Some Elements of High Tension Power Transmission.

Robert Lester Hutton,

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Robert Lester Hutton,

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SOME ELEMENTS OF HIGH TENSION TRANSMISSION.

-: INTRODUCTORY :-

This subject will be treated as follows:

First:- A general statement of the conditions which suggest a high tension transmission project, and the circumstances limiting the maximum transmission distance and maximum voltage.

Next in detail ~~is~~ several physical elements of a transmission system including some plates illustrating the lay-out of generator, line and substation connections and line construction. To this will be added a brief discussion of water power development.

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CONDITIONS SUGGESTION A HIGH TENSION PROJECT.

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A source of low priced power isolated from a center of large population, or community of industries to which power may be transmitted for consumption; or again may be transmitted to a point or points where industries are to be established as the receiving end and being more conveniently located on account of accessibility and transporation facilities afforded the manufactured products. Water power at present is the largest source employed in these enterprises, but it is suggested that on account of the probable electrification of steam roads that coal at the mines may be used. It is also a fruitful source of inquiry, as to whether or not coal could be turned into power at the mines and transmitted ~~or~~ economically, in the form of electricity, rather than as at present to haul it in freight cars.

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Second:- THE MAXIMUM DISTANCE TO WHICH POWER CAN BE TRANSMITTED:

As with most engineering enterprises the limitations which come through economic conditions ~~of~~, and the greatest distance to which power will ever be ~~economically~~ transmitted is the greatest distance to which it can be economically transmitted. The elements, which in the broadest sense, limit the distance to which ~~the~~ power can be economically transmitted are two; the cost of power at the generating station, and the price which can be obtained for the delivered power. The ~~distance~~ difference between these two elements must cover the cost of transmission, interest on the investment, and the profit. The cost of transmission comprises the loss of power in transmission, the cost of operating and the cost of maintenance and repairs. The value of the sum total of the interest which must be paid upon the investment, and the minimum profit, which is considered satisfactory, will have much weight in determining the limiting distance of transmission. The less this sum is, the farther power can be transmitted. A low interest rate and a low rate of dividend will, therefore, be conducive to long transmission. All the elements in the annual cost, except those dependent upon the line conductors, may be continually reduced by increasing the amount of power to be transmitted. The annual cost due to the line conductors cannot be reduced. It can be diminished only by such other means as will reduce the first cost of the conductors. As the first cost of the line conductors can be reduced only by increasing the voltage of transmission, and as there is a limit to which such increase can be carried, it follows that the limiting distance to which power can be economically transmitted will depend finally upon the cost of the line conductors and upon this alone. The elements which are affected by the voltage, are the transformers and insulators which increase in cost with the pressure, while the cost of line conductors and line losses decrease with the pressure. At present the continued high price of copper lends a special interest to the study of high voltages in power transmission. At the present values of copper, the economics of long lines are very seriously affected. A system which a few years ago would have invested say $100.00 per kw. now must invest not less than $150.00 per kw. in conductors. The difference is practically as great as the whole cost of the electrical machinery, including the transformers, and within this same period of years, there has been very little increase in working voltage. The average, it is true, has been raised, but the maximum has been but little raised. There has been indefinite talk about what was about to be done, and we believe some transformers designed for a maximum of 80,000 volts have been built and shipped. Now since an actual rise in working pressure from 60,000 to 75,000 volts, would fully compensate for the additional present price of copper, it would seem surely that engineers should be alive to this question. Looking over the transmission situation it will appear that the logical step first to be taken is to raise the normal transmission voltage considerably above its present figure. It has been demonstrated that pressure of 40,000 to 50,000 volts can be worked with entire success almost anywhere, and such plants are doing good work at or about 50,000. Why then build plants for compromise pressures like 20,000 and 25,000 volts and more than double the cost of the line? Further increase of voltage rests in the main with the insulation. There should be no hesitation about dealing with this problem wherever the copper question begins to get serious. The real serious part of the problem lies in the region above 60,000 volts.

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Third:- THE SEVERAL ELEMENTS OF A HIGH TENSION TRANSMISSION SYSTEM.

The system naturally divided itself into three sections, viz:-

The Power House, line and sub-station with its low voltage distribution;

(a) At the station we find the building, prime-movers, generators, swtich-boards, with their connections,

(1) The building should be well lighted and ventilated, large enough for probable additions. In its planning provision must be made for conduits, switch-board-gallery, transformer and circuit-breaker-vaults, and a special arrangement for receiving the high tension lines.

(2) Prime-movers, whether engines or turbines, will be direct connected to generators and provided with best obtainable governors.

(3) Generators. The selection of generators involves possibly the most important and careful consideration in the whole system. We are required to determine the frequency, phase, voltage and type. The most important of these points, is the choice of frequency. Shall it be high or low? By high frequency is generally understood, one of over 60 cycles per second. 60 cycles and less are considered low frequencies. The tendency of modern practice is in the direction of low frequencies, and in the organization or design of a new plant, the ~~direction~~ selection is most often that of a frequency of 60 cycles or under. Each particular case must be studied in the light of its special conditions before an intelligent decision can be made. The following general suggestions are offered as embodying the latest and standard practice.

For local lighting systems with incidental demand for power in small units, where old transformers have to be retained, and where a cheap plant is a first consideration, a high frequency may be used.

For general transmission and distribution for lighting and power purposes, conditions which ~~occupy~~ obtain in the majority of alternating current propositions, a standard frequency of 60 cycles can be used to advantage.

In power and lighting plants - where arc lighting is of secondary consideration - supplying current to induction motors as in mill work, and to rotary convertors, as in long distance railway transmissions, where the generators are direct driven by engines, and finally for very long transmissions of power, a frequency of 40 cycles may be used.

For exclusively power plants, where lighting is of no importance whatever, and where rotary convertors and motors of large size, or slow speed, are to be supplied, a frequency of 25 to 30 cycles may be used.

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PHASE

Although the continuous current system of electric power transmission has an extensive field of usefulness, it is limited by the low potential for which commutating machines can be wound, and the great cost of the copper necessary, if the distances are considerable. The alternating current systems in use, are the single-phase, two-phase, three-phase and to a limited extent the monocyclic. The single-phase alternating system was a step in advance, permitting power to be transmitted at high potential, which could be readily increased or reduced with the windings of station transformers. The single-phase system was limited, however, by the difficulty in obtaining a satisfactory self-starting motor, and its usefulness has been confined almost entirely to transmitting power for lighting. The development of the poly-phase alternating system, possessing all the advantages of the single-phase system, and at the same time permitting the use of motors, having not only most of the valuable features of the continuous current motor, but also ~~such~~ many important advantages over it has solved the problem of long distance transmission. The poly-phase systems in use ~~xxx~~ to be considered as applicable to high tension transmission ~~are~~: the two-phase, consisting of two separate single-phase circuits displaced 90 degrees from each other, and the three-phase system consisting of three interlinked single-phase circuits displaced 120 degrees from each other. These two systems are both in operation and while it is admitted that there is no fundamental difference between them, yet each has specific characteristics giving particular advantages. The self-induction of a three-phase circuit for transmitting a given amount of power under similar conditions of E. M. F. is the same as that which is incident to the two-phase four-wire circuit if the same size of wire is used in both cases, and the wires of the three-phase circuit are equally distant from one another, and this distance is equalled to that between the wires in each phase of the two-phase circuit. The loss and the regulation are the same as would be obtained in transmitting half the power at the same power factor over two wires of the three-phase circuit. The advantage of the three-phase transmission over single-phase is evident, as the addition of the third wire involving an increase of 50% in the weight of the conductor, enables twice the power to be transmitted with the same efficiency and regulation. A corresponding gain is of course obtained over the twophase system, as it is in effect the same as two ordinary singlephase circuits, in so far as the efficiency of conductors is concerned. A further advantage of three instead of four wires is the reduced cost of insulators and line construction, the reduced losses due to leakage and the lessened liability to break down resulting from the fewer insulators. While this advantage obtains in the three-phase system, yet an important point in the two-phase system is that of easier regulation. Other things being equal the unequality in the voltages on the different phases of a generator when the circuits are unequally loaded is much greater in the three-phase than it is in the two-phase type.

I am not prepared in this paper to decide definitely which system is the preferable, as one may be better suited under certain conditions than the other, but it is a fact, however, that the three-phase system is being more largely introduced in the ~~lightest~~ largest high tension power transmission enterprises.

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SIZE OF GENERATOR

Concentration of generator capacity in as few units as the station load will permit has long been recognized as a requisite to satisfactory and economical operation.

In general, the larger the machine the higher the efficiency; the size being limited only by the limitations to mechanical construction and the possibility of providing load for the generator during the light load. In the evolution of the modern station, groups of relatively small belt driven machines occupying much floor space and incurring heavy friction losses, have been replaced by a few large generators direct connected to engines or turbines. This change has resulted in superior service, higher efficiency of operation and diminished cost for repairs and station attendance. Above all, instal generators with some margin of capacity above immediate needs. In a word, the generator should be direct connected, engine - type, revolving field.

EXCITER.

Let the plant be equipped with two main exciters, one directly connected to an independent prime-mover, the other may be driven by a belt from a pulley on the shaft extension of either one of two of the main generators. The independently driven exciter gives somewhat better voltage regulation and is used in normal operation, the belted machine being held as a reserve. Each of the exciters should have sufficient capacity to excite all of the main generators under the extreme conditions of load & power factor met with in the operation of the plant. This reserve exciter is insisted upon because in this element of the plant is found one of the most frequent causes for interruption of service; and as continuity and reliability of service is under all circumstances demanded, there shall be no reasonable objection to using every effort to strengthen the weak points. It may be found advisable, as well as convenient, to light the station from the exciter current.

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SWITCH-BOARD.

The switch-board equipment will consist of generator, feeder, exciter, and step-up transformer panels. The switch-board should be mounted on a gallery or elevated platform at one end of the power house of sufficient height to enable the operator to have an unobstructed view of all the machinery. As the instrumnts found on these switch-boards are practically the same, it is needless to enumerate them, except as to mention particularly the oil switch, and oil circuit-breaker. The development of the oil switch and circuit-breaker has produced one of the most valuable additions to high potential apparatus made during the past decade. It is indeed likely that the development of high tension transmission of power would have been very seriously retarded, but for the invention of this piece of apparatus. High tension circuit-breakers are now designed for pressures up to 60,000 volts. The oil-switch and oil circuit-breakers for the generators and transformer panels are placed in separate cells or vaults.

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TRANSFORMERS.

The economical transmission of electrical energy requires in general a high voltage transformation, the ratio~~s~~ of which increases in almost direct ~~proposition~~ proportion to the distance to which the energy is carried. When the power units are large, as is usually the case, a consideration of the investment, attendance and practicable economy attainable in the transformers group leads to the selection of units of large size. These two requirements, ~~have~~ large capacity and high voltage are therefore directly responsible for the creation of transformers of a size gigantic as compared with those built only a few years ago. Transformers up to a certain size may be built self-cooling with the assistance of cases especially designed to promote radiation. A small transformer has naturally sufficient surface both of transformer power and of surrounding case to readily dissipate the heat produced in the interior. When we consider, however, that the capacity of a transformer increases approximately as the cube of its linear dimensions and the surface only as the square, it is evident that the problem of cooling becomes more difficult with increase in size. In order to maintain a uniform safe temperature throughout the body of a transformer it is not only necessary to provide ample exterior surface to the case, but sufficient surface to be readily given up to the cooling medium. Beyond about 500 kw. artificial cooling is employed because the bulk of a transformer and consequently the heat developed in it increases more rapidly than does the transformer surface. Some means therefore must be employed for carrying away the excess heat over and above that which the transformer surface can dispose of with a reasonable interior temperature. The methods of doing this are various, but practice has fairly well crystalized, and it has been found that water-cooling tubes in the oil surrounding the transformer give the best results. Oil-insulated water-cooled transformers are built in the largest sizes for any frequency and for the highest voltages that are successfully maintained on modern transmission lines. In long distance transmission work which involves step-up and step down transformers close regulation is of the hightest importance and for two reasons. The transformer drop appears twice between the generator and the load and because the power factor of such a load is usually low, the drop may be greater than with a non-inductive load. Manufacturers of oil-insulated, water-cooled transformers freely interlace the coils so that the drop between them is minimized with either inductive or non-inductive loads. Transformers are arranged when it is so specified for transforming two-phase current into three-phase currect and vica versa. Transformer leads should be lead encased cables and enter the cases from ducts run in enclosed air chanbers. Great precautions should be used to separate high tension leads and buses. A good plan is that each of the buses as well as all the leads to and from them, be completely separated from each other by concrete, soap-stone, or marble barriers, thus minimizing any spread of accident from one conductor to another.

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THE LINE.

Subdivided under the following heads, conductors, insulators, poles, towers and, protective devices.

The two vital factors in the line are loss and regulation. The losses are C^2R and should be expressed in watts or horse power, or as a per cent of the energy delivered to the line. The practical point in regulation is the difference in E.M.F. at the generator and the load. The word "drop" is applied to the difference in E. M. F. between the generator and the load. The regulation is generally expressed in per cent of generator E.M.F. Regulation in a circuit is, in general, determined by three elements, viz: The resistance, the counter E. M. F. of the circuit and the power factor of the load.

The counter E.M.F. of a line depends upon the size of wire and the distance between the wires, and it increases directly as the length of the circuit, the current and the alternations. The drop or difference of potential between generator terminals and the load terminals due to the counter E.M.F. of the line depends upon the self-induction of the load. In making calculations for size of conductors, reference should be made to standard tables, formulae and curves, which are accessible. Such tables, formulae and curves being explained: the relation of reactance to resistance is shown for a number of frequencies and for the sizes of Conductors ordinarily used in power transmission and also other constants of transmission circuits such as capacity inductance and charging current.

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INSULATION.

As electric power transmission cannot be successful unless it is able to deliver uninterrupted power, continuous operation so far as the transmission line is concerned depends largely upon the effectiveness of the insulator which is employed. Insulators must therefore be obtained which will not fail in service. The potential that can be employed safely is ~~not~~ limited by the pressure the insulators will bear, as transformers that are reliable and not excessive in cost, can be built for twice the voltage that any line yet constructed will withstand. The problems of insulation are becoming better understood. The capacity and the surface effects of line insulators have received but little attention from engineers, and many of the failures are due to this fact. The materials for construction of insulators are not so limited as assigned in the past. Glass and porcelain have been used almost exclusively, but other materials are being investigated. Organic material, such as paper, has great advantage and is well suited for this purpose. Compound insulators in which the petticoats and water sheds are made of metal and the core of glass, porcelain, paper and other insulating materials are also feasible. Experience has shown that porcelain insulators which are not absolutely non-absorbant, are worthless. If an insulator is built up of several parts, each part should be able to withstand a pressure greater than it will have to sustain when the complete insulator is tested. In no case should wooden pins be relied on for insulation as their value is only temporary. As wooden pins in time become dirty, absorb moisture and burn off. Experience points to the advisability of using iron pins with modern insulators properly chosen for the line potential.

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POLES AND TOWERS.

Long spans are advocated for transmission lines. This calls for a substitution of towers for wooden poles. Let us see what can be gained by substituting a steel tower construction with long spans for a wooden pole line. Short circuits are by far the most common line difficulty, the only remedy for which is to put the wires so far apart that they are unlikely to be bridged across. This can readily be done when a steel cross-arm is employed; burning is of course entirely done away with, where metal construction is used. Failure of insulators from electrical cases can be obviated by getting larger and better insulators. This is practicable where the spans are long and the number of insulators is small, each metal tower is a lightning arrester, and as they are the highest points in the line they materially assist in its discharge. The tower itself being a conductor, cannot be injured by lightning, as the wooden poles would be. Steel construction can be figured to meet safely any strains that can come upon them and can generally be located at safe places, where there is no danger of washouts, also no danger of burning from forest or prarie fires. Less liability from overturning by heavy winds. The deterioration of properly constructed and well galvanized steel towers is very slight and is practicably negligible, so far as the pins and cross-arms are concerned. Any part of a steel tower can be readily removed and replaced without interrupting the service. By far the greatest gain obtained from long spans is in the redu ction of the number of parts. If one insulating support takes the place of four or five, line troubles will be reduced nearly in direct proportion; the inspection and repair of the line will be much simplified and its cost of maintenance correspondingly diminished. In tropical countries wooden poles are practically inadmissable on account of their destruction by insects.

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PROTECTIVE DEVICES.

The line must be protected from lightning discharges and the probability of short circuiting by other lines falling upon it. The best practice is to employ three guard wires, one at the top of the pole, and one at each ~~extent~~ End of the cross-arm. These guard wires in addition to protecting the line from other lines or objects falling cross it, also may be used in conjunction with ground wires, as a protection from lightning. It is the practice in the ordinary line construction to ground the top wire at every 5th. or 6th. pole . Lightning arresters are to be installed, particularly at the ends of the lines. The line also could be divided into sections by suitable switches so as to loaclize troubles.

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~~THE LINE~~.

The line at each end should enter the station and sub-station through, preferably terra cotta pipes of suitable diameter according to the pressure.

These pipes to have in each end, heavy plate glass discs, drilled to the gauge of the wire. The outside ends of these pipes to have a shelter protection. The end strain of the line must not be borne by the building, but the last pole should be securely guyed.

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SUB-STATION.

The substation will contain lightning arresters, step-down transformers, oil circuit breakers and other instruments to be installed with the precautionary insulation as outlined in the station equipment. If the substation is located in the center of a City or densely populated community it would be necessary to bring the high tension wires under-ground to it or there may be two or more such substations involving two or more reductions of pressure. The distribution from the substation is shown in one of the appended diagrams.

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WATER POWER DEVELOPMENT.

Electrical power transmission has given a great impetus to the development of water powers and a clear understanding of these ~~xxxxx~~ is one of the duties of the electrical engineer. There is a great variation in hydraulic plants in the characteristics that determine their usefulness and these variations are the result of natural conditions and the manner of development. The value of water power is the resultant of two sets of factors; the size and natural opportunities of the power and the extent ~~of~~ and nearness of the market. The following is a specification of water powers according to the opportunities that affect their value:

1. Powers capable of continuous operation at their full capacity at all seasons. There are comparatively few belonging to this division.

2. Powers capable of continuous full operation only a part of each year, except at seasons when the flow of water does not reach its minimum, there are two sub-divisions of this class.

(a) Powers that are capable of being operated to their full capacity a portion of each day.

(b) Powers that, owing to natural conditions, are limited by the flow of water so that in dry seasons they cannot develop power to the full capacity of their machinery.

3. Powers that are occasionally interrupted in whole or in part by conditions other than low water, such as freshets and anchor ice. In investigating a water power, the following determinations must be made.

1. The minimum flow of water, together with the probable duration of low water periods.

2. The maximum flow of water from the effect of floods.

3. The available head.

4. Storage that can be utilized.

5. The effect of ice.

Having determined these, the engineer can decide whether the development will meet the requirements of the expected loads. Water flow is seldom capable of exact predetermination, except where water powers have long been established or gaugings made over a number of years by Government Observers. Don't accept the statement that "the river has never been lower than it is now".

Note:

In the preparation of this paper, I have freely consulted such authorities as the Publications of the General Electric Co., ~~of~~ Westinghouse Electric and Manufacturing Co., The Proceedings of the American Institute of electrical engineers, various text books and electrical Journals.

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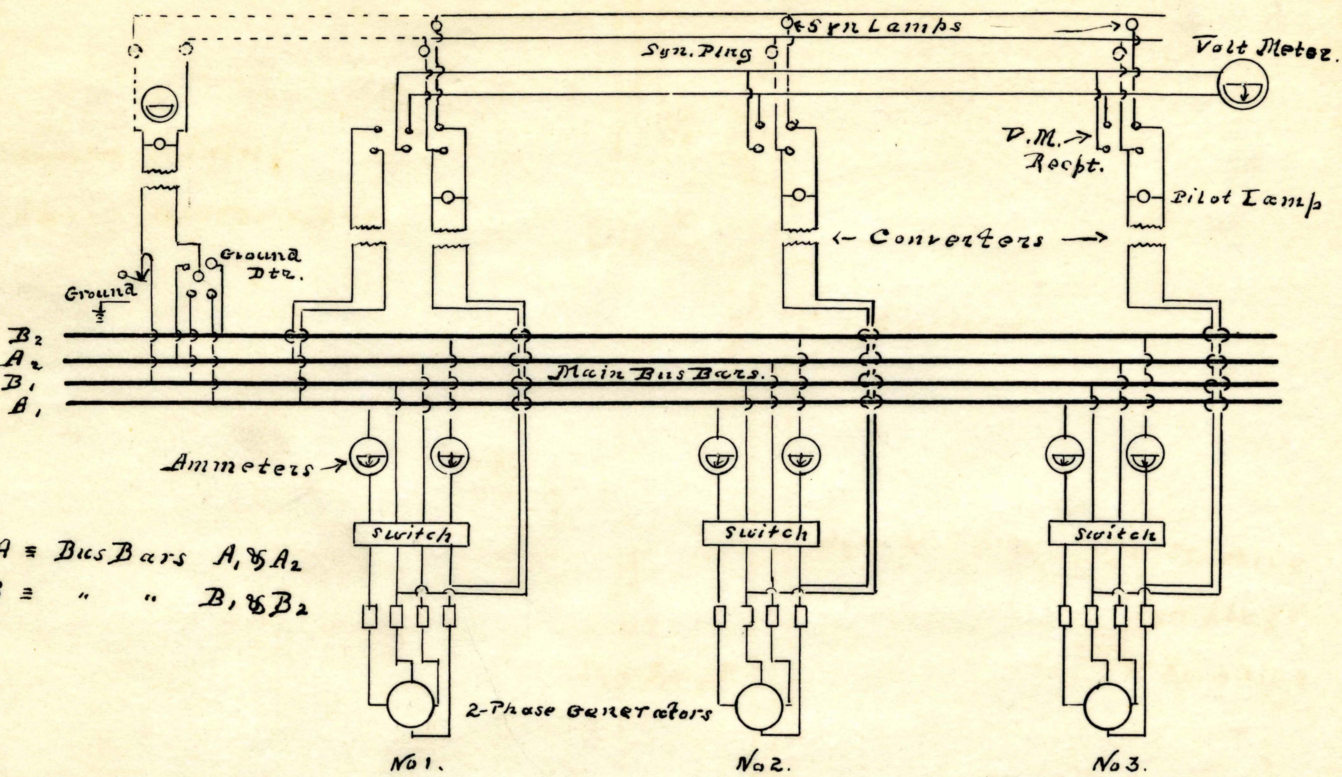


Diagram of Switchboard Connections for three Two-Phase 1100 or 2200 volt Generators Running in Parallel.

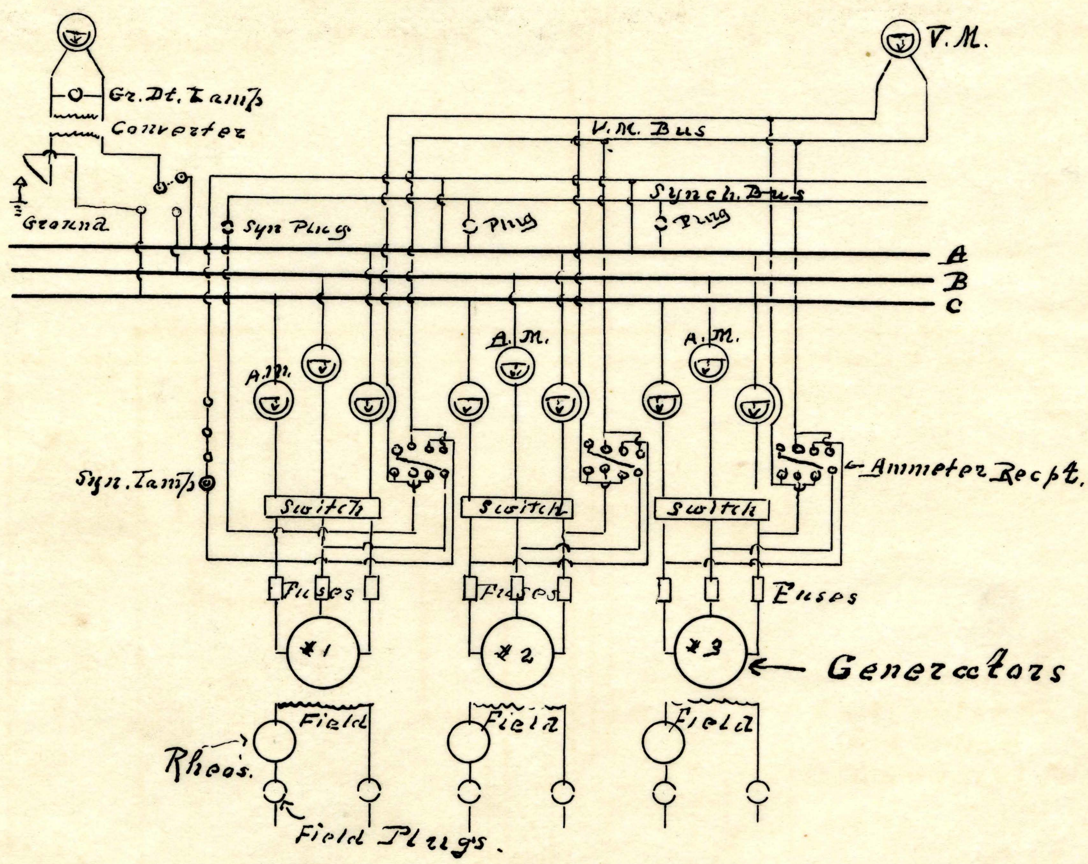
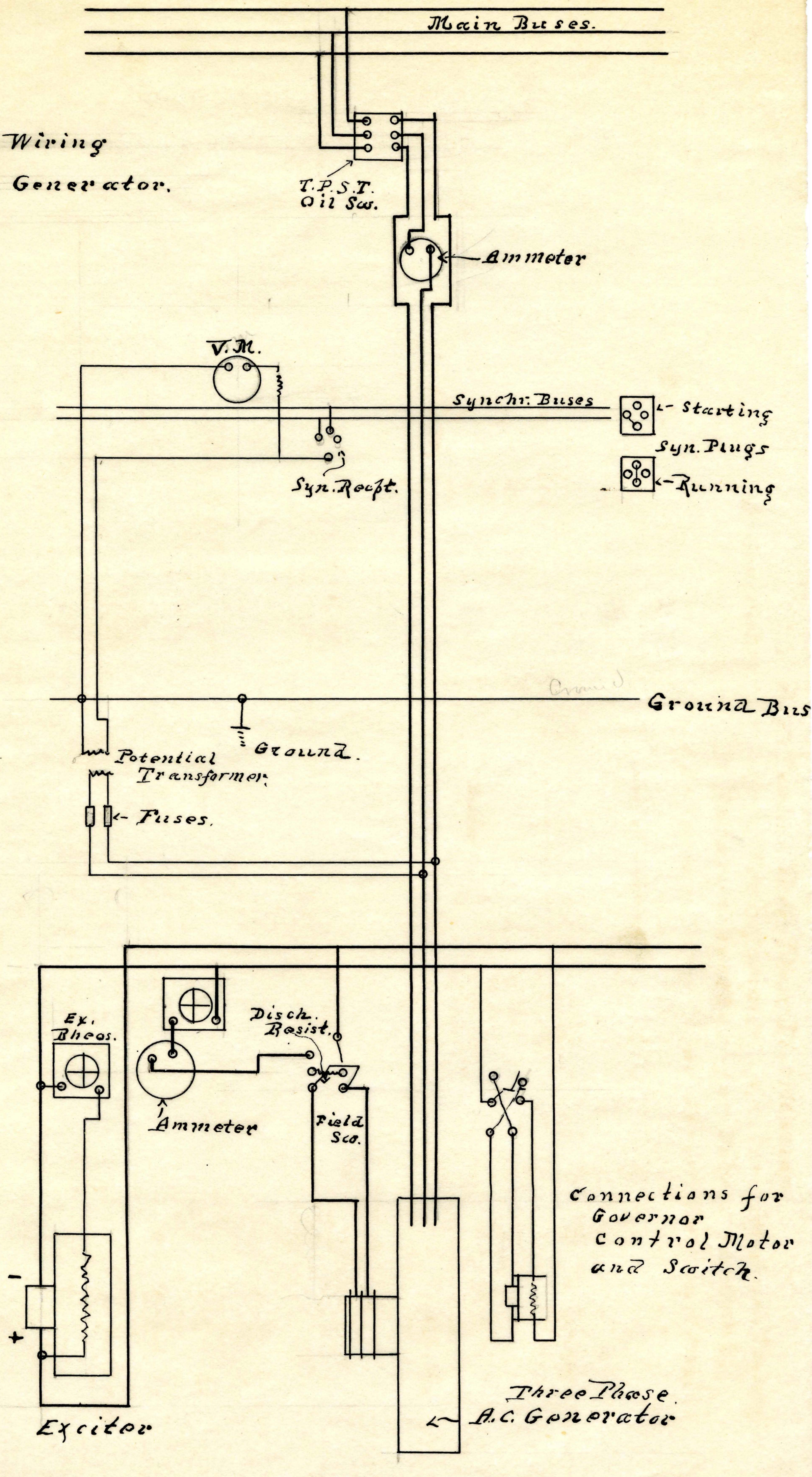


Diagram of Connections for three Three-Phase Generators.

Switchboard Wiring

Three Phase Generator.



High Tension Three-Phase Distribution

A = Generator. B = Step-up Transformers. C_1 C_2 C_3 = Step-down Transfs.
M = Sync. Motor. D = Rotary Converter for Direct Current.
S.B = Storage Battery or Street Rwy System.