(*Paper No. 3090.*)

# "Dublin Electric Tramway."

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The Dublin Electric Tramway, which was constructed for a service of twenty-five motor- and twenty-five trailer-cars, extends for about 8 miles along the south shore of Dublin Bay, Fig. 1, Plate 3.

*Preliminary.*—In the distribution of power to electric tramway systems in the United Kingdom, the Board of Trade Regulations [1] require that the negative terminal of the generator shall be connected with the rails or metallic return, and with two earth connections having such contact with the general mass of the earth that a difference of potential not exceeding 4 volts shall produce a current of at least 2 amperes from one earth contact to the other. The earth return must [2] also be so constructed that the current between these earth connections and the negative terminal of the generator shall not at any time exceed 2 amperes per mile of single line, or 5 per cent. of the total output of the station. The entire current must thus return along the rails or supplementary conductors attached to them; and the general use of the earth as a return circuit is practically debarred. Further, the difference of potential between the points of the uninsulated return furthest from and nearest to the generating station may not at any time exceed 7 volts. The distance to which current can be supplied direct by the ordinary system of distribution, or the amount of current that may be supplied to a tramway system at any one point is therefore limited. For example, in an average case of a double tramway line with 76-lb. to 80-lb. rails, bonded so that the joints do not appreciably increase the resistance, and with the ordinary service of about two cars per mile, each car

[1] "Regulations made by the Board of Trade . . . for regulating the employment of insulated returns, or of uninsulated metallic returns of low resistance; . . . ." London, 1897. Clause 5.

[2] *Ibid*, Clause 6.

consuming on an average about 1 Board of Trade unit per mile, the distance of transmission direct from the generating station is, under these regulations, with the rails as the return circuit, limited to between 3 miles and 4 miles. Beyond this distance of transmission, it is generally advisable either to have additional generating stations or to have substations, receiving their power from the primary generating station by a suitable transmission. The last method was adopted as the more economical, in that the duplication of staff is avoided, and increased economy is gained in a single station owing to the use of larger units and a more uniform load.

The 3-phase method of transmission was used because the cost for a given output of single-phase machines is somewhat higher and their efficiency somewhat lower than those of 3-phase machines. Further, with other conditions the same, a 3-phase line requires only three-quarters the weight of copper of either a single-phase alternating or continuous-current system.

For the purpose of calculating the difference of potential in the rails, it was assumed that the average consumption of energy per motor-car, with trailer-car, would be $1\frac{1}{4}$ Board of Trade unit per car-mile at a speed of 8 miles per hour, or that each car, with a trailer, would require an average current of 21 amperes at 500 volts. The Board of Trade Regulations require[1] that the maximum fall of potential shall not exceed 7 volts, and to allow for overlapping of loads, such as is liable to occur in a system of twenty-five cars, it was assumed that the maximum would exceed the average by 50 per cent., and that the average fall in the earth return should not exceed 5 volts. If all the current had been delivered direct to the line at Ballsbridge, the average fall would have amounted to approximately 14 volts, provided the rails were bonded so that the bonds did not increase the resistance beyond that of a solid rail. This fall might reasonably be expected to attain to 21 volts as a maximum; the conductivity of the rails being equal approximately to that of a copper conductor 6 square inches in section. To reduce this fall within the Board of Trade limits would require a copper conductor, or its equivalent, some 12 square inches in cross section, running from end to end of the line, the cost of which would be prohibitive. The cost of feeders for the overhead system would also be considerable. The

[1] "Regulations made by the Board of Trade . . . for regulating the employment of insulated returns, or of uninsulated metallic returns of low resistance; . . ." London, 1897. Clause 7.

only satisfactory alternative was to transmit the power to points over the line and transform it by suitable means for local supply.

In all the calculations as to the fall of potential in the rails it was assumed that 0000 Chicago Bonds with $\frac{7}{8}$-inch terminals would be used. These bonds were 30 inches in length, and in the four lines the contact surface amounted to 6·85 square inches. On the basis of 50 amperes per square inch as a safe limit, it was computed that 350 amperes could be taken through the rails at any point without deterioration of the contact surfaces. On this basis it was determined that the bonding would increase the electrical resistance of the line 60 per cent. beyond the figure arrived at on the supposition that the rail was continuous. The total resistance, therefore, of a four-railed line would amount to about 0·016 ohm per mile. The conductivity of the fish-plates was uncertain, and it was deemed an error on the safe side to consider that they would not contribute to the conductivity of the line.

It was convenient to express the consumption of current in terms of the length of the route, the constant being taken in the present system at 1 ampere per 79 feet of line, or an average of 67 amperes per mile. It follows under average conditions that the average fall of potential per mile of line would be 0·6 volt. When the load is concentrated at one end of a mile section the fall is doubled. The fall between any two points on a line with a given headway between cars increases with the square of the distance. Thus, for 1 mile the average is 0·54 volt and 1·07 volt with concentrated load, for 2 miles it is 2·16 volts and 4·32 volts, for 3 miles 4·8 volts and 9·6 volts, which exceeds the limit for a concentrated load of above value.

The distance from Ballsbridge to Blackrock is 18,150 feet, and Blackrock to Dalkey Station 19,900 feet, Fig. 2, Plate 3. At those two points the substations are situated. A single substation at Kingstown, about two-thirds the distance from Ballsbridge to Dalkey, would have answered the purpose of the two substations; but the tramway company desired to avoid purchasing new premises, and also to have the substations in the existing car-sheds so as to avoid duplicating staff as far as possible.

In deciding on the amount of power to be distributed at Blackrock and Dalkey, the Ballsbridge Station (which feeds current at 500 volts direct into the line) was designed to supply current to as great a portion of the distance from Blackrock as possible, having regard to the Board of Trade Regulations. Between the other two stations the power was made proportional to the extent of the line which it was to supply. Thus the average current delivered into the line at Ballsbridge towards Blackrock was 115 amperes, from Blackrock towards Ballsbridge the average current was 115 amperes, from Blackrock to Dalkey 126 amperes, and from Dalkey towards Blackrock 126 amperes; under which conditions it is found that the difference of potential in the earth return on the average amounts to 1·33 volt in the Ballsbridge and Blackrock section and about 1·81 volt in the Blackrock and Dalkey section. This is smaller than necessary, and smaller than would be inferred from the resistance of the rails; but, with the substations so placed, there would have been no appreciable saving in bonds by increasing the drop in the earth return.

*Generating Plant.*—The arrangement of the generating plant is shown in Fig. 3, Plate 3. The engine-house is 82 feet long by 32 feet wide, and contains four Willans compound condensing engines, each capable of giving 150 HP. continuously, and 175 HP. momentarily at a speed of 380 revolutions per minute with a steam-pressure of 140 lbs. per square inch. The generators are driven by belt from the fly-wheel, which was made unusually heavy and is supported by an outer bearing.

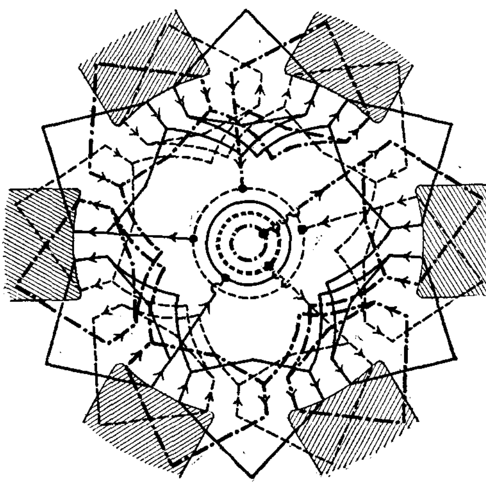
The two four-pole railway generators for feeding direct into the line at Ballsbridge are designed to give 100 kilowatts with 500 volts on the terminals at a speed of 650 revolutions per minute.

The two 3-phase generators have six poles, Figs. 4, and are of 150 kilowatts capacity, giving 2,500 volts between the collectors at a speed of 600 revolutions per minute, the periodicity being 30 per second. The armature structure consists of a cast-iron spider mounted, and keyed to the shaft. The core consists of iron sheets 0·014 inch thick, each sheet being a continuous ring. The spider is in two separate pieces, each keyed to the shaft, and bolted together so as to clamp the laminations forming the core, the laminas having a single key-way to keep them in line. The winding consists of copper coils formed and insulated, and laid in slots in the armature core, and secured against displacement by wooden wedges. There is one coil per pole-piece per phase, and the windings are Y connected, each giving 1,440 volts when run at the stated speed. The end windings and connections are supported and secured on cylindrical projections on each end of the armature. The magnetic densities in the machine are:—

| | Lines per Sq. Inch. |
|---|---|
| Teeth (full load) | 96,000 |
| Core, ,, ,, | 48,000 |
| Gap, ,, ,, | 45,500 |

The current density in the winding, at full load, is 1,300 amperes per square inch, and the temperature rise on the armature surface is 30° C. The arrangement of the spider and method of supporting the sheet-iron core is shown in Figs. 5, Plate 3, and a diagram of the winding is shown in *Fig. 6*. The field-magnet frame is of cast-iron, having inwardly projecting magnet cores of laminated iron cast into the yoke. The field-magnet coils are wound on separate spools, having a gun-metal flange, $\frac{3}{8}$ inch thick, for protecting the coils from armature reaction, and to dissipate the heat generated by the eddy currents. The yoke is divided on a diametral plane through the shaft to allow access to the armature. The collector-rings are mounted on a separate spider fixed to the shaft. The bearings are of the spherical type, and are self-oiling and self-aligning. The efficiency of these generators at full and half-load is 92 per cent. and 89·5 per cent. respectively.

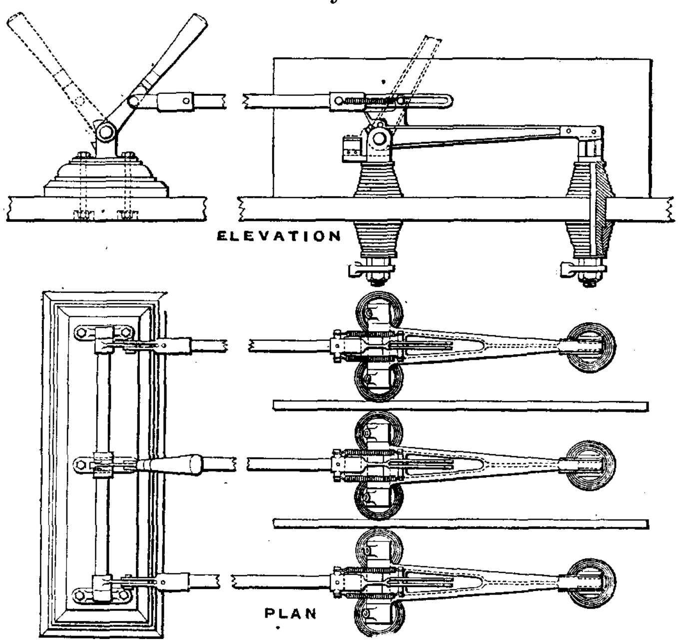
*Fig. 6.*



Since the opening of the line in May, 1896, the traffic has increased so largely, that at times sixty or seventy cars are required. To meet this increased load, a direct connected steam alternator, of 300 kilowatt capacity, has been installed at Ballsbridge. The engine is of the vertical cross compound side-crank type, and of the following principal dimensions:—

The diameters of the high- and low-pressure cylinders are 16 inches and 26 inches respectively, the stroke being 24 inches, and the speed 150 revolutions per minute. The initial steam-pressure is 160 lbs. per square inch. The economical load is at 0·38 cut-off, corresponding to 480 I.HP. non-condensing (the engine is generally worked condensing). A cut-off of 0·6 corresponds to 675 HP. The maximum cut-off is at 0·8 of the stroke. The total weight of the engine is 84,500 lbs., that of the fly-wheel, which is 11 feet in diameter, being 17,000 lbs. The bearings measure 10 inches by 20 inches. The regulation of the engine between no load and full load is within 2 per cent. The governor is of the shaft type, and the valves are of the grid-iron type. Such close regulation is found necessary in the case of multi-phase systems working rotary transformers. The generator has twenty-four poles and gives an output of 300 kilowatts, at 150 revolutions per minute. It is wound for 2,500 volts and 70 amperes per circuit. The armature is of the usual iron-clad type; the regulation is such that between full load and no load the increase of voltage is

*Figs. 8.*




Scale, $\frac{3}{4}$ inch = 1 foot.

somewhat less than 10 per cent. at constant excitation. The efficiency of the machine at full load is $94\frac{1}{2}$ per cent., and about $1\frac{1}{2}$ per cent. is required for excitation.

The main switchboard, Fig. 7, Plate 3, was placed at one end of the station and consists of seven panels, two for the 100-kilowatt 500-volt generators, two for the 3-phase machines, two for the two concentric 3-phase feeders, and a Board of Trade panel. The 3-phase panels are considerably longer than those for the 500-volt generators, to enable the high-tension switches to be placed out of reach; the three switches on each panel being simultaneously operated by three connecting-rods from a handle placed within convenient reach. Each direct-current generator panel carries an automatic circuit-breaker, with magnetic blow-out, a lightning-arrester, positive and negative quick-break switches, a field rheostat, a Weston ampere-meter, and a recording watt-meter, besides a pilot-lamp and volt-meter plug. The equalizing switches are mounted close to the machines. The bus-bars are permanently connected to the rails- and trolley-feeders. The necessary voltmeters are carried on brackets beside the board. Each 3-phase generator-panel carries the three simultaneously-operated switches, *Figs. 8*, three ampere-meters, one to each phase, a volt-meter connected to a small 25 to 1 transformer, synchronizing lamps, and a field rheostat. Three Ferranti oil-break fuses, one to each phase, are mounted on slate-shelves on the lower part of the board. The feeder-panels carry only the necessary 3-phase switches, which are similar in pattern to those on the generator-panels, and a single ampere-meter reading the current in one phase. The Board of Trade panel carries instruments necessary for recording the voltage at the remote ends of the rails, the current returning through the earth by the two earth-plates, and for making the various measurements stipulated in the Board of Trade Regulations.

The feed-pumps and stoker are actuated by railway motors, and the station is electrically lighted. A battery of fifty-five accumulators of 600 ampere-hours' capacity serves to light the station and to supply power to these when the main plant is not running. The cells are charged by a special 30-kilowatt motor-generator plant running at 1,000 revolutions per minute, consisting of two machines direct coupled on the same foundation-plate, one machine being wound for 500 volts, and the other for 100 volts to 140 volts. When the station is at work, the 500-volt machine takes current from the bus-bars and drives the low-voltage machine which charges the cells; the feed- and stoker-motors take current from the main bus-bars. When, however, the station is standing, the feed- and stoker-motors are operated from the 500-volt side of the motor-generator, the low-tension machine acting as motor with current supplied by the accumulators. A special switchboard is supplied for this motor-generator plant, having a high-tension panel carrying the switches for the high-tension side of the motor-generator, and for the station motors; and a second panel which carries all the switch-gear for the low-tension machine, with accumulator charge and discharge-switches, fuses, &c.

The boiler-house is 56·5 feet long, and 56 feet wide, and contains four Babcock-Wilcox water-tube boilers set in one battery. Each boiler has a heating-surface of 2,437 square feet, and grate-surface of 51 square feet, and develops 250 HP. They are constructed for a working pressure of 140 lbs. per square inch. The boilers are provided with Vicars mechanical stokers, worked from a shaft running in a trench in front of the boilers, and driven by a shunt-wound motor, worked from the 500-volt circuit, and regulated by a rheostat. The feed-water is heated by an economizer, consisting of one hundred and ninety-two tubes, arranged in two batteries. The tube-scrapers are driven by belt from the stoker shaft. The chimney shaft is 111 feet 8 inches high and 6 feet in diameter at top, and built of brick. The feed is obtained from three-throw plunger-pumps of $3\frac{1}{2}$ inches diameter and $5\frac{1}{2}$ inches stroke, each capable of delivering 1,600 lbs. of water per hour at 72 revolutions per minute. Railway motors are used for these pumps, and are fixed on brackets bolted to the pump base. An independent feed can also be obtained by injectors. The pipes are arranged so that the feed-water can be drawn either from a storage tank, from the town mains, or from the hot well of the condenser. The feed-water storage-tank is erected immediately above the pumps, Fig. 3, and holds 3,000 gallons. The feed delivery is arranged so as to form a duplicate system from the pumps to the boilers, either through the economiser, or direct into the boilers. The suction-pipes to the pumps have an inside diameter of $3\frac{1}{2}$ inches, and the delivery-pipes of 3 inches. The delivery range to the boilers is in the same trench as the stoker shaft in front of the boilers. The main steam-pipes are arranged on the ring principle, the diameter of the pipes being 8 inches, with one 5-inch branch pipe from each boiler. There is a stop-valve in the main range between each boiler, so that any defective part can easily be shut off without disturbing the running of the station. All these pipes are of mild wrought steel, with tees and flanges of cast steel. The surface-condensing plant, having a tube surface of 1,000 square feet, was placed in a pit at one end of the boiler-house. The air- and circulating-pumps placed beside the condenser are driven by a vertical tandem compound engine. This engine runs at a speed of 240 revolutions per minute, and drives, through three to one spur gearing, a rocking shaft, from which the pumps are worked. The air-pump is 21 inches diameter by 14 inches stroke, and the double-action circulating pump is 14 inches diameter by 12 inches stroke. The main exhaust-pipe is 16 inches, and the branches are 6 inches in diameter. The circulating pipes are

7 inches in diameter. The exhaust can, if desired, be turned into the atmosphere through a branch pipe running up the side of the building.

The arrangement of the repair shop is situated at the side of the engine-house, and is supplied with power by a railway motor driven from the 500-volt bus-bars.

*Substations.*—In designing the substations for the 3-phase transmission, the choice in the generating machinery lay between synchronous commutators with step-down transformers to reduce the line voltage to 330 volts at the 3-phase side of the synchronous commutator, and the use of motor generators consisting of a 3-phase synchronous motor driving an ordinary railway machine. The advantages of the synchronous commutator, or rotary converter, are that a single machine is required instead of two, and the efficiency of such a machine, on account of its dual function of a 3-phase motor and a commutating dynamo, is higher than in a machine of equal output having a single function. The effect of the current in the armature of a rotary converter may be determined by considering the machine, first, acting as a simple 3-phase machine, and secondly, as a continuous-current dynamo. Superimposing the conditions obtaining in the first condition on those obtaining in the second, it will be found that the resultant current in all the conductors of the rotary converter is less than is the case either with a 3-phase machine or a dynamo; consequently the heating of such a machine when operated as a rotary converter is less than when operated either as a 3-phase machine or dynamo. The reactions of the magnetism due to the current in the armature add together in such a way that the resultant interaction in the rotary converter is greatly less than when acting either as a dynamo or a 3-phase generator; consequently the distortion in the air-gap is small, and change of lead for varying load becomes negligible. The advantages of the rotary converter may be pointed out at length, since in installations differing only in magnitude from the original Dublin installation, as at first laid out, the rotary converter becomes by far the most desirable and economical machine. In large installations where 200-kilowatt machines or larger can be economically used for conversion, there is no question as to the greater efficiency and advantage of the use of rotary converters. In the present installation, however, the machines were of 75-kilowatt capacity, so that small reducing transformers would have to be used. These transformers are not so easily repaired as a synchronous motor. Further, to allow for the great fluctuations that would occur, these transformers would have to be made with a much greater margin than would be consistent with economy in so small a size. Hence the synchronous motors were finally decided upon as most suitable. Each station contains two motor generators, those at Blackrock developing 75 kilowatts, and those at Dalkey at 50 kilowatts. The arrangements are, in general, similar at the two stations. An existing building, formerly used as a stable, 40 feet in length by 24 feet wide, was utilized. Each motor generator consists of two entirely separate machines coupled together. The 3-phase motor is almost exactly similar in construction to the generators at Ballsbridge, and the same drawings will illustrate its design. The working of the machine has been very satisfactory; the Author has deliberately short-circuited the continuous current side when fully excited, without succeeding in making the motor fall out of step. The magnetic densities in the parts of the machine are:—

| | Lines per Square Inch. |
|---|---|
| Teeth | 105,000 |
| Core | 53,000 |
| Gap | 68,000 |

The current-density in the winding at full load is 1,220 amperes per square inch. The 500-volt generators coupled to the above are of the same general design as those used at the Ballsbridge station. The efficiency of these machines is about 80 per cent. at full load and 76·5 per cent. at half load. The substation plant is started from the direct-current side, current being taken for the purpose from the line through a starting rheostat. The switchboard connections are practically identical with those already given for the main station, Fig. 7, Plate 3, save for the presence of this starting rheostat, and of a synchronizing transformer placed across two of the 3-phase bus bars. The operation of the whole plant is very simple. The 3-phase motor is as readily thrown into circuit as an ordinary single-phase alternator. The plant having been started by current taken from the line into the continuous-current side and the rheostat of the latter cut out, the speed can be regulated by means of the rheostat in the field circuit.

It is not necessary to exercise great care in the adjustment of the 3-phase motor voltage before throwing it on to the 3-phase bus-bars. When once thrown in, the rheostat in the 3-phase field circuit can be altered so as to obtain the conditions of most economical transmission.

The substation requires, when running, very little attention, as the use of synchronous motors ensures that the speed will remain, under all conditions of load, exactly the same as that of the generators at the station. Moreover all the bearings are self-aligning and self-oiling, and the machines are so designed that the brushes can be maintained in a fixed position.

The efficiency of substations on this system may be kept high, as in the case of substations for lighting, by switching on more or less machines according to the load. Thus, for the ordinary light work at Dublin but one half the substation capacity is used. On days and hours when the load is expected to exceed a certain amount the second machines are put in use. Thus, the average, daily output of each of the stations is as follows:—

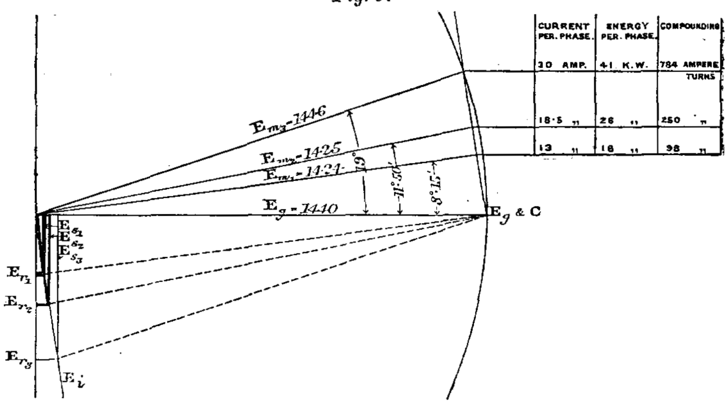
| —— | Board of Trade Units. | Kilowatts. |
|---|---|---|
| Ballsbridge . . . . | 675 | 37 |
| Blackrock . . . . | 848 | 57 |
| Dalkey . . . . . | 459 | 31 |

During certain hours the values are considerably exceeded, and temporary fluctuations are constantly occurring, which require an output of 50 per cent. or more in excess of the average. During exceptional days, such as Saturday, Sunday, and holidays, the output has amounted to 2,590 kilowatt-hours and the maximum output to perhaps 400 kilowatts. Momentarily it would considerably exceed this amount.

The sizes of conductors and the electromotive forces and currents in all parts of the system at rated load are shown in Fig. 2, from which it appears that, under the conditions specified, the efficiency of transmission from Ballsbridge to the substations is about 92·5 per cent. when transmitting 250 kilowatts at 2,500 volts. The periodicity of the circuit was taken arbitrarily at 30, since at this value the cost of efficient machinery and the effect of inductance, which acts to diminish the maximum power of such machines, are comparatively small.

The field excitation of these synchronous motors may be varied within wide limits without causing the motor to fall out of step, but the efficiency of transmission does not remain the same. In systems where the effect of any one motor on the phase relations between the current and electromotive force at the generator is inappreciable, the phase relations between the current, impressed electromotive force, and counter electromotive force in the synchronous motor, may be independently examined and adjusted by varying the field excitation to suit the terminal voltage, which may be taken as constant. When, however, the number of motors becomes so limited that the effect of any one may considerably modify the phase relations between current and electromotive force at the generator, the effect of the motor and the transmitting line have to be referred to the generator, and the phase relations must be referred to the impressed electromotive force of the generator, the counter electromotive force of the motor and the total impedance of the circuit, *i.e.*, the impedance of the generator armature, of the motor armature, and of the line. The impedance is a constant of the circuit. The electromotive force of the

*Fig. 9.*




generator may be taken to be the resultant of the impedance and the counter electromotive force of the motor; and the phase relations between the motor electromotive force, generator electromotive force, and current, may be predicted by vector diagrams. The efficiency of the entire system will be a maximum when the current is in phase with electromotive force of the generator. In *Fig. 9* the relations between the various quantities are shown. The lines Eg and Em represent the electromotive forces of generator and motor respectively, while Ei is the electromotive force necessary to overcome the total impedance of the circuit. The conditions are supposed to have been adjusted to give greatest efficiency; the current and generator electromotive force are in phase, and the direction of the Eg vector is that also of the current C; the electromotive force necessary to overcome the impedance of the circuit, is compounded of Es and Er, the electromotive forces necessary to overcome inductance and resistance of generator, motor and line combined. Es and Er are both proportional to the current, and the impedance vector is therefore unaffected in direction by changes in output, as long as the generator electromotive force and current are kept in phase. The generator electromotive force Eg has to supply the electromotive force Ei to overcome the inductance and resistance of the circuit, and the electromotive force Em to overcome the counter electromotive force of the motor. It must always therefore be the diagonal of a parallelogram, of which these quantities form the sides. Thus, the locus of all the values of counter electromotive force is a line parallel to the impedance line. The values of Es and Er were calculated from the drawings, and afterwards verified by special tests upon the machines. The numerical results are indicated upon the diagram, from which the magnitude and phase relations of the motor electromotive force for three different loads may be read off. The product of the component of the electromotive force Em taken in the direction of the current multipled by the current, gives the mechanical work done by the motor. The product of the component of the generator impressed electromotive force Eg in the direction of the current multiplied by the current, the power supplied by the generator to the line. More complicated mathematical methods for obtaining these results were known to the Author at the time the installation was designed, but this method was the simplest and in practice, as was expected, has proved sufficiently accurate. It may here be pointed out that by the term "work done by the motor," is not meant the work that it delivers externally, but the total work of the motor, which includes core loss and friction losses in the bearings. The external work that the motor may deliver is the total work minus these losses. A further reference to these diagrams will show that the current is always leading the electromotive force of the motor. The normal output of the motor per circuit may be taken as 25 kilowatts. The maximum may be taken as 50 kilowatts, and the minimum 5 kilowatts. Through this range it will be noticed on the diagram that the current leads the electromotive force of the motor by an amount approximately proportional to the load on the motor. The armature re-action will be proportional to the turns per pole on the armature, to the armature current, and, for small angles, to the amount by which the current leads the electromotive force of the motor; hence the additional ampere turns necessary to overcome armature re-action will be approximately proportional to the square of the load. At the same time, the electromotive force of the motor to satisfy the conditions of the diagram must not remain constant. Combining this variation with that due to armature re-action, the values in the last column of the diagram are obtained. Examination of the machines during the working of the station has confirmed the general accuracy of the predictions.

It would be desirable to obtain the necessary variation in the field of the motor by winding on a few turns of low resistance, and placing them in series with the direct current passing from the commutating-machine to the line. The excitation in this case, however, can only vary as a linear function of the load, and consequently the range through which this method of compounding is effective becomes limited. The range through which the present machines are worked is sufficiently small, so that this difference, under the phase-relations existing, is negligible for all practical purposes, the amount of auxiliary compounding in the motor being comparatively small.

Three-phase synchronous motors, with comparatively small armature reaction, require an excessive amount of current when starting themselves from the line. It is possible to start a single machine in this way from the generator, but when two or three machines are being operated on the same circuit, it is objectionable to attempt to start another machine direct from the line, since starting-currents of the 3-phase motor are displaced approximately 90° in phase behind the line electromotive force. The tendency is to demagnetize the generator and to throw all the other motors out of synchronism. Arrangements were therefore made for starting the motor-generator from the trolley line by means of a suitable rheostat; after the 3-phase motor had been brought to approximately synchronous speed it was thrown on the 3-phase circuits. This method has proved very satisfactory, since, during the year and a half that the line has been in operation, the machine has never been out of synchronism, and there has never been any interruption in the supply to the line from this cause.

Since the completion of the line, the Blackrock Station has been re-designed for two six-pole 200-kilowatt rotary-transformers, running at 600 revolutions per minute. There are three high-tension switches, two for the two cables from Ballsbridge, and one for the outgoing cable to Dalkey. The transformer switchboard is arranged so that any one transformer may be taken out of circuit. The transformers are connected delta, consequently any two of them will supply the rotary convertor with 3-phase currents, and in case of failure of any transformer the corresponding rotary convertor may carry approximately two-thirds of its rated load.

The rotary convertors are started from the 3-phase or continuous-current side. In starting the substation, one is usually started from the 3-phase side. If it is necessary to use the additional machine, this can be started from the continuous-current side, without the demagnetization of the generator and the consequent lowering of the voltage in the system.

There are four low-tension switchboards, two for each rotary convertor, provided with the necessary synchronizing appliances, and also a polarity indicator, so that when a rotary is started from the 3-phase side it will be known whether or not it is synchronized in the proper polarity. A rotary convertor, starting as it does as an induction motor, may synchronize at either pole. In case it synchronizes at the wrong pole and is not separately excited, it is necessary to synchronize again in respect to the proper pole. If, however, it is separately excited, the polarity is changed by reversing the field magnet. There are two 500-volt feeder panels, one to connect to the cable extending towards Dalkey, and the other to connect the cable towards Ballsbridge. There is, in addition, the Board of Trade panel, indicating the voltage drop in the earth return.

The rotaries are compound-wound to secure the result explained. The efficiency of the rotaries at full load is about 94 per cent. and the static transformers 97 per cent. At half-load the efficiency of the rotaries is some 92 per cent., and the transformers approximately the same as at full load. These machines are running in parallel with the continuous-current machines at Ballsbridge, Fig. 2, Plate 3. The small engines at Ballsbridge do not regulate very closely, consequently all of the continuous-current machines are compounded for as nearly as possible constant voltage. Experience shows that unless all of the engines regulate very closely, say within 2 per cent. variation as a maximum, it is best to operate the plant entirely as a 3-phase one, in which case engines maintain synchronism at variable loads. The advantages of rotary converters in each substation have been discussed, and all the points brought out there have been fully demonstrated in practice.

*The Trolley-Wire.*—The trolley-wire is broken by section insulators at ½-mile intervals, and connected at feeder pillars containing a switchboard which allows of the isolation of each ½-mile section of trolley-wire, or of each ½-mile of distributing feeder. The pillar carries also a lightning-arrester, fitted with a magnetic blow-out. Any discharge leaps across a spark-gap and passes to earth, a part of the discharge being passed round a coil and producing a field which operates to blow out the flash. The conductors are armoured and laid straight in the ground. The poles for supporting the trolley-wire are 31 feet long, and weigh approximately 1,200 lbs. They are spaced, on the average, 43 yards apart. Each pole is let into the ground 6 feet, and is surrounded by concrete in the usual way. The tension on the trolley- and span-wires is about 700 lbs.

*Permanent Way.*—The rails weigh 76 lbs. per yard, and are laid to a gauge of 5 feet $2\frac{3}{16}$ inches, being bonded by single 0000 Chicago bonds, and cross-bonded every 120 feet. They are laid on a bed of concrete 17 feet 6 inches wide and 1 foot deep, and consisting of one part Portland cement, two clean sand, four crushed granite. The paving-sets used were Scotch and Welsh, 4 inches by 5 inches by 6 inches to 9 inches, 1 ton covering about $3\frac{1}{2}$ square yards. The maximum gradient is 1 in 16, and the sharpest curve is of 30 feet radius. The total length of single line is about 3,000 feet, and of double line 38,000 feet.

*Rolling Stock.*—The car bodies are mounted on Peckham standard cantilever extension trucks. The motor-cars have a wheel-base of 6 feet, the diameter of the wheels being 2 feet 6 inches, and the truck gauge is 5 feet $2\frac{3}{16}$ inches. The seating capacity of these cars is fifty-three, and their weight approximately 7 tons. The carrying capacity is increased by the attachment, when necessary, of trailer-cars capable of carrying forty-six persons. The trailer-cars have a wheel-base of 5 feet 6 inches, the wheels being 2 feet 6 inches in diameter, and weigh, approximately, 4 tons. Two motors are used to each motor-car. The armature is wound for compliance with the Board of Trade speed limitations, a gear ratio of 4·78 being used. The regulation is obtained by the use of series parallel controllers, with magnetic blow-out to eliminate the trouble of arcing at the contacts. The cars are electrically lighted; five lamps are driven in series from the trolley circuit.

*Car-Sheds.*—The car-house at Ballsbridge is divided into two parts by the repair shop. The part nearer the gates has four lines, and the inner part seven, with a total capacity for holding forty-four cars. The lines have pits 4 feet 3 inches deep to give access for inspecting and cleaning the trucks. The cars are shunted by an electric traverser crossing all the lines in the car-house. The ordinary overhead trolley and railway motor are used, with controller and resistances. In addition to the car-house at Ballsbridge, there is one at Blackrock and one at Dalkey, each capable of holding ten cars.

*Tests.*—Tests made in the station from June 1st to June 16th, 1896, gave the following as averages, the engines being worked non-condensing—

| | | |
|---|---|---|
| Number of double cars running | | 18 |
| Car-miles | | 1,967 |
| Energy on line | B.T.U. | 1,948 |
| „ per car-mile | „ | 0·99 |
| Current per car | amperes | 12·8 |
| Coal per car-mile | lbs. | 10·6 |
| Coal per E.H.P. | „ | 7·2 |

The cars ran at this time at a higher speed than was afterwards allowed by the Board of Trade, namely, an average of 8 miles per hour.

Recording watt-meters in the stations during August, 1896, enabled the following results to be obtained:—

| | | |
|---|---|---|
| Ballsbridge | B.T.U. | 376 |
| Blackrock | „ | 769 |
| Dalkey | „ | 503 |
| Total to line | | 1,648 |
| Train-miles run | | 2,051 |
| B.T.U. per train-mile | | 0·803 |

A recording watt-meter, placed on a car with trailer attached in August, 1896, showed that 0·786 B.T.U. was required on the average per car-mile. The tests were continued through a complete week, the train making $92\frac{3}{4}$ miles on week days, and $77\frac{1}{2}$ on Sundays, or an average current of 10·6 amperes. A recording meter was placed on a car in March, 1897. The car ran with trailer for 2 days and without for 4 days. The presence of the trailer required the supply of about 25 per cent. more energy per car-mile. So short a test, however, is not sufficient to determine an average figure, and in estimating the power required by a trailer, it is usually taken as equivalent to one-third of a motor-car. This test again indicates an average current of 10·6 for combined motor- and trailer-cars. The following data referring to the half year's working from January to June of 1897, have been supplied by the Tramway Company. The generators run as follows:—

| | |
|---|---|
| Ballsbridge | One 100-kilowatt generator from 7 A.M. to 1 or 1.30 A.M. |
| Blackrock | Two 75-kilowatt generators from 7.30 A.M. to 12.15 A.M. |
| Dalkey | One 50-kilowatt generator from 8.15 A.M. to 11 P.M. |

The difference of potential on the bus-bars at all stations is maintained at 500 volts, unless there is a specially heavy load, when two 100-kilowatt generators are thrown in at Ballsbridge, and the voltage slightly increased, so as to make them take up a greater proportion of the load. Twenty-five motor-cars run alone from 7.45 A.M. till noon or 1 P.M., when twenty trailers are gradually added, and an extra motor-car sent out. The trailers begin to come in again at about 8 P.M., some running as late as 11 P.M. The result for the half-year was:—

| | |
|---|---|
| Motor-car mileage . . . . . . . . . . . . . . | 408,685 |
| Trailer „ . . . . . . . . . . . . . | 177,807 |
| Average motor-car mileage per day . . . . . . . | 91·88 |
| „ trailer „ „ . . . . . . . | 63·98 |

The schedule time of running is 68 minutes for 7⅝ miles, or an average of 6·75 miles per hour.

| | | |
|---|---|---|
| Output, all stations for the half year . . . . . . | 362,764 | B.T.U. |
| Energy for lighting station estimated at . . . . | 34,000 | „ |
| „ „ station motors and line . . . . . . | 328,764 | „ |
| „ per car-mile . . . . . . . . . . | 0·703 | „ |
| Three trailer-cars are reckoned as one motor-car, and no deduction is made for the energy used for station motors. The true figure is therefore less. | | |
| Average current per motor-car . . . . . . . . | 9·5 | amperes. |
| „ „ „ „ and trailer . . . | 12·65 | „ |

(These figures are based on the half-year totals.)

The average daily output at Ballsbridge is 675 B.T.U.; at Blackrock, 848 B.T.U.; at Dalkey, 459 B.T.U.—a total of 1,982 B.T.U.

*Station Expenses.*—The following results were obtained during the six months, January to June, 1897, the engines working non-condensing:—

| | | | |
|---|---|---|---|
| Number of passengers carried . . . . . . . . | | | 2,100,128 |
| B.T.U. generated . . . . . . . . . . . . . | | | 362,764 |
| Motor-car . . . . . . . . . . . . . . | miles | | 408,685 |
| Trailer . . . . . . . . . . . . . . | „ | | 177,807 |
| | | *d.* | |
| Cost of coal per car-mile . . . . . . . . | | 0·5733 | |
| „ water, oil, waste, &c. . . . . . . . . | | 0·1003 | |
| Wages, generating plant . . . . . . . . | | 0·3443 | 1·0179 |
| Maintenance and repairs . . . . . . | cars | 0·2675 | |
| „ „ . . . . . . | line | 0·0088 | |
| „ „ . | generating plant | 0·0907 | |
| „ „ misc.: | lighting, tools, &c. | 0·0250 | 0·3920 |
| Total cost per car-mile . . . | | | 1·4099*d.* |

Welsh steam-nuts, at 13*s.* 6*d.* per ton, were used. The maximum current from the earth-plates as required by the Board of Trade seldom exceeds 2·5 amperes, and there is no deterioration apparent in the bonding. The economy of working is largely dependent upon the motor-men. The controller can be used economically or otherwise, and it is probable that in the tests made by a recording wattmeter on a car the controller would be used more carefully than usual. This must be remembered in comparing the current per car, 10·6 amperes, with the 12·65 amperes found as an average of the half-year's working, together with the fact that in the latter value trailer-cars are considered when making up accounts as equivalent to one-third motor-car, and the energy required for station-motors has not been deducted. If one trailer is considered equivalent to one-quarter motor-car, the 12·65 amperes is reduced to 12·2 amperes. It will be observed that the working of the line has been throughout less costly than was assumed for the preliminary calculations. These calculations, however, were for fully-loaded cars, and this condition, while it has to be provided for to comply with the Board of Trade Regulations, is far from being the average state of working.

The Paper is accompanied by eleven drawings, from which Plate 3 and the *Figs.* in the text have been prepared.

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# DUBLIN ELECTRIC TRAMWAY.

Fig: 1.


Fig: 2.

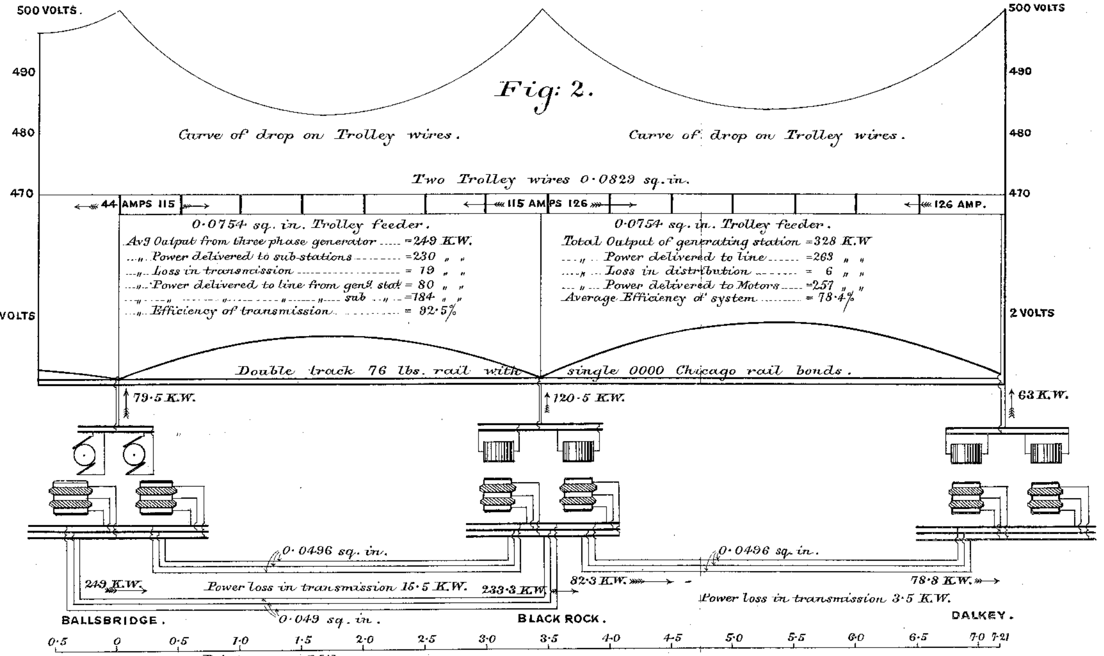
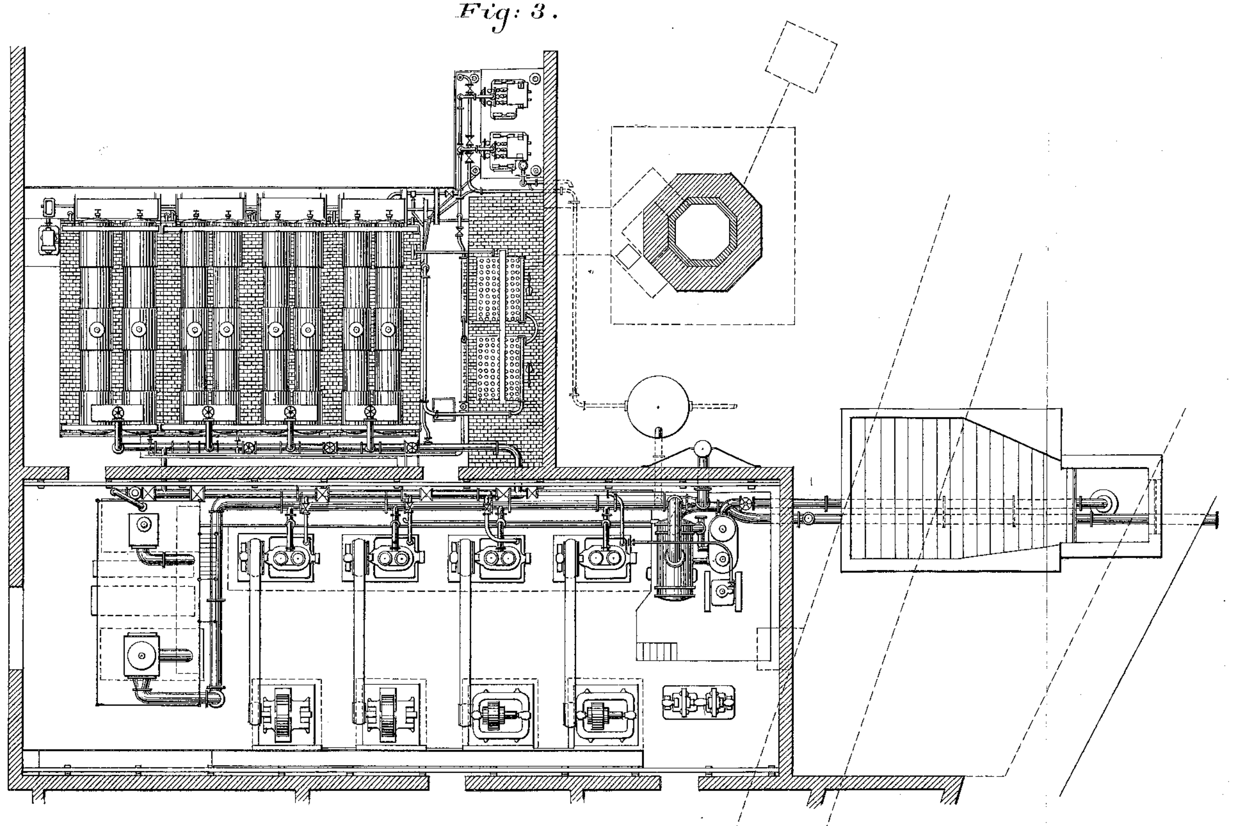



Fig: 3.



Scale for Fig: 1, ½ Inch = 1 Foot.

Mile 1 ½ 0 1 2 3 4 5 Miles.

Scale for Figs. 4, ¾ Inch = 1 Foot.

Inches 12 6 0 1 2 3 4 5 Feet.

Scale for Fig: 3, 1 Inch = 20 Feet.

Feet 10 5 0 10 20 30 40 50 Feet.

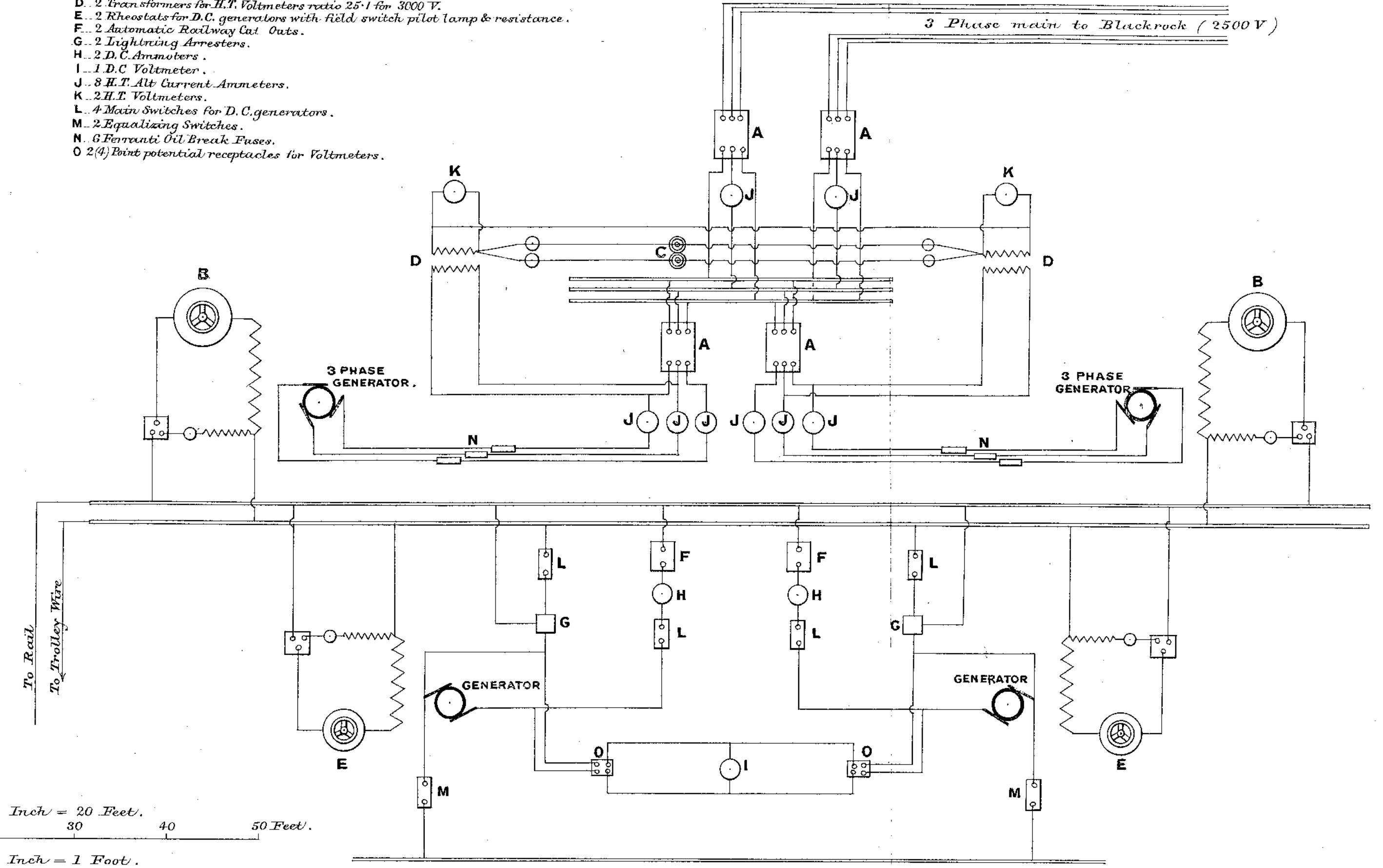
Scale for Figs. 5, ¾ Inch = 1 Foot.

Inches 12 9 6 3 0 1 2 3 Feet.

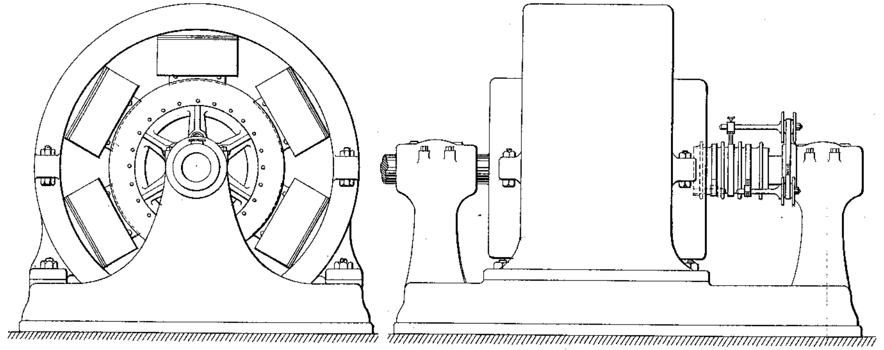
Fig: 7.

REFERENCE.

A .. 4 Three pole switches capacity 50 Amps @ 2500 Volts
B .. 2 Type EF 52 Rheostat for Generator Fields with field-switches pilot lamps & res.
C .. 2 S.P. Snap Switches for phase Lamps.
D .. 2 Transformers for H.T. Voltmeters ratio 25·1 for 3000 V.
E .. 2 Rheostats for D.C. generators with field switch pilot lamp & resistance.
F .. 2 Automatic Railway Cut Outs.
G .. 2 Lightning Arresters.
H .. 2 D.C. Ammeters.
I .. 1 D.C Voltmeter.
J .. 8 H.T. Alt Current Ammeters.
K .. 2 H.T. Voltmeters.
L .. 4 Main Switches for D.C. generators.
M .. 2 Equalizing Switches.
N .. 6 Ferranti Oil Break Fuses.
O 2(4) Point potential receptacles for Voltmeters.

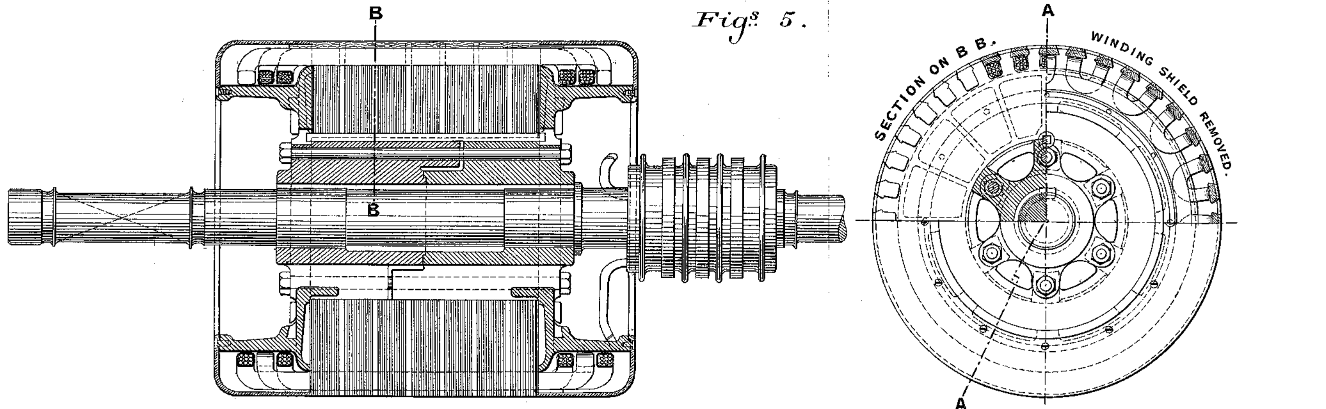



Figs. 4.



END VIEW. ELEVATION.

Figs. 5.




SECTION ON A A.

H. F. PARSHALL.



THOS KELL & SON LITH. 40 KING ST COVENT GARDEN.