COMPARISON OF ROTARY AND STATIC
PHASE CONVERTERS

By

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PREFACE

The advantages of the operating characteristics, the performance and the cost of three-phase motors over the characteristics, performance, and cost of single-phase motors has lead to the need for some improved method of operating three-phase motors where only single-phase voltage is accessible.

This thesis will explain the various methods used to convert from single-phase voltage to three-phase voltage and discuss the respective merits of each.

ACKNOWLEDGEMENT

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I. INTRODUCTION

The object of this thesis is to study the different methods of obtaining three-phase power from a single-phase source. The accomplishment of this objective requires two major steps:

(1) Review of literature on the subject of phase converters and their use.

(2) Comparison of various methods of phase conversion by testing each of them on the same motor.

Recent and present day conditions have lead to the construction of small factories and plants in residential areas. In most of these areas only single-phase power is available which is ill-adapted for driving machine tools. This condition and the growth of rural electrification, which is mostly single-phase, have brought about the need for some economical means of converting single-phase power to three-phase power.

This thesis is a discussion of the methods of phase conversion now in use and a summary of tests of some of these methods.

II. PHASE CONVERTERS

A. Arguments for Use

The situation quite often arises when it is desirable to use three-phase motors when only single-phase power is available. The reason for this desirability is obvious. The initial cost of three-phase motors is much less than the cost of single-phase motors and the operating characteristics are very much better. The efficiency is higher which saves money and the power-factor is higher which results in better rates and more savings. Also, some power companies limit the size of single-phase motors which can be operated on their system because of the high starting current.

These advantages of the three-phase motor over the single-phase motor compel the search for some method of converting single-phase power to polyphase power. There have been several solutions suggested for this problem but mostly for special cases of operation with no general solution which will apply to all cases.

Besides the advantages of three-phase motors over single-phase motors already mentioned there are others which could be considered, especially in installations of several motors. If several motors are apt to be started at the same time the currents for single-phase motors could be prohibitive. Because of the lower starting currents of three-phase motors, several can be started at the same time without too much ill effect.

If there is a possibility of three-phase power being available at a later date, the motor connections can be made in such a way that the only requirements necessary for converting the plant are the disconnecting of the phase converter and the connecting of the third line where the phase converter was disconnected.

Another advantage is where three-phase motors and starters are available. This will especially be true where lathes and other machine shop tools with built-in motors and control devices are to be used. Even if the efficiency were no higher, the savings from not having to buy especially built machines or from having to convert the machines to single-phase operation would be a strong argument for the use of phase converters.

B. Requirements

The same general problem arises in an attempt to balance a single-phase load on a polyphase circuit as in the operation of a polyphase load on a single-phase circuit. Bailey[1] has this to say about single-phase loads on polyphase circuits:

> No system of transformer connection is possible from polyphase to single-phase and have the polyphase system balanced. In general, power in a single-phase circuit falls to zero four times in each cycle (voltage equals zero twice and current equals zero twice). The power in a polyphase line must also fall to zero, unless some means of storing energy in the system is provided. The kinetic energy of the rotor of an induction motor, used as a phase converter, supplies a means of storing this energy. The angular velocity of the rotor is not constant, but varies during the revolution. The machine takes energy in approximately equal amounts from all the phases of the supply system. When no energy is demanded by the single-phase system, the motor is being accelerated, and energy is being stored as kinetic energy in the rotor. During the part of the cycle when the energy demand of the single-phase system is heaviest, the rotor is retarded and gives up a part of its kinetic energy.

This idea will work in reverse if it is possible to operate a polyphase machine from a single-phase source. In this case the polyphase load draws a constant power from the machine which acts as a phase-converter. The phase converter is accelerated during the time when maximum energy is delivered by the single-phase source and energy is stored. The phase converter is retarded and gives up energy when the energy from the single-phase source drops to zero.

The question of operating a polyphase motor from a single-phase source can be clearly illustrated by a question and answer from the Question Box of the Electric Journal.[2] The question:

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[1] Benj. F. Bailey, Induction Motors, pp. 68.

[2] Question Box, Electric Journal, XI (May, 1914), pp. 291.

> A three-phase, delta connected motor was being used on a 10-ton crane. The operator was hoisting and a fuse burned out, allowing the motor to run single-phase. When the hoist block neared the drum, the operator, instead of placing his controller on center, reversed it and the block continued to hoist and broke the cable. Please explain.
>
> The following was given as an answer:
>
> A single-phase induction motor has inherently no starting torque from rest and when once started by external means will run equally well in either direction of rotation, depending upon which way it is started. In this case, the motor, which was running at normal speed, continued to run in the same direction regardless of the reversal of the two leads. When one considers that in this case the current supplied is straight alternating, i.e., simply reverses in direction, it is evident that reversing the two leads produces no change in the relations existing between the direction of the current supplied and the coils themselves.

This example demonstrates the fact that polyphase motors will operate on a single-phase source and that considerable power will be developed. The characteristics will not be as good on single-phase as they will on polyphase, nor as good as the characteristics of a motor designed to operate on single-phase. However, the load characteristics are not the important consideration. The important consideration is the degree of balance obtained.

An induction motor operating on unbalanced voltages will tend to draw more energy from the phase which is at the highest voltage and less energy from the phases which are at the lowest voltages.[3] Since a single-phase source can be considered a polyphase source with extreme unbalance this will still hold true. The energy will all be drawn from the phase, the voltage of which is highest, and part of this energy will be fed to the phases of which the source voltage was zero. This energy balance is a natural tendency of all polyphase synchronous and induction machines.[4] In the motor

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[3] Bailey, loc. cit.

[4] B. G. Lamme, "Single-phase Loads from Polyphase Systems," Electric Journal, XII (June, 1915), pp. 261-264.

itself, this tendency to balance the voltages and phase relations in the source, will be accompanied by a tendency to distort the internal phase relations to match those of the source. The internal distortions must be corrected if the motor is to transfer energy between phases in such a manner as to give balanced polyphase voltages.

C. Rotary

1. Two-phase Motor

In Figure 1 one winding (1) of a two-phase motor is connected across the secondary of a transformer as are also two terminals A and B of the three-phase load. The other winding (2) of the two-phase motor is connected from an intermediate point C on the transformer to the third terminal C of the three-phase load. If the two-phase motor is started by some means, it will continue to run on single-phase and an emf will be generated in phase two. If the winding is wound at 90° to phase one and the turns ratio is of such a value as to induce an emf of 0.866 that of phase one then the relation will be that of the Scott transformer connection from two-phase to three-phase. The terminals A, B, and C will give a balanced three-phase load.

The effect of a load on this phase converter, B. G. Lamme[5] says:

> Assuming that a three-phase load is carried, then due to internal distortions, fc (Figure 2) is both reduced in value and shifted in phase to the position fd. The three-phase voltage relations are then indicated by ab, ad, and bd. To correct this distortion condition, assume (1) that the emf across one phase of the phase converter is increased sufficiently to increase the emf of phase two, so that it will be represented by fc, instead of fd, the increase being such that a line connecting c and e will be parallel with ab. Then assume (2) that the connection at f is moved along ab to a point such that fg equals ce. This brings terminal e to the position c, and the internal phase relations will then be such that balanced emfs corresponding to ab, ac, and bc will be delivered to the three-phase circuit when carrying load, and the three-phase circuit will necessarily carry balanced three-phase load, although the source of power is single-phase.

The above described characteristics can be built into a phase converter by having the windings distributed in a special manner and by having the ratios of the two windings of the correct value. It is also necessary to be

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[5] Lamme, loc. cit.

Fig. 1. Two-phase Motor As A Phase Converter.

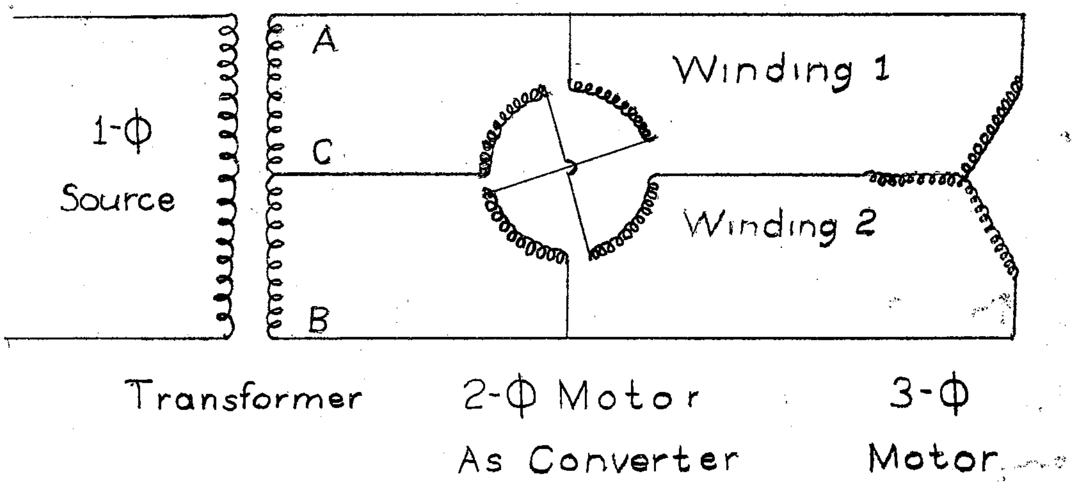
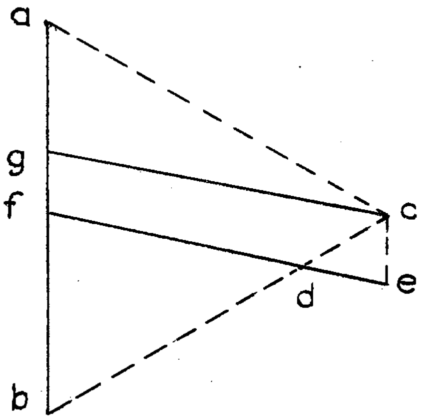


Fig. 2. Voltage Relations Of A Two-phase Motor As A Phase Converter.



able to shift the position of the intermediate tap on the transformer. This is the method, to be described later, used by the Norfolk and Western Railway.

The action which takes place in the phase converter is comparable to the action in a single-phase motor with a slight addition. The main winding (Winding 1, Figure 1) which is connected to the single-phase source produces a flux which lags the source voltage by 90° in time phase. This flux induces a counter-, or back-emf in the stator which is in phase opposition to the source, and another emf in the rotor, by transformer action, also in phase opposition to the source. Since the rotor can be considered as a short-circuited transformer winding, the emf induced in the rotor will cause a current to flow which is in time phase with the main axis flux.

The rotation of the rotor in the main axis field of the stator produces an emf in the rotor in time phase with the main axis flux and in time quadrature with the applied voltage. This emf causes a quadrature current to flow in the rotor which in turn produces a quadrature flux.

The interaction of the main axis flux with the quadrature current and the inter action of the quadrature flux with the main axis current produce a rotating torque which drives the motor.

The alternating quadrature axis flux produces an emf in phase 2 (Figure 1) of the phase converter which is in phase opposition to the emf produced in the rotor by rotation and is therefore in time quadrature with the single-phase voltage. These two voltages at 90°, or nearly so, may be connected by the Scott method as previously stated to give a three-phase source.

2. <u>Three-phase Motor</u>

A three-phase motor can be used much the same way as a two-phase motor and without the benefit of a transformer. The action is fundamentally no different in a three-phase motor from the action in a two-phase motor,[6] since each of the phases can be resolved into two quadrature-phases. In Figure 3 the main axis can be assured along a line joining A and B, the single-phase terminals, and the quadrature axis along the third winding. The effective turns along AB are 0.866 times total turns in phases A and B. The effective turns along the quadrature axis are total turns in phase C plus half the turns in either phase A or B.

These relations would indicate that voltages would be balanced, however this is not the case since the impedances of the respective windings will alter the phase relations in the motor and cause an unbalance at all times.

3. Parallel Capacitor

As the voltage in the auxiliary phase is less than that for the other two phases, the current which will flow in that phase will also be less. Some means is necessary to raise this current. If a capacitor is connected from one line to the auxiliary phase, as in Figure 4, a current will flow through the capacitor, into the auxiliary line. Because of the angle at which this current will flow, part of it will feed the three-phase load directly and part will flow back through the auxiliary winding and out the opposite single-phase line. The current flowing through the auxiliary winding acts as a magnetizing current and increases the voltage in the third phase. The current flowing to the three-phase load provides for more balanced currents in the load.

4. Series Capacitor

Somewhat better voltage regulation may be obtained by connecting a

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[6] A. H. Maggs, "Single-phase to three-phase conversion by the Ferraris-Arno System," Institute of Electrical Engineering, 11 (April, 1946), pp. 133-136.

Fig. 3. Three-phase Motor On Single-phase Source

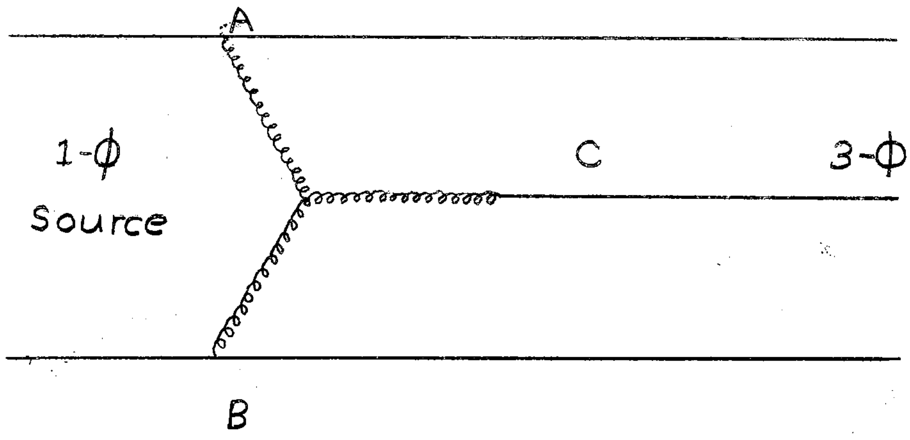
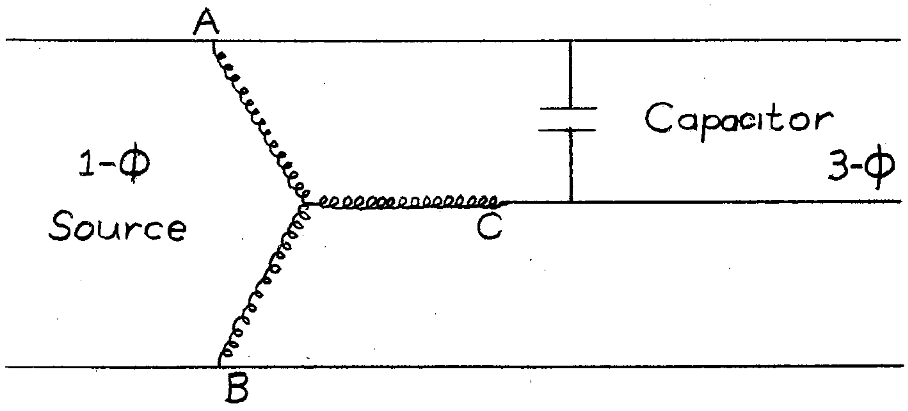


Fig. 4. Three-phase Motor With Parallel Capacitor



capacitor in series with the third phase. The capacitive reactance will tend to neutralize the inductive reactance of the winding and will provide a smaller voltage drop in that phase under load. A tendency to oscillate at a low frequency can be suppressed by connecting a resistance in parallel with the capacitor,[7] the size of the resistance being large enough to waste very little power.

5. Three-phase Motor with Special Winding

If the number of turns on the auxiliary phase of a phase converter is increased by 15 or 20% above that of the other two phases the voltage at no-load will be greater from the auxiliary terminal to the other terminals than the source voltage between the other terminals. Under load these voltages fall below the source voltage, but not as low as on a balanced three-phase motor used as a converter.

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[7] Ibid., p. 136.

D. Non-rotary

Operation of three-phase motors from single-phase source without recourse to rotating machinery is described by J. J. Taylor[8] in "Letters to the Editor" of Electrical Engineering.

As has been previously discussed, to operate a machine which draws steady power from a pulsating source, it is necessary to have some method of storing energy. Both inductance and capacitance have this ability to store energy.

By connecting the proper amount of inductance or capacitance across each of the two open phases of the load, performance at any particular loading is comparative to that with a three-phase supply. The operation also improves the single-phase power factor. The chief disadvantages of using reactance are the high cost of the elements, the losses in the elements, and the fact that their optimum values change with a change in load. One set of values is required for full starting torque and another set of values is required for full load running conditions. Recent developments in static capacitors and improved transformer cores tend to reduce the cost and the losses, and switching can be arranged to take care of major load changes.

According to Mr. Taylor,[9] "Balanced three-phase voltages can be obtained across balanced loads of any power-factor, by use of correct amounts of quadrature reactance." On unbalanced loads, balanced three-phase voltage can be obtained by adjustment of both angle and magnitude of one of the reactances. In the balanced case the line current and the power-factor are

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[8] J. J. Taylor, "Letters to the Editor," AIEE Transactions, Vol. 60, (November, 1941), p. 565.

[9] Ibid., p. 565.

usually known and the ratios of quadrature currents to the three-phase line currents are obtained by some method which Mr. Taylor does not mention.

To obtain the required reactance in ohms, the line voltage is divided by the quadrature current or the line voltage is divided by the three-phase line current times the ratio of quadrature current to line current.

The size of the capacitor in farads is quite large but can be reduced by connecting it to the high voltage side of a step-up transformer. The size of the capacitor is reduced by the square of the ratio of the turns of the transformer.

The inductance is preferably a laminated-core reactor with adjustable air-gap in order to produce a linear response under load, although a closed core with taps, to vary the number of turns, can be used. The disadvantages of the latter method are saturation of the core and distortion of the voltage wave shape.

In cases of extreme lagging power-factor the reactor can be omitted with very little effect on the circuit. This may be comparable to the starting of a three-phase induction motor. In this case, the capacitance across the other phase is calculated from the three-phase blocked rotor current. The higher capacitance for starting can be obtained by tapping the step-up transformer to produce a higher ration.

An interesting situation[10] which might arise is that in which one phase of a three-phase system becomes open at a point some distance from a motor installation and the capacitance between the load side of the open line and the other two lines are unequal. Considerable starting torque of three-phase motors on the line might be available. The direction of rotation might

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[10] <u>Ibid</u>., p. 565.

be normal or it might be incorrect with dangerous or even amusing results.

Different combinations of impedance can be used to obtain a rotating field from a single-phase source without recourse to rotating equipment.

If impedances are connected from each line of a single-phase source to the third phase of a three-phase motor connected to the source (Figure 5), current will flow through the impedances producing a difference of potential between each of the lines and the third phase. If either of these impedances is a reactance, a triangle of voltages will be formed. In the case where $Z_{ac} = R$ and $Z_{cb} = X_L$, (Figure 6a), the voltage relations will be as indicated in Figure 6b. This system of voltages provides a three-phase source suitable for starting a three-phase motor. After a motor is started from this source, the third phase current will alter the voltage relations. In any event, the loss in the resistance would prohibit the continuous use of the device with the motor running. Also, the inductance would draw a lagging current which would reduce the power-factor of the system. This device is only suitable for starting a three-phase motor on a single-phase source and is not suitable for running conditions.

If Z_{ac} is a resistance and Z_{cb} is a capacitive reactance, as in Figure 7a, the voltage relations will be as those in Figure 7b. Here again, a three-phase source is available for starting a three-phase motor. After starting it would be necessary to remove the resistance because of the losses. The capacitor could remain in the circuit and would even be desirable since it draws a leading current and tends to improve the power-factor of the system.

A third combination for split-phase operation is the use of capacitance and inductance as in Figure 8. This method has been partially described previously. If, instead of a three-phase motor, three pure resistors are

Fig.5. Split-phase Operation

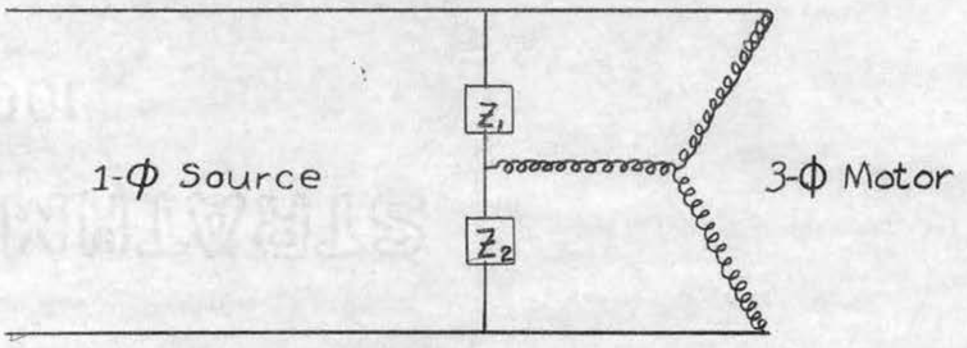


Fig.6. R-L Split-phase Operation

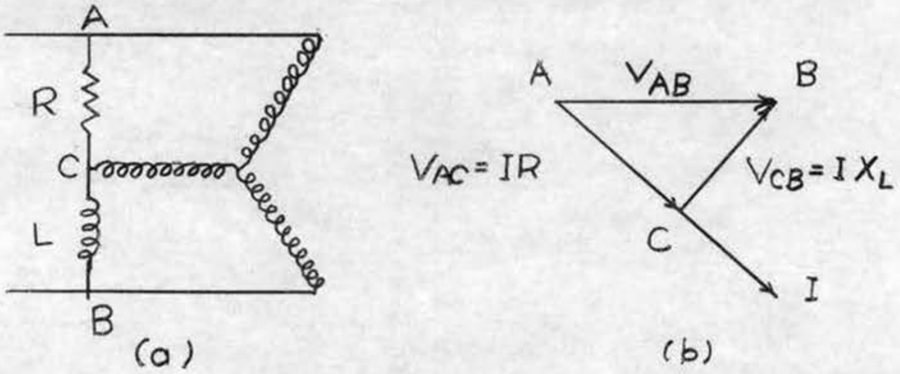


Fig. 7. R-C Split-phase Operation

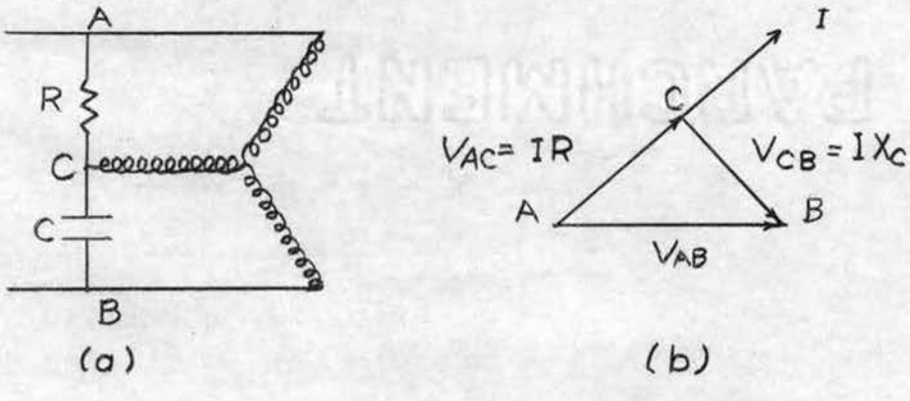


Fig.8. L-C Split phase Operation

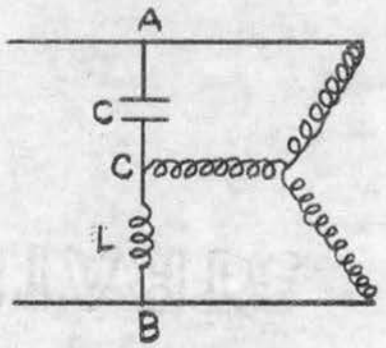


Fig.9. Balanced Resistance Load

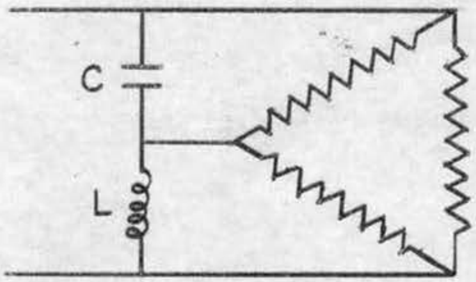
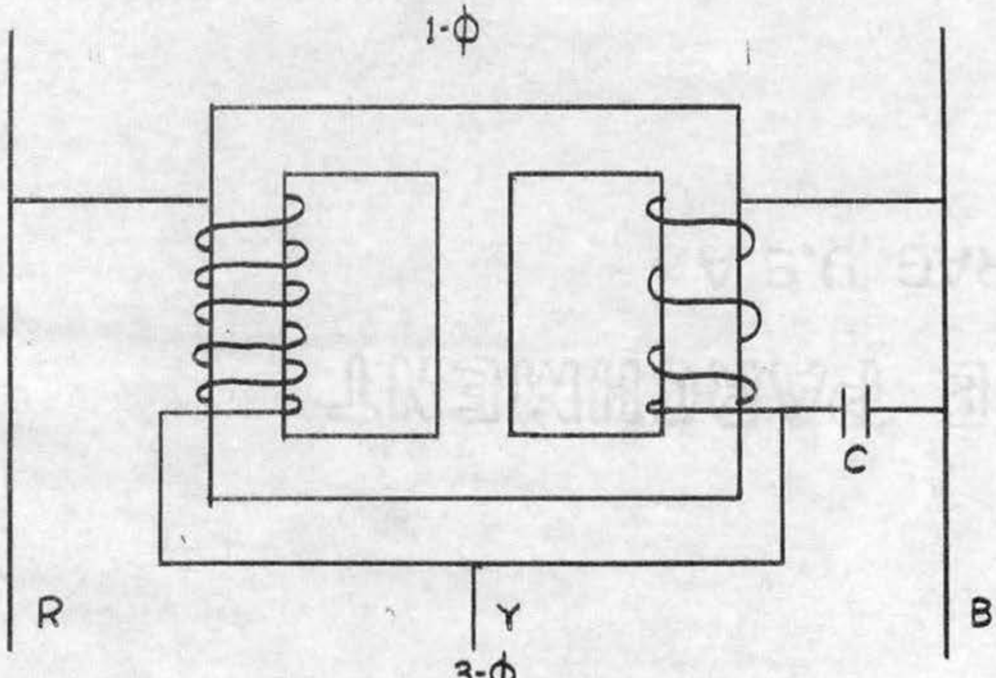


Fig. 10. Diagram of Static Phase Converter



used in balanced delta as in Figure 9, and the values L and $1/\omega C$ are both equal to $R/\sqrt{3}$, balanced three-phase voltages will be obtained. This is possible because capacitors and inductors have the ability to store energy, which is a requirement, as previously stated, necessary for the operation of a three-phase load from a single-phase source. Because the value ωL is equal to $1/\omega C$, series resonance occurs between the capacitor and the inductor if the load resistors are removed. This is effectively a short-circuit which could cause considerable damage and consequently the method is suitable only for small fixed loads.

A converter[11] of this type is manufactured by Messrs. Westinghouse Brake and Signal Company, Limited, Chippenham, Wilts., England. In the Westinghouse converter the problem of adjusting the values of the capacitance and the inductance for varying loads is solved by connecting another inductance in parallel with the capacitor and constructing the inductors so that saturation will vary their values at different loads. The parallel combination of capacitance and inductance acts as a variable capacitor which changes automatically with load. In practice, the construction used is similar to a three-phase core-type transformer with the two windings on the outer legs, as in Figure 10. Further consideration of this type of converter will be given in examples of uses and rating of machines.

An American version of the static phase converter has been placed on the market recently by the Henry Company of Saginaw, Michigan. No data is available on the construction of the Henry phase converter, but it is believed to be two sets of capacitors, one set being automatically removed from the circuit as the motor comes up to speed. Experimental data will be given on the Henry converter in this thesis and a more complete discussion will be given by Mr. Douglas Lloyd at a later date.

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[11] "Static Phase Converters", Engineering, Vol. 153 (May 15, 1942), p. 385

E. Examples of Use

1. Railroads

A good example of the use of the rotary phase converter is on the Norfolk and Western Railway. In order that proper appreciation of some of the problems involved be gained, the electrified section of the railway will be described.

The section of the railroad which is electrified is known as the Elkhorn Grade.[12] It is located about 105 miles west of Roanoke, on the main line, and extends about thirty miles from Bluefield to Vivian in West Virginia. The grades on the line vary from 1.0 to 2.5 percent and there are many curves. On the electrified section, loaded cars of coal are collected on the east bound trip and empty cars are returned on the west bound trip. The section was electrified to increase the capacity of the railway by speeding up service and to provide a more efficient and economical service over the heavy grades. With electric locomotives, the speed at which traffic is handled up the grades is fourteen miles per hour whereas by steam locomotives the speed was seven and one-half miles per hour.

The electrical system used is single-phase. The power is generated, transmitted and distributed single-phase at a frequency of 25 cps and is collected from the overhead catenary lines at 11,000 volts. Single-phase distribution at high voltage is the most desirable method of delivering and collecting power since only one line must be maintained and a small current transfer is required. The step-down transformer lends itself to the use of the two-phase rotary phase converter to transform the single-phase power to three-phase induction motors. One of the chief advantages of three-phase

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[12] Staff, "Electrification of the Norfolk and Western Railway," Electric Journal, XII (July, 1915), p. 309.

motors, aside from their better overall operating characteristics, is their adaptability to regenerative braking. The braking has proved highly satisfactory on the line, with the heaviest trains held to fifteen miles per hour down the steepest grades with the utmost ease. The train drives the motor as a generator and feeds power back into the lines. The air brakes are held in reserve for emergency or to bring the train to a stand still. This method reduces wear on the brakes and reduces demand on the generating system at times when power is being drawn from the lines for other trains or other purposes.

In favor of phase converters some of the essential merits of the phase converter locomotive must be given.

As was stated previously, power is transferred at a high voltage and must be stepped down to a lower voltage for use. This step-down transformer lends itself to the phase converter operation.

The phase converter permits the use of three-phase induction motors with several advantages.

The induction motor has no commutator which means that troubles inherent to commutator motors are eliminated and, more important, the space normally taken up by the commutator can be used for active core iron in the induction machine.[13] The available space in an electric locomotive for driving motors is limited. The diameter of a motor is limited by the safe peripheral speed of the rotor, gear ratio, wheel size and other factors. The length of the motor is limited by the space available between the wheels of the locomotive. In some cases of commutator motors only 20 to 30 percent of the space between

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[13] R. E. Hellmund, "The Field of Application of the Phase Converter Locomotive," Electric Journal, XII (October, 1915), p. 462.

the wheels is available for the core iron of the motor. Since the core iron is that part of the armature which actually determines motor output, any extra width gained is very important. By using phase converters and induction motors, more space can be used for core iron and a larger power output can be obtained. The slip rings necessary on a wound rotor induction motor can be located underneath the end connections of the rotor winding or outside the motor by bringing the leads through a hole in the shaft. The extra space available permits the utilization of 40 to 50 percent of the space for active core iron which is 33 to 100 percent more than is possible with a commutator motor.[14] Considering the above discussion, it is evident that it is possible to employ more powerful motors by using induction motors than is possible by using either alternating or direct-current commutator motors.

The phase converter locomotive with induction motor has even more merit over the single-phase commutator motor in some of the ways in which it meets some special service conditions to a better degree.

One of these conditions is a method of starting, whereby a pusher locomotive takes the slack out of the train by applying power on the pusher first and holding it until the pulling locomotive puts on enough power to accelerate the train. It sometimes happens that signals get mixed or the brakes fail to release properly and the pusher locomotive has to stand still for as long as ten minutes. In the single-phase commutator motor this condition can be damaging. At standstill the pulsating flux caused by the alternating stator voltage induces voltages in the rotor. Those armature coils short-circuited by the brushes will have a short-circuit current flow which, over a prolonged period of five to ten minutes, may be sufficient to damage the insulation or

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[14] *Ibid*.

melt the solder at the joints of the coils. With the three-phase induction motor, the heating conditions are not a great deal different at stand still from full speed operation if the ventilation is not dependent upon the rotation of the motor. In most cases the phase converter is used to drive the ventilating fans. This use of the phase converter to drive a load brings up a point which might be considered a disadvantage but is not necessarily a great disadvantage in many case.

The phase converter method requires another piece of rotating equipment. In first cost and in weight this is not as bad as it might seem at first. For a given horsepower rating and a given speed the cost and weight of an induction motor is about 60 to 90 percent of the cost and weight of an equivalent single-phase motor and the cost and weight of the phase converters is 30 to 60 percent of that of a single-phase motor. From this comparison it is seen that the total cost and weight of three-phase motor and phase converter is very little more than the cost and weight of an equivalent single-phase motor. It is sometimes necessary in railroad work to design single-phase motors at a lower speed because of peripheral speed of the commutators. When this is done it often swings the cost and weight comparisons in favor of the phase converter.

The maintenance on the converter and induction motor, both of which are very simple and very rugged, will be less than the maintenance on one or more single-phase commutator motors. The phase converter can be used to drive auxiliary equipment such as blowers and air compressors without affecting its voltage balancing ability.

The necessity of using starting rheostats in the phase converter locomotive might appear to be a disadvantage not present in the single-phase commutator locomotive. However, water rheostats can be used from which it is possible to secure exceedingly smooth acceleration--a very desirable feature in handling heavy freight trains. To obtain the same starting characteristics with a single-phase commutator motor it would be necessary to have a large number of steps with many heavy switches. The advantage, here again, falls to the phase converter locomotive. In comparison with direct current locomotives, any savings in first cost of direct current locomotives are more than balanced by savings in sub-stations and transmission lines. In addition, for the very heavy freight work, the starting resistors for the direct current locomotives would be much heavier and more bulky than would those of the phase converter locomotives.

In light freight and passenger service the advantages discussed are not nearly as great, therefore, the choice would depend on minor advantages and in general probably favor direct or single-phase commutator locomotives.

2. Machine Shop

One case[15] arose in World War II in which three-phase power was desired and only single-phase power was available. The obvious answer was to use a phase converter.

The case was that of a small machine shop working on government contracts. The shop was assigned lathes by the government, which were equipped with three-phase motors and controls. The shop was in a residential area with only single-phase power available, no standard motor-generator set was available and it was undesirable to install an internal combustion engine-driven unit. A conversion to single-phase motors was undesirable because of the cost, time, and motor controls. The solution to the problem, worked out by the sales department of the local utility company, was found when it was

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[15] "Getting Three-phase from Single-phase," Electrical World, Vol. 123, (January, 1945), p. 160.

remembered that the Norfolk and Western Railroad supplied single-phase energy which was converted by an induction motor-generator set to polyphase energy for use with three-phase traction motors as has previously been discussed.

In the particular case of the industrial plant, a motor-generator set was made up of a 10 horsepower, single-phase induction motor, V-belted to a 10 horsepower, three-phase induction motor.

The three-phase motor was driven at a slightly higher speed than the single-phase motor, the three-phase motor at 1850 rpm and the single-phase motor at 1750 rpm. The connected load was only three horsepower and a smaller motor could have been used for a converter, however, the ten horsepower motors were available and were used. The set was very inefficient but the motors were available and other methods required capacitors and reactors which were not readily available.

3. Induction Motor as Phase Converter

The system of an induction motor as a phase converter, as has been described previously, is a method which has been used in England for practical results. The system is known by the name of the Ferraris-Arno system.[16] The name is from Professor Arno who first proposed the use of a three-phase induction motor as a phase converter and who proposed to start the converter by means of a resistance-inductance type of phase splitter which had originally been proposed by Professor Ferraris as a method of starting induction motors from single-phase sources. The converter is called a pilot motor and is generally of the type having the third phase wound with a larger number of turns.

In actual practice a capacitor is quite often connected from the line to the third phase of the pilot motor as it dispenses with the resistance-inductance starter and improves the power-factor and voltage characteristics.

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[16] Magg, loc. cit.

In some installations, two or more pilot motors are used and individual capacitors are used with the larger motors of a system. This practice provides a more flexible and efficient system with better voltage stability.

4. Westinghouse Static Phase Converter

The Westinghouse (of England) static phase converter has been found satisfactory in many installations in England.[17] One installation of Westinghouse phase converters is a combination of two 4-KVA converters in parallel. These two converters supply power to four capstan lathes, two with 2-horsepower motors and two with 3-horsepower motors; a center lathe with a 2-horsepower motor; a 3-horsepower milling machine; a 1-horsepower grinder; and a 0.5-horsepower drill making a total of 16.5 horsepower. Another installation in which a 4-KVA converter is used with an auto transformer, operates from a 230 volt single-phase supply to drive a surface grinder, a milling machine, and a number of machines from line shafting. The total connected load is 7-horsepower. A third example of the use of the Westinghouse static converter is in a foundry installation in which a 4-KVA converter, operating from a 400 volt single-phase main, is supplying power to a number of blowers for oil fired furnaces and a cutting-off machine for the production of lead-bronze bearings.

The characteristic curves of a 4-KVA static phase converter loaded with pure resistance are shown in Figure 11. The single-phase input voltage which is constant is marked R-B. The inductance phase voltage is marked R-Y and the capacitor phase voltage is marked Y-B. With a balanced resistive load the voltages, from no load to full load, stay within ten percent of the applied voltage.

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[17] "Static Phase Converters," Engineering, Vol. 153, (May 15, 1942), p. 385.

voltage. The voltage wave form[18] "is entirely satisfactory for normal commercial requirements." If a pure wave form is desired for testing or other special uses, it can be obtained by adding a filter. Phase converters, in general, will not be used for resistive loads but on loads having a lagging power-factor. Figure 12 shows the voltage characteristics of a Westinghouse static phase converter with a reactive load of 0.8 lagging power-factor.

An induction motor used with the static phase converter will have better characteristics than those shown in Figure 12 because of the balancing effect of the motor itself.

The efficiency of a 4-KVA static phase converter at full load is around 95 percent.[19] At lighter loads, the efficiency falls off rapidly because of the high iron losses. The iron must operate at high flux densities to balance the voltages at the lighter loads. At one-half load the efficiency is only 88 percent, therefore, it is undesirable to operate the converter at reduced load for long periods of time unless the insulation is of a type to operate at high temperature rise. The same property of the converter limits its size unless special insulation and cooling are used. Parallel operation of small units can be used for the larger loads. Parallel operation has the advantage of flexibility when alterations in the loads are expected.

The Westinghouse static phase converter was first developed for the operation of cinema arcs and was later applied to three-phase battery charging equipment. The more recent application, however, has been as a power source in small factories and plants in residential areas where three-phase power is not available.

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[18] Ibid., p. 385.

[19] Ibid., p. 385.

Fig 11 Static Phase Converter With Resistance Load.

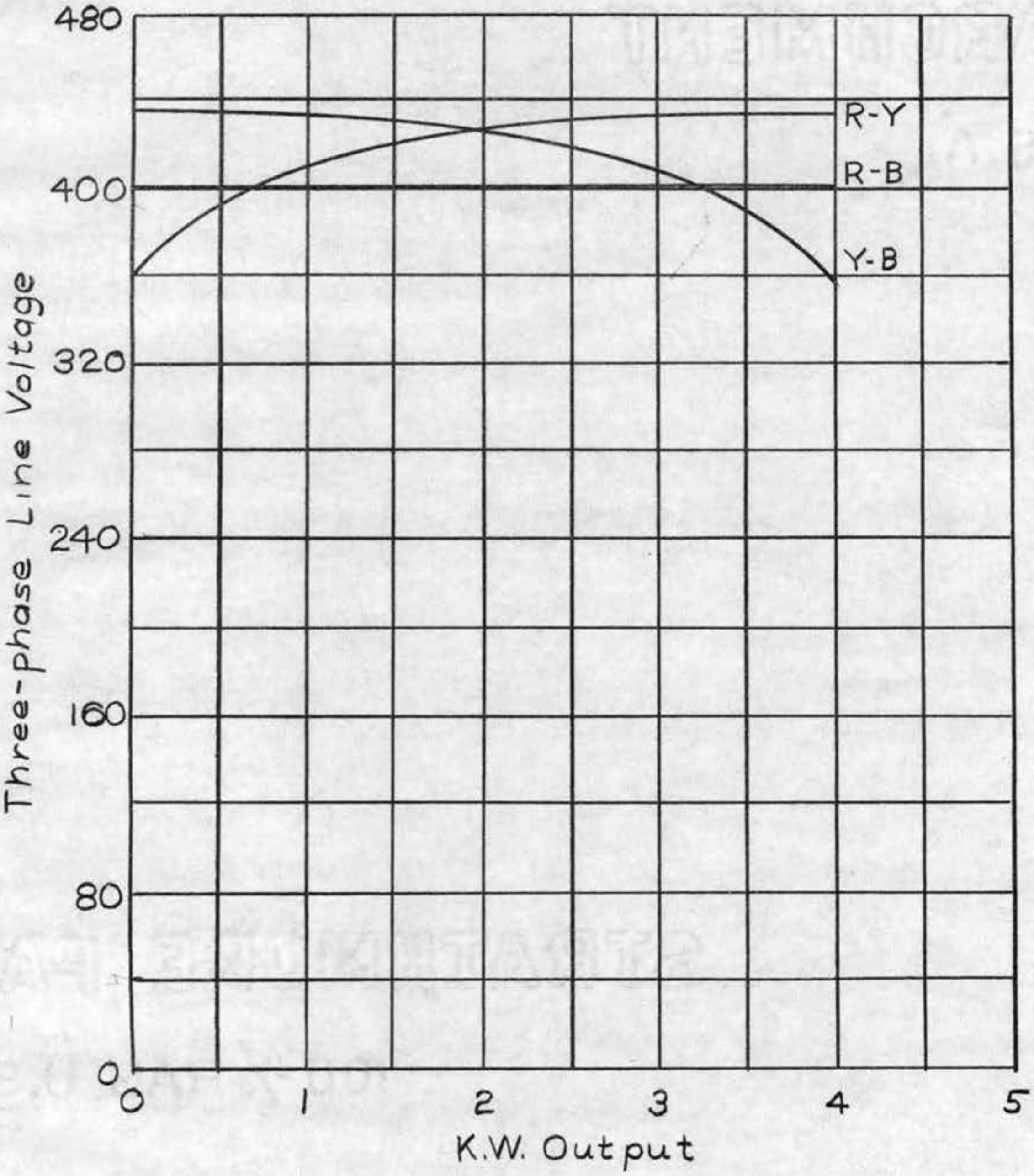
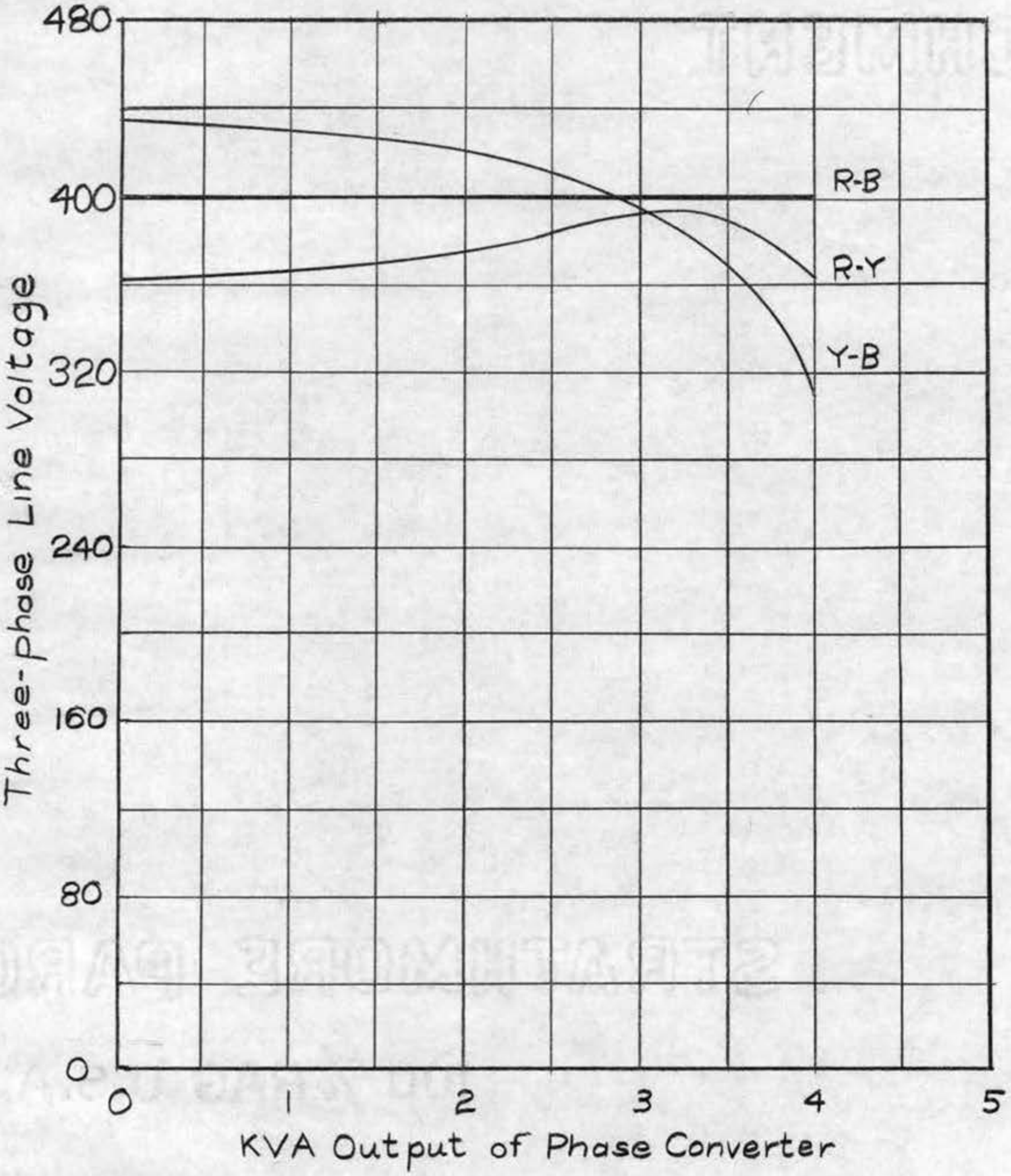


Fig 12. Static Converter With 0.8 P.F. Inductive Load



F. Selection and Rating

Some characteristics of a polyphase motor on a single-phase supply are given as a quotation from an article "Polyphase Motors on Single-phase Circuits" by G. H. Garcelon in the Electric Journal, August, 1905, page 501. The original article was not available therefore the quotation will be given.[20]

> The characteristics of the motor will not be as good on single-phase as when operated on a polyphase circuit for which it is designed, and some special device will have to be employed to make it self starting. Motors with squirrel cage rotors in general give better performance under abnormal conditions than wound secondary motors. With a given slip and given temperature rise, operation on single-phase circuits will reduce the available capacity to approximately 70% of normal polyphase rating. The maximum running or pull-out torque will be decreased one-half or one third, depending on slip; the motor having the smallest slip gives the greater pull-out torque. The efficiency and power factor will be in general, highest at 70% of the normal polyphase load but will be from 6 to 12% lower than with normal operation. As a single-phase motor, the machine will not develop any starting torque; it is not necessary, however, to bring the motor up to more than one-fifth of normal speed in order to allow it to pick up, provided the load is very light. Hence, unless the motor is too large, it may usually be started by a vigorous pull on the belt.

Curves of a three-phase motor on single-phase supply are given in Figure 13. The curves were taken from an article by C. A. M. Weber.[21] The motor was operated at one-half voltage to hold the current as low as possible. From the curves it can be seen that the maximum efficiency reaches slightly more than 75% and then falls off rapidly. The current also rises rapidly as load is added and the speed regulation is poor. A correct analysis of the operation would require a comparison with balanced three-phase operation on the reduced voltage of 110 volts.

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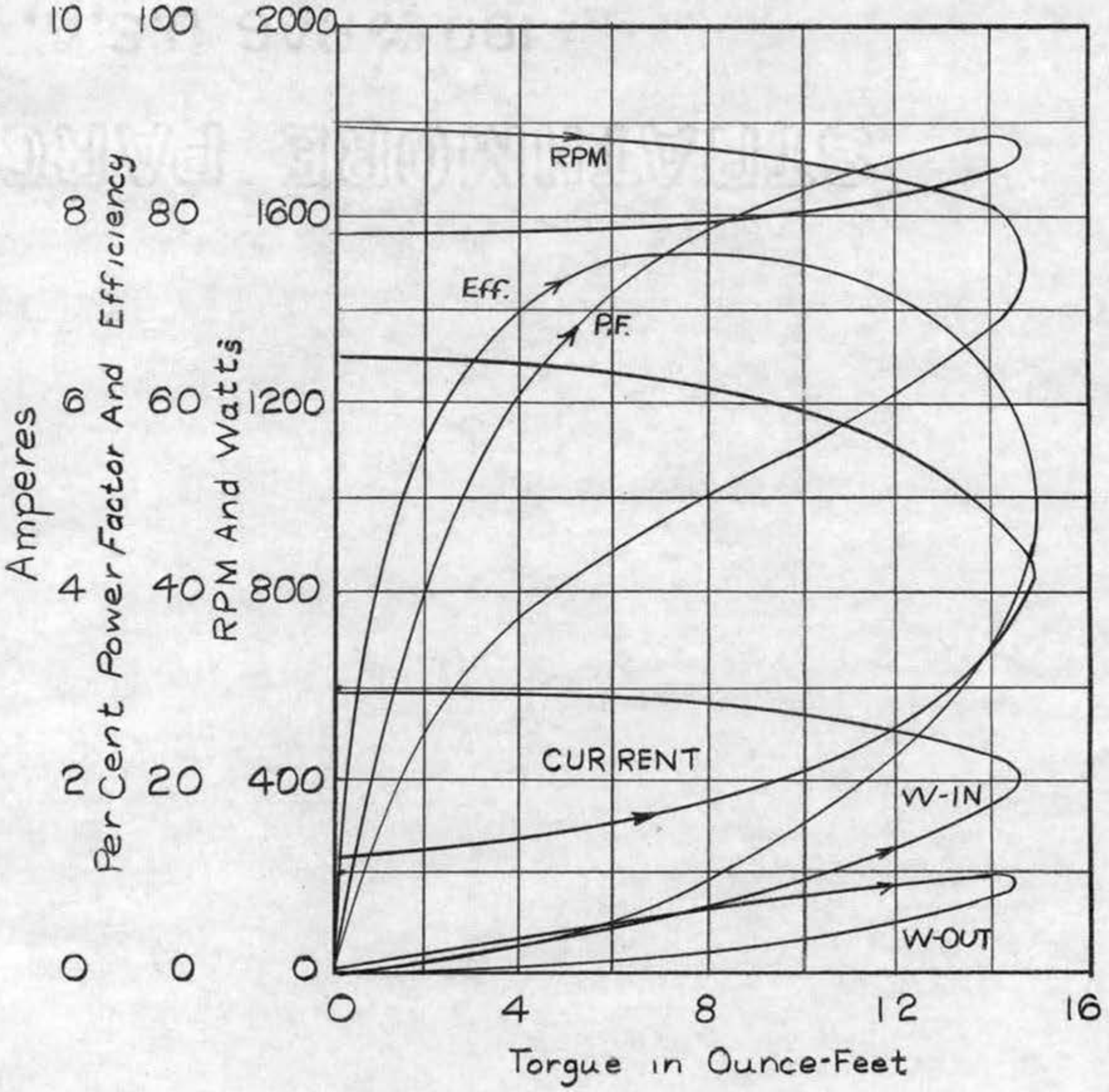
[20] G. H. Garcelon, "Polyphase Motors on Single-phase Circuits," Electric Journal, IX, (September, 1912), p. 797.

[21] C. A. M. Weber, "Characteristic Curves of the Induction Motor" Electric Journal, II (September, 1914), p. 484.

Fig. 13. Three-phase Motor on a single-phase source



Determining the size of motors and phase converters for a specific installation is a very special problem. Over half the power of a motor operating from a phase converter is passed directly through the single-phase source and will deliver one-half of rated horsepower without the aid of a phase converter. One motor, operating full load, requires a converter of a rating equal to its own. At lesser loads the rating of the converter can be less. For starting a motor, the converter must be large enough to supply the starting KVA. The starting KVA will depend on the method of starting and the percentage of full load against which the motor must start. A squirrel cage induction motor started with full load will require a phase converter with a rating considerably larger than its own. In most cases, the converter will be used in conjunction with several motors of which the total demand at any time is less than one-half the total connected horsepower. In the case of several motors connected in parallel, the lightly loaded motors help to balance the voltages of those which are heavily loaded. The capacity of the phase converter will be determined by the starting KVA of the largest motor in the group. In these multi-motor installations, there is usually little difficulty in arranging that the starting demands of the first motor are well within the limits of the converter. Many successful installations are in operation in which the total connected load is considerably greater than the rating of the phase converter.

III. THE EXPERIMENT

A. Introduction

The objective of the experiment was to gain a comparison of the operation of a three-phase induction motor on balanced three-phase voltages with the operation on single-phase voltage, using various methods of phase conversion.

B. Equipment

1. Dynamometer

The tests were made on a Diehl K-7 dynamometer. The dynamometer combines the prony brake method and the connected generator method for determining the output of a motor. The dynamometer is a direct current generator, the housing of which is free to rotate except as limited by the scales. The scales are attached to the frame of the machine and measure the torque reaction.

The length of the brake arm of the dynamometer used was 1.05 feet and the horsepower output was computed by the following equation:

$$\text{H. P.} = \frac{(2\pi)\ (\text{RPM})\ (\text{Weight on scales})}{33000}$$

$$= \frac{(2\pi 1.05)}{33000}(\text{RPM})(\text{Weight}) = \frac{(\text{RPM})\ (\text{Weight})}{5000}$$

The speed was measured by an electric tachometer which was an integral part of the dynamometer.

The generator of the dynamometer was separately excited from a 220 volt direct current source. The separate excitation was necessary so that all energy transferred to the generator was measured on the scales except for a constant value of friction and windage loss.

The generator housing and the scales were balanced at standstill. The input to the motor while disconnected from the dynamometer was measured for the no-load input to the motor. The input to the motor, with the dynamometer connected, but with the field open, was measured and the scale deflection was recorded. The difference between the input to the motor for the two cases gave the total bearing, friction and windage losses in the dynamometer. The scale reading does not include the total losses, therefore, it must be converted to watts and subtracted from the total bearing, friction and windage losses to find a constant loss which is to be added to the output of the motor as calculated from the scale reading.

2. Measuring Instruments

The instruments used were those instruments in the machinery laboratory, Room 101, Engineering building and were subject to an error of possibly 2 percent.

3. Motor

The motor tested under the various conditions was a Reliance Type AA, Induction motor with Type H insulation. The motor was rated at 5 horsepower, continuous duty, with a 40° C. temperature rise. The voltage rating was 220 or 440 Volts, three-phase at 60 cps.

4. Phase converters

Conversion was obtained through the use of a 5 horsepower, 220 Volt, Henry phase converter and, also, by the use of a 5 horsepower Life Line induction motor running at no-load in parallel with the test motor.

C. Procedure

The tests were made to obtain data for the efficiency, voltage, and current characteristics for the various types of operation. The procedure was to apply small increments of load to the motor and record all pertinent data. The load was increased in most cases until the motor stalled. These overloads were possible because of the Type H insulation on the test motor.

D. Data

TABLE I

Dynamometer Test of 3-Phase Induction Motor on Balanced three-phase Voltages

No.	V_{12}	V_{23}	V_{31}	RPM	WT	I_1	I_2	I_3	Kw
1	220	220	220	1190	3	5.4	6	6	0.67
2	220	220	220	1190	3.2	5.5	6	6	0.77
3	220	220	220	1185	6.7	6.2	7.0	6.8	1.4
4	220	220	220	1180	9.0	7.1	7.6	7.9	1.84
5	220	220	220	1175	12.0	8.4	8.9	9.2	2.38
6	220	220	220	1170	15	9.8	10.2	10.6	3.0
7	220	220	220	1165	18	11.3	12.1	12.4	3.6
8	220	220	220	1160	21	13.1	13.8	14.2	4.2
9	220	220	220	1150	24	15.0	15.7	16.2	4.9
10	220	220	220	1145	27	17.0	17.7	18.2	5.6
11	219	219	219	1130	30	19.4	20.1	20.2	6.3
12	219	219	219	1120	33	21.9	22.9	23.4	7.0
13	219	219	219	1110	36	25.4	26.4	26.7	7.9
14	219	219	219	1085	39	29.1	30.2	31.2	9.0
15	218	218	218	1050	42	34.5	35.0	36	10.0
	Breakdown								

April 15, 1950

C. F. Cameron
Douglas Lloyd
P. D. Arnett

Reliance Type AA Induction Motor
5 H. P., Continuous Duty, 30° C Temp.
Rise 220 V., 13.7 A., 60 cps
440 V., 6.85 A., 3-Phase Form O
1155 RPM Frame C - 284 No. B-98429
Code H. Rotor 43020-R
Reliance Elec. and Engr. Co.
Cleveland, Ohio

1	V_{13}
2	V_{12}
3	V_{23}
4,5	W
6	I_1
7	I_2
8	I_3

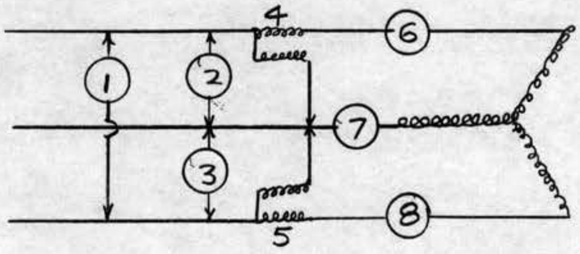


TABLE II

Characteristics of a Three-phase Motor

from Dynamometer Test

No.	Horsepower	KW Output	Efficiency	Power Factor
1	0.670	0.499	0.745	0.293
2	0.715	0.533	0.693	0.337
3	1.540	1.147	0.819	0.550
4	2.080	1.550	0.843	0.643
5	2.785	2.075	0.871	0.703
6	3.475	2.590	0.864	0.770
7	4.155	3.100	0.862	0.782
8	4.830	3.600	0.858	0.799
9	5.480	4.080	0.833	0.819
10	6.135	4.580	0.818	0.830
11	6.735	5.030	0.799	0.827
12	7.355	5.480	0.783	0.807
13	7.955	5.930	0.751	0.789
14	8.415	6.280	0.699	0.787
15	8.775	6.550	0.655	0.757

TABLE III

Dynamometer Test of 3-Phase Induction Motor

Supplied by Henry Phase Converter

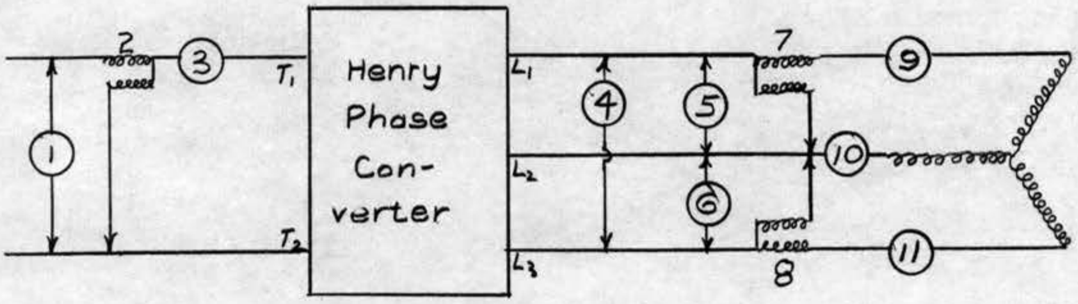
No.	V_{12}	V_{23}	V_{31}	RPM	Wt	I_1	I_2	I_3	KW	Vin	Iin	Win
1	221	266	266	1190	3.3	6.6	8.9	15.1	1.1	220	6.4	1.196
2	218	246	260	1180	9.0	10.0	4.5	14.1	2.0	219	10.1	2.08
3	218	233	254	1170	12.0	12.0	5.0	12.7	2.6	220	12.1	2.64
4	217	216	244	1170	15.0	14.6	5.8	12.4	3.1	220	14.7	3.2
5	216	198	235	1160	18.0	16.7	9.6	11.4	3.8	220	17.8	3.84
6	214	172	216	1145	21.0	21.8	16.3	10.0	4.6	219	22.7	4.66
7	214	168	214	1140	21.5	22.4	17.4	10.0	4.8	220	22.7	4.84
8	214	157	208	1135	22.0	24.6	20.2	9.3	5.0	220	25.5	5.16
9	215	144	192	1130	225	26.	23.4	10.0	5.3	220	27.	5.44

Breakdown

C. F. Cameron
Douglas Lloyd
P. D. Arnett

April 15, 1950
Reliance Motor

Henry Phase Converter
5 H. P., 220 V., B115
Henry Electric Company
Saginaw, Michigan



1 Vin
2 Win
3 Iin
4 V_{13}
5 V_{12}
6 V_{23}
7,8 W
9 I_1
10 I_2
11 I_3

TABLE IV

Characteristics of a Three-phase Induction Motor

Supplied by Henry Phase Converter

from Dynamometer Test

No.	Horsepower	KW Output	Efficiency	Power Factor
1	0.74	0.55	0.462	0.85
2	2.08	1.55	0.744	0.94
3	2.77	2.06	0.780	0.993
4	3.47	2.58	0.806	0.99
5	4.13	3.08	0.800	0.981
6	4.77	3.55	0.762	0.938
7	4.87	3.63	0.750	0.97
8	4.97	3.70	0.718	0.92
9	5.05	3.76	0.692	0.916

TABLE V

Dynamometer Test of a Three-phase Induction Motor

Supplied by Henry Phase Converter, with Constant Load

No.	Vin	Iin	KWin	V_{12}	V_{23}	V_{13}	I_1	I_2	I_3	KW	RPM	#
1	238	14.2	3.34	237	246	266	14.1	4.6	14.0	3.2	1175	15
2	219	15.1	3.34	218	218	240	14.9	6.0	12.4	3.305	1175	15
3	210	15.6	3.26	210	205	232	14.1	7.05	10.0	3.23	1175	15
4	200	17.1	3.34	196	194	208	16.0	9.85	10.0	3.34	1165	15
5	189	19.8	3.54	186	156	193	18.5	14.5	8.6	3.46	1155	15

TABLE VI

Characteristics of a Three-phase Induction Motor

Supplied by Henry Phase Converter, with Constant Load

from Dynamometer Test

No.	Horsepower	KW Output	Efficiency	Power Factor
1	3.38	2.52	0.753	0.989
2	3.38	2.52	0.753	1.00
3	3.38	2.52	0.771	0.996
4	3.35	2.50	0.748	0.976
5	3.32	2.47	0.699	0.946

TABLE VII

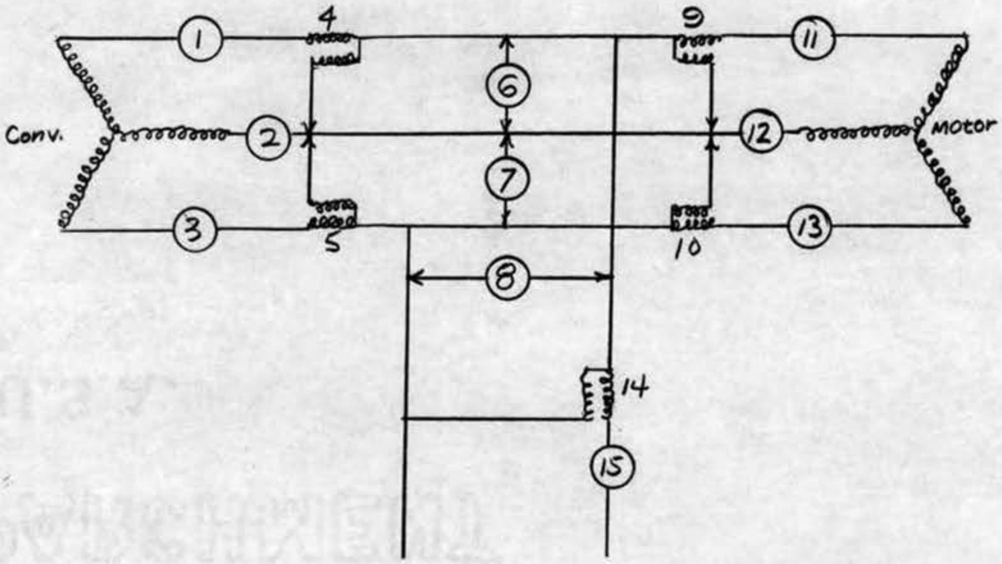
Dynamometer Test of a Three-phase Induction Motor in Parallel with an Unloaded Three-phase Induction Motor

WT_1	0	3	6	9	12	15	18
I_{m1}	8.9	9.3	10.1	11.8	13.2	15.4	17.1
I_{m2}	1.04	2.0	2.6	3.5	4.1	5.0	6.1
I_{m3}	9.52	10.68	12.2	14.2	15.72	18.0	21.6
W_M	650	1276	1880	2430	3130	4180	4480
V_{12}	212	214	212	212	210	210	205
V_{23}	219	215	211	207	201	201	186
V_{31}	244	244.5	242.5	242	240	240	238
RPM	1190	1185	1180	1175	1170	1165	1150
W_c	518	512	587	560	532	630	680
I_{c1}	12.08	12.58	12.85	13.2	13.94	14.2	15.
I_{c2}	1.04	2.0	2.6	3.5	4.1	5.0	6.1
Win	1160	1788	2467	3000	3750	4820	5250
Iin	20.8	21.85	22.5	24	27.3	29.2	33.3

TABLE VIII

Characteristics from Dynamometer Test

H.P.	0.577	1.29	1.996	2.692	2.387	4.067	4.717
KW	0.430	0.963	1.486	2.005	2.525	3.03	3.52
M Eff.	0.662	0.755	0.790	0.825	0.808	0.725	0.785
Overall Eff.	0.371	0.537	0.603	0.670	0.674	0.630	0.670
P.F.	0.229	0.334	0.452	0.519	0.571	0.687	0.661



1	I_{c1}	8	V_{31}
2	I_{c2}	9 & 10	W_m
3	I_{c3}	11	I_{m1}
4 & 5	W_c	12	I_{m2}
6	V_{12}	13	I_{m3}
7	V_{23}	14	W_{in}
		15	I_{in}

Fig. 14. Voltage Characteristics of Phase Converters

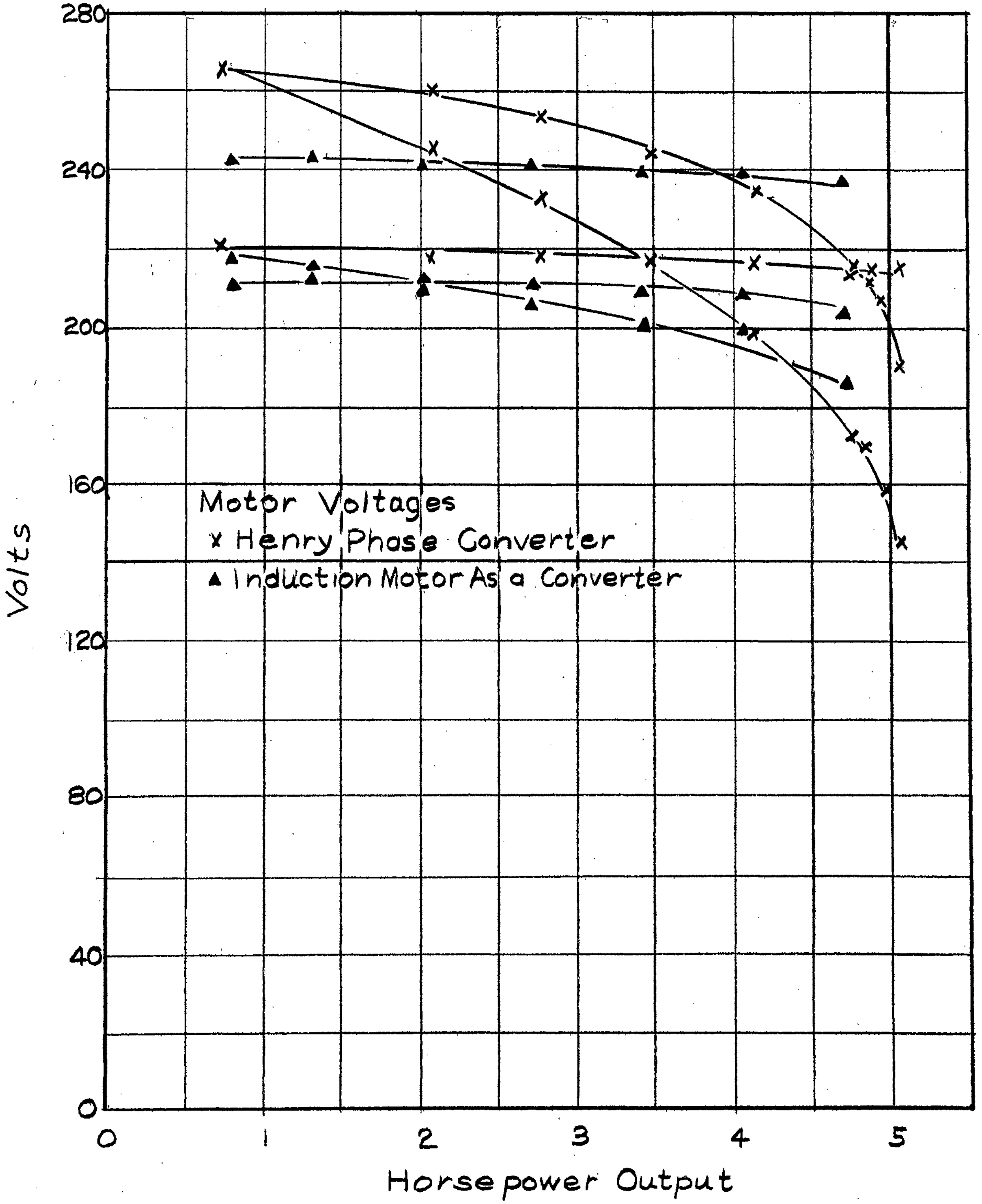


Fig. 15. Current Characteristics With Henry Converter

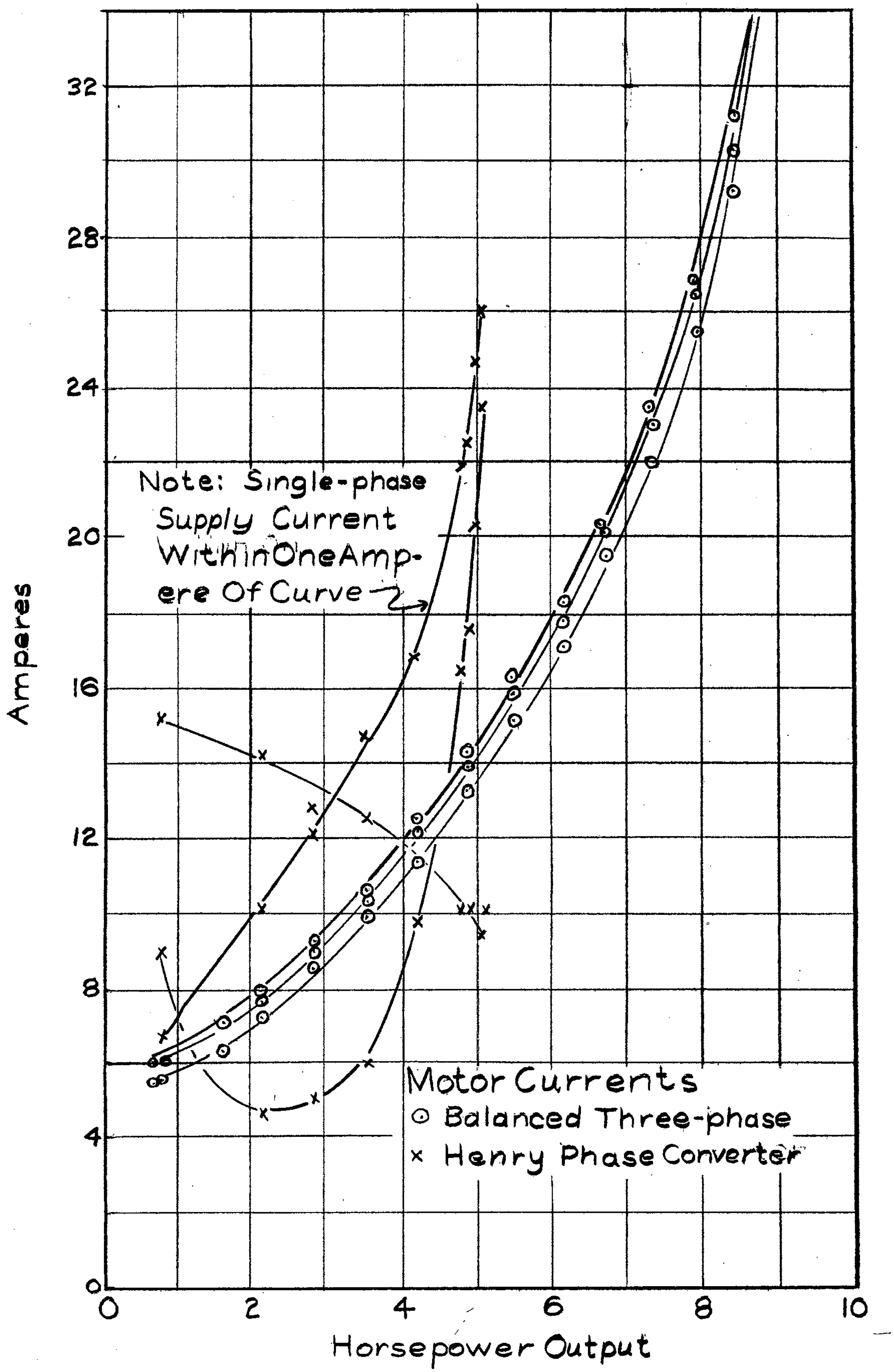


Fig.16. Current Characteristics With Induction Motor As Phase Converter

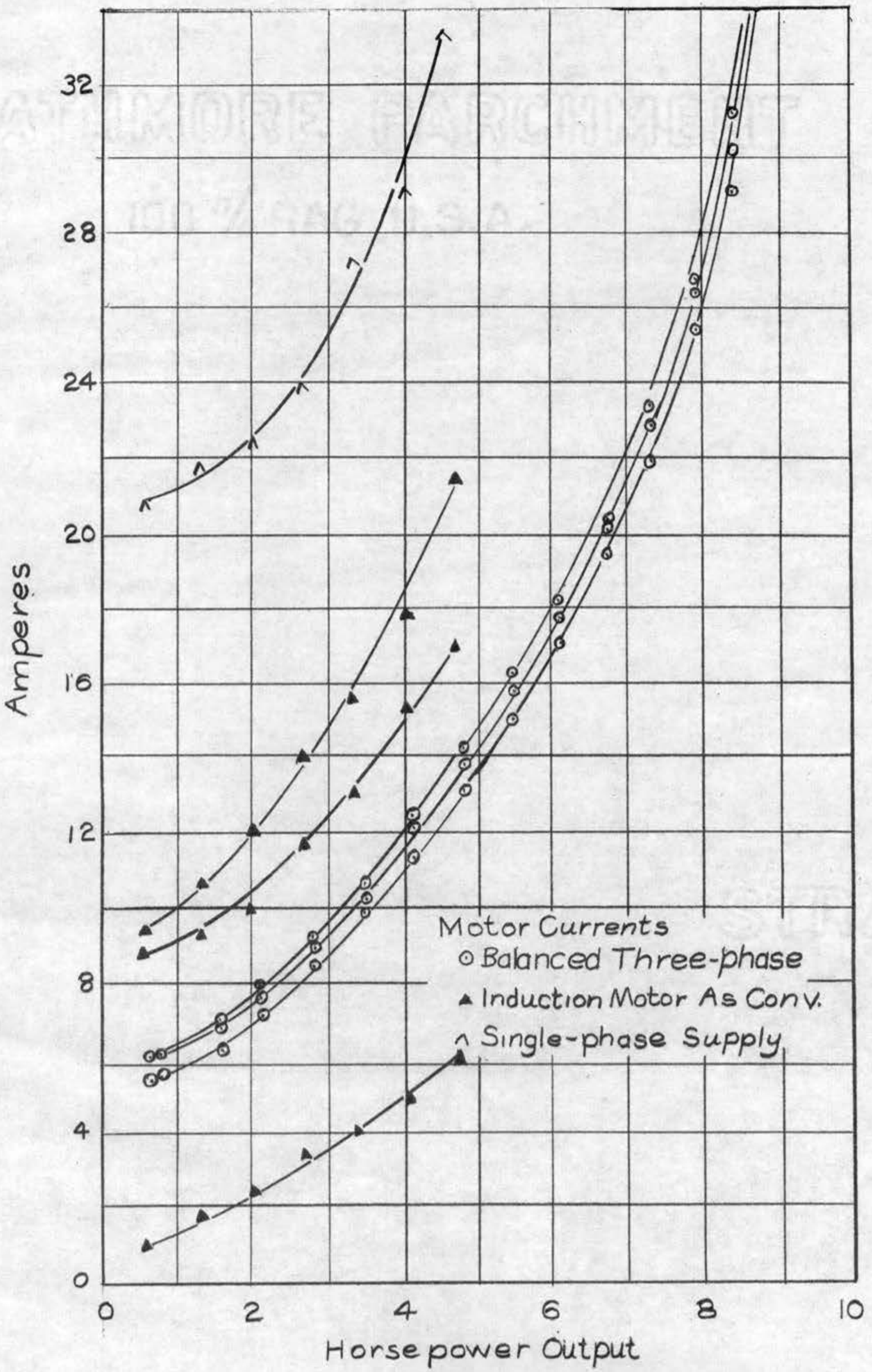
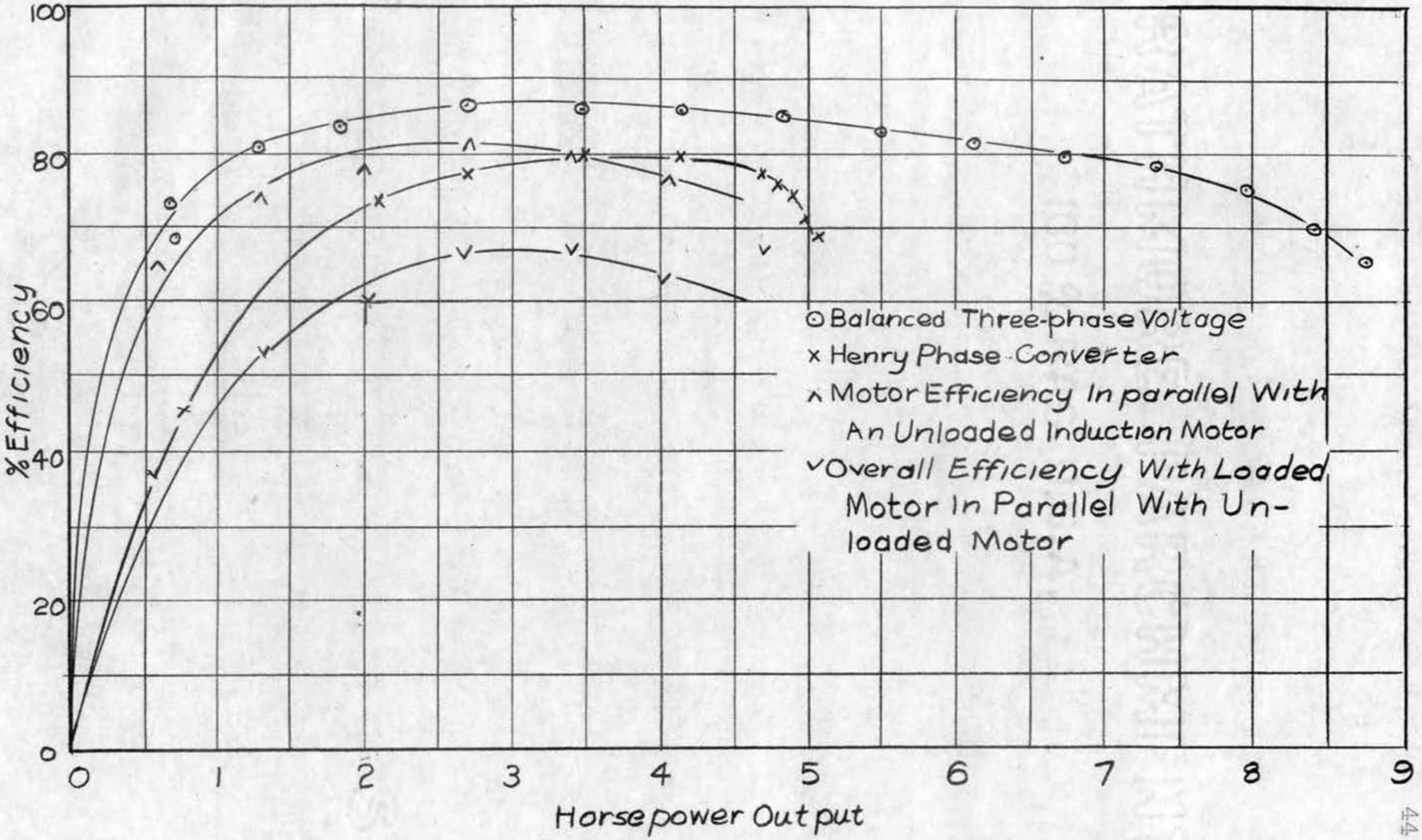


Fig. 17 Efficiency Of A Three-phase Motor With Different Type Phase Converters



E. Comparison of Results

The motor used in the tests of phase converters was first tested on balanced three-phase voltages to obtain a standard of comparison. The motor, which was rated at 5 horsepower, was operated at loads ranging from no-load to breakdown. Breakdown occurred at approximately 9 horsepower, which was 80 percent overload. The source voltage was held constant and was kept balanced at all times.

The current characteristics (Figure 15) were very good, the current ranging from 5.4 amperes at no-load to 36 amperes at breakdown. Normal full-load current was 13.7 amperes.

The efficiency (Figure 17) reached a maximum of 87 percent, near one-half of rated load, and was above 85 percent from 1.75 horsepower to 5 horsepower. The efficiency was above 75 percent from 0.75 horsepower to 8.0 horsepower. From these figures and from the curve of Figure 17, it can be seen that the efficiency remains consistently high over a wide range of loads.

The very good characteristics of the Reliance Motor made it ideal for the testing of phase converters, all of which have some degree of unbalance.

Operating the same motor on a single-phase supply with a 5 horsepower Henry Phase Converter, breakdown occurred at 5.05 horsepower which was an overload of only 1 percent. The values obtained should not be strictly regarded as the exact characteristics of the equipment involved because of the discrepancy in rating between the dynamometer and the motor being tested. The dynamometer was rated at 20 horsepower and was regarded as accurate from 4 to 30 horsepower. The accuracy in that range would depend upon the degree of accuracy to which the dynamometer was balanced at standstill.

The maximum efficiency (Figure 17) of the motor operating with the Henry Phase Converter was 80.5 percent at 3.5 horsepower, which was 70 percent of the rating of the motor and is the single-phase rating of the motor. At this load the power-factor of the single-phase source was at its highest value which was 99 percent. The ideal loading of the motor on the Henry Phase Converter would seem to be 70 percent of rated load, or at the single-phase rating of the machine.

The currents at 70 percent of full-load were far from equal but the largest was only 14.7 amperes, or one ampere above rated full-load current. At full load, currents in two of the lines were excessively high for continuous operation. The heating in a motor with normal insulation would limit the load which could be safely carried while operating on the phase converter.

Besides the test on the Henry Phase Converter, the motor was tested while operating in parallel with an unloaded induction motor acting as a phase converter. The efficiency of the test motor was very good near one-half rated load, although the overall efficiency, including losses in the phase converter motor, was quite low. The currents (Figure 16) were considerably more unbalanced than those with the Henry Phase Converter (Figure 15). The single-phase supply current was quite high which meant a very low power factor for the supply circuit.

Several more tests would have been desirable but were not made because of lack of time and equipment. Multi-motor tests should have been made for each of the systems to find some optimum loading combination.

A very desirable test would be one with an induction motor operating as a phase converter with a parallel capacitor across one phase. To gain maximum benefit from the test the capacitor should be varied in steps to determine the value of capacitance that should be used for specific loads.

Oscillogram pictures of the starting currents for the various systems would prove quite valuable for a comparison of the different systems of obtaining three-phase power from a single-phase source.

IV CONCLUSIONS

This thesis has been a study of the various known methods of deriving three-phase power from a single-phase source and an attempt to find the most feasible and practical method of accomplishing the conversion.

It was found, from the literature available and the tests made, that several methods of converting single-phase to three-phase are practical. Also, it was found that no rigid rules can be made as to what method should be used. Each type of phase converter has its own special application.

In general, for single motor installations, static converters are more practical. The reason for the choice of the static converter over the rotary converter is the lack of friction and windage losses. In multi-motor installations, where the rotating losses can be divided among several motors, the rotary converters become more desirable.

The type of rotary converter most desirable in permanent, multi-motor installations is a three-phase induction motor with extra turns on the third phase winding and with a capacitor connected from the third phase to one of the other phases.

In any temporary installation, where three-phase power will be available at a later date, an induction motor as a phase converter is preferable because the change-over of the installation from single-phase to three-phase is so simple and because the induction motor which was used as a phase converter will then be available as a motor.

A choice of the type of phase converter to use, in any installation where it is necessary to derive three-phase power from a single-phase source, depends on many conditions, such as, the number of machines to be operated, the maximum load factor, the space available, the equipment available, the future plans and others.

The operation of three-phase equipment where only single-phase voltage is available is very desirable and it is economically feasible at the present time. However, much work needs to be done on the problem of converting single-phase to three- phase and many improvements can be made.

BIBLIOGRAPHY

Bailey, Benj. F. *Induction Motors*. New York: McGraw-Hill Book Company, 1911.

Dawes, Chester L. *Electrical Engineering*, Vol. II. New York: McGraw-Hill Book Company, 1934.

"Electrification of the Norfolk and Western Railway." *Electric Journal*, XII (June, 1915), 309.

Garcelon, G. H. "Polyphase Motors on Single-phase." Electrical World, Vol. 123 (January, 1945), 160.

"Getting Three-phase from Single-phase." *Electrical World*, Vol. 123 (January, 1945), 160.

Hellmund, R. E. "The Field of Application of the Phase Converter Locomotive." *Electric Journal*, XII (October, 1915), 462.

Lamme, B. G. "Single-phase Loads from Polyphase Systems." *Electric Journal*, XII (June, 1915) 261-269.

Lawrence, Ralph R. *Principals of Alternating Current Machinery*. New York: McGraw-Hill Book Company, 1940.

Lyon, Waldo V. *Applications of the Method of Symmetrical Components*. New York: McGraw-Hill Book Company, 1937.

Maggs, A. H. "Single-phase to Three-phase Conversion by the Ferraris-Arno System." *Institute of Electrical Engineers Journal*, Vol. 12 (April, 1946) 133-136.

Operating Instructions for Diehl K-7 Dynamometer. Electrical Engineering Department of Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma.

"Static Phase Converters." Engineering, Vol. 153 (May 15, 1942) 385-386.

Suhr, F. W. "Analysis of Single-phase Motor Operation by Method of Symmetrical Components." *Electrical Engineering*, Vol. 64 (September, 1945) 651.

Taylor, J. J. "Letters to the Editor." Electrical Engineering, Vol. 60 (November, 1941) 565.

Vickers, Herbert P. Induction Motors. London: Sir Isaac Pitman and Sons, Ltd.

Weber, C. A. M. "Characteristic Curves of the Induction Motor." Electric Journal, XI (September, 1914) 484.

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