Westinghouse

Frequency-Converters

INSTRUCTION BOOK

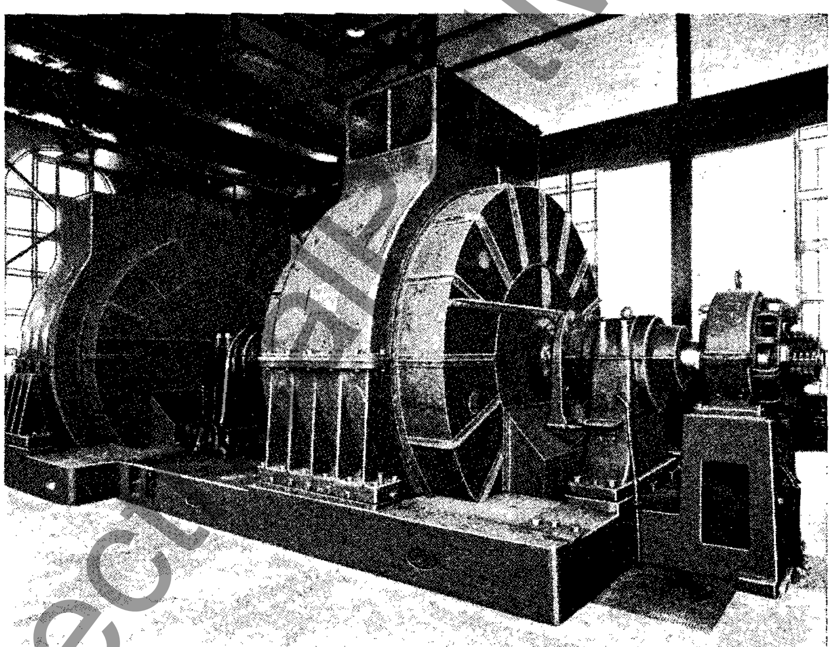

FIG. 1—13,900 KV-A. FREQUENCY-CONVERTER

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INTRODUCTION

A frequency converter is a combination of two or more machines which converts the power of an alternating current system from one frequency to another, with or without a change in the number of phases, or in voltage. The scope of this instruction book is confined to "fixed ratio" frequency converters in which the frequency on one machine bears a certain fixed ratio to that on the other machine.

Fixed ratio frequency converters may consist of two synchronous machines or one synchronous and one induction machine. The latter type has not, strictly speaking, a fixed ratio between its frequencies due to the slight change in slip of the induction machine as the load changes. However, as the term is used here it distinguishes between frequency converters having a ratio of frequencies which is essentially constant and those in which the ratio may be varied through a wide range by means of auxiliary apparatus. The majority of applications require a synchronous-synchronous frequency converter; this instruction book will deal largely with the synchronous type although, where essential differences exist between the synchronous and induction types, exceptions will be made to cover the latter.

As discussed in later sections dealing with the flow of power through frequency converters, the synchronous set cannot in any way affect the transfer of power between the connected systems. Since a fixed ratio must be maintained between the two mechanically connected machines, the frequencies on the two systems cannot change their relative values. In other words, if the frequency of one system changes, the other must follow it. In the readjustment, however, sufficient power must flow through the set to bring about equilibrium, and before the final conditions are established a transient condition is set up which causes a surging of power through the set. For instance, if one system starts to speed up, the machine on that end of the set will try to follow, but the machine on the other end will endeavor to stay with its system. The result of one machine tending to speed up and the other holding back is that the set becomes more heavily loaded. If sufficient load can be transferred through the set to relieve the second system of an appreciable amount of load, the inherent regulation of the prime mover governors will cause the system to speed up. The first system now supplying more load will drop back somewhat and a steady-state condition between these two extremes will eventually be established. Due to inherent inertia of the systems and machines involved, however, this point of equilibrium will be reached only after some oscillatory transfer of power through the set.

Such transient disturbances take place whenever the frequency on one system changes, and since it is impossible to hold the system frequency absolutely constant, the frequency converter must be applied with this in mind. In order to insure satisfactory operation, the set must be capable of passing sufficient power to cause the smaller system to follow along behind the larger. Any set has a certain pull-out point, beyond which it cannot be loaded, and the power surges through the set, during the transient condition, must be kept below this point if the systems are to remain connected. Therefore, it is necessary to use a set of sufficient size to keep the surges below this limit. The exact size depends upon severity of the transients, quality of the frequency regulation, type of the prime movers, characteristic of the load, and the design of the converter. With so many factors involved, it is very difficult to decide on the size of the set and past experience must be relied upon to give the answer.

It has been found in the past that in order to ride through minor disturbances encountered in average operation and insure adequate performance, the rating of the frequency converter to tie two central station systems together should be at least 10% to 15% of the generator capacity normally in operation on the smaller system when the prime movers are mainly steam turbines; and 15% to 20% when the prime movers are mainly waterwheels. Where the load of the smaller systems consists primarily of railway load the capacity of the frequency converter should be of the order of 30 to 40% of that system to insure satisfactory performance.

Even with sets of this size it cannot, of course, be expected that the two systems will be held together during major disturbances such as a severe short circuit, but the degree of stability will ordinarily be satisfactory if these limits are adhered to. A fixed ratio induction set will be less likely to pull out, because of the cushioning effect of the drop in speed as the load increases. However, the difference is not great and the other advantages of the synchronous set, such as adjustable power factor, high efficiency, constant speed and reversible operation, are usually considered sufficiently important to swing the choice to a synchronous set.

Frequency converters of the type considered, unlike a static transformer, form only a mechanical and not an electrical tie between two systems. Any disturbance on the one system is, therefore, isolated from the other, except for the effect of the change in power flow through the set which is ordinarily not important. For instance, the rupturing duty of the breakers on one system is not affected by the connected generating capacity of the other system.

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Frequency-Converters

Construction

General

The smaller sets are built with the two machines mounted on a single bedplate and with three pedestal-bearings for supporting the rotors. The shafts are coupled together solidly with either cast iron couplings which are pressed on the shaft ends or, more often, with flanges which are forged as part of the shafts.

Large sets have four pedestal bearings with the shafts coupled together between the two center bearings.

Exciters

Exciters may be mounted on either or both ends of the set. The exciter frame is usually supported by a stand which is bolted to an extension of the bedplate. This allows the stand and the exciter stator to be removed in case it becomes necessary to remove one of the main rotors for repairs. The exciter armature may be mounted on an extension of the main shaft or on a small shaft coupled to the end of the main shaft.

Ventilation

Small sets are usually constructed so that ventilating air is drawn in directly from the room and, after passing through the machine, is discharged back into the room.

For larger sets the incoming air may be drawn through enclosing end bells which are connected to ducts leading to a source of cool air. After passing through the machine the air is discharged through a single opening in the frame to which a duct may be attached for discharging the air out of the building.

Fans

Fans or blowers are attached to the rotors of most generators and motors to assist in forcing ventilating air through the machines. In some cases these are straight radial vanes each of which is bolted to the rotor. For other machines a completely assembled blower having inclined blades is bolted to each side of the rotor. The blades are inclined in such a way that they are not radial, the edge of the blade nearest the shaft being ahead of the outer edge in the direction of rotation. It is important that the set be run in such a direction that this relation is obtained since the amount of air delivered by the fan is greatly reduced when it is run in the opposite direction.

Bedplates

The bedplates are fabricated from structural steel beams. For very large sets it may be necessary to make the bedplate in sections bolted together or to use separate side rails and end rails which are not joined at the corners but which are mounted separately on the foundation. Cast iron bedplates were used formerly but these have been superseded by the fabricated steel structures. The cross member of the bedplate which carries the center pedestal bearing of a three-bearing set is sometimes made removable. This allows greater accessibility when repairs are made. Four-bearing sets have two cross members or bridges for the two center pedestals and these are always removable. It is sometimes necessary to support the bridges in the center by means of vertical columns which extend into the pit and rest on concrete piers. These are bolted to sole plates at the bottom and to the bridge at the top.

Bearings

The bearings are lubricated by means of oil rings. There are openings at the top of the bearing cap which permit inspection of the rings. The oil level can be determined by raising the spring cover on the sight hole which is provided on the pedestal, or, in some cases, by a sight gauge. There is a drain plug which allows all of the oil in the reservoir to be removed. For large high speed machines it is often necessary to water-cool the bearings. Water inlet and outlet pipe connections are attached to the bearings in these cases. Large sets are provided with a high pressure oil system for lubricating the bearings during starting. A small inlet pipe and a larger return pipe are furnished with the bearing when this system is used. In some cases a gravity oil feed system is used and an additional inlet pipe is furnished. The outlet for the gravity feed system is through the same return as is used with the oil lift system.

Insulated Pedestals

Slight variations in the magnetic circuit of an a-c. machine may cause a periodic change in the amount of flux linking the shaft. The result of this is that a small voltage is generated in the shaft which tends to set up a current through the circuit formed by the shaft bearings and bedplate. If such a current is allowed to flow it soon has a destructive effect upon the journals and bearings. Small pits are usually formed on the surface of the shaft and these are sufficiently rough to score the surface of the bearing. Occasionally, the babbitt itself appears to be eaten away by the current.

To avoid this trouble certain of the pedestals are insulated from the bed-

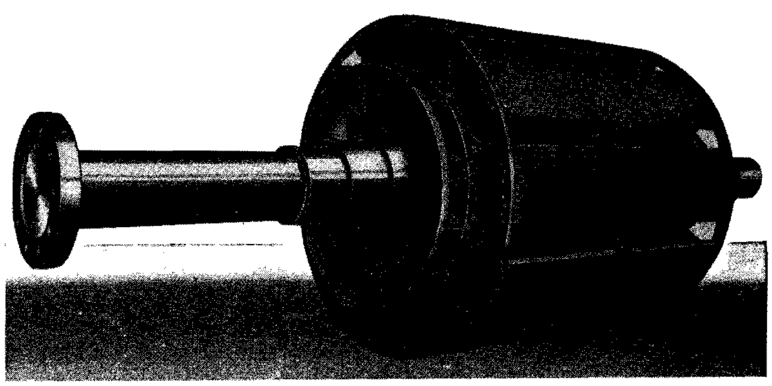

Fig. 2—Rotor Completely Assembled

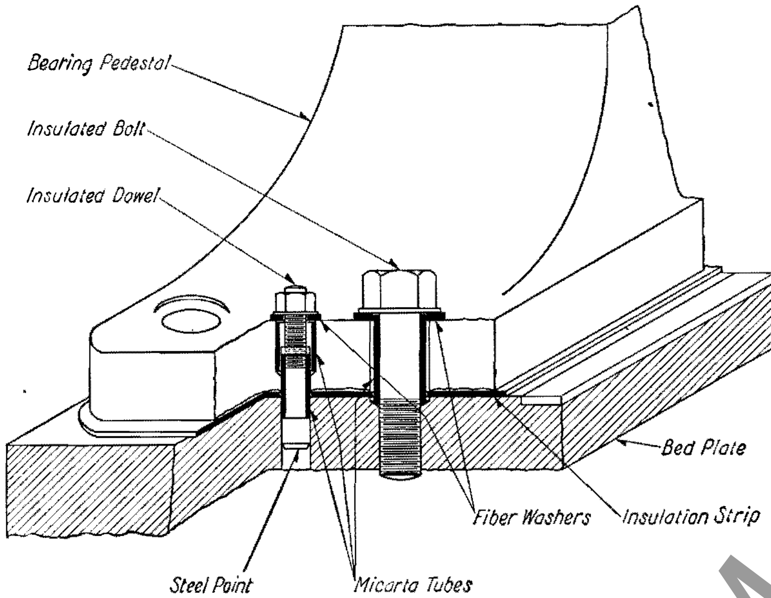

FIG. 3—METHOD OF INSULATING BEARING PEDESTAL FROM BEDPLATE

plate so as to break up the flow of current. Usually, the two-end pedestals are insulated, although this practice varies with the design of the particular set involved. A sheet of insulation about $\frac{1}{16}''$ thick is placed between the bottom of the pedestal and the bedplate, and insulating tubes and washers are used around the bolts and dowels as shown in Fig. 3. If water or oil piping is connected to the bearing, an insulating union is used. Care should be taken to see that there is no metallic connection between an insulated pedestal and the bedplate. If this precaution is not observed, the insulation becomes useless and bearing current is permitted to flow. Such metallic connection may be any of the following: Piping which touches both the pedestal and bedplate and which has no insulating union; guard rail; metal ladder set against the pedestal; tools left in contact with both pedestal and bedplate; pump or other device geared to the main shaft. A break in the insulation may occur during erection due to careless handling and it is well to test for this with a bell and battery or with a test lamp. If a machine has bearing currents it is usually possible to detect this by placing one end of a copper wire on the pedestal and by touching the other end on the shaft from which sparks can be drawn. The wire simply shunts part of the current which otherwise flows through the bearing surfaces

Many of the smaller sets have very little tendency to produce bearing currents and these may be operated safely without pedestal insulation. No insulation is furnished with machines in this class.

Movable Stator

When two synchronous sets are to be operated in parallel the stator of either the motor or generator of at least one of the sets is mounted in a cradle which permits it to be rotated through a few degrees. This arrangement is necessary in order to obtain the proper phase relation between the generator voltages as explained on page 2. When the sets are put into operation and the correct stator position is found, the frame is doweled and bolted down to its cradle base so as to prevent further movement. In some of the larger sets it is desirable to rotate the stator during operation so as to be able to control the division of load between the sets which are in parallel. This is needed principally when one set is being put into service or when one set is about to be shut down. To fill this requirement, a small auxiliary motor and suitable gearing are used to move the stator in its cradle. (See page 16.)

Oil Pressure for Starting

The use of a high pressure oil system reduces the starting friction of large frequency converters and permits the use of lower starting voltages and currents. The equipment consists of a four-cylinder pump driven by a small motor and the necessary piping, including inlet and return pipes.

The pressure developed by the pump is about 1000 lbs. per square inch which is sufficient to lift the shaft from the bearing and provide a perfect oil film.

If any of the bearings are insulated from the bedplate the piping connected to them should be equipped with insulating unions.

Methods of Disassembly for Repairs

The following general directions for removing the stators and rotors or for making them accessible for repairs apply to machines of standard design. For sets having special constructional features, there may be exceptions to these rules.

Large Four-Bearing Sets

Remove the bearing and pedestal which are between the main coupling and the machine to be repaired. The weight of the rotor can be supported from the coupling when the bearing is removed. Remove the bridge on which the pedestal rests, and if there are supporting columns under the bridge these must be taken out also. The end bells should be removed and the stator shifted toward the center until the windings are clear of the rotor. Both rotor and stator are then accessible for repair.

Three-Bearing Sets

(a) For cases in which either of the rotors is too large in diameter to be entirely removed from the stator, due to interference with the end member of the bedplate, the center bridge is made removable. This allows the center pedestal and bridge to be taken out and the stator of either machine to be shifted toward the center a sufficient distance to clear its rotor. The coupling bolts should be removed before the bearing is taken out so as to prevent an excessive strain on them. The rotor of the machine to be repaired should be supported at the inner end by a rope from a crane or by jacks or blocking from below. The other rotor may be allowed to rest against the stator.

(b) When both rotors are small enough in diameter to clear the bedplate the center bridge is not removable and the rotors should then be taken out of the stators in a direction away from the center. If there is a direct connected exciter it is necessary first to remove the exciter frame and its supporting stand. If the exciter rotor is coupled to the main shaft it should be removed also.

Leads

The arrangement of leads for various type of windings is shown in Fig. 5. The leads are brought out normally at the bottom of the frame on the collector end of the machine and are equipped with terminals into which the purchaser's cables may be inserted.

Phase Sequence

The phase sequence, or phase rotation as it is sometimes called, is in the order of T_1, T_2, etc., when the mechanical rotation is in a clockwise direction viewed from the collector end of the machine. When the rotation is counter-clockwise, viewed from the collector end, the phase sequence is in the reverse order. Since the collector of each machine of a frequency converter set is on the outside end, one machine always rotates clockwise and one always rotates counter-clockwise.

Installation

General

The following instructions and precautions are intended to aid in the installation of frequency-converters. In many cases the instructions are of a very general nature since the wide variety of types and sizes and the numerous special features that may be included make it difficult to give detailed instructions that are applicable to all units. The services of an experienced erection engineer are invaluable and must be relied upon for a great many of the details of installation. For diagrams of connections, see Figs. 18 and 19.

Foundations

The foundation should consist of solid concrete walls or piers whenever possible and should be carried down far enough to rest on a solid sub base. A competent engineer who is familiar with local conditions should lay out this part of the work. If it is necessary to support the bedplate on steel work instead of concrete, the girders should be well braced and supported by columns so as to prevent vibration.

The pits beneath the machines should be made deep enough to give plenty of working space for connecting the leads. They should be properly drained and if possible should be ventilated.

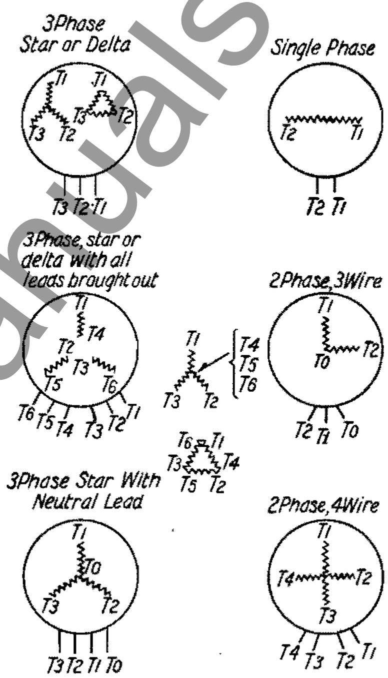

FIG. 5—STANDARD ARRANGEMENT OF LEADS FOR VARIOUS WINDINGS

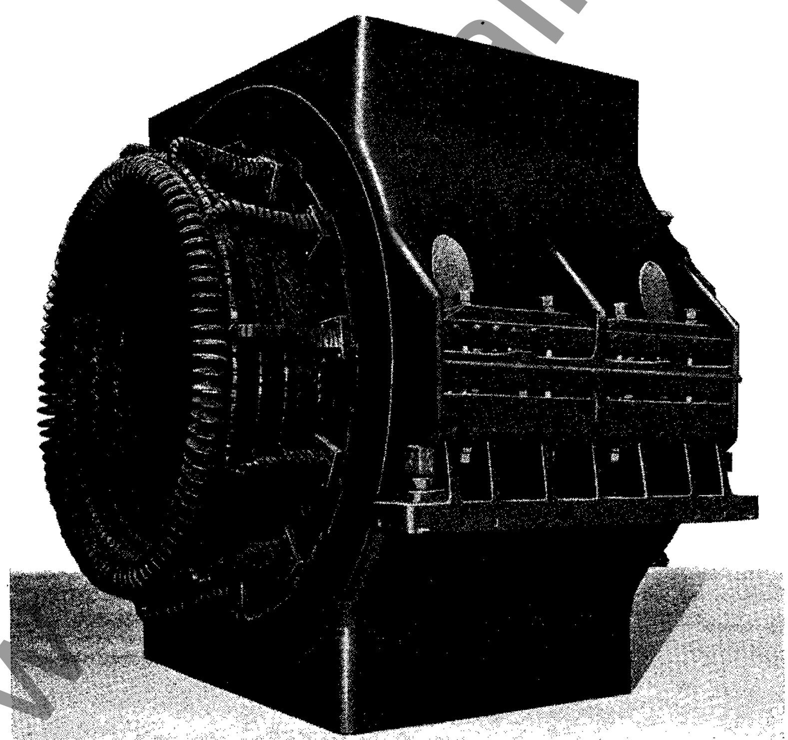

FIG. 4—STATOR—SPRING MOUNTING

Spring Mounted Stator

Spring mounted stators, shown in Fig. 4, are used for large single phase synchronous machines. All single phase generators develop an oscillating torque which in machines of certain sizes and speeds results in a severe vibration of the bedplate and the surrounding structures. In order to overcome this difficulty the stator is mounted on a set of springs, consisting of rectangular bars of steel, which prevents the vibration from reaching the foundation.

Erection

Addenda

Aligning Motor-Generator Sets

When considering the installation of motor-generator sets, such apparatus may be divided into two general classes, namely:

(1) Units shipped assembled.
(2) Units shipped unassembled.

Each class may again be divided into two-bearing and multi-bearing units.

Two Bearing Units—The aligning and leveling of two bearing units that have been shipped assembled is a relatively simple operation. The unit should be placed on the foundation with the bedplate resting on steel plates, shims or wedges. These supports should be of sufficient height to permit satisfactory grouting and they should be so located that they will carry the weight of the pedestals, rotor and the frame without distorting the bedplate. The unit should be brought into alignment with, and also leveled to the elevation of other apparatus or "bench marks" as required. The foundation bolts must have sufficient freedom of movement to permit such alignment. The pedestal caps should be removed so that the bearing alignment may be checked. Most satisfactory results in leveling horizontal electrical apparatus are usually secured by using a very accurate spirit level on the shaft or bedplate pads. It is sometimes desirable to use a piano wire "line" in checking the alignment of the pedestals or the stator bore, or in determining if the bedplate is distorted, but this is seldom necessary when a two bearing unit is being installed.

When the alignment (including the level) is satisfactory the nuts on the foundation bolts should be tightened snugly and the level should be again checked to make sure that the bedplate has not been distorted. If this check is satisfactory, the bedplate should be grouted. When the grout has hardened the nuts on the foundation bolts should be drawn down tight.

The grouting should be carried up nearly to the top surface of the bedplate so as to give rigid support for the machine. (See Figure X).

Multiple Bearing Units—All standard modern multiple bearing motor-generator sets are made with two separate shafts bolted together by the use of flanged couplings. These couplings may be either of the pressed on type or with half couplings forged integral with the shaft.

Multiple bearing units may be classified for methods of shipment and alignment as:

1. Small motor-generator sets.
2. Large motor-generator sets.

Small Motor-Generator Sets—Standard units of this classification are provided with three main pedestal type bearings. When additional bearings are provided for exciters they are usually of the bracket type. This classification covers units that may be shipped with the main elements assembled. They will have a maximum rating of approximately 1500 kv-a., although this will depend to a considerable extent on the speed, which of course directly affects the dimensions and weights, which in turn control the method of shipment.

The method previously described, for aligning two bearing motor-generator sets should be used in the preliminary alignment of three bearing units. Before grouting the bedplate, however, the shaft alignment must be checked. Since the coupling faces are always machined perpendicularly true to the shaft axis, the shaft alignment can be checked very satisfactorily by loosening the coupling bolts and "breaking" the coupling so that a thickness (feeler) gauge may be inserted between the half coupling faces. The factory allowable tolerances for such alignment are:—

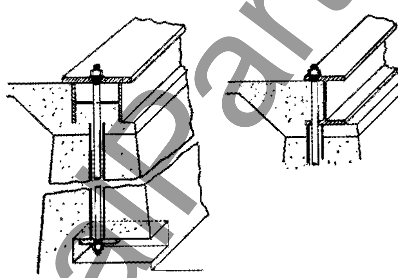

Fig. X—Setting of Structural Steel Bedplates

(A) The difference between the readings at either side—.001″ for any size flange.

(B) The difference between the readings at the top and bottom—not to exceed .002″ per 12″ of flange diameter, but a maximum of .004″ for any diameter of flange.

If the opening at the top and bottom of the coupling faces are not uniform the larger opening must always be at the top.

When the small motor-generator sets are being aligned, the adjustments to secure top and bottom flange alignment are made by elevating the ends of the bedplate. Care must be used to insure both ends being raised as near as possible the same amount.

During the coupling alignment the shafts should be rotated in the bearings 180° from the original checking position and the coupling separation should be re-checked at top, bottom and sides to again prove the shaft alignment and the truth of the coupling faces.

Large Motor-Generator Sets—As it concerns shipment and installation methods, this classification covers units that because of weight and dimension limitations must be shipped unassembled. The bedplate for a large motor-generator set should be aligned and leveled and it is usually grouted in before the various parts of the unit are assembled on it. These parts are assembled in accordance with regular practice for apparatus of this type. The final alignment is secured as described for small multiple bearing motor-generator sets except that the bedplate is maintained level from end to end and the shaft coupling faces are brought into alignment by the adjustment of the bearing pedestals by means of the use of steel shims between the pedestal and the bedplate pads. The tolerances given for small motor-generator set couplings also apply to large motor-generator sets.

Briefly, the steps for alignment are as follows:—

Small Motor-Generator Sets Shipped Unassembled—

1. Set the bedplate approximately level.
2. Mount the bearing pedestals, taking care to match the center line markings.
3. Mount the stators and rotors in the conventional manner.
4. Open the couplings enough to allow checking with a feeler gauge between the coupling faces.
5. Adjust the alignment to the following allowances:
   A. The allowable tolerance at either side is .001″ for any size flange.
   B. The allowable tolerance at the top or bottom is not to exceed .002″ per 12″ of flange diameter with a maximum of .004″ for any flange diameter.

Note—The adjustments to secure top and bottom flange alignment are made by elevating the bedplate. Care must be used to insure that both ends are raised an equal amount. If the opening at the top and bottom coupling faces is not uniform, the larger opening must always be at the top of the coupling.

6. Rotate the rotors in their bearings 180° from the original checking position and repeat the measurements made with the feeler gauge to prove the shaft alignment and the truth of the coupling faces.

Small Motor-Generator Sets Shipped Assembled—The same steps should be taken as for sets shipped unassembled with the exception of 1, 2 and 3 being omitted.

Large Motor-Generator Sets Shipped Unassembled—Large motor-generator sets are to be assembled much the same as the small motor-generator sets except that the bedplate must be equally level at all times.

To secure coupling alignment an equal amount, as near as possible, of sheet steel shims should be placed under both outboard pedestals. The same tolerances apply to all machines regardless of size.

The division line between small and large motor-generator sets is approximately 1500 kv-a., but will vary to some extent with the speed.

Insulation Resistance

The insulation resistance of windings is measured, usually, with an instrument called a megger. This measurement gives an indication of the condition of the insulation particularly with regard to moisture and dirt. The actual value of resistance varies greatly in different machines depending on the size and voltage. The chief value of the measurement therefore, is in the relative values of resistance of the same machine taken at various times. During a drying out run, for example, the insulation resistance rises as the winding dries out. When measurements are made at regular intervals as part of the maintenance routine, it is thus possible to detect an abnormal condition of the insulation and take steps to remedy it before a failure occurs.

The insulation resistance of stator windings of machines in good condition is usually not less than the following:

$$\text{Insulation Resistance (in megohms)} = \frac{\text{machine voltage}}{\text{Rated Kv-a.} + 1000}$$

Protection

The machines should be protected carefully against moisture both before and after erection. Water or steam from leaking pipes, rain, snow or condensation from the atmosphere should be excluded. It is particularly important to keep the windings dry since moisture lowers the insulation resistance and increases the likelihood of a breakdown. If a machine is brought from cold surroundings into a warm room, it should be kept covered until its temperature has risen to room temperature so as to prevent condensation on the windings and other parts. (See page 7 for methods of drying out windings.)

Care should be taken in transporting and handling the machines to see that the windings are not damaged. A blow upon any part of the windings is liable to injure the insulation and result in a burn out of the coil.

Lifting of the machines by cranes should be done with the greatest care. The stators are usually provided with lifting holes in the sides of the frame into which the crane hooks may be inserted. The rotors should be lifted preferably with rope slings looped around the shafts. In no case should the ropes or chains be allowed to exert pressure on the windings or collector rings. The entire set should never be lifted by the bedplate since the bedplate has not sufficient strength to carry the weight except when it is resting on a solid foundation. In the case of small sets which are shipped assembled and are to be lifted as a whole the crane hooks should be attached to the stator frames and one or more pieces of heavy timber should be wedged between the two frames at the top to prevent distortion.

Drying Out Windings

If there is reason to believe that the windings have been exposed to moisture during shipment or erection, it is well to subject them to a drying process

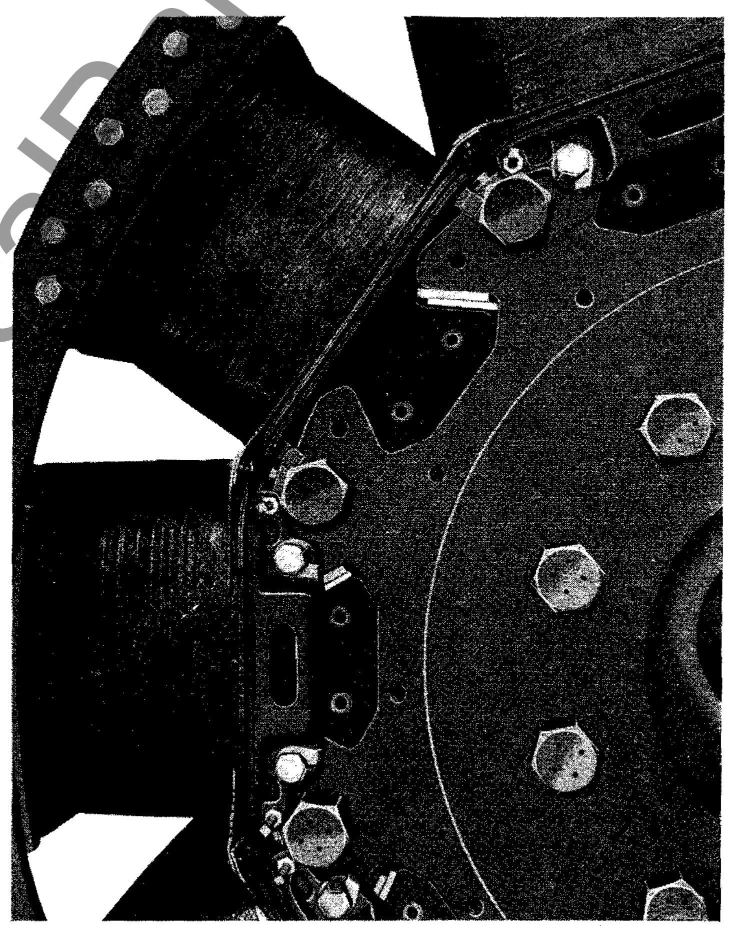

Fig. 6—Plate Rotor, Details of Lower Coil Supports and Coil Wedges

before putting the machine into regular operation. The windings can be dried by passing current through them or by the use of external heat.

One way of circulating current through the windings without subjecting them to full voltage, is to drive the machine and short circuit the armature applying enough field excitation to give somewhat less than full load armature current. This implies that the other machine of the set can be used as a dribing motor, but if both machines are in need of drying, as is usually the case, this method is not applicable. That is, the drying process should not involve subjecting either machine to full voltage.

A second method is to apply a low voltage, from an external source, to the armature winding. If the current is kept down to less than full load current there is a possibility that the machine will not rotate. If it does not rotate or if it rotates at less than synchronous speed, the damper winding should be watched to see that it does not overheat. The field winding should be short circuited during the drying operation.

In all cases of drying by means of current in the windings, the temperature measured by thermometer should not be allowed to exceed 65°C. If the temperature is measured by imbedded temperature detectors it may be allowed to go as high as 80°C. In general, the drying should proceed slowly at first and the heating gradually increased as the insulation dries. It is well to take readings of insulation resistance by means of a megger at intervals as this gives a good indication of the state of the insulation.

In many cases, it is impracticable to dry the windings by heat generated within the machine and external heat must be used. A tarpaulin should be used to cover the machine and some source of heat, preferably electric heaters, placed within the enclosure. In the case of machines having external fans or blowers, the heaters can be placed in the incoming air stream.

Operation

Starting a Synchronous Frequency-Converter

If the machine is equipped with a high pressure oil system to reduce starting friction the oil pump should be started first. Full pressure will be built up, normally, in a few seconds.

A-C. Self-Starting—Close the starting switch applying reduced voltage from the starting transformers to the stator windings. During this time, the field winding should be closed through a short-circuiting switch, or, if the motor has a direct connected exciter, it may be connected across the exciter terminals. A rheostat may or may not be in the circuit with the field in either case. In no case should direct-current be applied to the field when the machine is to be started, nor should the field be left open circuited.

When the machine has begun to turn freely the oil pump may be shut down.

When approximately full speed has been attained, the field winding should be excited. If the field is connected directly to the terminals of the direct connected exciter, the excitation is applied automatically.

The running switch can then be closed transferring the machine from the starting voltage to full line voltage.

The alternative method of switching to full voltage first and then applying the exciting current, is sometimes used. With this method, there may be less line disturbances when the full voltage is applied if the switching arrangement is such as to open the circuit during the transfer for an appreciable interval.

The generator field may be excited now and if the generator does not parallel with other generators, the main line switch may be closed.

If the generator is to be paralleled with other generators or with a power system, it is necessary to synchronize before the line switch is closed. (See Synchronizing.)

This means that the opertaor should have control of the speed of the prime movers of one of the power systems so that the voltages may be brought to exact phase coincidence before the switch is closed.

If the generator is to be paralleled with the generator of another synchronous frequency converter, it is necessary to bring the voltages into phase, or as nearly so as possible by the method described on pages 10 to 16.

Motor Starting—In cases where system operation will not permit the Kv-a. inrush required for A-C. self-starting, a starting motor is coupled to one end of the shaft. Induction motors of the variable speed wound rotor type are used for this service.

The control consists of a secondary resistance with several operating points secured by panel mounted contactors. The contactors are closed by a combination current limit and time acceleration, controlled from the switchboard.

Closing the main circuit breaker to the starting motor starts the motor and completes the circuit for the operation of the "Increase" and "Decrease" control switch on the secondary control. In the "Increase" position the motor operated timing relay is started and after a definite time interval closes the first contactor which cuts out a section of resistance provided the secondary current has decreased to the setting of the current limiting accelerating relay. The contact of the current limit relay is in series with that of the timing relay and the coil of the next contactor so that both must be closed before the contactor operates.

If the control switch is held in the "Increase" position for an instant then released the control will advance one step and if held in that position the contactors will close in the proper sequence up to full speed of the motor. The "Decrease" operation is the reverse of the above. In order to have a visual indication of the steps of the control equipment a lamp may be mounted on the switchboard to blink as each point is passed.

The control is arranged as shown in Fig. 19 so that if the motor breaker opens, full resistance will be inserted in the rotor circuit.

When the speed of the converter has approached synchronous speed the starting operation is the same as given for A-C. self-starting.

Starting an Induction Motor Driven Set

An induction motor which is part of a frequency converter set is usually started by means of a secondary controller. Full line voltage is applied to the stator windings with the starting resistance connected across the secondary terminals. The controller decreases this resistance in several steps as the motor speeds up.

After full speed has been reached, the synchronous machine should be excited so as to give rated voltage. If it is to parallel with other generators or with a power system, it must syn-

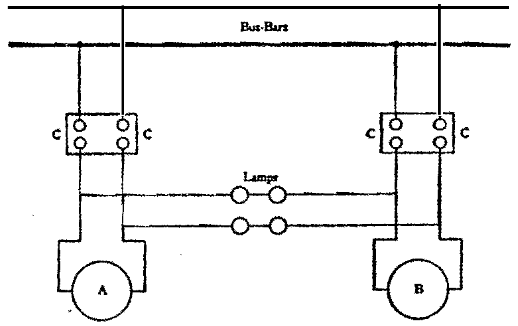

Fig. 7—Connection for Synchronizing Low Voltage Single Phase Generators

chronize before the line switch is closed. If the frequencies of the two systems are in the correct ratio, or nearly so, synchronizing will not be difficult. If the ratio is not correct, it will be necessary to adjust the frequency of one system.

Synchronizing A-C. Generators

The condition to be fulfilled in order that synchronous apparatus may be connected to a system already in operation is that the electromotive forces of the incoming machine and of the system to which it is connected shall be approximately the same at each instant. This requires that the frequencies be the same; that the two voltages be equal, as indicated by a voltmeter, and that the two voltages be in phase.

The elementary principle employed in determining when generators are at the same frequency and in phase is illustrated by Fig. 7 in which A and B represent two single-phase generators. The leads are connected to switches C and two series of incandescent lamps are connected as shown. The switches are left open as the electromotive forces change from the condition of phase coincidence to that of phase opposition, the flow of current through the lamps varies from a minimum to a maximum.

When the electromotive forces of the two machines are exactly equal and in phase, the current through the lamps is zero. As the difference in phase increases, the lamps light up and increase to a maximum brilliancy when corresponding phases are in exact opposition. From this condition the lamps will decrease in brilliancy until completely dark, indicating that the machines are again in phase. The rate of pulsation of the lamps depends upon the difference in frequency, i.e., upon the relative speeds of the machines.

When the voltage of the system is too high for any of the synchronizing apparatus it is usual to place voltage transformers between the main circuits and the synchronizing circuits to reduce the voltage at the switchboard to safe limits, as shown in Fig. 9.

If the connections of either the primary or secondary of either transformer be revered from those shown in the diagram, the indications of the lamps will be reversed, i. e., when the generators are in phase, the lamps will burn at maximum brilliancy and vice versa. In order to make certain that the lamps will be dark instead of bright when the machines are in phase, disconnect the main leads of the first generator at the generator and throw in the main switches of both generators with full voltage on the second generator. Since both machine circuits are then connected to one machine, the lamp indication will be the same as when the main or paralleling switches are open and both machines are in phase. If the lamps burn brightly and it is desired that they be dark for an indication of synchronism the connections of one of the voltage transformer primaries or one of the secondaries should be reversed. **Dark lamps as an indication of synchronism are recommended.** The lamps should be adapted for the highest voltage which they will receive, i.e., double the normal voltage.

Phase Sequence

In the case of polyphase machines, it is not only necessary that one phase be in synchronism with one phase of another generator but the sequence of maximum values of voltage in the several phases must be the same. The phase sequence must therefore be checked. The necessary connections for two three-phase generators are shown in Fig. 9.

Connect the generators temporarily to their switches, but with the switches open, so that the phases of D will be in parallel with those of E. Connect synchronizing apparatus in any two phases. Test out the synchronizing connections with machine D running at normal speed and voltage, the leads disconnected from E at the generator, and the paralleling switches closed. Having changed the synchronizing connections, if necessary, so that both sets of lamps will be the same when indicating synchronism, open the paralleling switches, reconnect the leads of machine E and bring it up to normal speed and voltage. Then observe the two sets of synchronizing lamps. If their pulsations come together, i.e., if both sets are dark and both are bright at the same time, the phase sequences of the two generators are the same, and the connections are correct for paralleling the generators when the lamps are dark. If, however, the pulsations of the lamps alternate, i.e., if one is dark when the other is bright, reverse any two leads of one machine and test out the synchronizing connections again, changing them if necessary so that they are the same when indicating synchronism. The lamps will now be found to pulsate together and the generators may be thrown in parallel at the proper indication. Synchronizing apparatus in one phase only is sufficient for paralleling the generators after the first time.

The procedure in synchronizing a generator with an existing power system is the same, the phase sequence of the generator being changed, if necessary, to agree with that of the system.

The paralleling of two-phase generators is accomplished in a similar manner. In case of incorrect sequence the two leads belonging to either phase must be reversed instead of any two leads.

Synchronoscope

A synchronoscope is an instrument that indicates the difference in phase between two electromotive forces at every instant. By its aid the operator can see whether the incoming machine is running fast or slow, what the difference in speed is, and the exact instant when it is in synchronism. These conditions cannot be observed with certainty by the use of lamps alone.

The synchronoscope has a pointer which shows the phase angle between the incoming and running machines. This angle is always equal to the angle between the pointer and the vertical position marked on the dial of the instrument. When the frequencies of the two machines are equal the pointer stops at some position on the scale and when the machines are in phase the pointer coincides with the marker at the top of the scale.

In order to check the synchronoscope connections, proceed in the same manner as previously described for determining whether lamps will be right or dark for a given synchronizing connection. If the synchronoscope pointer stops at the bottom, reverse the leads at the upper terminals. If it stops in the same position the connections to the upper terminals are made to the wrong phase.

Field Current Adjustment

I. Motor—The power factor of any synchronous motor may be controlled by varying the field current. Motors are rated at either 100 per cent power factor or at some leading power factor, usually 80 per cent. The field current necessary to give the rated power factor at full load is recorded on the motor nameplate. If the maximum leading kv-a. is wanted at all times, the field current should be set at this value even though the load is less than rated output. With this excitation motors that are rated at 100 per cent power factor will give a small amount of leading kv-a. at reduced loads. A machine of usual proportions will have about 30 per cent reactive kv-a. at no load and this will decrease to zero reactive kv-a. at full load. A motor rated at 80 per cent power factor has 60 per cent reactive kv-a. at full load. If the excitation is kept constant, the reactive kv-a. increases slightly as the load is reduced, rising to about 75 per cent of rated kv-a. at no load. The total kv-a. is reduced, from 100 per cent to 75 per cent as the load decreases.

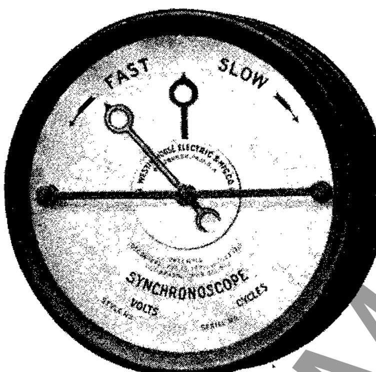

Fig. 8—Synchronoscope

If there is no need for supplying reactive kv-a. the excitation may be adjusted so as to maintain 100 per cent power factor at all times. This will result in minimum losses and highest economy. There is one objection, however, to lowering the excitation below the rated value and that is the reduction of pull out torque. A machine rated at 80 per cent power factor and operated at 100 per cent power factor, may pull out of step with a fairly small increase in load whereas a motor rated at 100 per cent power factor usually has a momentary overload capacity of at least 50 per cent.

An increase in field current will increase the pull out torque. Thus, in an emergency, a motor could be made to hold in step at a considerable overload by overexciting the field. The length of time that this could be continued is limited by heating.

II. Generator—Field current adjustment of a generator which is paralleled with other generators, produces results similar to those described for synchronous motors. With a given kilowatt load, an increase in field current beyond that required to unity power factor, increases the reactive kv-a. and relieves the other generators of part of their burden of kv-a. If the kilowatt load varies over a wide range, it is permissible to set the field at the rated value, just as for the motor, and allow the power factor to vary.

The phenomenon of pull-out occurs with a generator just as with a motor. In the case of a generator, however, the machine is forced above synchronism by an excess driving torque if the field current is low. In order to carry momentary load peaks, it is essential that the excitation be kept at its rated value.

III. Effect on Load Division of Parallel Sets—The effect of variation of the field current of either motor or generator on the load division between parallel sets is discussed on page 14.

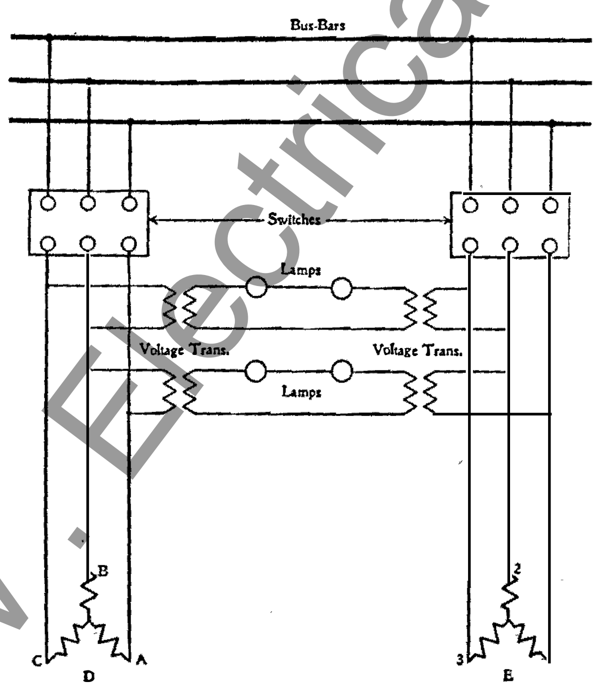

Fig. 9—Connections for Synchronizing Three-Phase Generators

Unbalanced Voltage and Single Phase Operation

The ability of a synchronous motor or generator to operate on unbalanced voltage or, in the extreme case, to operate single phase, depends largely on the design of the amortisseur or damper winding. Single phase operation produces heavy currents in the damper winding, if there is one, which may cause overheating in a machine not designed for such operation. If there is no damper winding, the field current required for a given load is increased to such an extent that the output is seriously

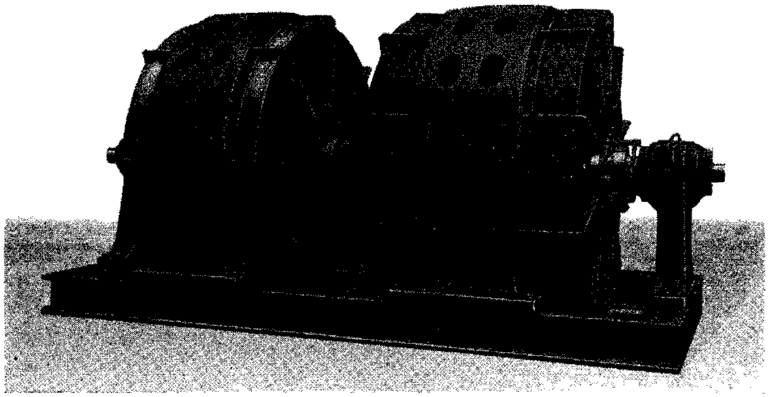

Fig. 10—1540 Kv-a. Frequency-Converter

limited. Vibration of the stator and surrounding parts may also result from single phase operation. See page (5). Operation as a motor with unbalanced voltage, or as a generator with unbalanced load, has the same effect as single phase operation but in a less degree.

For machines not designed for single phase operation, 20 to 30 per cent of normal current single phase is usually safe. Higher values may be permissible if the damper winding is liberal. The degree of unbalanced polyphase operation that is permissible depends likewise on the design of the individual machine. In any case of unbalancing of more than five per cent at full load, it is advisable to watch the temperatures of all parts closely.

Flow of Power Through a Synchronous Frequency-Converter Connecting Two Power Systems

The direction and magnitude of the flow of power from one power system to another through a synchronous frequency-converter, is independent of the converter itself and depends only on the characteristics of the power systems. If there is a tendency for the prime movers and generators of one power station to speed up due to a change in governor setting or to a decrease in load on that system, there is an immediate transfer of power through the frequency-converter to the other system and a consequent decrease in load on the generators of the second station. The problem is similar to the load division between two generators in which the amount of kilowatt load on each generator, for the same total load, depends entirely on the speed-load characteristics of the prime movers. In the case of two power stations or systems of different frequency tied together through a synchronous set, the division of power between the systems must be controlled at the prime movers. The power transferred by the frequency-converter is independent of any adjustment that may be made at the converter itself. If the power systems are large and if there are wide fluctuations in load, it is possible to impose a heavy overload on the set, or even to pull it out of synchronism. For that reason, it may be unsatisfactory to tie two large systems together through a small set, unless the speed or frequency regulation of each system is nearly the same as the other.

If there are two or more sets operating in parallel, the total load transferred is independent of any adjustment made on them although the proportion of the total load carried by each can be varied as explained on page 14.

Reversible Operation

Either machine of a synchronous set may act as a motor or a generator so that the flow of power may be in either direction. The reversal of power flow takes place automatically depending on the load demands of each system and requires no adjustment of the frequency converter itself.

Power Flow with Induction Motor Driven Set

The amount of power flowing between two power systems tied together by an induction frequency-converter depends upon the relative frequencies of the two systems for any one value of resistance in the secondary circuit. By a change in secondary resistance, the motor slip for any load can be changed and thus with the same ratio of frequencies the amount of power which is transferred can be varied. With this type of set, therefore, the power flow is controllable at the set itself if secondary resistance is used.

Parallel Operation of Synchronous Sets

The operation of two or more synchronous frequency-converters in parallel on both the motor and generator ends introduces certain problems which are not encountered in the operation of a single set. These problems are concerned chiefly with the procedure to be followed in synchronizing two sets and adjusting them so that they will share their load properly. In the paragraphs which follow these points will be discussed in detail under four headings:

First, the possible synchronizing positions and the means of locating them.

Second, the necessity of frame adjustment when sets are paralleled for the first time.

Third, load division between parallel sets.

Fourth, the paralleling of a loaded and unloaded set and the use of a frame rotating device.

Determination of Synchronizing Position

In order that this explanation may be simplified, it will be assumed that the armature windings of the various machines are identical in location and sequence of terminal coils. Then the position, at some chosen time, of a pole of the rotating field (with respect to a group of armature coils covering one pole pitch), represents the phase of a voltage generated in the motor or generator winding; accordingly, in the following explanation the "position of the rotor pole", or, "polar position" will signify the voltage phase. Thus, if two synchronous motors are operating from the same supply system without load the polar positions of the two motors will be the same. Likewise, before two generators can be synchronized, the polar positions of the two rotors must be made the same.

A distinction will also be made between "polar position" and "rotor position"; the former will mean the phase of the generator voltage, while "rotor position" will mean the mechanical position of the rotor without reference to magnetic or electrical conditions. This distinction may be illustrated in the following way: If a synchronous motor is in synchronism with the generator and is then caused to slip two poles its polar position will not have been changed while its rotor position will have been changed.

In synchronizing two engine-driven generators, it is not difficult to bring the two rotors into the same polar position, since the two rotors may be independently controlled in speed and the relative polar positions are continuously changing. Moreover, the two generators will have the same polar positions (that is, will be in synchronism) when any pole of one generator has the same position as any pole of the same polarity of the other generator. There are as many positions of the rotor that are correct for synchronizing as there are poles of the same polarity on the incoming generator.

When a synchronous motor driven frequency-converter is to be synchronized with another similar set, the same general principles apply, but the rigid mechanical connection between the poles of the motor and the poles of the generator considerably reduces the number of correct rotor positions of the motor. In the case of two sets, the two motors must have the same polar positions and at the same time the two generators must have the same polar positions. Referring to Fig. 11, which represents a 4-pole—6-pole set, if the two motors are connected to the same position, then the generator poles N_1 in both sets will have the same position and the sets will be in synchronism on both ends. If, however, the two motors are connected to the supply circuit so that pole N_1 in one motor has the same position as pole N_2 in the other motor (which is a possibility considering the motors alone) then pole N_1 in one generator will have the same position as pole S_2 in the generator and the two generators will be 180 degrees out of phase at the same time the two motors are in phase. If the two motors are considered alone, there are two correct rotor positions; if the two generators are considered alone, there are three correct rotor positions; but if the motor and generator are tied rigidly together, as in a frequency-converter, there is only one correct rotor position for the incoming motor. For the sake of brevity "synchronizing position" will be used to denote that rotor position of the incoming motor in which both motor polar positions will be the same and both generator polar positions will be the same. In general the number of synchronizing positions in any pair of sets is equal to the greatest common divisor of the number of possible synchronizing positions of the motor and of the generator considered as separate machines. The synchronizing positions for the separate machines are equal in number to the number of pairs of poles. Thus in the 4-pole—10-pole set shown in Fig. 12, there are two synchronizing positions for the motor, considered alone; there are five synchronizing positions for the generator, considered alone; and there is only one synchronizing position for the set; in the 4-pole—8-pole set, in Fig. 13 there are two synchronizing positions for the set; or as many as for the motor, considered alone; in the 10-pole—24-pole sets in Fig. 14, there is, again, only one synchronizing position for the second set.

If the number of correct synchronizing positions of the motors or generators, considered separately, is increased, the number of synchronizing positions for the second set will also be increased.

Thus, if the polarity of the south poles of the incoming generator, considering the two generators as separate engine-driven units, be changed, each of the generator poles, at one time or another, will be a north pole, and there will be as many synchronizing positions as there are poles. Considering the motors alone, by reversing the motor excitation, the number of motor synchronizing positions may also be doubled. In the 4-pole—6-pole set (Fig. 11) it was shown that if pole N_1 of one motor had the same position as pole N_2 of the second motor, the pole N_1 of the first generator would have the same position as pole S_2 in the second generator, and that the two generators would be 180 degrees out of phase. Obviously, by reversing the excitation of the second generator, the south pole is changed to a north pole, thereby bringing two generator poles of the same polarity into the same position, and the two sets into synchronism.

In the 10-pole—24-pole combination (Fig. 14) the number of set synchronizing positions can be increased by reversing the motor excitation. Consider that the two motors are connected to the supply circuit so that the poles N_1 of both motors are in the same position. Generator poles of the same polarity will also be in the same position, but the generators are not connected in parallel.

Now assume that the excitation of one motor is reversed. The pole N (which is now a south pole) will drop back and the pole S_1 will occupy the position that N_1 occupied. The motor has dropped back one pole—or as it is called has "slipped a pole"—and its new position is 180 magnetic degrees or 36 mechanical degrees behind its original position. The generator of the second frequency-converter has been pulled back 36 mechanical degrees or 432 magnetic degrees. Pole N_2 of the second generator is now six mechanical degrees or 72 magnetic degrees back of pole N_1 of the first generator. If this process of slipping a pole is repeated until pole S_2 of the second motor is in the same position as pole N_1 of the first motor pole, N, of the second generator will be in the same position as pole N_1 of the first generator, and the two sets will be in synchronism on both ends. In practical operation, the second motor may be connected to the circuit in any one of five polar positions (considering only one direction of excitation); if the generator poles have

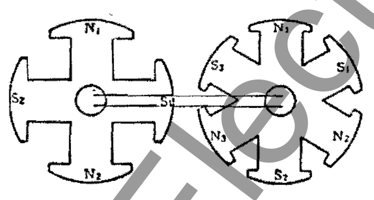

Fig. 11—40 to 60 Cycles; 4 and 6 Poles

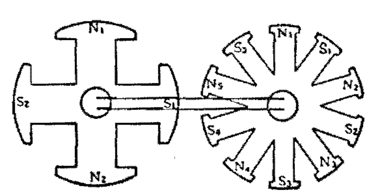

Fig. 12—25 to 62.5 Cycles; 4 and 10 Poles

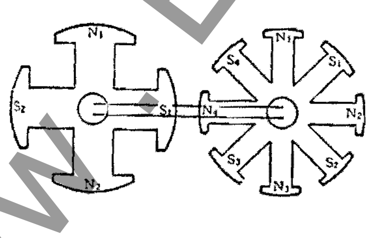

Fig. 13—25 to 50 Cycles; 4 and 8 Poles

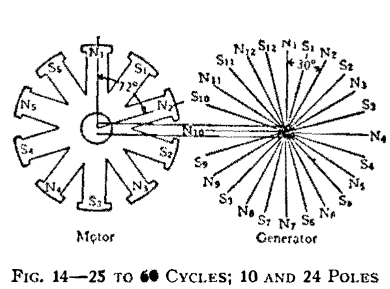

Fig. 14—25 to 60 Cycles; 10 and 24 Poles

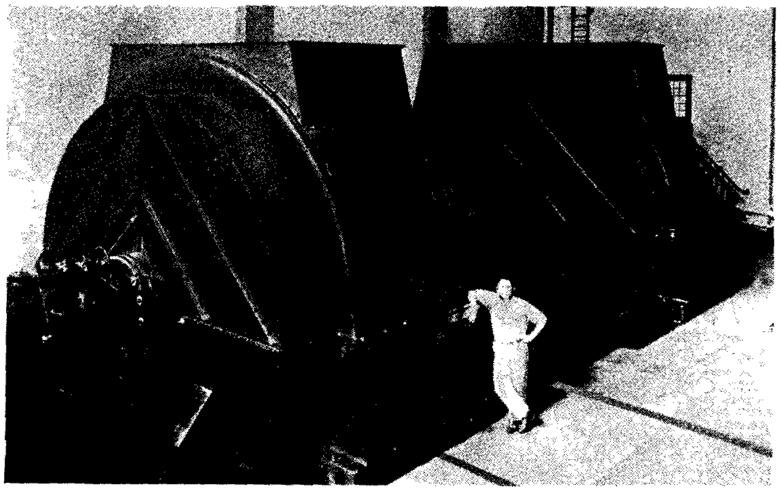

Fig. 15—30,000 Kv-a. Frequency-Converter

different positions, they may be brought into the same position by slipping a motor pole as often as may be necessary.

It will be noted from the preceding discussion that the number of synchronizing positions depends on the number of poles in the motor and the generator of the frequency-converter; that with some pole combinations number of correct position is increased by reversing the generator excitation, and, in others, by reversing the motor excitation. These results may be summarized as follows:

(1) The number of synchronizing **positions of the incoming** set with a single direction of excitation, in **both motor and generator,** is the greatest common divisor of the number of **pairs of poles** in motor and generator of the incoming frequency-converter;

(2) The number of synchronizing **positions of the incoming** frequency-converter, with both directions of excitation in **both motor and generator,** is the greatest common divisor of the number of **poles** in motor and generator of the incoming frequency-converter.

(3) The number of synchronizing positions of the incoming frequency-converter with both directions of excitation in **either** motor or generator, is the greatest common divisor of the number of pairs of poles of the machine with a single direction of excitation and the number of poles of the machine with both directions of excitation.

Whether the installation of a field reversing switch for the motor or generator or for both is of any value, may be determined from the rule just given. Thus in the 10-pole—24-pole set with both directions of excitation for the motor, the number of synchronizing positions is 2 (the greatest common divisor of 10 and 12); with both directions of excitation for the generator, the number of synchronizing positions is 1 (the greatest common divisor of 5 and 24); with both directions of excitation for both generator and motor the number of synchronizing positions is 2 (the greatest common divisor of 10 and 24). Therefore, a field reversing switch for the motor is desirable, but a similar switch for the generator is of no benefit.

Initial Adjustment of Cradle Frame

The foregoing explanation assumes that it is possible to bring both ends of the set into phase with the corresponding machines of the set with which it is to parallel, by selecting the proper polar position. With sets which are exact duplicates this is true. If, however, there are certain minor differences, it may not be possible to bring the machines exactly in phase. For example, if the rotor of one generator has a slightly different position on the shaft relative to the motor than that of the other set, due, perhaps, to a variation in the machining of the keyways or to the drilling of the coupling bolt holes, it will not be possible to have the voltages exactly in phase. Similarly, if the terminal coils of the stator windings do not lie in corresponding slots in the two similar machines, the generator voltages will not agree. It will be possible to find a position which is nearly correct but not exactly so. To take care of such discrepancies, the stator of one machine of the set is mounted in a cradle which permits it to be rotated through a small angle. If the set is never to be operated in parallel with other synchronous sets, the cradle may be omitted. Or if it is operated in parallel but all other sets are equipped with movable stators, it may be omitted.

Table I—Polar Connections of Frequency-Converters

Motor Poles	Gen. Poles	Direction of Excitation Mot.	Direction of Excitation Gen.	Synchronizing Pos. Mot. Alone	Synchronizing Pos. Gen. Alone	Synchronizing Pos. Set	Motor (Low Freq.) Field Sw. Rq.	Gen. (High Freq.) Field Sw. Rq.
4	10	Single	Single	2	5	1	..	..
..	..	Both	Single	4	5	1	..	..
..	..	Single	Both	2	10	2	..	Yes
8	20	Single	Single	4	10	2	..	..
..	..	Both	Single	8	10	2	No	..
..	..	Single	Both	4	20	4	..	Yes
6	14	Single	Single	3	7	1	..	..
..	..	Both	Single	6	7	1	No	..
..	..	Single	Both	3	14	1	..	No
..	..	Both	Both	6	14	2	Yes	Yes
10	24	Single	Single	5	12	1	..	..
..	..	Both	Single	10	12	2	Yes	..
..	..	Single	Both	5	24	1	..	No

This information for the pole combinations ordinarily used is given in the table on Page 12.

This information applies whether the frequency-converter is started from the low frequency or from the high frequency end.

When two synchronous sets are to be paralleled for the first time, it is necessary to find the polar positions which gives the minimum phase difference between the generator voltages and then to shift one or both movable stators sufficiently to bring the voltages into exact phase coincidence. The stators can then be bolted and doweled in position as there will be no further need for adjustment.

Procedure for Adjusting Frame—The two frequency-converters to be adjusted should be synchronized on the motor ends until the least possible difference exists in the generator phase. If the generator switchboard contains a synchronoscope, this adjustment will be greatly facilitated. If any difficulty is experienced in determining the best motor synchronizing position, a systematic study, as outlined below, should be made.

(1) Mark a radial line on some accessible part of a motor pole and place a mark on a generator pole that is in line with it, the two marks lying in the same radial plane. It will be found convenient to use the motor pole and the generator pole that are approximately in line, if such exist. Place the rotor of both frequency-converters in such positions that the lines of the motor poles are in line with the armature slots containing the terminal coil of the A-phase. Observe the angular difference, if any, between the mark on the generator pole and the slot containing the terminal coil of the A-phase of the generator in both sets. If this angular difference is the same in the two frequency-converters, no frame adjustment will be required. If it is not the same, the frames of one or both frequency-converters will have to be moved to make it the same. An approximate adjustment of the frame can be made from these mechanical measurements, but the final accurate adjustment must be made by operating the two frequency-converters. If these mechanical measurements indicate that the two frequency-converters are widely different (more than three or four degrees difference in general rotor position with respect to the terminal coil) the difference can be reduced by electrical adjustments described later.

(2) With one frequency-converter running with full voltage on the motor and with the generator on open circuit, start the second frequency-converter, synchronizing the motor with the supply system. Note the synchronoscope reading. Cause the second motor to slip a pole by reversing the field excitation (see page 10) and again note the synchronoscope reading. Note the reading of the synchronoscope for each rotor position of the second motor. It is not necessary to observe the synchronoscope readings with reversed generator excitation, as these will be 180 degrees displaced from the corresponding reading with the original direction of excitation. These should be set down together with the observed readings and these readings should be compared with the theoretical difference in generator rotor position. Such a set of readings for a 4-pole-10-pole frequency-converter is given in Table II for purposes of illustration.

Table II—Comparison of Synchronoscope Position for Different Rotor Positions

Rotor Position of Second Motor	Actual Difference in Gen. Phase by Synchronoscope Orig. Excitation	Rev. Excitation
1	100° Fast	80° Slow
2	10° Fast	170° Slow
3	80° Slow	100° Fast
4	170° Slow	10° Fast

The theoretical difference in generator rotor position, assuming correct mechanical adjustment, is shown in the following Table III:

Table III—Difference in Generator Rotor Position of a 4-Pole-10-Pole Set

Rotor Position of Second Motor—Rotor Position of First Motor $=N_1$	Rotor Position of Second Gen. as Compared with N_1 of First Generator Orig. Excitation	Rev. Excitation
N_1	0°	180°
S_1	90° Behind	90° Ahead
N_2	180°	0°
S_2	90° Ahead	90° Ahead

Comparing the figures in Tables II and III, it is evident that the second generator is set 10 electrical degrees ahead (i.e., **"FAST"** as indicated by the synchronoscope) of its correct position, with the motor in No. 2 position. The two generators will be brought into the same polar position if the second motor is synchronized in No. 2 position and the frame of the second motor is moved 10 electrical degrees (2 mechanical degrees) in the direction of rotation.*

The theoretical differences in generator rotor position, assuming correct mechanical adjustment for 10-pole-24-pole set, are shown in the following table:

Table IV—Theoretical Differences in Generator Rotor Positions

Rotor Position of Second Motor—Rotor Position of First Motor $=N_1$	Rotor Position of Second Gen. as Compared with N_1 of First Generator Orig. Excitation	Rev. Excitation
N_1	0°	180°
S_1	72° Behind	108° Ahead
N_2	144° Behind	36° Ahead
S_2	144° Ahead	36° Behind
N_3	72° Ahead	108° Behind
S_3	0°	180°
N_4	72° Behind	108° Ahead
S_4	144° Behind	36° Ahead
N_5	144° Ahead	36° Behind
S_5	72° Ahead	108° Behind

*The movement of a pole in the direction of rotation advances the phase of the generated voltage and a movement of an armature coil (or frame) in the direction of rotation retards the phase. This is true whether the motor or the generator frame, is moved to adjust the generator phase.

(3) It is possible, if the two frequency-converters are of dissimilar manufacture, for the second generator to be out of phase, when tested as just described, by a larger angle than can be corrected by the maximum frame movement permitted by the cradle. The out of-phase angle may be reduced in most frequency-converters by ad-

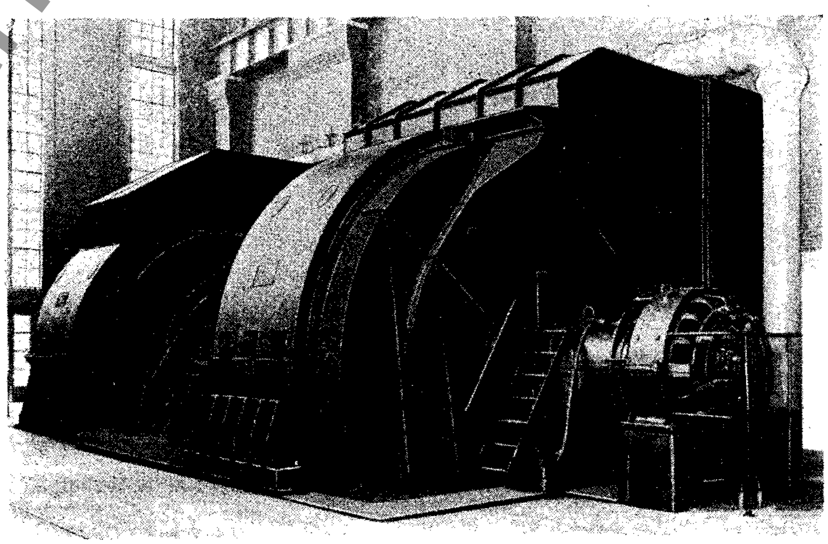

FIG. 16—40,000 KV-A. FREQUENCY-CONVERTER

vancing all motor armature leads so as to change the motor phase 120 electrical degrees (in a three-phase motor) or 90 electrical degrees (in a two-phase motor). A change of one electrical degree in the motor phase results in a change of 2.5 degrees in the generator phase in the 4-pole–10-pole set or a change of 2.4 degrees in the 10-pole–24-pole set. The generator phase can similarly be changed by changing the generator winding 120 degrees or 90 degrees (depending on the number of phases). These changes do no good in the case of a four-pole motor having a two-phase armature winding, or, for example in the case of a six-pole motor having a three-phase winding.

If all the possible electrical adjustments are made—that is, if the motor is synchronized in all possible positions, if the generator field is reversed and if the motor and generator leads are interchanged as described—the frequency-converters can be synchronized within a very small angle (in mechanical degrees). If, after attempting to adjust two frequency-converters and the smallest obtainable generator phase difference is greater than can be corrected by the frame movement provided further electrical adjustments should be made, making use of the mechanical measurements described on page 12 as a first approximation to the change in phase angle that is required.

The electrical adjustments that can be made are indicated by the following example showing the maximum frame movement that would be required in a frequency-converter having a **four-pole, three-phase motor, and a ten-pole, three-phase generator:** Assume that one frequency-converter differs from the other in generator phase to the greatest possible extent. Obviously, it can differ by no more than 180 electrical degrees. However, any difference greater than 90 degrees can be changed to a difference less than 90 degrees by reversing the generator field excitation. If in any synchronizing position of the second motor the generator phase difference is 90 degrees, this can be reduced to zero by making the motor slip a pole. Therefore, any phase difference greater than 45 degrees can be changed to a difference of less than 45 degrees by reversing the motor field excitation. If the motor armature leads are advanced one terminal, the motor phase will be changed 120 degrees or 300 degrees in generator phase $(120 \times 10/4)$. If this change be added to the previously existing difference of 45 degrees, there will be a difference of 345 degrees which is equivalent to a difference (in the opposite direction) of 15 degrees (360—345). In this frequency-converter, a change in generator terminals produces the same change in generator phase as does a change in motor terminals. If the motor armature is two-phase, no new combinations can be obtained that could not be obtained by slipping a motor pole, for both changes result in a change of 90 degrees in motor phase.

If no generator synchronoscope is available, lamps may be used. Since lamps give no definite indications of the angle of generator phase difference, greater dependence must be placed on the mechanical measurement of generator phase difference described on page 12.

When the generators are nearly in phase, they may be connected in parallel and a more accurate adjustment made. The field currents should be adjusted for equal voltages before the generators are connected together and the field currents should not be changed thereafter. A current will flow in the generator armatures that will be proportional (for small angles) to the phase difference. The frame should be moved slightly and the effect on the current noted. The frame should then be moved in the proper direction until no current flows in the generator circuit. If the field excitation is not correctly adjusted as described above before the generators are paralleled, the armature current cannot be reduced to zero by moving the frame. The current that circulates in the two-generator armatures due to phase differences is an energy current—one greater will be acting as a generator supplying power to the other generator, driving it as a motor. The two motors of the frequency-converters will, therefore, indicate whether the current flowing in the generators are due to mechanical phase differences or to differences in field excitation. In the former case, the currents taken by the motors will be much greater than required by the losses of the frequency-converter, and one motor will be acting as a generator (a wattmeter will show reverse power).

The position of the frame which is determined in this way is usually the best position in which to fasten it permanently. There is one further consideration however, which will be discussed in the following paragraphs.

Load Division between Synchronous Sets Operating in Parallel

As a synchronous motor is loaded, its rotor drops back in phase position a few degrees, the displacement being roughly proportional to the load for constant field current. Similarly, the phase position of the voltage of a generator varies with the load. In a synchronous frequency-converter, the motor and generator displacement angles combine so as to produce a fairly large variation on the phase position of the generator voltage with respect to its no-load voltage. When two sets are operated in parallel the two generator voltages are necessarily in phase at all loads and the motor voltages are in phase, so it follows that the total displacement angle due to load must be the same for each set. But with sets which are not duplicates, there is a probability that the displacement angles of both sets—when each is carrying its rated load—are not the same. Thus, when they are paralleled, the load will not be divided between them in proportion to their ratings, but will divide in such a way as to produce the same total displacement in each set.

In order to compensate for these differences in characteristics of the two sets and to produce the proper division of load, it would be necessary to make a further adjustment of the movable stator. By moving the stator in one direction or the other, the load could be made to divide in the desired proportion. This adjustment, however, would be correct for only one value of total load. At all other loads the proportion taken by each set would be different and with no external load there would be a circulation of power between the two sets which would result in unnecessary losses. Thus it is usually best to set the movable frame in the correct position at no load as described on page 12. If the sets have different characteristics, it will be impossible to find any one position which will give correct load division at all loads. The only way in which this can be accomplished, is to make use of a motor operated frame rotating device which permits easy adjustment of the movable stator as the load changes. This device is described in more detail on page 16.

Effect of Field Current Adjustment

It is possible to make some change in the load division between synchronous sets which are operating in parallel by adjusting the field current. If the motor or generator of one set is overexcited and one or both of the machines of the other set are underexcited, some of the kilowatt load will be shifted from the underexcited to the overexcited set. The explanation lies in the fact that the change of excitation changes the power-angle characteristic of each machine and thus requires a different distribution of load to produce the same total angular displacement in both sets. Changes of excitation in the low frequency machines are more effective in producing a re-distribution of load than similar changes in the high frequency machines.

The proportion of load which can be transferred from one set to the other is limited by the permissible changes in field current. With 25-60 cycle sets of normal design and equal rating, it is usually possible to carry 50 per cent more kw. load on one set than the other. This implies, of course, that the total load is low enough to prevent overloading the set which is overexcited. The objection to this method of re-distributing the load, is that it is accompanied by changes in power factor which may not be desirable. A further limitation is that it cannot prevent a circulation of power between two sets which are paralleled at no load with improper frame adjustment. Or, similarly, adjustment of the fields will not permit an unloaded set to be brought into phase with a loaded set when the frames have been correctly adjusted. This point is discussed under the next heading.

Paralleling an Unloaded Set with a Loaded Set

If two frequency converters are brought into the correct position for paralleling as described on page 10, and if the frames have been previously adjusted correctly as detailed on page 12, the generator voltages will be exactly in phase; and if the generators are paralleled, there will be no flow of current between the machines. Suppose, however, that one set is connected to the station bus and is loaded before the parallel connection is made. The effect of the load will be to change the phase position of the voltage of the loaded set by an amount which may be considerable, depending upon the amount of load and upon the ratio of the numbers of poles of the motor and generator. Thus, if one set is loaded, even though the correct polar position has been found, the two sets cannot be paralleled without causing a momentary rush of current and a corresponding voltage disturbance. After the initial disturbance, however, the sets will divide the load and operate without further difficulty, just as though they had been paralleled at no load. If one set is taken out of service when carrying load there is a similar, though less severe, disturbance.

If it becomes necessary to parallel a loaded set and an unloaded set, neither of which has a frame rotating device, the operator has no choice but to close the switches and allow the momentary rush of current to occur.

Variation of the field current, while having the effect of transferring load from one set to the other after they are paralleled, is of little value usually in changing the angular difference between a loaded and an unloaded set. Any advantage that is possible from this procedure will be obtained by raising the excitation of both machines of the loaded set.

High Frequency Versus Low Frequency Paralleling

It is important to note that the possible phase difference with one set loaded is less when the high frequency machine of the unloaded set is acting as a motor and the final parallel connection is made on the low frequency side, than when the reverse is true. For example, if two 25 to 60 cycle sets are to be paralleled, and if one set is already loaded, it would be preferable to start up the second set from the 60 cycle side and to make the final connection on the 25 cycle side. The reason for this will be clear from the following: Suppose each machine of the loaded set has a displacement of 20 electrical degrees due to load. The 20 degrees of the 60 cycle machine is equivalent to 20 x $^{25}/_{60}$ or 8⅓ degrees in the 25 cycle machine. This added to the 20 degrees displacement in the 25 cycle machine, gives a total phase difference of 28⅓ degrees between the 60 cycle voltages of the loaded and the unloaded machines. Suppose now that the unloaded set is to be started up from the 25 cycle end and the final paralleling done on the 60 cycle end. The 20 degrees displacement of the loaded 25 cycle machine is equivalent to 20 x $^{60}/_{25}$ or 48 degrees in the 60 cycle machine When this is added to 20 degrees displacement in the 60 cycle machine, the result is 68 degrees for the set. Since the two 25 cycle voltages are now in phase, the angle of 68 degrees is the amount by which the 60 cycle voltages are out of phase. Paralleling under these conditions would result in a severe shock to the machines although after the first disturbance the sets would divide the load and operate with entire satisfaction. From the standpoint of initial disturbance then, it is preferable to start the unloaded set from the high frequency system and make the final connection on the low frequency end. This holds true whether the flow of power through the loaded set is from the high frequency to the low frequency end, or in the reverse direction.

Difficulty of Finding Correct Polar Position When One Set Is Loaded

Suppose the stators of two frequency-converters have been adjusted so that when the proper polar position is found as explained on page 10, correct parallel operation is possible. If the two sets are to be paralleled with no load on either, the proper polar position will be found when the synchronoscope shows zero angular difference between the generator voltages. If one set is loaded when the other is to be paralleled with it, there will be considerable phase difference between the generator voltages when the correct polar position has been found. The question then arises as to how to determine the correct polar position—the position which will give proper load division—under this condition. For example, if one set is carrying full load, the angular variation of the voltage on the high frequency end of a 25–60 cycle set may be, say, 70 degrees. Thus it becomes necessary to vary the polar position of the incoming set until the synchronoscope shows 70° instead of zero. There are other polar positions which will give smaller readings on the synchronoscope.

In fact, a change of one pole pitch on the 25 cycle end will make a change of 72 degrees on the 60 cycle end, so that it would be possible to have the voltage practically in phase. If, however, the machines were paralleled in any of these other positions, the load would not divide correctly and there would be a circulation of power at no load.

To take care of this condition, it is convenient to prepare a chart or curve showing the angular difference that must exist for various values of load in order to give correct parallel operation. To obtain such data the sets should be brought into the correct relation for paralleling at no load and then one set should be loaded. With the synchronoscope connected between the generator voltages of the loaded and the unloaded set, a reading of angular difference should be taken for various values of kilowatts on the loaded set. If the power factor of the load is subject to wide variation, it may be necessary to take a curve for each of several values of power factor. A set of data of this kind will enable the operator to find the correct polar position with little delay.

Use of Frame Rotating Device

Most of the difficulties of synchronizing and of load division are overcome by the use of a motor operated frame rotating device. The stator of one of the machines can be rotated through a small angle at will, so that it is always possible to bring the generator voltages exactly into phase for paralleling. If one set is already loaded when the second set is paralleled, it is then necessary to shift the stator again until the desired load division is obtained. With this arrangement the kilowatt load on each set can be controlled independently of the power factor. If one set is to be taken out of service, the rotating device makes it possible to transfer all of the load to the other set so that when the switches are opened there is no disturbance.

Parallel Operation—Summary

The following brief summary will help to bring out the important points in the foregoing discussion of parallel operation.

I. Determination of Polar Position.

A. There are one or more relative positions between the motor poles which will allow the generator poles to line up exactly so that parallel operation is possible.

B. The number of such positions depends on the numbers of poles and upon whether or not generator field reversing switches are used.

II. Initial Adjustment of Cradle Frame.

A. The movable stators of one or both sets must be set so that exact phase coincidence is possible.

B. Synchroscope readings will indicate the correct position. This can be checked further by paralleling the sets at no load and noting whether or not there is an exchange of power between the sets.

III. Load Division.

A. With the requirements of I and II fulfilled the load will divide between two sets in proportion to their ratings, provided the angular displacement of each is the same for the same per cent load; that is, if the power-angle characteristics are the same.

B. If the power-angle characteristics are different the load can be made to divide properly by shifting the position of the movable frame. This will give correct division for one value of load only and usually is not satisfactory if the load is variable. There will be an exchange of power between the sets when there is no external load, unless the cradle frame is left in the position specified under I.

C. Adjustment of the field current of either or both machines affects the load division. The overexcited set takes increased load and relieves the underexcited set. This method involves a change in power factor which is not always permissible.

D. A motor operated frame rotating device gives the operator complete control of the division of load at all times.

IV. Paralleling a Loaded Set with an Unloaded Set.

A. If two sets are brought to the correct position for paralleling but one of them is loaded there is a phase difference between the generator voltages. If they are then paralleled, there will be a momentary rush of current depending on the phase difference but the load will divide between the two sets just as though they had been paralleled at no load.

B. The phase difference between a loaded and an unloaded set cannot be overcome entirely by adjustment of the excitation. The minimum phase difference will exist when the motor and generator of the loaded set are overexcited.

C. The phase difference is less when the final parallel connection is made on the low frequency machines than when it is made on the high frequency machines.

D. If one set is loaded when the second set is started, it is difficult to find the correct polar position. A curve or chart may be prepared which will simplify this procedure.

E. A motor operated frame shifting device will permit two sets to be brought into phase even though one of them is loaded. The frame can then

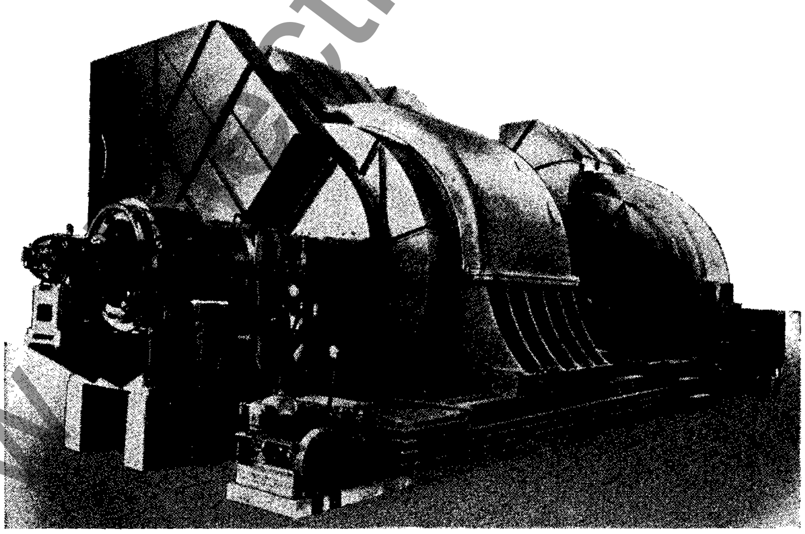

FIG. 17—30,000 KV-A. FREQUENCY-CONVERTER

be moved back into the position which will give correct load division.

Parallel Operation of Induction Motor Driven Frequency-Converters

Induction type sets operated in parallel will divide the total load in such a way that the slip of each set is the same. It is possible to change the distribution of load by secondary control of the induction motors.

An induction type set operated in parallel with a synchronous set having the same ratio of numbers of poles, would carry no load. If the numbers of poles are such that the induction set gives the correct frequency ratio at full load, it will continue to carry that load and all variations in total load will be taken by the synchronous set. If the total load is reduced to zero, the induction set will continue to deliver its constant output which will be returned again through the synchronous set. The arrangement is quite unsatisfactory except under conditions of constant load or where complicated control schemes are used.

Maintenance

Cleaning

The insulation should be kept free from dirt and oil. An occasional cleaning of the coil ends with an air hose is recommended and this should be followed by a thorough wiping with a cloth. The dirt which clings to the field coil washers should be removed carefully since it may accumulate and form a conducting path from coil to ground. A coat of insulating varnish applied to the armature and field coils after they have been cleaned will protect the insulation. An air hose should be applied to the air ducts through the stator punchings since an accumulation of dirt at this point will impede the free flow of cooling air.

Bearings

When a machine is started particular attention should be given to the bearings to see that they are well supplied with lubricant. The oil rings should revolve freely and carry oil to the top of the journals.

Bearings may be operated safely at a temperature of 80° C. (176° F.) and, for a limited time, they may operate as high as 100°C. (212° F.). It should be remembered that a bearing may be below this temperature and may be safe even though it is hot enough to burn the hand when held against the outside.

A rapid rise in the temperature of a bearing is usually an indication of trouble and requires prompt attention. The machine should be taken out of service immediately, but, if possible, it should be kept rotating at low speed until the bearing has cooled. Fresh oil should be fed into the bearing and onto the journal through the openings over the oil rings.

The cause of overheating may be any of the following:

- Insufficient oil in the reservoir.
- Dirty oil or oil of poor quality.
- Failure of oil rings to revolve.
- Excessive pressure or end thrust caused by poor alignment of the machine.
- Bent shaft.
- Rough bearing surface, which may have been the result of careless handling.

Keep the oil in the bearings clean—The frequency with which the bearings must be refilled depends so much on local conditions, such as the severity and continuity of the service, the room temperature, the state of cleanliness, etc., that no definite instructions can be given. Until local conditions show another interval to be more suitable, bearing should be refilled every six months.

Oil

Only the very best grade of oil—having a viscosity of from 185 to 200 seconds, Saybolt—should be used. In the long run it always proves a false economy to use cheap oil. If the oil is to be used a second time it should be filtered and if warm allowed to cool before the bearings are refilled. Even new oil should be examined carefully and filtered or rejected if it is found to be gritty.

Collector Rings

Sparking at the collector rings may be due to any of the following causes:

- Rough surface of ring. (This condition usually follows prolonged sparking originating from some other cause.)
- Eccentric rings.
- Brushes tight in holders.
- Oil on collector rings.
- Vibration of brush rigging.

If sparking exists, the rings should be stoned or turned to give a smooth surface and, if possible, the source of the trouble removed. The brushes should have a close fit on the rings and should slide freely in the holders.

Renewal Parts

Repairing

Repair work can be done most satisfactorily accomplished at our nearest Service Shop. However, interchangeable renewal parts can be furnished, as listed below, to customers, who are equipped for doing repair work.

Recommended Stock for Renewal Parts

Preceding is a list of the renewal parts and the minimum quantities of each that should be carried in stock. These are the parts most subject to wear in ordinary operation and damage, or breakage due to possible abnormal conditions. The maintenance of such stock will minimize service interruptions due to breakdowns.

Ordering Instructions

When ordering renewal parts give, the name plate reading. Always give the name of the part wanted, also the stock order number of the apparatus on which the part is to be used. Refer to the back of this book for the nearest District Office from which to order parts.

Recommended Stock of Renewal Parts

Frequency-Converters in use up to and including	2	4	6
Name of Part	Quantity Recommended for Stock		
Armature coils	1/3 Set	2/3 Set	1 Set
Rewinding material	1/2 Set	1 Set	1 Set
Field coils complete—Open	1	1	2
Field coils complete—Closed	1	1	2
Brushes	1 Set	2 Sets	3 Sets
Brushholders	2	4	6
Mechanical Parts			
*Bearings	1	2	3
*Oil Ring	1	2	2

*The above recommendation is for each different kind.

A recommended list of Renewal Parts for your complete equipment will be supplied upon request to the nearest District Office.

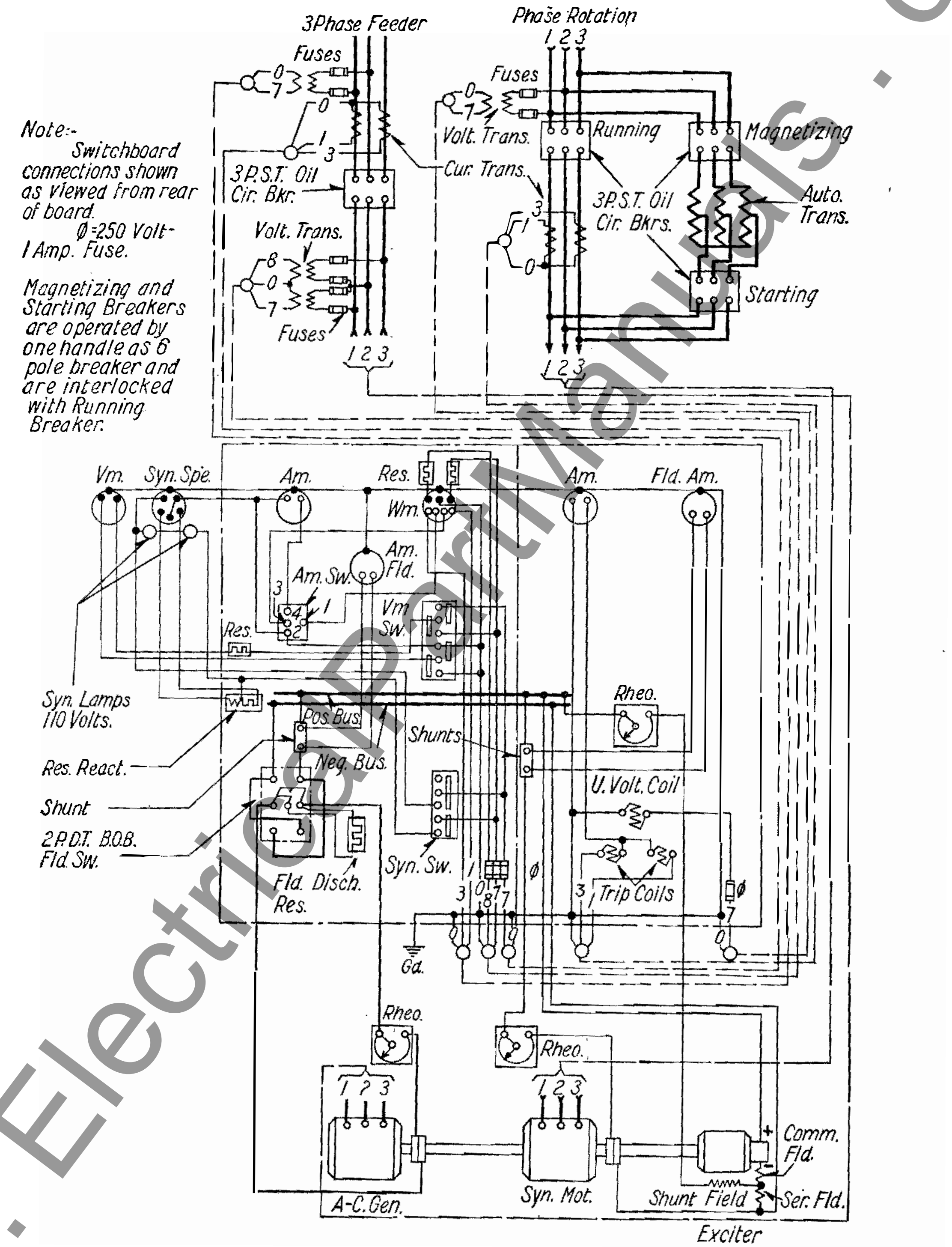

Fig. 18—Synchronous—Synchronous Frequency Converter Arranged for A-C. Self-Starting, Using Three-Phase Auto-Transformers. A-C. Machines Have Individual Exciters.

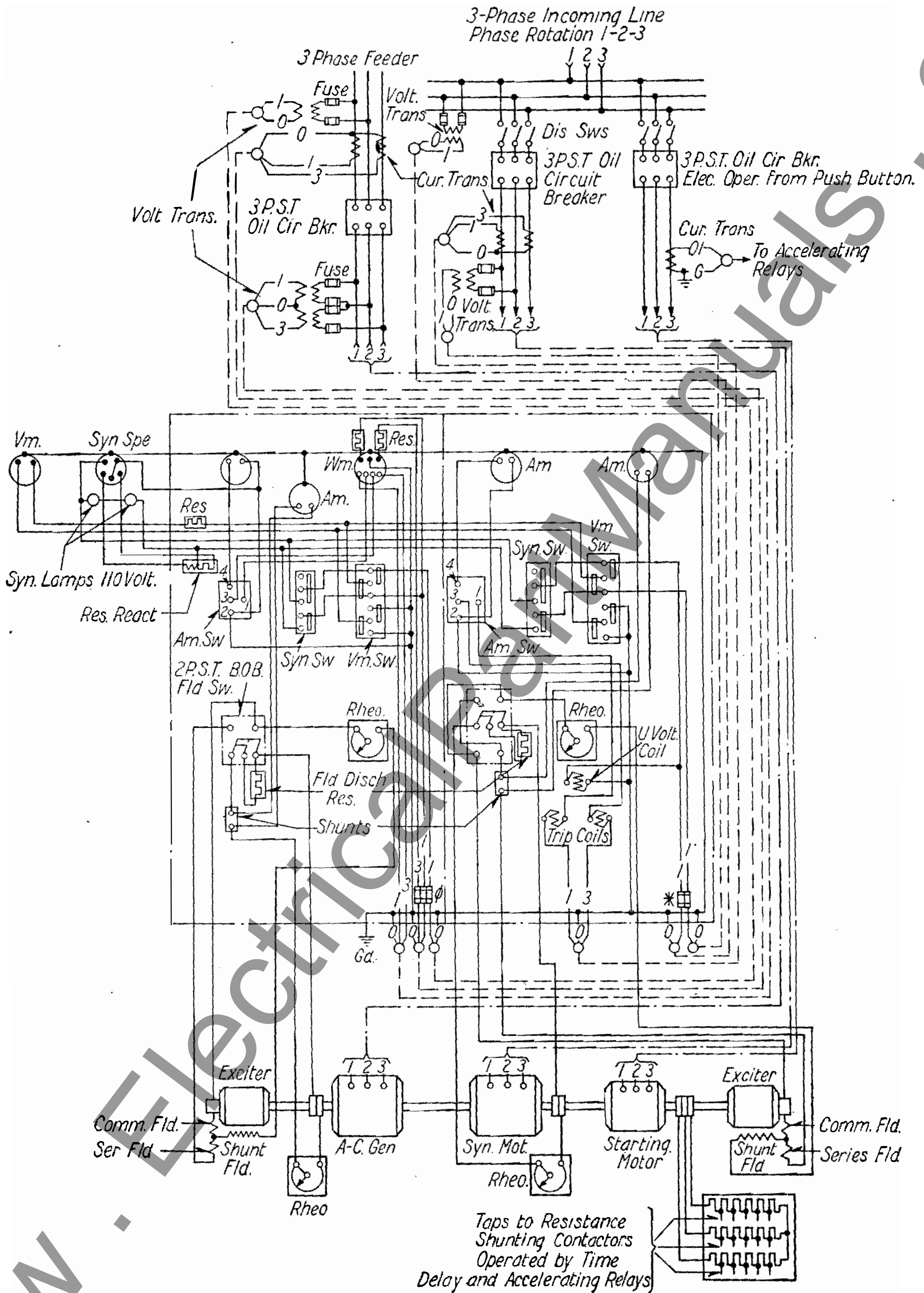

Fig. 19—Synchronous—Synchronous Frequency-Converter Arranged for Motor-Starting, Using Wound-Rotor Induction-Starting Motor. A-C. Machines, Have Individual Exciters.