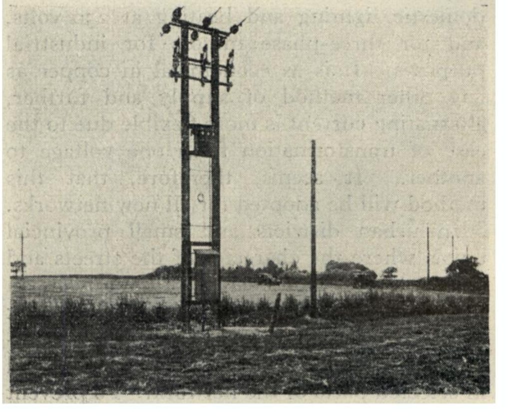

FIG 11.—*Overhead line showing pole mounted transformer.*

of demand, if this be small, a small transformer is fixed to the supporting structure from which a low-voltage supply is fed by a short length of underground cable or, alternatively, overhead wires, to the consumers. Where the demand is much greater, the transformer is placed in a weatherproof kiosk which contains also the necessary high-voltage switch (Fig. 12). The connection between the overhead line and the transformer is made by a cable which is led down the terminal support. As before, the low-voltage distribution may be effected by an underground cable or, alternatively, a low-voltage overhead line, depending on the configuration of the load centres.

CONCLUSIONS

With regard to future development, it would seem that higher voltages will be used for distribution both for overhead and underground supplies, but no change of voltage at the consumer's premises, however, can be contemplated. The high efficiency transformers now available with their increased reliability, and the reliability of modern cables make for added security and continuity of supply.

A possible line of improvement is the solid low-voltage network with its associated high-voltage distribution transformers, but some further experience is required with this method. It is felt by some engineers that fuses are not required in the low-voltage network; others think that, with an improved type of fuse, the network should be fused, as were the older networks. This and many other technical points require investigation

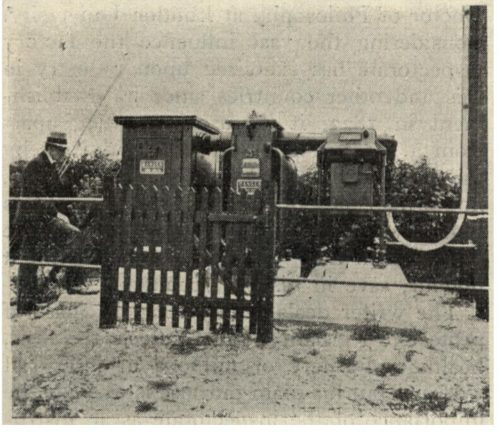

FIG. 12.—*Outdoor transformer and switch kiosk.*

before its characteristics and general suitability can be determined.

There seems no doubt that for densely loaded cities, with large blocks of offices, stores, buildings and flat dwellings, distribution is moving towards the practice of installing large transformers fed from a high-voltage network to supply one or more blocks of buildings. In this way, low-voltage networks requiring cables of large cross section will tend to become smaller.

With regard to cable development, the oil-filled principle has been established, but more recent developments have been in connection with various forms of the gas-pressure type. These types are concerned with the higher voltages, but the necessity for finding alternative materials has led to a considerable development in the use of plastic insulation for lower voltage cables, and this may well foreshadow widespread changes in the future.

ACKNOWLEDGMENTS

The author expresses his thanks to the following firms for the loan of lantern slides or specimens. The British Thomson-Houston Co. Ltd.; Crompton Parkinson Ltd.; the Chloride Electrical Storage Co. Ltd.; Siemens Brothers & Co. Ltd.; the Pirelli-General Cable Works Ltd; also to Phillip Kemp, Esq., Head of the Electrical Department of the Regent Street Polytechnic, for the loan of lantern slides; to J. W. Leach, Esq., Engineer-in-Chief of the Central London Electricity Company; to H. Gurney Wood, Esq., for specimen of the Edison cable and interesting information; to M. C. Timms, Esq., and J. T. Hazell, Esq., for early reminiscences; and to the *Electrical Times* Publishing Company for historical notes.

OBITUARY

SIR SAXTON W. ARMSTRONG NOBLE, Bart., M.INST.C.E., F.S.A., who died on October 12th at the age of 79, had been a Fellow since 1909—the year in which his father, the late Sir Andrew Noble, Bart., K.C.B., D.SC., D.C.L., F.R.S., was awarded the Albert Medal of the Society.

Educated at Winchester, Noble joined the Board of Directors of Sir W. G. Armstrong Whitworth & Co., Ltd., in 1915, and later became Managing Director of this concern and a Director of the Mond Nickel and Whitehead Torpedo Companies. He was also a Director of the Royal Academy of Music, a connoisseur of Russian ballet, and the possessor of a fine collection of pictures and Chinese jade.

MEETINGS OF THE SOCIETY BEFORE CHRISTMAS

ORDINARY MEETINGS

Wednesdays, at 1.45 p.m.

NOVEMBER 4.—Inaugural Address by the President of the Society, and Chairman of the Examinations Committee, Sir Edward Crowe, K.C.M.G., "EXAMINATIONS and 'THE ROYAL SOCIETY FOR THE ENCOURAGEMENT OF ARTS, MANUFACTURES AND COMMERCE'."

NOVEMBER 11.—"AGRICULTURE TO-DAY AND TO-MORROW": (1) "EFFICIENCY AND OUTPUT IN AGRICULTURAL SYSTEMS." By Professor A. W. Ashby, M.A., Professor and Adviser in Agricultural Economics,