THE THREE PHASE GENERATION, TRANSMISSION, AND CONVERSION SYSTEM OF THE SYDNEY ELECTRIC TRAMWAYS.

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Introductory.

On July 11th, 1900, a paper was read before the Society by Mr. Brearley, describing the Sydney Electric Tramway system as it then existed, and in that paper mention was made of the proposal to extend the power-house for the purpose of installing additional machinery of a different type to that then in use, and the purpose of this paper is to briefly describe the new system which has now been in operation for about two years.

A description of the A.C. system is quite sufficient for the scope of this paper, and it is therefore not proposed to treat of any of the other parts of the tramway system, the direct current feeder system, the overhead line, track and return circuits, car and motor equipments, which do not differ materially, except in degree, from those described in Mr. Brearley's paper.

It is necessary, however, to say a few words as to the growth of the Sydney tramway system, and to indicate why its growth and extension rendered advisable a departure from the system of power supply then in use, in which the whole of the power was generated and transmitted at the potential at which it is used on the trolley wire, viz., 600 volts.

At that time there were operated electrically ten miles fifty-four chains of double track, and nine miles fifteen chains of single track; there were about 100 motor cars in service, and the greatest distance of transmission from Ultimo power house was about five and a quarter miles. These figures have now been increased to forty-six miles of double track and twenty-eight miles of single track, on which are running 500 cars, the power for which is, in some cases, transmitted eight miles and over.

In the Ultimo power house extension, alternating current is generated at 6,600 volts, twenty-five cycles three-phase, and is transmitted thence, through underground cables, to five substations, and there transformed and converted to 600 volts direct current for distribution to the trolley wire.

It is proposed now to indicate briefly and in general terms why it should have appeared advisable to extend the plant in this way rather than by adding new direct current generators, and thus saving the capital cost and operating expenses of the high tension feeders and the substations. The proper choice of a system for any tramway or railway will not be discussed, but it is merely intended to show why such a system as the one to be described becomes more economical than the old D.C. system as the system expands.

As you are all aware, when current is transmitted through a conductor offering any resistance, a certain amount of energy is lost in heat, the loss varying as the square of the current and as the resistance; and as for a given quantity of energy the current varies inversely as the voltage, it follows that the loss in transmitting a given quantity of energy varies inversely as the voltage at which it is transmitted, so that, as far as efficiency of transmission is concerned it pays to transmit at high voltages.

The energy lost in the cables with a given current, depending as it does upon the resistance, may be decreased by increasing the sectional area; and, consequently, the cost of the cables employed; and it may easily be shown that the most economical sectional area of the copper to be employed to transmit a given current is that for which the annual cost of the energy wasted in the cables is equal to the interest on the capital invested in the cables.

Thus, given the rate of interest to be paid on the capital invested, the value of the unit of energy, and the load factor of the line to be fed, it is possible to determine the most economical current density to be employed quite irrespective of the distance of transmission and of the voltage.

The economical current density being thus fixed, the amount of copper required can be obtained, and it will be found that at distances over a few miles it becomes necessary, if current be transmitted at 600 volts, to increase the amount of copper beyond that required by economy, in order to keep the drop in voltage within proper limits, and this fact indicates that, at such distances, the voltages chosen is not the most economical.

Inasmuch, however, as the voltage of the direct current motors in use on the cars has already been fixed at 600, it becomes necessary if the power be transmitted at a high voltage to lower it to 600 volts before it is distributed to the trolly wire.

This necessity forces us to introduce a substation where the lowering operation can be performed; and the interest on the first cost of the transmission line, the substation, and its apparatus and the shortened 600 volt feeders, togther with their operating expenses, and the annual value of the energy lost in transmission, conversion, and distribution, is to be balanced against the interest on the cost of the longer 600 volt feeders, and the annual value of the energy lost in them, on the low tension system.

The exact distance at which it becomes cheaper to introduce such substations depends on a variety of circumstances, and is therefore diffiult to determine accurately, especially with a tramway load; but where the traffic is so heavy that return feeders and boosters are required to keep the drop along the rail within the limits imposed in England by the Board of Trade, and in Australia by the Postal authorities, it may be stated that generally it does not pay here to transmit any considerable current at 600 volts beyond four miles.

The simplicity and economy of the alternating current transformer as a means of transforming from high to low voltage, or vice versa, renders advisable in such cases the use of alternating currents; while, for conversion, three-phase apparatus is simpler and more economical than two-phase for reasons which need not be detailed here. Except where it is necessary to have a close control of the voltage of different machines, or of different parts of the system, rotary converters are preferable to motor generators as being cheaper, more efficient, and having fewer parts to maintain. The use of rotary converters forces the adoption of a low frequency as commutator and other troubles are inherent in converters of high frequency, delivering direct current at 600 volts, and so the standard frequency of twenty-five cycles was adopted.

It may be asked why a still higher voltage was not preferred, but a little consideration on the lines of the foregoing discussion will show that there is no advantage in increasing the voltage beyond a determinable limit, especially as the cost of the insulation of the cables and apparatus increases rapidly as the voltage is raised. The standard voltage of 6,600 was therefore adopted.

As the particular object of this paper is to describe the electrical portion of the system, only a very brief description of the steam plant will be attempted.

The extension to the power house comprises the addition of a length of 170 feet to both the engine and boiler rooms, the old and new rooms being continuous in each case. The moving of the coal and ashes is all done by machinery, the coal being delivered from the trucks into a crusher, where it is reduced to three-inch gauge; it then passes by a bucket elevator at the rate of forty tons per hour into the bunkers above the upper boiler room, where a storage capacity of 2,500 tons is provided, this being equivalent to about a fortnight's consumption for the two plants at the present time.

From these bunkers the coal passes through chutes into the hoppers of the B. and W. chain grate stokers; the ashes are finally removed by the same conveyor as elevated the coal, and are by it elevated to a steel tower outside the building, and delivered thence to the trucks. The crusher and conveyor are worked by electric motors.

Natural draft is provided by two chimneys, each 227 feet high, and having an internal diameter of about eleven feet. The new boilers so far installed are thirty-two of the Babcock and

Wilcox water tube type and make. They are each of 250 nominal horse-power, working at a pressure of 160lb., and are furnished with the B. and W. chain grate stokers, which are operated by a small vertical engine.

The feed water is passed through two feed water heaters, each having a heating surface of 1,200 square feet, heated by the exhaust from the auxiliaries. The feed pumps are steam driven.

The three main engines so far installed are vertical cross compound, of the Allis-Reynolds type, with Corliss valve gear. They operate at a speed of seventy-five revolutions per minute, and each is capable of developing 2,300 horse-power with an overload capacity of 50 per cent. for three hours.

The diameters of the high and low pressure cylinders are thirty-two inches and sixty-four inches respectively, and the stroke is sixty inches.

The generators, which are direct-coupled to the engines, and placed between the two cranks, are of the fly-wheel-field type; that is to say, the fly-wheel forms an integral part of the generator, the forty field poles being bolted on to the outside of the rim of the fly-wheel, which revolves within the external fixed armature.

The total weight of the fly-wheel and field poles is 215,000lb. These generators are each capable of delivering continuously 1,500 kilowatts three-phase at 6,600 volts, with a temperature rise not exceeding thirty-five degrees C., and will carry an overload of twenty-five per cent. for two hours, with a temperature rise not exceeding fifty degrees C. The size of 1,500 kilowatts was chosen as being the largest standard size, which could be conveniently erected at this distance from the manufacturers. The armature frame is of cast-iron, while the core is built up of laminated sheet-iron punchings fourteen mils. thick, slotted on the inside to receive the coils, and furnished on the outside with dovetailed projections, by which they are attached to the frame. The frame is made up in six pieces for ease in erection, and the whole frame is so mounted that it can be moved parallel to the shaft clear of the fields to permit of inspection and repairs of both armature and field.

The armature coils, which are wound of pressed cable ·4 inches square, were not placed in the armature till after their arrival in Sydney, where they were again baked. The armature when wound and connected up had to withstand a high potential test of 15,000 volts effective for one minute, so that the insulation between the coils and core has to be very good. To ensure this the coils when wound, and in addition to the insulation put on during the winding, are covered with nine separate layers of linen tape, ·007 inch thick, wound with a half lap, and each layer is varnished six times and baked after each coating of varnish.

The coils were placed in the six portions of the armature before erection, with the exception of those few coils which lie partly in one portion and partly in another.

The field poles are built up of sheet-iron punchings, while the coils consist of copper strip one inch x one-eighth inch, wound on edge on an insulating frame, the insulation between each turn consisting of a single thickness of red paper, while the edges of the strip are left bare. The resistance of the field is about half an ohm. The exciting current, which at full non-inductive load is about 200 amperes, is led into the fields through carbon brushes, working on the cast-iron slip rings mounted on the shaft close to the hub of the fly-wheel.

The two exciters are six-pole compound wound machines, each giving 800 amperes at 125 volts. They are direct coupled to Harrison tandem compound self-oiling engines, running at a speed of 270 revolutions per minute. Each exciter is capable of supplying the exciting current of the three generators, and, in addition, is used to supply current for the lighting in the power house.

The cables from the machines to the switchboard are lead-covered paper-insulated cables, laid in ducts beneath the floor of the basement. The generator cables are three core, and the exciter and field leads single core.

The switchboard, which is thirty-nine feet long, is mounted on a gallery, fifty-four feet long by nineteen feet wide, raised about twelve feet above the floor of the engine-room, and consists of the following sixteen panels of blue Vermont marble:—

Three exciter panels.
One exciter summation panel.
Six generator panels.
One summation panel.
Five feeder panels.

The generator panels and main summation panel are ninety inches high by thirty-six inches wide by two inches thick, the remaining panels being twenty-four inches wide.

About three feet behind the panels is a series of brick chambers lined with opalite, and having iron doors in front and soapstone slabs on top. Each of these chambers or cells contains one pole of the high-tension oil switches, one switch being provided for each of the six generators it is proposed to erect, and one for each of the five pairs of high-tension feeders so far in use. There are two breaks in each pole, and the contacts are enclosed in a can filled with oil, the whole being bolted to the back of the cell, and operated by a system of bell-cranks and rods passing down beneath the floor of the gallery, and up behind the panels to the handles mounted thereon. One of the rods is of wood, so that the handle is safely insulated from the high potentiol current on the switch.

The oil used to prevent arcing in these switches is a heavy mineral oil, with a high flashing point, and, as far as experience goes, it preserves for years its property of preventing arcs.

Above the cells is an iron framework, on which are mounted the potential and current transformers to the secondaries of which the instruments, meters and relays, mounted on the panels, are connected. As the ironwork and the secondaries of all these transformers are earthed, there is no danger of the operators receiving a shock off any of the gear on the marble panels, which indeed contain no circuits having a potential exceeding 125 volts. Above, but to the back of the brick cells, are three compartments formed by four soap-stone shelves or barriers, running the full length of the board. These contain the three high-tension bus-bars of bare copper, which are mounted on large glass insulators placed in a vertical piece of soap-stone, forming the back of the compartments. The leads from the switches are brought up through the top of the cells, and thence pass through the glass insulators to the bus-bars. The leads from the other sides of the switches are brought out through porcelain insulators in the back of the cells into the disconnecting boxes and brass bells hereinafter described.

It is not proposed to particularise the instruments mounted on panels, consisting as they do of the usual ammeters, voltmeters, indicating and recording watt-meters, the latter measuring the output of each generator, and the energy supplied to the various substations. For synchronising purposes a voltmeter and a lamp are mounted on a pivoted bracket above the centre of the board, and can be connected to any generator it is desired to synchronise by means of a plug switch on the generator panel. It is proposed, however, to replace this synchronising apparatus by one of the modern types of rotary synchroscopes, which give a more exact definition of the proper instant at which the generator should be connected to the bus-bars.

To give the switchboard attendant control of the speed of the engine, either during synchronising or for dividing the load, a small series motor is geared to the sliding weight on the expansion governor, and is controlled by the switchboard attendant by means of a switch on the corresponding generator panel.

Two lamps, one red and the other green, are mounted on each of the generator and feeder panels, one indicating when the corresponding oil switch is open, and the other when it is closed. Overload relays are provided in the feeder circuits to open the switch automatically should the current passing through it exceed a safe limit. These are worked as follows:—The secondary of a current transformer, the primary of which is inserted in the circuit it is desired to govern, is connected to a small magnet coil, through which a soft iron plunger, normally suspended below the coil, is free to move. When under the action of a heavy current this plunger moves up into the coil, it operates a small switch, which closes a circuit from the 125 volt bus-bars, through a magnet coil fixed to the frame of the oil switch. The keeper of this magnet is connected to the switch levers in such a way that its movement releases the catch which keeps the switch closed against the action of gravity. The switch handles are so constructed that the switch is free to open, if the relay is working, even while the handle is held in the closed position, so that the attendant cannot keep the switch closed under a short circuit or severe overload.

Reverse current relays are provided on the generator switches.

Beneath the floor of the switchboard gallery are suspended the field rheostats of the generators, their switches being worked by bevel gearing from the hand wheels mounted on the panels.

The lightning or surge arresters, referred to later, are also mounted below the gallery in a series of marble chambers.

The machine and feeder cables, which pass in ducts beneath the floor of the basement, are brought up to the underside of the gallery, through large rectangular cable uptakes, consisting of sheet-iron mounted on an angle iron framework. The cables are from these distributed under the floor of the gallery, and brought separately through the floor through porcelain insulators, into the cable standards and bells referred to later. Above the switchboard is suspended a canopy of corrugated iron to protect the apparatus from moisture which may condense inside the roof or leak through during rain storms. An electrically-operated crane, capable of lifting thirty tons, spans the engine-room.

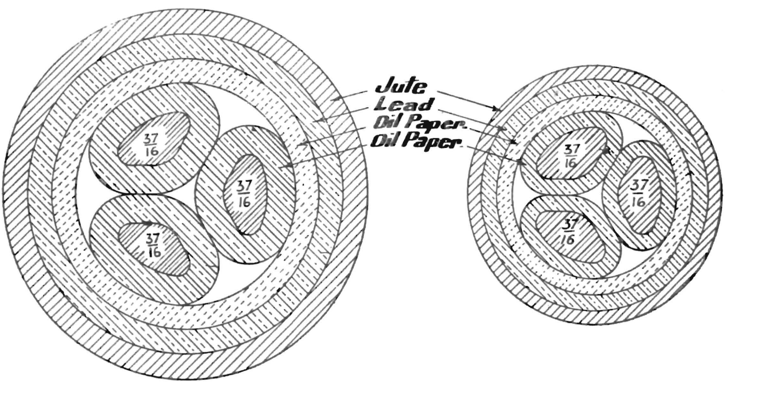
Space and the necessary foundations have been provided for three more similar generating units and one more exciter.

Between the power house, and each substation, two high tension cables are laid underground, the approximate lengths of the respective routes being as follows:—

	Yards.
Ultimo power house to City substation	3,200
Ultimo power house to Newtown substations	4,050
Ultimo power house to Waverley substation	5,500
Ultimo power house to Randwick substation	6,000
Ultimo power house to North Sydney substation	7,000

eight hundred yards of the last length being submarine.

The cables, which were manufactured and laid by the British Insulated Wire Company, are three core paper insulated lead-covered cables of the clover leaf type, the cross section being shown in the drawing. Each core consists of nineteen strands, and



— Sydney Cable — — British Standard —

has a sectional area of about ·12 square inch. The insulating material consists of paper impregnated with oil, and is seven-sixteenth inch thick between cores, and between each core and the lead sheathing which is three-sixteenth inch, in thickness. The sheathing is protected from mechanical injury by a layer of impregnated jute.

The cables are laid underground on what is known as the solid laid system, enclosed in a hardwood trough filled in with an insulating compound having the following composition:—Stockholm tar, 1·29 gallons; dark resin, one cwt.; sand, one cwt. All the cables following the same route are placed in the same troughing, the cross section of which varies in accordance with the number of cables it contains.

The sides and bottom of the troughing are formed of one inch planks, and the cover of one and a half inch planking, the whole being fastened together by means of two and a half inch wood screws, with one inch cover pieces three feet long.

The trench is taken out to such a depth as to give a covering of about two feet, though this is necessarily varied to pass under or over pipes, sewers and other obstacles. The troughing being placed in the trench, a layer of about half inch of the compound is run in hot, and when this is partially set, wooden bridges are set two feet six inches apart, and in these bridges the cables are supported. The troughing is then filled with compound, and while this is still hot the cover is screwed on, and a layer of bricks placed on top to afford some protection against picks and gads.

The cables are supplied on drums in lengths of about 200 yards, and it is necessary to join up the lengths, so as to make not only the cores, but the lead sheathing, continuous from end to end.

The cores are united by means of a married joint, and thoroughly insulated with white linen tape boiled in resin oil, sheets of mica being inserted between the last few layers, of which there are about sixteen wound with a half lap. All cores thus insulated are bound together, and the whole again suitably insulated, after which a four-inch sleeve is placed round the joint, and wiped on to the lead sheathing at either end. The sleeve is then filled with hot resin oil through a small opening, which is finally closed with a lead cap and soldered over.

The submarine cables between Dawes Point and Blue's Point differ from the land cables by the addition of a layer of steel armouring between the lead sheathing and the jute serving. Some difficulty was experienced in finding a suitable joint to withstand the pressure of the water at the great depth at which the cables lie.

The connection between the submarine and the land cables is made in an underground cast-iron junction box, with interior partitions of earthenware, provision being made for readily separating the submarine from the land section, and also for cross-connecting one submarine cable with the second shore cable, or vice versa. These boxes are filled with resin oil, and covered with a water-tight cast-iron cover, securely bolted down.