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Optimization of phase converter parameters and effects of voltage variation on their performance

by

Roshan Lal Chhabra

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
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For the Graduate College

Iowa State University
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LIST OF SYMBOLS AND ABBREVIATIONS

a	operator (characteristic angle)
a.c.	alternating current
AWG	American Wire Gauge
c,C	capacitance
CM	circular mils
CT	current transformer
D/A	digital to analog
D.C.	direct current
f	Frequency
H_z	hertz (cycles per second)
hp	horsepower
I	current
$I_{1,2,3}$	current in line 1, 2, or 3
IEEE	Institute of Electrical and Electronic Engineers
j	imaginary components of complex quantities, $\sqrt{-1}$
K	constant
KV	kilovolt
KVA	kilovolt ampere
KVAR	reactive kilovolt ampere (reactive power)
KW	kilowatt
KWhr	kilowatt hour
L	length
$L_{1,2,3}$	line 1, 2, or 3

LB-FT	pound - feet
LB-IN	pound - inch
LRT	locked-rotor torque
n,N	turns ratio
N.C.	normally closed
NEC	National Electrical Code
N.O.	normally opened
NEMA	National Electrical Manufacturers Association
O.L.	over load
PF	power factor
R.P.M.	revolution per minute
SPDT	single pole double throw
SPST	single pole single throw
$T_{1,2,3}$	terminal 1, 2, or 3
TPDT	triple pole double throw
V	voltage
V_{AB}	voltage between phase A and phase B
V_{AN}	voltage between phase A and neutral phase
V_{1NO}	zero sequence component of V_{1N}
V_{1N1}	positive sequence component of V_{1N}
V_{1N2}	negative sequence component of V_{1N}
w,W	watts
X_C	capacitive reactance
Z	impedance per phase of the motor

π	3.142
μF	microfarads
η	efficiency
$\eta_{S,T,C}$	efficiency of single-phase, three-phase, or converter
θ_{mi}	positive sequence power factor angle
ϕ	phase angle
$1-\phi$	single-phase
$3-\phi$	three-phase
^oC	degrees centigrade
^oF	degrees Fahrenheit
%	per cent

INTRODUCTION

Most rural electric power lines are single-phase. For many years, single-phase lines have served admirably as a means of utilizing incandescent lighting and single-phase appliances. But farms in the United States have been growing steadily larger. A report, prepared by the Iowa Crop and Livestock Reporting Service shows 135,264 farms in Iowa in 1970, 1340 fewer than in 1969 and 5,583 less than in 1965. Larger farms broaden the scope of farm operations and make necessary more use of electric power.

The population census showed a 16,000 drop in farm population in the State of Iowa in 1969, and a drop of 6,641 in 1970. According to the U. S. Statistical Abstract, it is estimated that by 1980 we can expect about 2 million farms in this country, 800,000 fewer than the latest census figure, 2.8 million in 1972. The reduction in manual labor available on farms makes it necessary that machines be available to do the farm operations faster and at a lower cost. A higher profit with less effort being a part of modernization, it is not unreasonable to predict that the trend towards mechanization of farms as well as need for larger motors on the farmstead will continue.

To meet the need for larger motors, three-phase motors are the ideal type. There are several reasons for the choice of three-phase motors. Three-phase motors generally are readily available and provide a wide choice of performance characteristics. They are smaller, lighter, and simpler in construction than single-phase motors. Single-phase motors are higher in initial cost than three-phase motors in integral horsepower sizes, particularly for motors larger than 3 hp. Single-phase motors, because of starting windings and switching devices, also require more maintenance. Most manufacturers do not offer single-phase motors above 10 hp.

Perhaps of more importance, single-phase motors require a starting inrush current 2 to 3 times higher than the same size three-phase motors, and thus limits the size of motors permissible on many single-phase lines. For example, most 7.5 hp single-phase, 230 volt, 60 H_z motors have a name plate rating of about 40 amperes at full load and require an inrush current over 200 amperes. A three-phase motor of similar hp and voltage rating requires about 20 amperes at full load and 100 amperes at starting (33, 72).

Three-phase service, a preferable power source to operate three-phase motors, is readily available to only a small percentage of farms, except for some areas of the west coast where irrigation is necessary for farming. Most rural lines are single-phase because three-phase service normally requires a greater investment in transformers and lines, which is not always profitable because most of the farms have low annual energy consumption and poor load factor. Feedlot equipment is operated only for an hour or two per day;

drying systems may be operated for only a few weeks per year; and irrigation systems may be used for a few days to several weeks per season (23).

As a result of an increase in the number of large crop-drying, large feeding and irrigation systems on farms, motors have become larger, with 10 to 20 hp becoming common. For example, crop drying systems matched to picker-sheller harvest rates may require 15, 20 hp and even larger motors. To meet this demand for larger electric motors, without requiring the installation of three-phase service, phase converters have offered a solution for some farmers and power suppliers.

A phase converter is a device that permits the use of three-phase motors from a single-phase power source. The application of a phase converter operated three-phase motor is recommended in the following situations (22, 86, 87, 88).

1) When the cost of extending three-phase power is relatively high and the annual energy consumption is relatively low.

2) When the customer has to pay the cost for the extension of three-phase service. For example, Baebler reported (5) that

> "one power company serves its customers under a residential rate which provides a single-phase service as standard. The company will extend the three-phase service irrespective of the amount of connected load provided the customer pays for the non standard facilities".

3) When the rate structure is higher for three-phase service than for single-phase service.

4) When the hp of motor needed exceeds the largest size allowed by the power supplier because of the limitation on inrush currents with across-the-line starting. Some power suppliers have set inrush current limitations on the basis of the ASAE rural motor starting application guide (90, 95):

> "Single-phase motors shall be permitted on a distribution system if the designed locked-rotor current at 230 volts is no more than 260 amperes and if no more than 260 amperes at any time during the starting cycle".

and also

> "Phase converters supplying three phase motors shall be permitted anywhere on a system if the design inrush current to the phase converter does not exceed 260 amperes at 230 volts".

These guidelines limit the single-phase motor's size to about 7.5 hp, however, a phase converter operated, three-phase, 20 hp motor with an inrush current of approximately 200 amperes may be used without violating the recommendations.

5) When a three-phase power supply is expected to replace the existing single-phase lines in the near future, the customer can plan for the future and purchase three-phase motors and, with the help of phase converters, can operate them from a single-phase supply until the three-phase service is installed.

6) When equipment has a three-phase motor as an integral part of the unit, and replacement of the three-phase motor

by a single-phase motor is not feasible. Examples are some irrigation pumps and floating lagoon pumps.

Phase converter three-phase motor combinations are being used to operate many types of farm loads. In a study conducted by the Edison Electric Institute it was found that 50 of the 88 power companies surveyed are serving some kind of phase conversion equipment on their lines (79). The number of units connected to a single company's lines ranged from 1 to 200. The largest three-phase motor operating in conjunction with a phase converter was a 75 hp motor. The most common ratings reported, however, were 15, 20, and 25 hp. Some of the typical applications of phase converter operated motors reported in the study are listed below:

1. Grain dryers (15 and 20 hp motors)
2. Irrigation pumps (10, 25, and 50 hp motors)
3. Feed mills, Hammer mills (25 and 40 hp motors)
4. Fertilizer mixers
5. Silo unloaders
6. Cattle-feeding systems (15 hp and larger motors)
7. Deep well pumps
8. Air compressors (5, 10, and 15 hp motors)
9. Air conditioners
10. Power tools - power saws, turret lathe.

Phase converters, when properly selected, installed, and maintained, have satisfactorily operated three-phase motors from single-phase lines. In many cases, however, because of the wide variations in the design of phase converters available and a lack of knowledge for their application, some power suppliers have discouraged the use of phase converters on their lines. The author believes that much improvement and greater knowledge of the design and applications are needed to eliminate the difficulties in the use of phase converters for farm loads.

REVIEW OF LITERATURE

Phase converters have been in use for several decades. According to Robert Cotanch (4) the first phase converter was invented more than 60 years ago. Much of the improvement and development was accomplished in the 1960's. Improved performance of phase converters has resulted in steadily increasing applications. Also, strong efforts by the power supplier to serve the farmer's need for larger motors in the most economical way possible, has accelerated the demand and subsequently improved reliability of phase conversion systems.

In a wider sense, any device permitting the conversion of a m-phase system into a n-phase system may be properly called a phase converter. This would include, for example, a Scott transformer used for converting two-phase into three-phase currents or vice versa. A rotary converter for conversion of three-phase current into 6, 9, or 12-phase current is also an example of phase converters. Even the choking coil and condensers which for starting purposes split the phase for feeding the auxiliary winding of a single-phase motor could be called a phase converter.

According to the definition in text books, a phase converter is a machine that converts power from an a.c. system of one or more phases to an a.c. system of a different number of phases, both systems of the same frequency. Most common applications of phase converters are limited to the conversion of single-phase power to three-phase power. In this study, phase converters in a narrow sense will be considered a device that permits the use of a three-phase induction motor on a single-phase power source.

Originally phase converters (rotary type) were used to electrify railways where locomotives equipped with three-phase motors received power from a single-phase source. An early phase converter used on railways, shown in Figure 1, was designed and operated upon the principle that a single-phase induction motor develops a rotating magnetic field (64). If the motor were to run at synchronous speed, the magnetic field would not only rotate uniformly at synchronous speed, but its magnitude would also remain constant. Therefore, if the stator of a single-phase induction motor is designed with an auxiliary winding placed in slots, symmetrically spaced midway between the slots of the main winding, the auxiliary winding will become the source of an induced voltage. This voltage is in time quadrature with the supply voltage.

As illustrated in Figure 1, the main stator of the induction motor was supplied from a step-down transformer which reduced the voltage to a value suitable for the motor. The auxiliary winding was designed to develop a voltage equal to 86.6 per cent of the secondary voltage of the

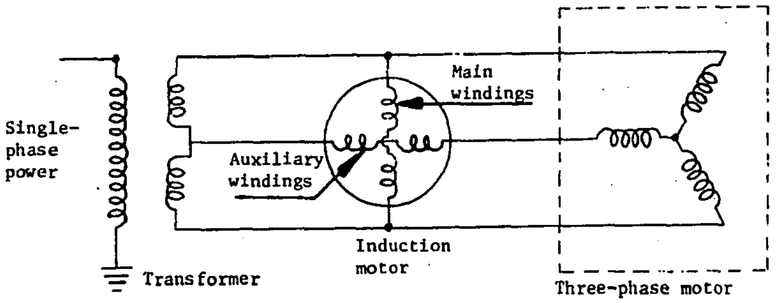


Figure 1. Phase converter used on railways (64).

transformer. Thus, by the use of Scott connections the original single-phase line is connected to supply power to a three-phase circuit (64, 112).

Commercially available phase converters are of two basic types:

1. Static phase converters
2. Rotary phase converters

Static phase converters can further be subdivided as:

1. Capacitor type
2. Open-wye capacitor type
3. Autotransformer-capacitor type
4. New designs.

A great number of reports have been published on the performance and applications of static as well as rotary phase converters. In this research project, the published literature that related directly or indirectly to the understanding of phase converters was reviewed. A brief resume is presented of a few pertinent articles on the various types of phase converters.

Static Phase Converters

Static phase converters, as the name implies, have no moving parts other than switching relays which operate during the starting of the three-phase motor.

Capacitor type

This is also called a capacitor-only phase converter. It is the least expensive and simplest kind of converter. Figure 2 is a simplified diagram of a capacitor type phase converter. Two of the three-phase motor leads are connected directly to the single-phase line. The third lead of the motor is connected to one of the single-phase through a bank of oil capacitors. The capacitors shift the phase of the voltage to the third winding. The phase-shifted voltage in combination with the physical position of the motor windings, produces the rotating magnetic field to start and run the motor (94).

A motor operated on a capacitor type converter normally would not be used at full horsepower rating because current unbalances will overheat the motor for other than a short period of operation. According to Soderholm (92, 94), capacitor type converters require that loading of the motor be limited to 75 per cent of the normal horsepower rating

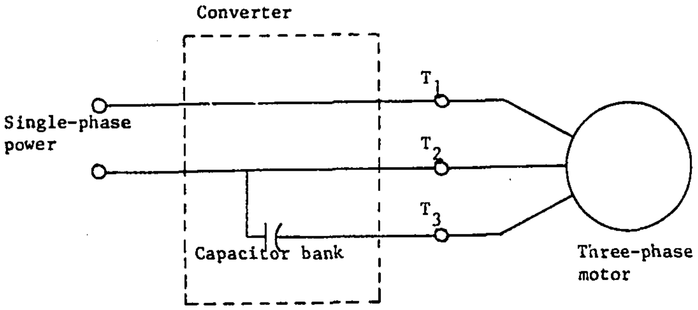


Figure 2. Capacitor-only phase converter.

of the motor. Figure 3 illustrates the variations in line currents with respect to load on the motor. Test data from a 10 hp, NEMA design B motor and capacitor type converter showed that current in one phase of the motor exceeded its rated value when the load exceeded 70 per cent of rated load.

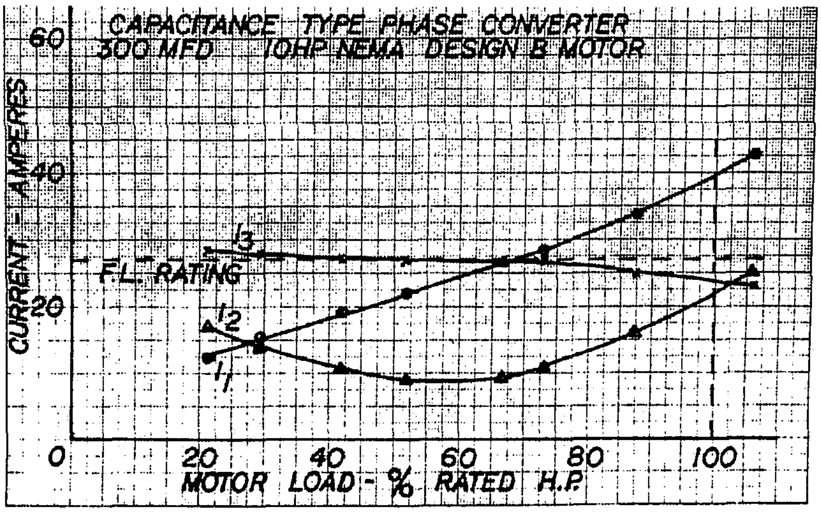


Figure 3. Line currents vs. load on the motor (92).

Satisfactory operation of a capacitor-only converter is limited to low starting torque and constant loads. Ager (1), in studying the use of auxiliary impedances in the single-phase operation of polyphase induction machines, concluded that no appropriate value of impedance can be found that will give polyphase performance for more than a single load. He stated several benefits of using capacitors, but, according to him, these capacitors do not make single-phase performance of the motor equivalent to the polyphase through out the range of normal operation.

Bakes (6) found that a capacitor type phase converter operated motor could not be loaded beyond the motor rating without causing severe motor unbalance, excessive vibration, noise and overheating. He also found that the starting torque of a converter operated motor is 70% less than that of a single-phase repulsion induction motor of the same horsepower rating. Like many research reports, Bake's study suggests that capacitor-only phase converter operated three-phase motors are not suitable for loads that require high starting torque, such as a high pressure compressor. These converters, however, are being used satisfactorily to power small ventilating fans, blowers, and power saws.

In 1953, Haberman (38) studied a capacitor type phase converter operating a 5 hp, three-phase induction motor. He concluded that the proper rating of a three-phase motor with such a phase converter is not more than:

1. Sixty per cent of the three-phase rating if the standard per cent locked rotor torque and break down torque are required.
2. Sixty to seventy per cent of the three-phase rating if no more than a ten per cent higher temperature rise is to be tolerated.

He suggested that for the highest obtainable locked rotor and running torques, the capacitors should be sized at 200 μF for starting and 26.5 μF for running per motor horsepower.

Hogan (44) from his theoretical analysis of capacitor type converters found that a three-phase motor operated from this type of converter can be balanced only if the power factor of the motor is held at 50 per cent.

According to Brown et al. (14, 15, 17), a perfect balance of a three-phase induction motor operating from a capacitor type converter can be realized only when the negative sequence component of the motor voltage is zero. This is possible only when the phase angle of the machine is less than 30°. Thus the power factor should not exceed 0.866 for an exactly balanced condition. When, as usually happens, power factor is better than 0.866, the negative sequence voltage is minimum but different than zero.

In comparison with straight single-phase steady state operation of a three-phase motor, the addition of appropriate balancing capacitors at the normal running speed results in a significant reduction in copper losses and a modest improvement in the torque.

Open-wye capacitor type

In 1957, Henry Steelman was the first to obtain patent rights on open-wye type capacitor converters (41). This converter, like capacitor-only converters, does not convert single-phase electrical service to three-phase, however, it does make it possible to operate a three-phase induction motor on single-phase service.

Each unit needs to be matched to the horsepower rating of a standard, dual voltage, single-speed, three-phase motor. As shown in Figure 4, it is necessary to pull out three additional leads on the motor making it a 12-lead motor. For proper connection, phase C is isolated from phase A and B. With the modified connection, windings are virtually the same as in a two-phase motor with the A and B phases constituting one winding and the C phase constituting a second winding 90° out of phase therewith. The path formed by the combination of A and B phases, since it includes parallel connections, is of lower resistance and higher inductance than the path formed by phase C in series with the capacitor bank.

Figure 4 illustrates the low voltage connections of the phase conversion system using parallel connections on the motor winding. For the higher voltage operation of a motor, the phase windings should be connected in series.

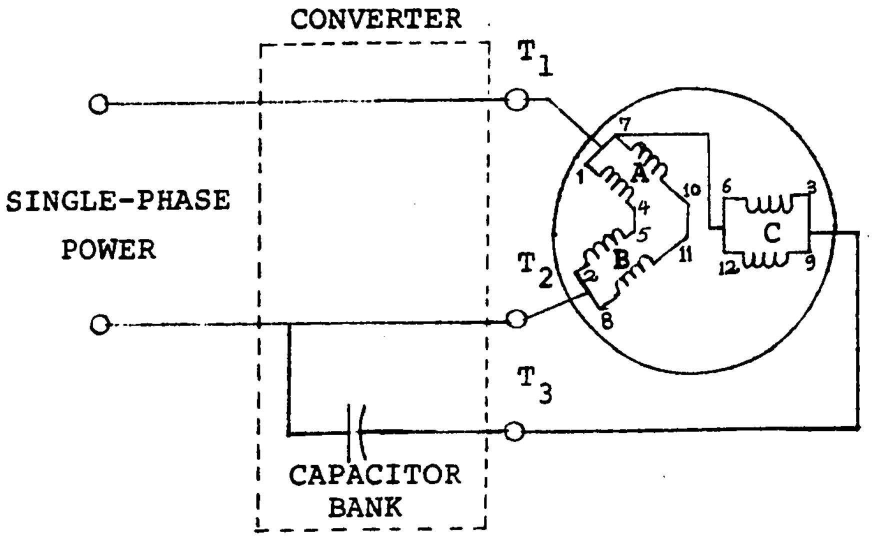


Figure 4. Open-wye type phase converter.

Phases A and B of the motor have the usual single-phase voltage applied. Phase C in series with capacitors has an effective voltage of 130 volts applied (32). The line current is the vector sum of currents in phase A B and phase C, which is much less than their arithmetical sum. Therefore, the volt-amperes drawn from the supply line are less than would be drawn by a two-phase motor. A motor connected as shown in Figure 4 will operate under a steady load with nearly the same efficiency as that of a two-phase motor and with higher torque, much better power factor, and substantially less current (41).

The KVAR of a capacitor on 60 H_z power supply can be expressed by the following relationship:

$$KVAR = 0.377 \ (KV)^2 \ C \qquad (1)$$

where KV is voltage drop across the capacitor and C is capacitance in microfarads. From Equation 1, the effective KVAR of a fixed capacitor is increased when the voltage drop across its terminal increases. According to Elliot and Elliot (31), the compensation effect of the capacitors in the circuit allows a fixed quantity of capacitance to be used and eliminates the "phase balancing" common to other types of static phase converters.

To gain more starting torque from the motor, electrolytic capacitors should be connected across the oil capacitor bank. These additional capacitors must be removed from the circuit when the motor reaches its rated speed. This can be accomplished by a N.C. time delay relay or a voltage sensing relay.

A few examples of the successful applications of open-wye type capacitor converters given in (32) are irrigation pumps, oil wells, centrifugal pumps, compressors, hydraulic pumps, hammer mills, feed mixers, grain dryers, punch presses and a 100 hp rock crushing mill.

This type of phase converter is not recommended for overloaded motors and for rapidly and widely fluctuating load applications.

Autotransformer-capacitor type

The autotransformer-capacitor phase converter is an improvement over the capacitor-only type converter. This type of converter is of the same basic design as the capacitor type converter. The major difference is the addition of an autotransformer that allows the operation of a motor at full horsepower output (94).

A simplified diagram of an autotransformer-capacitor converter is shown in Figure 5. Hogan (44) referred to the autotransformer converter as an "add-a-phase" converter. According to him, this type of converter adds a phase to the already present single-phase. Through the combination of transformer, capacitor and impedance of the motor, a third phase is introduced whose relation to the other two phases comprises symmetrical three-phase power (86).

Autotransformer-capacitor converters have been used to operate 1 to 100 horsepower three-phase motors. In any case it is not recommended that an autotransformer-capacitor type converter be used to operate a motor larger than the rating of the converter (86).

According to Ronk (87), the autotransformer-capacitor converter has overcome all of the shortcomings of the capacitor-only and open-wye type converters. A three-phase motor with this converter can be made to produce about the same locked-rotor and pull-up torque as the three-phase motor on

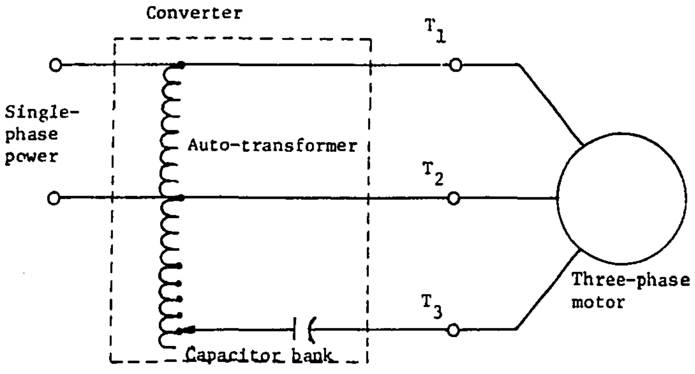


Figure 5. Autotransformer-capacitor phase converter.

three-phase line power. The autotransformer and running capacitors during the starting cycle cause a voltage rise. This voltage rise, in most cases, will offset the voltage drop caused by the inrush current of the motor. Ronk (87) reported that an autotransformer converter operated motor can produce 225% locked-rotor torque, 175 to 190% pull-up torque and up to 250% breakdown torque.

According to Huber, a squirrel cage, three-phase, 4-pole NEMA design A or B motor should develop a minimum of 165% full load torque. When such a motor is connected to an autotransformer-capacitor converter, the motor's locked rotor torque will be somewhat decreased, usually 10 to 25% depending upon the amount of starting capacitance used in the converter. Similarly, breakdown torque is reduced from 200% to 150% full load torque (47).

Huber also reported that for a three-phase motor requiring a starting current of six times the running current, the use of a phase converter will reduce the starting current to approximately three times the running current (47). The starting current of a motor on an autotransformer-capacitor phase converter ranges from 2.5 to 3 times the rated full load current (86). The single-phase starting amperes on the 230-volt line are found to be approximately 12 ampere per horsepower. Hogan (45) found that starting KVA of an autotransformer converter is much less than that of a single-phase motor on a single-phase line or a three-phase motor on a balanced three-phase power source.

Line currents for a motor used on this type of phase converter over a range of motor loads, as found by Soderholm and Charity (94) are shown in Figure 6. Taps on the autotransformer allow for adjustment of the voltage for different motor characteristics and loads. The transformer voltage and the capacitance in the oil capacitors can be adjusted to provide balanced phase currents at full load (52).

Several motors may be operated from an autotransformer-capacitor converter, if at least 75% of the connected load is in operation at any one time. This means that 75% of the load must start and stop simultaneously (51). This is important because the current unbalance is higher at loads less than full load. Huber has shown in Figure 7 that the

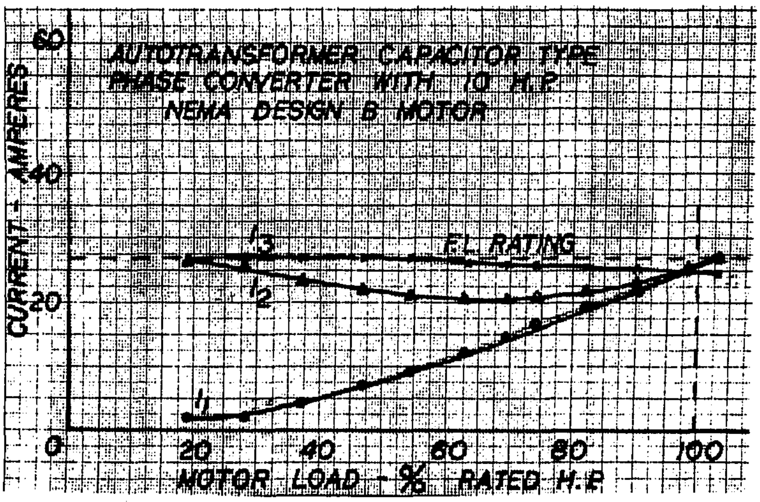


Figure 6. Line current vs. load on an autotransformer-capacitor converter operated three-phase T-frame motor (94).

greatest unbalance in line currents occurs when the motor is running under no load conditions (49).

Hogan (44, 45, 46) developed the following two equations for determining the value of the capacitors and the transformer ratio needed for the given motor and load.

$$X_c = \frac{3}{2} \frac{|Z_{mi}|}{\sin \theta_{mi}} \tag{2}$$

$$N = \frac{\text{Cos } (\theta_{mi} + 30)}{\text{Sin } \theta_{mi}} \tag{3}$$

where X_c = capacitive reactance

Z_{mi} = positive-sequence impedance per phase of the induction motor.

θ_{mi} = positive-sequence power factor angle of the motor

N = transformer turn ratio

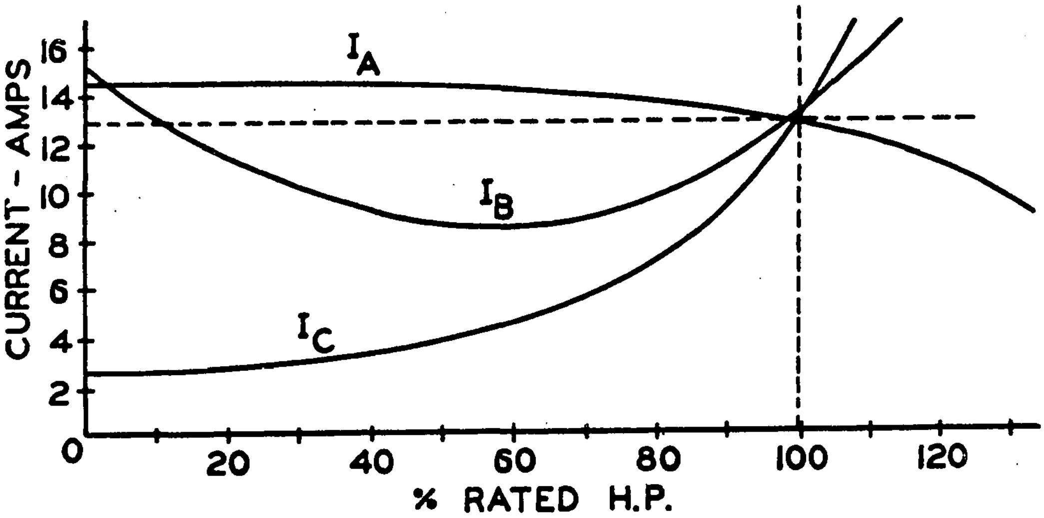


Figure 7. Typical line currents vs. load on the autotransformer-capacitor phase converter operated motor (49).

The use of Equations 2 and 3 requires values of Z_{mi} and θ_{mi}. In many cases these may not be easy to obtain. Equation 3 indicates that as the load changes, the phase angle of the motor will change and the motor will no longer have exactly balanced currents. It is, therefore, important to adjust initially the value of N and X_c so as to give balanced operation for the particular load conditions most usually encountered.

The most common applications of autotransformer-capacitor converters on farms are for three-phase motors on irrigation pumps, material handling augers, grain dryers, etc.

This type of converter is also being used for air conditioners and oil well pumps. Power consumption of a 25 hp motor and autotransformer-capacitor phase converter in filling a 20' x 60' silo with corn silage was found to be approximately 1.5 KWhr per ton (13). Harisha (39) reported a successful application of a 75 hp, 480-volt motor and an autotransformer-capacitor converter on an irrigation pump. Single-phase inrush current was 340 amperes and full load current was 150 amperes. Running currents for the 75 hp three-phase motor were 88, 88, and 95 ampere.

Parvis (77) and Price (81), in a survey of farm loads, found numerous installations where autotransformer-capacitor type phase converters have been in regular use. The majority of the operators were reported to be fairly satisfied by the performance of the units. They found that in many applications, the size of the heater coil in the magnetic motor starter had to be increased.

Brooks (11) reported a multi-motor application of an autotransformer-capacitor converter. The converter rated at 30 hp was being used for a 20 hp blower motor and a 10 hp elevator motor at a city incinerator. The equipment had been in service for five years and was used 50 hours per week.

Manufacturer's literature and the findings of several studies do not recommend the use of autotransformer-capacitor converters for multispeed and variable speed motor applications (11, 28, 39, 86).

New designs

There have been continuous efforts by manufacturers and researchers to improve the design of static phase converters so that they can provide a balanced output voltage for a wider range of loads. A variety of proposals have been made for phase converter systems that are different in basic design from conventional systems. A few of these are described briefly in this section.

Buffington (19) has proposed a static phase converter shown in Figure 8. The primary of transformer A is adjusted to provide greater control and stability of output voltage. The secondary windings of both transformers connected in series with oil capacitors act as a feed back loop. According to Buffington this design of static phase converter will adjust itself to variations in load and provide nearly balanced three-phase voltage over a wider range of loads than possible with current static type converters.

Lewus (58) suggested the use of a current balancing reactor to improve the performance of capacitor-only phase converters. As shown in Figure 9, a reactor is connected across terminals T_2 and T_3 of the motor. The reactor is designed to provide relatively high reactance to resistance ratio and is preferably operated near the saturation level of the core. The core is usually made from high permeability steel laminations. It is reported that, by the use of a current balancing reactor, phase relation between the phase currents in the motor is greatly improved.

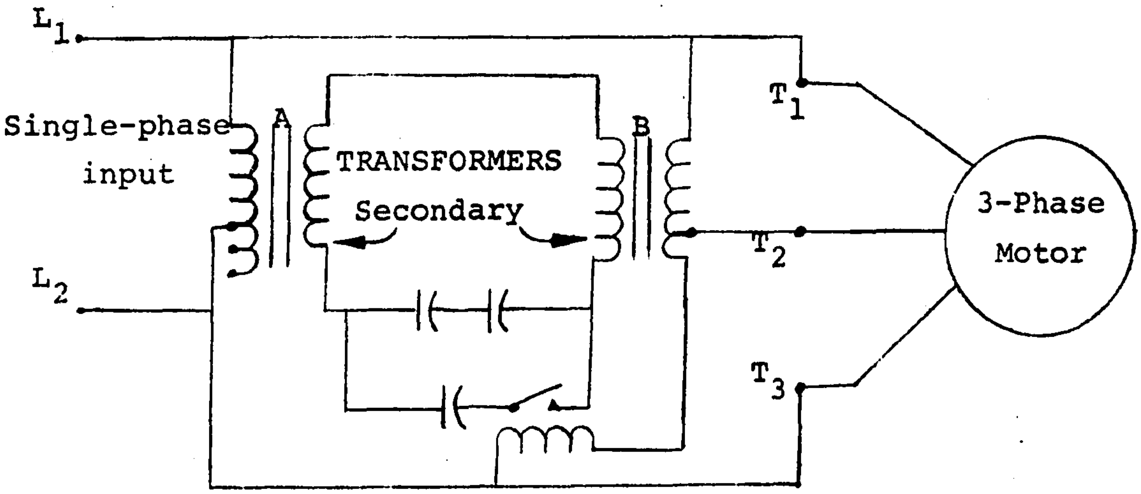


Figure 8. Static phase converter of Buffington (19).

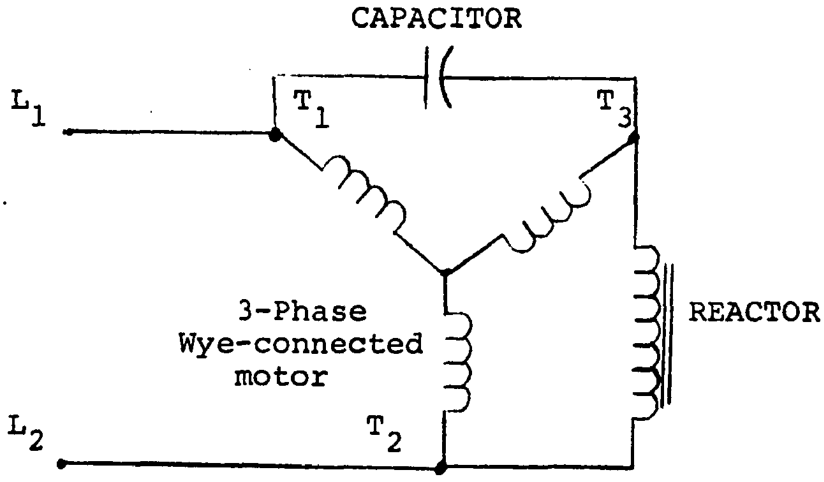


Figure 9. Lewus phase converter with a current balancing reactor.

When a three-phase ferroresonance circuit is operated from a single-phase source, the jump phenomenon of the fundamental frequency voltage occurs. Based on this principle, Tadokoro (103), and Tanno (104, 105) constructed a phase conversion system shown in Figure 10. When a single-phase voltage is applied to the terminals L_1 and L_2, flux jump occurs in the center leg of the core and, as a result, voltages of different phases (a three-phase voltage) are obtained at terminals T_1, T_2 and T_3. In these papers authors

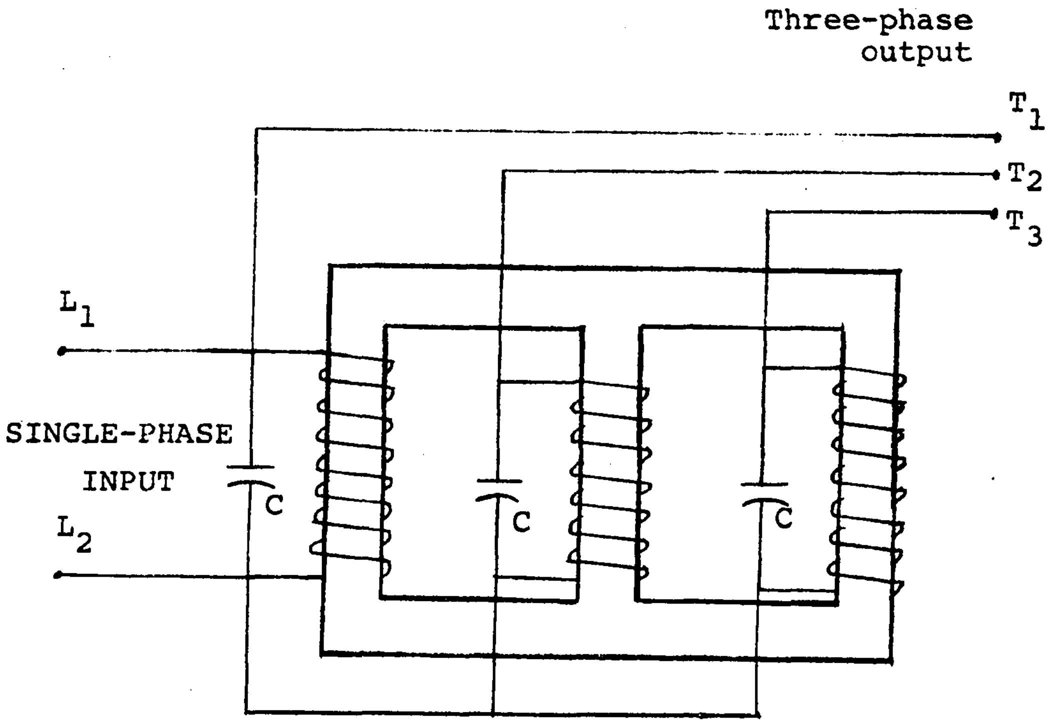


Figure 10. Fundamental circuit of a three-phase ferroresonance phase converter (103).

have described in great detail the theoretical analysis of the circuit used in the device. No experimental data was reported and the device has not been tested to supply power to three-phase motors (103, 104, 105).

Bessho (9, 10) constructed a 5 KVA static phase converter using a ferroresonance silicon iron core. The core consisted of a leakage-flux path between the input and output windings. The device was made of two parallel ferroresonance circuits connected in series. He found that this type of phase converter performed effectively as a voltage regulator, however, its application to supply three-phase power to motor loads was not satisfactory.

Hisano et al. (43) modified the circuit proposed by Bessho and called it a voltano converter. A simplified wiring diagram is shown in Figure 11. The voltano converter consists of a three-phase saturable reactor with windings wound on a 3-legged core. A capacitor C acts as a ferroresonant capacitance.

Hisano et al. (43) studied the effects of variation in load, source voltage, power factor, and various core material on the three-phase output voltage. A graph of output voltage at various loads was presented in the report. Hisano concluded that a voltano converter was approximately 90% efficient and can supply fairly well-balanced three-phase output.

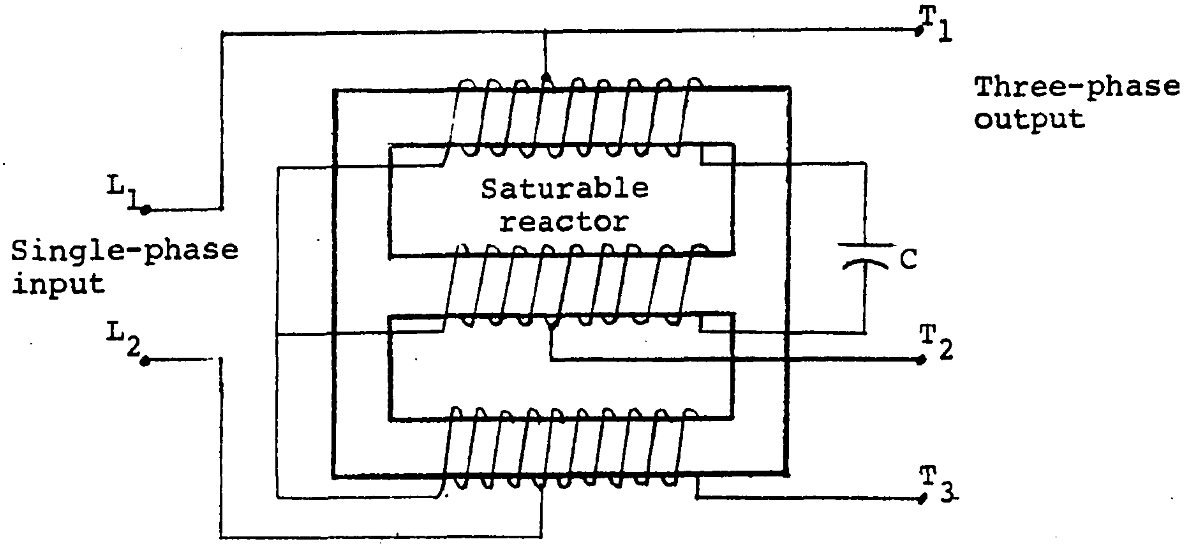


Figure 11. Simplified circuit diagram of the voltano single-phase to three-phase converter.

Rotary Phase Converter

As the name implies, a rotary phase converter consists of a rotating unit. Physically, it resembles an induction motor with rotor and stator but with no external shaft. The unit has an additional enclosure containing capacitors. This type of phase converter has been given various names by different manufacturers; such as, phase generator, rotary transformer, rotoverter, roto-phase, and a self-driven generator.

Professor Arno was the first to propose the use of a three-phase induction motor as a phase converter (66).

In the 1900's, he discovered that once an induction motor is started across a single-phase line and allowed to run idle, it can serve as a source of three-phase power for additional three-phase motors. He called the first motor a pilot motor. An induction motor with a phase splitting reactor, for starting purposes, was known as a Ferraris-Arno phase conversion system. Figure 12 is a diagram showing the essential connections of the Ferraris-Arno phase converter.

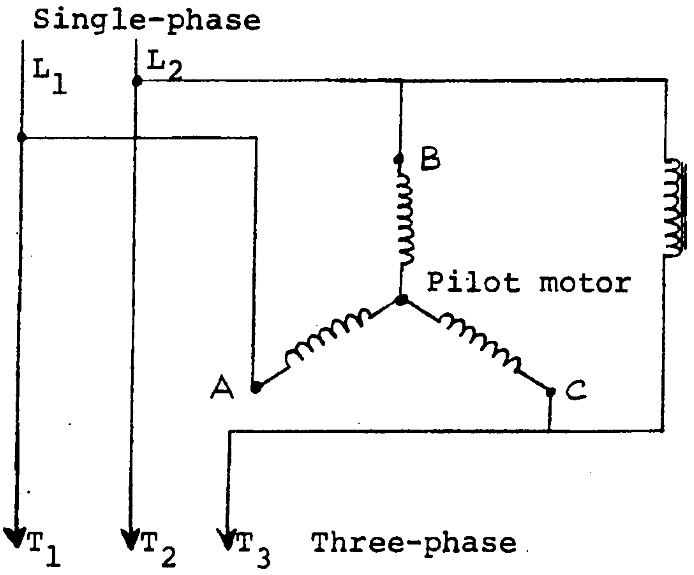


Figure 12. Connections of Ferraris-Arno phase converter.

An ordinary three-phase induction motor can be used as a phase converter only if the electrical load is small and considerable voltage unbalance can be tolerated. To reduce the voltage unbalance the motor must be designed for low leakage reactance with open and shallow slots and a few number of turns per slot (97).

Figure 13 shows a simplified diagram of the rotary converter. Two of the three rotary converter terminals are connected directly to the single-phase power lines. The third terminal of the rotary converter is connected to one of the single-phase lines through capacitors. The capacitors provide the rotating magnetic field to start the converter. The generating action of the rotary converter, in combination with the phase shift of the capacitor, produces the third phase voltage to operate a three-phase motor (22).

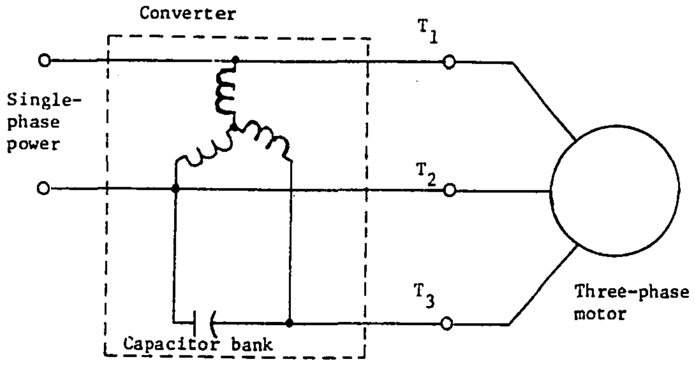


Figure 13. Rotary phase converter.

According to Cotanch (4) a "rotary converter" is not a converter at all. More accurately it is a "phase generator". One phase is generated by the rotary unit and oil capacitors and the other two phases are supplied from the single-phase source. The rotary converter also receives energy from the same source. With the rotary unit energized, three distinct phases and voltages are produced at the terminals. Hence, any three-phase load within the rating of the stator winding of the motor can be handled whether it is inductive or resistive or any combination (4).

For the operation of several motors from one converter, the rotary converter is usually the best choice. One motor, or any combination of motors may be operated, provided the total horsepower load, or amperage drawn is no larger than the continuous load rating of the converter. Also, one motor or any combination of motors may be started at the same time as long as the sum of the total horsepower of the motors starting does not exceed the rated starting horsepower of the rotary converter (4).

To place a rotary converter in operation all three-phase motors must be disconnected. When the rotary converter is started and full speed has been obtained the various three-phase motors are then connected as required. Each of the motors operated on the rotary converter has a separate capacitor panel. On starting a motor, its capacitor panel should be connected across the same phases as the main capacitor bank in the basic unit (47).

In many cases, the largest motor to be operated is the main factor in determining the size of the rotary converter and main capacitor bank. If the largest motor is driving a high starting torque load a rotary converter larger than normal size should be selected (4).

The starting current of a rotary converter may be as large or larger than the current drawn when the largest permitted size three-phase motor is started on the converter (22). Inrush current of a converter is, however, usually less than that of a three-phase motor of the same size starting on three-phase line power or a single-phase motor starting on a single-phase source. Single-phase inrush current of a 20 hp converter is about the same as that of a 7.5 hp single-phase motor (4).

Even with a carefully matched motor and rotary converter, currents are always somewhat unbalanced, because of the variations in their internal parameters, resistance, reactance, and core losses. The unbalance of currents is rapidly magnified when the motor is overloaded. Soderholm (92), from a study of various brands of phase converters, found that performance characteristics of rotary phase converters vary widely depending upon the design. Figure 14 shows the phase current variations in a motor operated on a rotary phase converter over a range of motor loads (94).

To avoid the possibilities of excessive unbalance in motor currents, several technical reports have recommended that motors should be oversized. Following are a few examples:

> "Motors must have horsepower ratings greater than or equal to their actual loads, oversizing of motors is desirable" (24).

> "Care must be exercised in selecting the design and size of motors. One way to provide adequate starting torque is to use one size larger motor" (22).

> "In multi-motor installations using rotary converters, motors should be oversized in order to compensate for current unbalance. A general rule for oversizing the motor would be to provide at least 25% excess capacity for unity service factor motors and 10% excess capacity on motors with 1.15 service factor" (78).

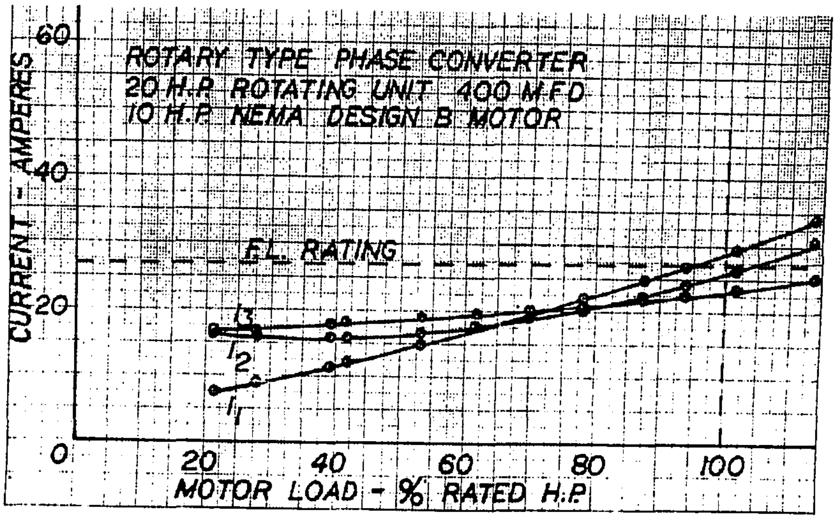


Figure 14. Motor phase currents vs. load for a three-phase motor operated on a rotary phase converter (92).

According to Spindler (96), one way to get increased torque is to use the next larger converter. In the case of 5 hp air compressor, he suggested using a 10 hp converter.

Locked-rotor torque of phase converter operated three-phase motors is less than that available when a motor is started on three-phase line power. Applications which require a high starting torque are not recommended for use with a rotary phase converter. The maximum motor starting torque required should be limited to approximately 100 to 150% of full load torque (24).

Charity and Soderholm (23) found that when one motor is fully loaded and running, the starting torque of a second motor is improved slightly. Locked rotor torque limitations can be increased somewhat for a specific motor by having other motors started but idling on the line before the higher locked rotor torque motor is started (24). According to Huber (47), as subsequent motors are started the starting torque will be increased since each motor in effect serves as a generator once the motor has acquired its full speed. Maggs et al. (67) have made similar observations. They have reported that the pilot motor (phase converter) as well as all additional motors running at any instant in combination act as phase converters. Voltage stability, as distinct from voltage balance, of the three-phase output increases with the number of motors running.

Rotary phase converters under idle conditions will run considerably hotter than under load conditions. This is due to the greater "no load" unbalance in voltage and, therefore, large circulating currents. Under load, the voltages become more balanced and circulating currents and heating are reduced. Charity and Soderholm (23) have reported that the temperature rise in a wye wound motor operating from a converter with a horsepower rating equal to that of the motor is about the same as would be experienced for the motor operating on three-phase line power.

The power loss in rotary converters is higher than that in static converters. Patterson and Carroll (78) found that a 10 hp rotary converter had losses of 1.5 KW while the converter was running whether loaded or not. A 15 hp rotary converter is reported to have a constant demand of 2.7 KW regardless of motor load (24). According to Charity et al. (22), losses in an idling converter are higher than a loaded converter. They found that a 20 hp continuous rating converter required 1.72 KW input power to operate unloaded and 1.0 KW when loaded. Huber (51) found that leaving the rotary converter energized is not practical since the power loss in the converter is greatest when the load is not in operation.

Applications of rotary phase converters include motors driving augers, bucket elevators, silo unloaders, hoists, fans, blowers, grain dryers, center pivot irrigation systems, compressors, machine tools, corn shellers, and saw mills (12, 26, 29, 37, 78, 81). Reports show that rotary phase converters have been successfully used on applications like computers, radio stations, rectifiers, SCR drives, electromagnets, grape presses, and resistance welders (4, 24). These loads are not adaptable to any type of static phase converter.

Rotary phase converters are also suitable for multi-speed motors. Either wye or delta connected motors can be operated from rotary phase converters (4, 88).

Photographs of some of the commercially available phase converters are shown in Appendix B. Figures 77 through 80 are for capacitor-only phase converters. Figures 81 throgh 85 illustrate autotransformer-capacitor and rotary phase converters.

OBJECTIVES

A review of research literature revealed that phase converters have been in use for several decades. The research papers published dealt with theoretical approaches made to develop analytical equations to predict the performance of phase converter operated three-phase motors. In most cases, these equations are in terms of the motor's internal parameters and are of little practical use in adjusting a converter for balanced currents in a motor to run a given load. These equations are also very complicated and require a lengthy computational procedure.

Most of the single-phase rural loads today experience a wide variation of voltage because of the power line characteristics. There is a limited amount of information available on the effects of line voltage variation on phase converter performance.

To develop design equations for phase converters that are simple and practicable and to provide needed information on phase converter applications, the objectives of the study are:

1. To develop analytical equations to determine the value of capacitance bank and the transformer turns-ratio of autotransformer-capacitor type phase converter for balanced currents of a three-phase motor for a given load. The accuracy of the analytical

equations will be verified with experimental data.

2. To optimize the size of capacitors and autotransformer turns-ratio for the best results with varying motor loads.
3. To determine the effects of variations in single-phase line voltage on the performance of three-phase motors operating on an autotransformer-capacitor and rotary phase converters.
4. To determine the current values and winding temperature rise in three-phase U-frame and T-frame motors with unbalanced three-phase voltages at the terminals of the motors.
5. To study the performance characteristics of three-phase motors operating from an open-wye type phase converter.
6. To determine the optimum value of starting capacitance for the maximum locked rotor torque of motors operated from an autotransformer capacitor type phase converter.
7. To develop a design procedure for power service for phase converters and associated three-phase motors and to verify the theoretical equation for determining phase converter ampere load by experimental data.

MEASUREMENTS AND PROCEDURES

The research lab was equipped with single-phase and three-phase power supplies. The wiring circuits needed for the testing of motors were added to the load side of the main disconnects.

Instruments were required for the following three types of measurements:

1. Electrical measurements for voltage, current, power, and power factor.
2. Torque measurements for locked rotor torque and the dynamic torque-speed curves of the test motor.
3. Temperature measurements for estimates of the hot-spot temperature in the windings of the motors.

Electrical

The voltage regulation circuits for single-phase and three-phase power are shown in Figure 15. A variac was connected across the line to line voltage. The voltage at the adjustable tap of the variac fed the primary of a low turns-ratio transformer. The secondary winding of the transformer, a source of voltage, was connected in series with the line voltage. By reversing the polarity on the primary winding, transformers were used to buck or boost the line voltage. The magnitude of the secondary voltage was varied by adjusting the tap on the variac.

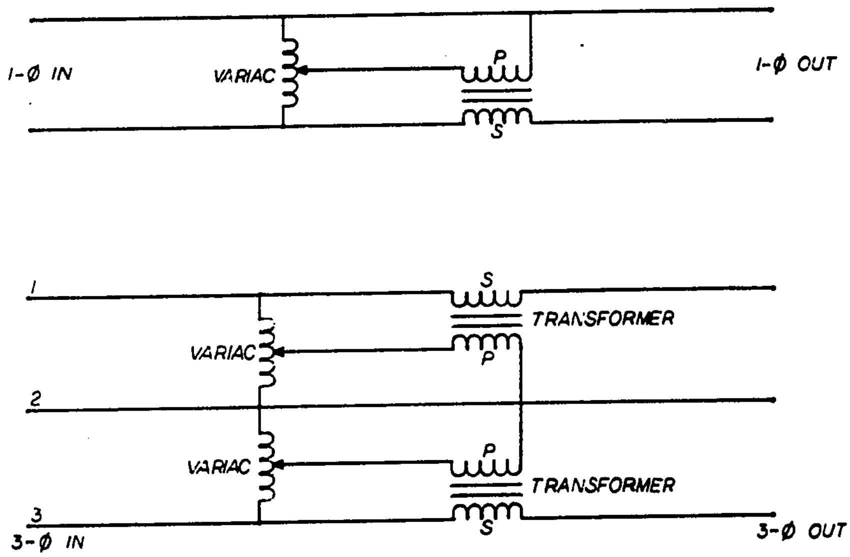


Figure 15. Regulation of line voltage with variacs and transformers.

For the tests conducted in this study both source voltages, single-phase and three-phase,were not required to be regulated simultaneously. Two variacs and two transformers were used for the regulation of three-phase line voltage. When three-phase power was not needed, one of the two variacs and transformers were disconnected from the three-phase line and were used to supply regulated single-phase voltage for the phase converter. To eliminate rewiring of the variac and transformer from three-phase to single-phase and vice versa, two TPDT switches were used. The circuit arrangement used for three-phase and single-phase power is shown in Figure 16.

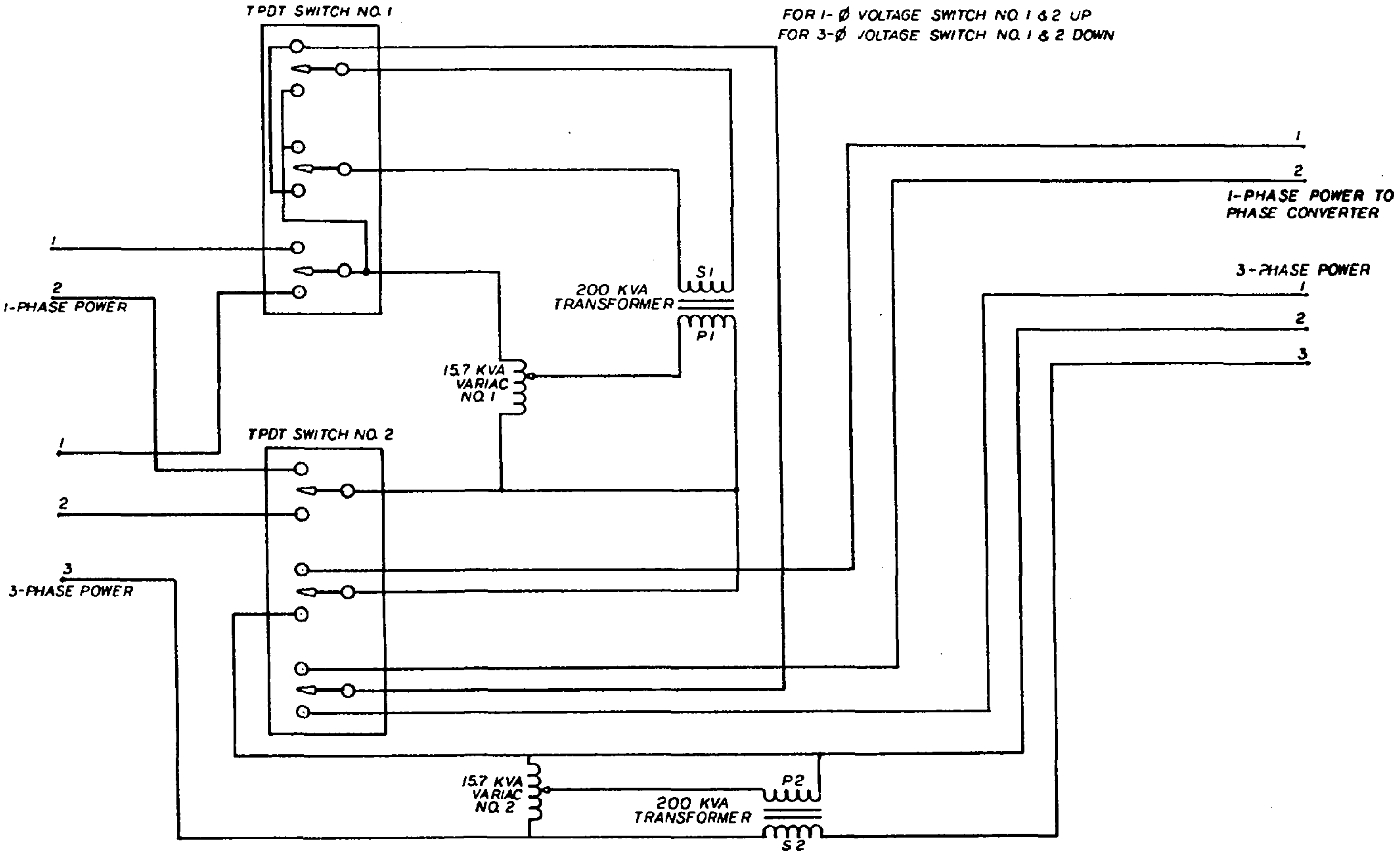


Figure 16. Wiring diagram for the regulation of single-phase and three-phase voltages.

Regulated single-phase voltage was provided when switches 1 and 2 were in the "UP" position. When switches 1 and 2 were in the "DOWN" position, the single-phase line was disconnected and the circuit was changed to regulated three-phase voltages for three-phase testing of the motors.

A schematic diagram of the metering arrangement is shown in Figure 17. The instruments are voltmeters, ammeters, wattmeters, and power factor meters. Description of meters, motors, and phase converters is given in Appendix A. Current transformers were used to measure the line currents of the motor. A bypass switch, 4, protected the ammeters and wattmeters from being damaged by the high inrush currents at motor starting. A TPDT switch allowed the use of the same meters, without any rewiring, for measurements in tests on three-phase line power and on three-phase power supply from the phase converters. Pictorial views of the dynamometer and metering arrangement are shown in Figures 18 and 19.

Torque

A block diagram of the instruments used in measuring locked rotor torque and for plotting dynamic torque-speed curves of motors is shown in Figure 20. The major components are a strain guage reaction torque table, a signal conditioning unit (transducer amplifier), a digital to analog converter (frequency meter), an X-Y recorder, and a D.C. dynamometer.

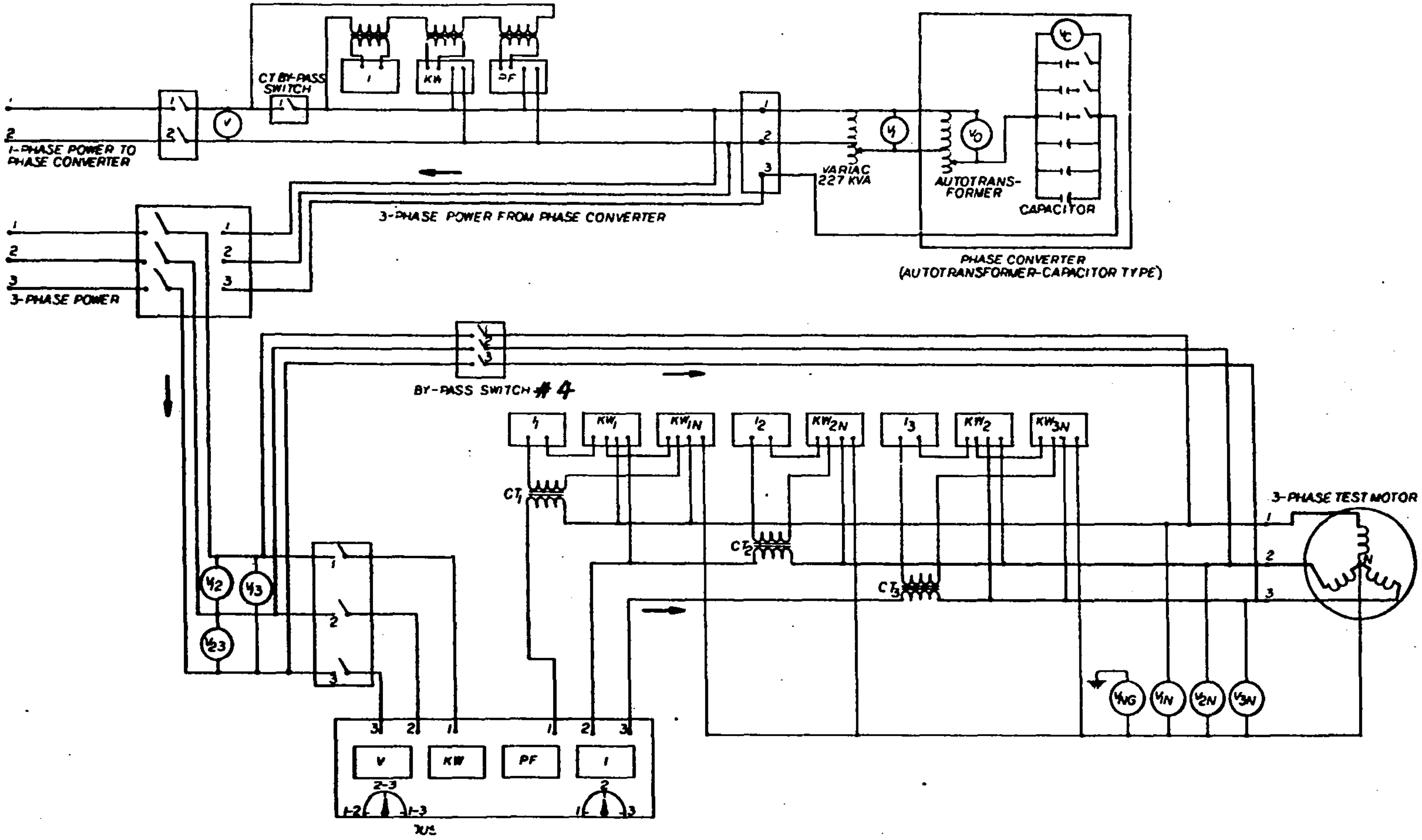


Figure 17. Schematic diagram of the metering arrangement used for electrical measurements.

The test motor, as shown in Figure 18, was mounted on the reaction torque table. When the test motor was loaded with the dynamometer, a signal from the strain guage bridge in the reaction torque table, proportional to the torque of the motor, was fed to a signal conditioning device. The torque signal was amplified to a level that was suitable for the X-Y recorder.

The speed sensing device, an electromagnetic pickup, consisted of a 60-tooth gear mounted on the shaft. By interrupting the magnetic field sixty pulses were generated for each shaft revolution, thus, number of pulses varied directly with speed. Pulse signals were fed to a frequency meter, a digital to analog conversion device. The D.C. signal of the frequency meter was proportional to the speed of the motor shaft.

When the two signals, torque signal from the transducer amplifier and speed signal from the frequency meter, were fed to the X and Y axis of a recorder simultaneously, a dynamic torque-speed curve of the test motor was obtained. Figure 21 shows a typical torque-speed curve of a 10 horsepower, NEMA design B, three-phase motor operated on a 230 volt, three-phase power supply.

The locked rotor torque was obtained by locking the shaft of the motor. With the voltage regulation circuits the line voltage was raised to compensate for the drop due

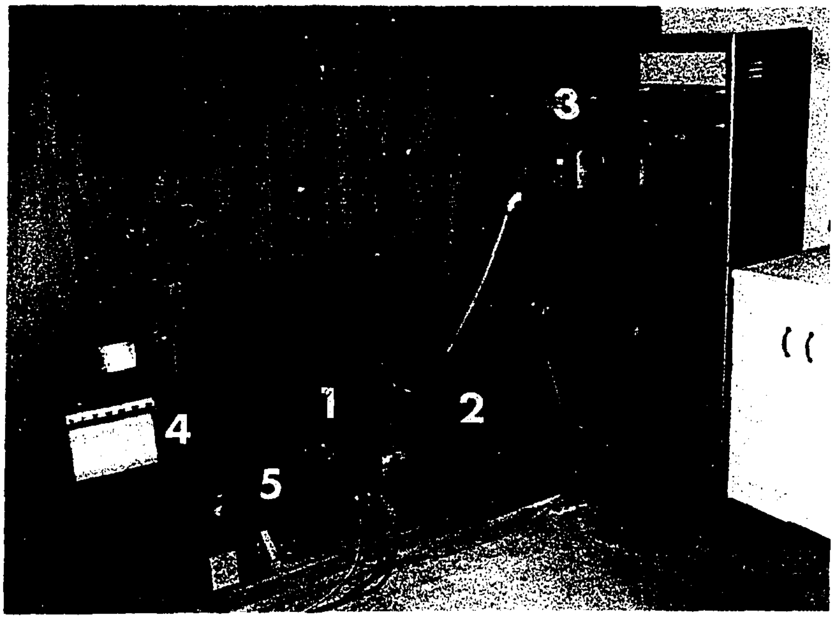


Figure 18. Test motor setup, 1. 5 hp motor, 2. dynamometer, 3. frequency meter, 4. temperature recorder, 5. reaction torque table.

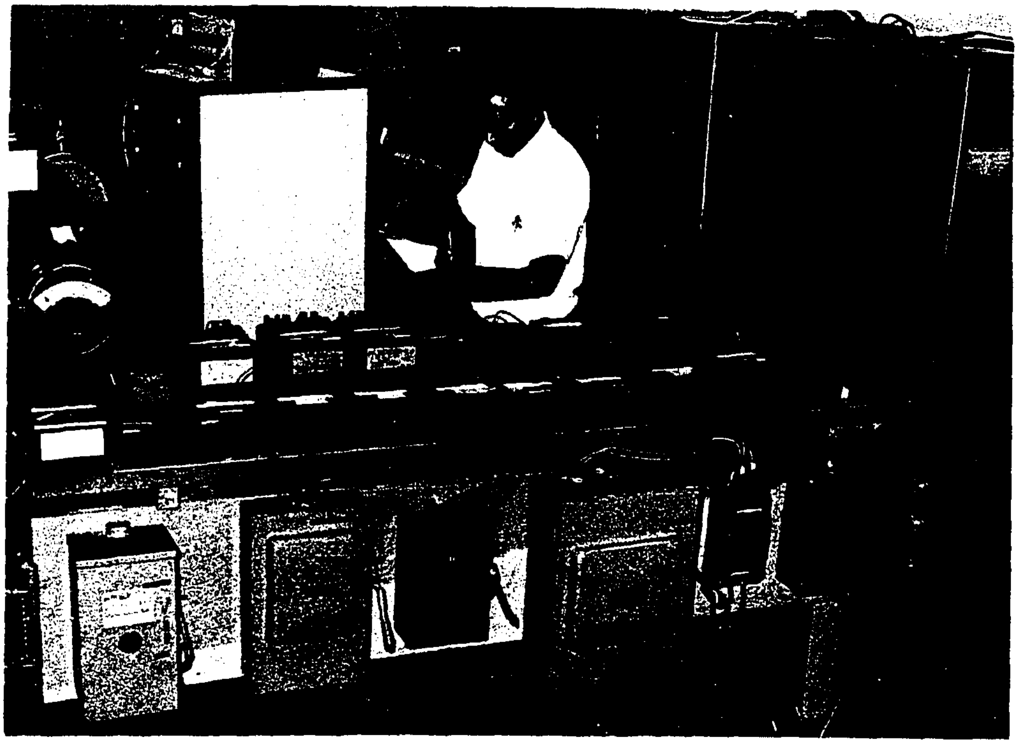


Figure 19. Switching and metering equipment for V, I, KW, and PF measurements.

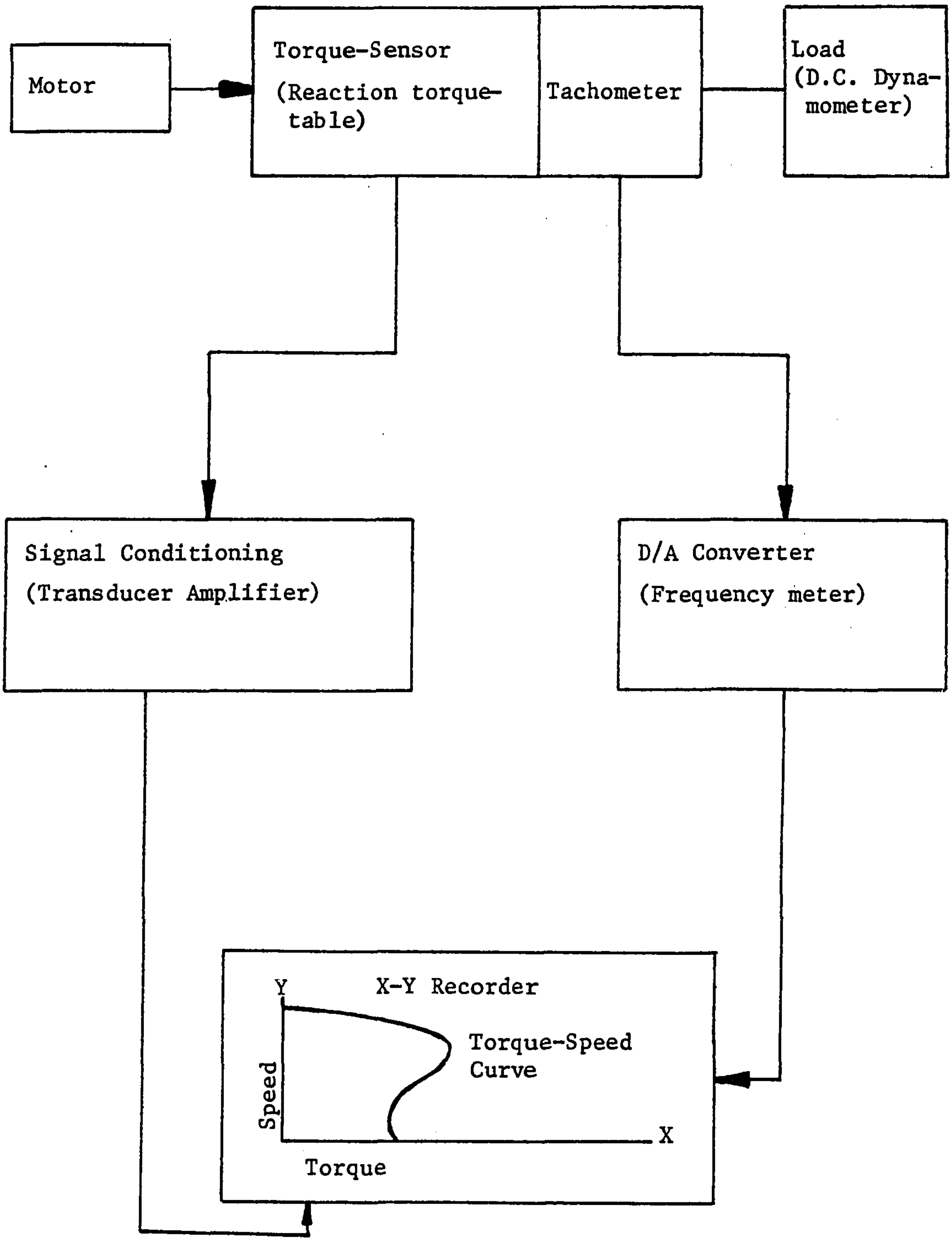


Figure 20. A block diagram of the instruments used in torque measurements.

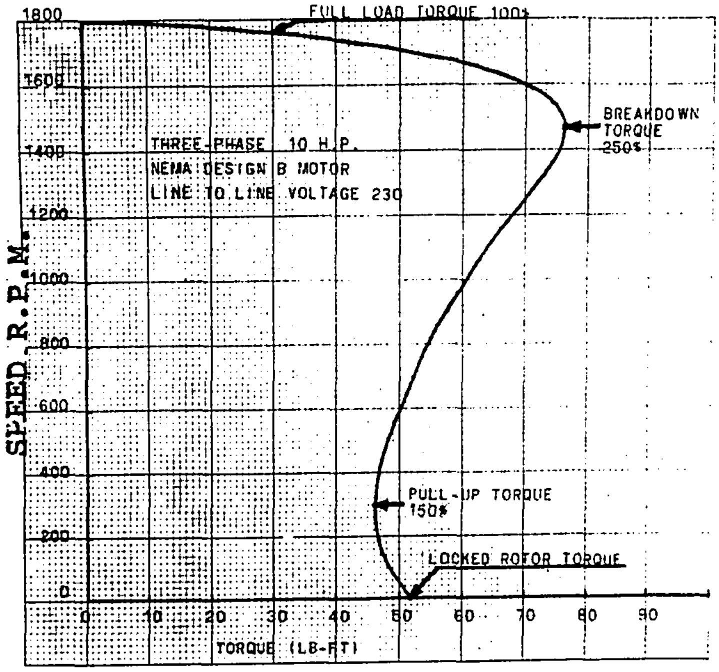


Figure 21. A typical torque-speed curve for a 10 hp NEMA design B, T-frame, three-phase motor.

to high inrush current. The motor under locked rotor conditions, because of the high inrush current, heats up very rapidly. The locked rotor torque of a motor is reduced when motor windings are hot. After taking a locked rotor torque measurement, to avoid nonrepresentative readings due to the higher temperature of the winding, the motor was allowed to attain room temperature before the next reading was taken.

Temperature

A thermo-conductive body, developing heat at a constant rate, will have a maximum temperature rise directly proportional to the heat developed in unit time and inversely proportional to the dissipation per degree rise per second. In an induction motor, from a cold start to the final steady state, the temperature rises exponentially with time.

An electric motor comprises several parts, each with a characteristic surface area, mass, heat capacity, and thermal conductivity. The temperature rise of different parts, or even of various points within the same part, may be very uneven. Therefore, it is necessary to make estimates of hot-spot temperatures of motor windings.

Several methods have been suggested to measure the temperature rise of electric motors (3, 33, 72, 106). Resistance and embedded thermocouple methods were applied to estimate the hot-spot temperature of the motors tested for this study. These two methods give different bases for estimating hot-spot temperature. Table 1 shows the maximum allowable temperature and temperature-rise of various classes of insulations determined by resistance and embedded thermocouple methods (72).

Resistance method

The resistance method gives the average temperature of the stator winding. The temperature is determined by

Table 1. Temperature limits (°C) for A-C motors 1500 hp or below (72).

Temperature measured by resistance method				
Insulation class	A	B	F	H
Temperature rise	60(108)[a]	80(144)	105(189)	125(225)
Ambient	40(104)	40(104)	40(104)	40(104)
Total observable	100(212)	120(248)	145(293)	165(329)
Hot spot allowance	5(9)	10(18)	10(18)	15(27)
Total temperature	105(221)	130(266)	155(311)	180(356)
Temperature measured by embedded thermocouples				
Insulation class	A	B	F	H
Temperature rise	70(126)	90(162)	115(207)	140(252)
Ambient	40(104)	40(104)	40(104)	40(104)
Total observable	110(230)	130(266)	155(311)	180(356)
Hot spot allowance	0(0)	0(0)	0(0)	0(0)
Total temperature	110(230)	130(266)	155(311)	180(356)

[a] Numbers in parentheses are temperature °F

comparing winding resistance at the test condition to that measured when the entire motor was at a known temperature, preferably room temperature. A formula given in Equation 4 was used to estimate the winding temperature (106).

$$T_h = \frac{R_h}{R_c} (K + T_c) - K \qquad (4)$$

where T_h = average hot temperature °C

T_c = average cold temperature ^{o}C

R_h = hot resistance, ohms

R_c = cold resistance, ohms

K = constant; for copper, K = 234.5 and for aluminum, K = 225

Resistance R_c was measured at ambient temperature. The test motor was loaded to the desired horsepower and run for a specified time until a constant temperature had been reached. Measurement of the hot resistance requires quick stopping of the motor at the end of the heat run. Resistance after shutdown is measured as frequently as possible until resistance readings have begun a slow decline from the maximum value. Knowing the hot resistance values, temperature T_h is computed from Equation 4.

If a motor of 50 horsepower or smaller is stopped within one minute after the shutdown, no extrapolation of observed resistance and corresponding T_h is necessary. However, if a motor cannot be stopped within the specified time, resistance readings are taken at intervals of approximately one minute. A curve of these readings is plotted as a function of time and extrapolated to the time of shutdown. The value of temperature thus obtained is considered as the maximum temperature of the test motor. If successive measurements show increasing temperature after shutdown, the highest value is considered (106).

The following two methods were used to obtain the resistance of windings.

a. Kelvin bridge method

b. Voltage drop method

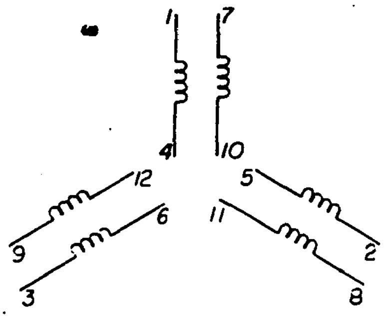
Kelvin bridge method This method employed direct measurement of winding resistance. Figure 22(a) shows terminal markings according to the NEMA standards MG1-2.62 (72). Terminals 10, 11, and 12 are seldom accessible, however, test motors were supplied with their 12 terminals brought out. Resistance of all the six windings of the motor were measured with a Kelvin bridge instrument (James Bridle Bridge Instrument Co.). Equivalent circuits shown in Figure 20 (c,d,e) were used to compute the resistance across two lines. A sample calculation for R_{L1-L2} of a 10 hp motor are given below. Line to line resistance values for the test motors were also measured. Computed and measured values of the line to line resistance of windings are given in Table 2.

$$R_{A-Y} = \frac{R_{1-4}\ R_{7-10}}{R_{1-4} + R_{7-10} + (R_{2-5} + R_{8-11})}$$

$$= \frac{.3206\ (.3107)}{.3206 + .3107 + (.319 + .319)} = .0785$$

$$R_{C-Y} = \frac{R_{7-10}(R_{2-5} + R_{8-11})}{R_{1-4} + R_{7-10} + (R_{2-5} + R_{8-11})}$$

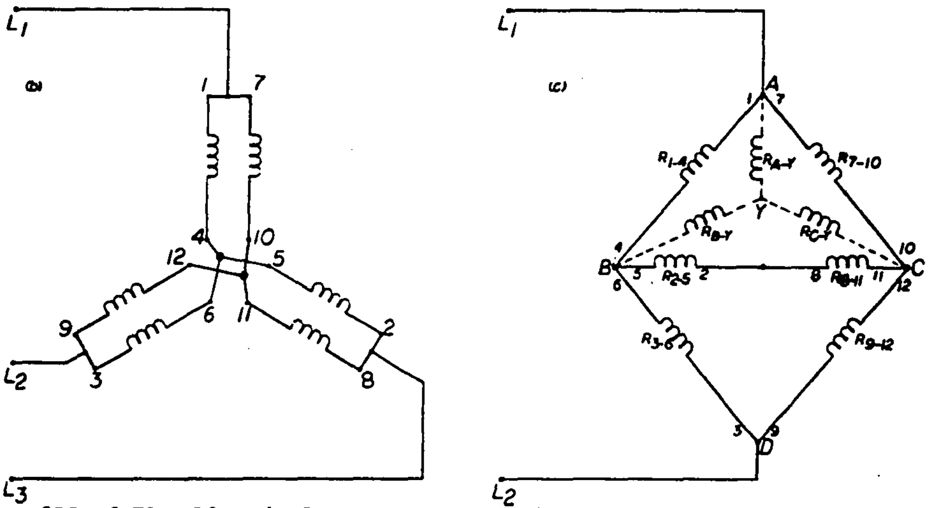
$$= \frac{.3107(.3190 + .3190)}{1.269} = .156$$



Y-CONNECTION FOR DUAL VOLTAGE

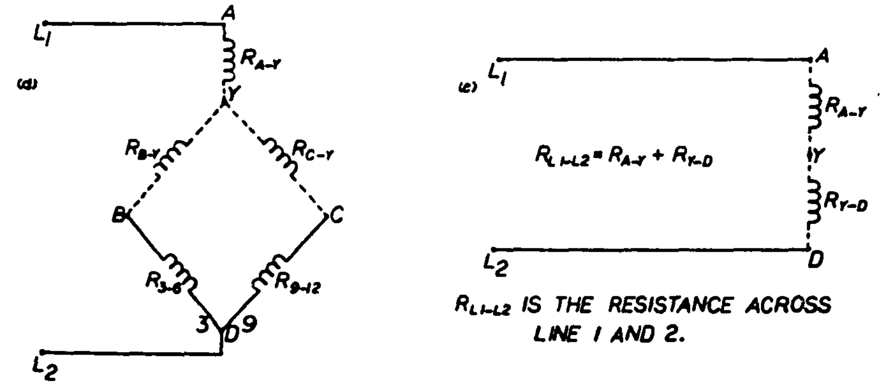
VOLTAGE	L_1	L_2	L_3	TIE TOGETHER
LOW	(1,7)	(2,8)	(3,9)	(4,5,6)
HIGH	(1)	(2)	(3)	(4,7), (5,8) (6,9)

TERMINAL MARKINGS FOR THREE-PHASE DUAL VOLTAGE (230/460) INDUCTION MOTOR (NEMA MG1-2.62)



230 VOLTS, Y-CONNECTED THREE-PHASE MOTOR

EQUIVALENT CIRCUIT: DOTTED Y-CIRCUIT REPLACES Δ-CIRCUIT ABC



R_{L1-L2} IS THE RESISTANCE ACROSS LINE 1 AND 2.

Figure 22. Terminal markings and winding resistance.

$$R_{B-Y} = \frac{R_{1-4}(R_{2-5} + R_{8-11})}{R_{1-4} + R_{7-10} + (R_{2-5} + R_{8-11})}$$

$$= \frac{.3206(.3190 + .3190)}{1.209} = .1612$$

$$R_{Y-9} = R_{C-Y} + R_{9-12} = .156 + .3170 = .4730$$

$$R_{Y-3} = R_{B-Y} + R_{3-6} = .1612 + .3143 = .4755$$

$$R_{Y-D} = \frac{R_{Y-9}\ R_{Y-3}}{R_{Y-9} + R_{Y-3}} = \frac{(.4730)\ (.4755)}{.4730 + .4755} = \frac{.225}{.9485} = .237$$

$$R_{L1\ -\ L2} = R_{A-D} = R_{A-Y} + R_{Y-D} = .0785 + .237 = .3155$$

Voltage drop method To eliminate the variable human element involved in reading a manually balanced kelvin bridge, an automatic recording technique was used. Figure 23 shows an instrumentation arrangement used in determining resistance by measuring voltage drop across the winding. The current in the winding was supplied by a constant current D.C. power supply.

A TPDT switch disconnected the motor from the three-phase power supply and the winding of the motor was connected to associated apparatus. Switch number 2 closed at the instant when the power to the motor was turned off. A preset time delay relay completed the circuit between a constant current D.C. power source and the motor windings two seconds after the motor came to rest. This prevented

Table 2. Line to line resistance of motor windings

Resistance	R_{L1-L2} (ohm)		R_{L1-L3} (ohm)		R_{L2-L3} (ohm)	
Motor	Computed	Measured	Computed	Measured	Computed	Measured
10 HP	.315	.314	.315	.315	.314	.315
5 HP Brand (1)	.956	.955	.960	.956	.950	.954
5 HP Brand (2)	1.00	1.05	.955	1.05	1.100	1.05

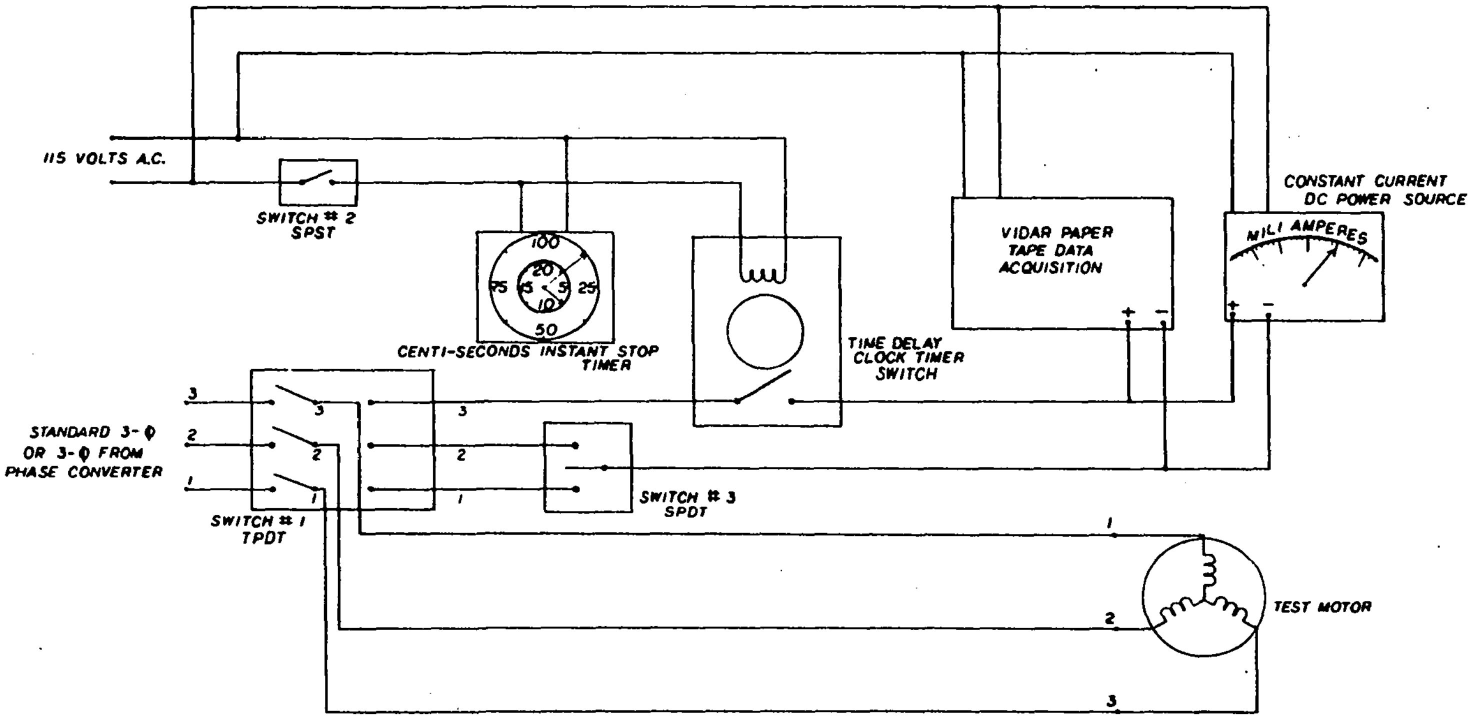


Figure 23. Schematic diagram for resistance measurement by voltage drop method.

the D.C. power supply and data acquisition system from being damaged by any induced voltage present at the motor terminal due to its generator action. The voltage drop, due to D.C. current, across the winding of the motor was recorded on a paper tape data acquisition system. Twenty successive data points were recorded during the cooling period. Knowing the magnitude of D.C. current and the voltage drop, the resistance of the winding was computed.

Thermocouple method

The thermocouple method for determining hot-spot temperature is recommended by IEEE and is used widely in the electrical industry (106). In this method, the temperature of the winding is recorded under steady state operation of a loaded motor. Unlike the resistance method, the test motor need not be stopped. Thermocouple detectors are placed in intimate contact with the insulation of coils. A bonding epoxy is used to hold the thermocouple in place.

Impregnation of the stator winding provides a random buildup of varnish on the windings, thus resulting in variation of thermal resistance between the thermocouple and the winding and the variation in temperature at different pointt of the winding (106). To increase the probability of finding the hottest accessible area 15 thermocouples were embedded around the circumference of the stator winding.

The thermocouples were copper-constantan, American National Standard Institute (ANSI) type-T, made of .01 inch diameter wire. Distribution of thermocouples in the winding is given in Table 3.

Table 3. Location and distribution of thermocouples in test motors

Thermocouple Number	Location
1	Ambient
2	Phase 1 winding, at 12.0 o'clock
3	Phase 1 winding, at 12.05 o'clock
4	Phase 1 winding, at 12.10 o'clock
5	Random, below a coil at 1.30 o'clock
6	Phase 2 winding at 4.00 o'clock
7	Phase 2 winding at 4.05 o'clock
8	Phase 2 winding at 4.10 o'clock
9	Random, above a coil at 5.30 o'clock
10	Random at 5.50 o'clock
11	Phase 3 winding at 7.0 o'clock
12	Phase 3 winding at 7.05 o'clock
13	Phase 3 winding at 7.10 o'clock
14	Random at 9.30 o'clock
15	Random at 10.00 o'clock
16	In iron core at 11.30 o'clock

Locations of the 15 thermocouples in the stator winding are shown in Figure 24. Each thermocouple was installed and its lead brought out in such a manner that the thermocouple detector is effectively protected from contact with cooling air. After inserting the thermocouple between the coils, the epoxy was placed in the vicinity of the thermocouple.

The epoxy used had the characteristics of being thermally conductive and electrically insulative.

Thermocouple lead wires were tied against the motor winding several inches before being brought out. This minimized the transfer of heat from the junction to the lead and also, as shown in Figure 25, kept the leads from rubbing against the rotor and the shaft.

A 16 point 8 minutes per cycle honeywell recorder was used to monitor the temperature of the motor winding. To check the recorder for accuracy and calibration all thermocouples were placed in boiling water and test points recorded. Then, a voltage signal from a potentiometer, equivalent to the voltage output of a type-T thermocouple at 212°F, was fed to the recorder. For proper calibration, data from the two sources should be closely matched. The calibration apparatus is shown in Figure 26. A sample calibration chart is illustrated in Figure 27.

A steady state condition for testing motors was considered to be reached when the increase in the hottest-spot reading declined to 1 degree rise for the three consecutive cycles. The temperature rise of the motor is the maximum temperature reading recorded prior to or after the shutdown less the ambient temperature of the immediate surrounding air. A typical recorder temperature curve for the 16 thermocouples is shown in Figure 28. Several temperature

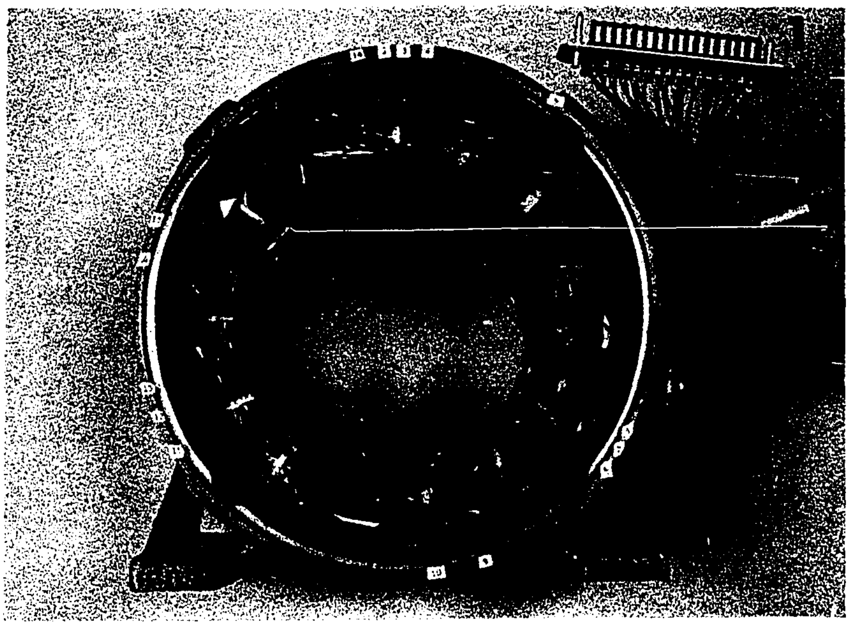


Figure 24. Thermocouples embedded in the stator winding, 1. Thermocouple connector for recorder.

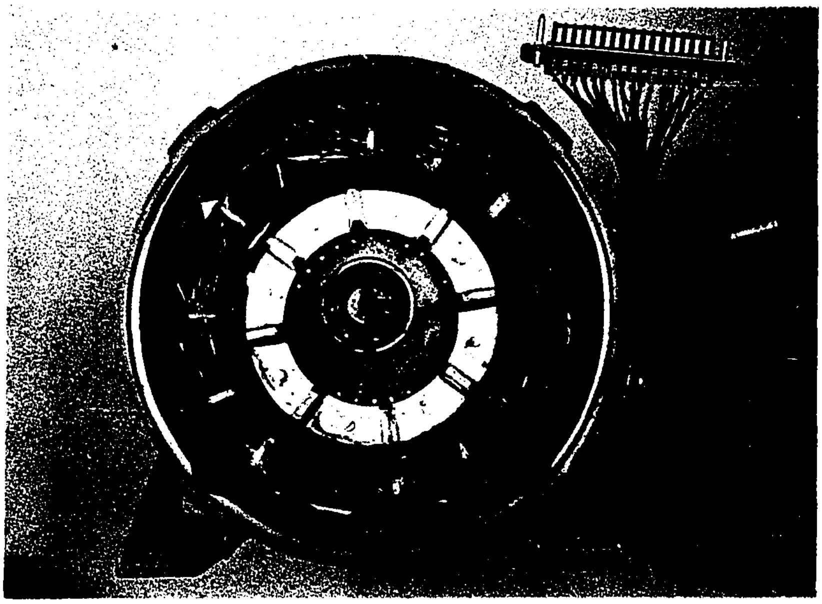


Figure 25. Motor, squirrel cage rotor and embedded thermocouple.

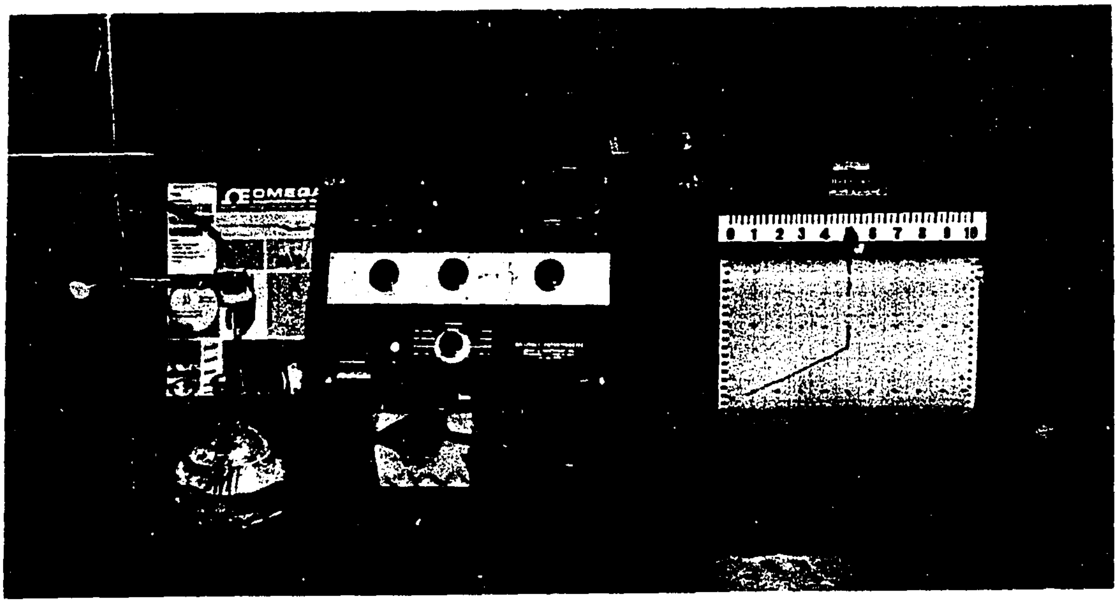


Figure 26. Calibration of recorder.

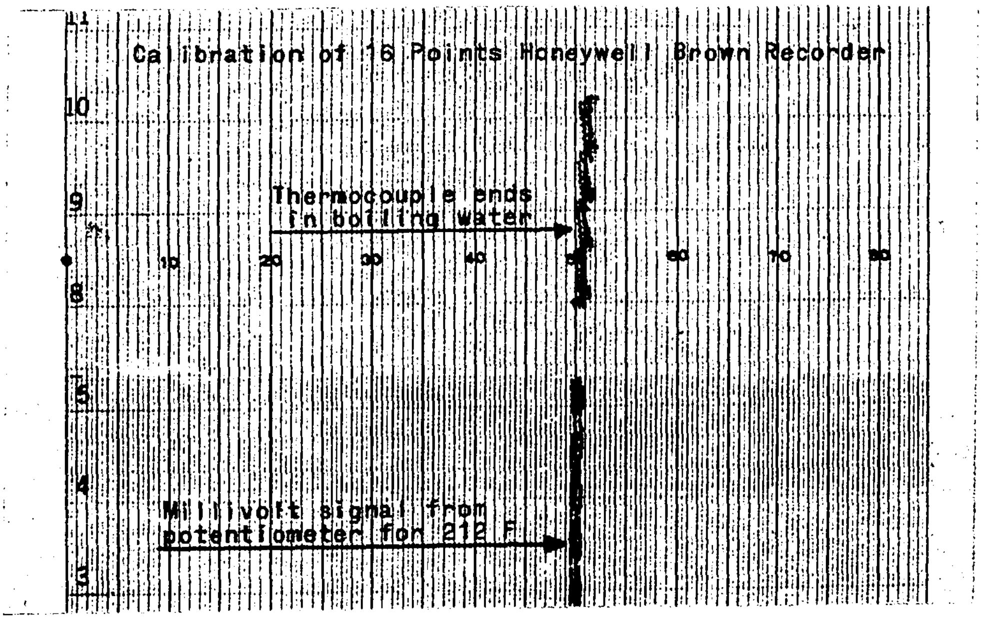


Figure 27. Calibration chart.

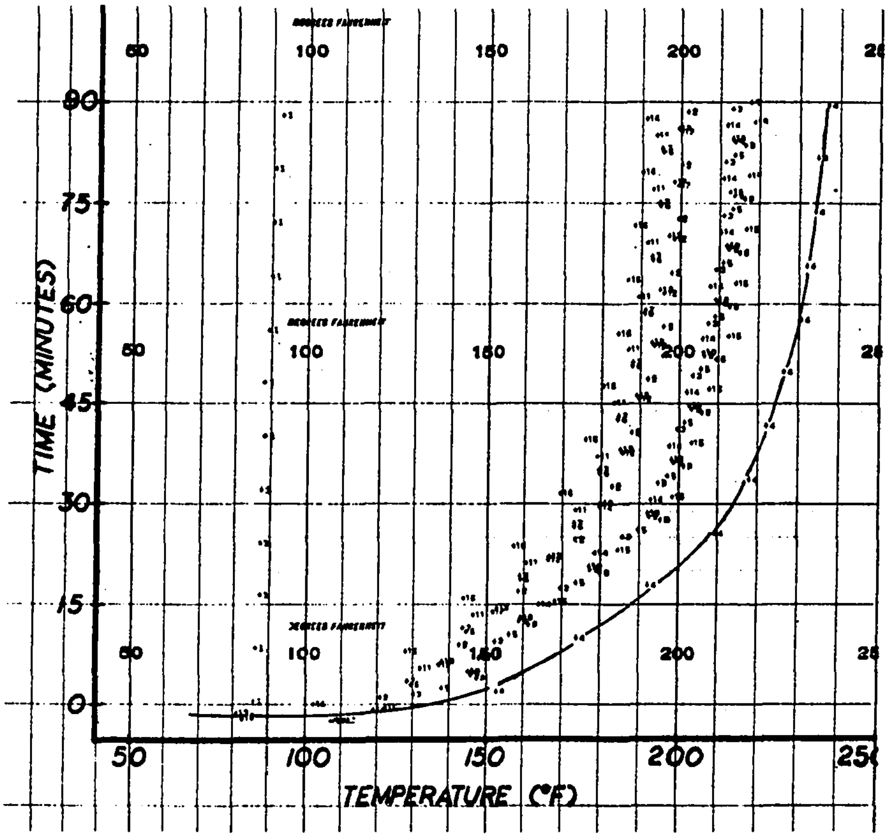


Figure 28. A typical hottest-spot temperature rise curve from embedded thermocouples.

measurement data were taken in similar tests with both methods, resistance and thermocouple. The maximum temperature rise of the windings indicated by the two methods were approximately the same.

The resistance method of temperature determination involves a lengthy computation and also measurement of cold resistance. It is necessary to stop the motor and change the wiring connections of associated apparatuses to measure the hot resistance of the windings. After confirming that there was no significant difference in the results obtained from the two methods, temperature was measured by the thermocouple method in subsequent tests.

Complete specifications of the instruments used in this study are given in Appendix A.

DETERMINATION OF AUTOTRANSFORMER-CAPACITOR PHASE CONVERTER PARAMETERS

Reports have been made on the optimum size capacitor and transformer turns-ratio that will produce balanced motor voltages and currents (40, 45). These values generally have been determined by empirical methods. Analytical equations were developed, in this study, to determine the capacitor size and the transformer turns-ratio for balanced currents in the motor by using basic principles of circuit analysis. The equations are in terms of readily available motor parameters: nameplate current, voltage and power factor angle. Two methods were used in developing the equations, vector diagrams and symmetrical components.

Converter Parameter Equations

A simplified diagram of an autotransformer-capacitor phase converter is shown in Figure 29. Single-phase lines are connected to the primary of the transformer and also to two of the terminals of the three-phase motor. Capacitors are connected between the step-up secondary terminal of the transformer and the third terminal of the motor.

Vector method

Figure 30 shows a vector diagram for a phase-converter, three-phase motor combination for the motor operating under balanced conditions. Single-phase voltage V is equal to

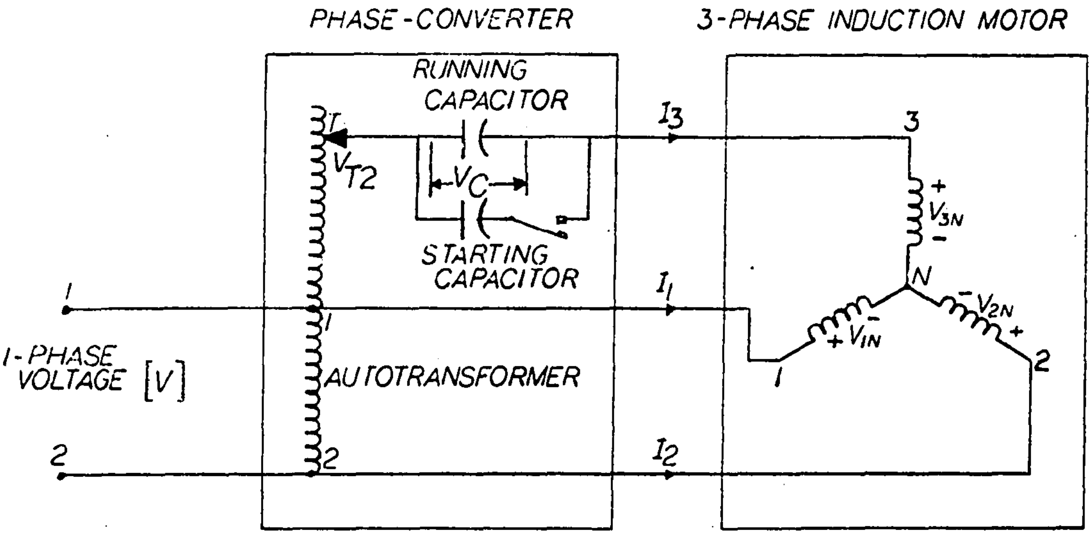


Figure 29. Simplified diagram of autotransformer-capacitor phase converter three-phase motor combination.

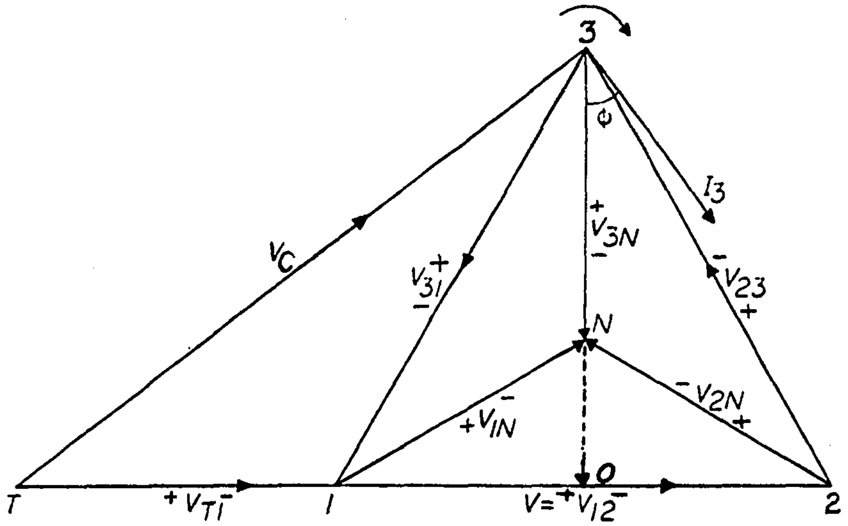


Figure 30. Vector diagram showing balanced conditions for the converter-motor combination in Figure 29.

V_{12}, the rated voltage of the motor. The autotransformer voltage V_{T2} is in phase with V and therefore lies along the vector V_{12}. Currents I_1, I_2 and I_3 in the three windings of the motor lag behind the corresponding voltages by an angle ϕ, the phase angle. In Figure 30, only I_3 is shown. Voltage at terminal 3 of the motor is determined by the voltage across the capacitor V_c and output voltage of the autotransformer V_{T2}.

The capacitor voltage, V_c, is at a right angle to the current I_3. Vector V_c, when extended, intersects the transformer output voltage vector V_{T2} at point T. To operate a three-phase motor with balanced voltages and currents, the output voltage of the transformer should be equal to V_{T2}, and voltage drop across the capacitor should be V_c. The capacitor size and the transformer turns-ratio are derived as follows:

From Figure 30

$$V_{NO} = V_{1N} \sin 30 = \frac{V_{1N}}{2}$$

$$V = V_{12} = \sqrt{3}\ V_{1N}$$

$$V_{1N} = V_{2N} = V_{3N}$$

$$V_{30} = V_{1N} + \frac{V_{1N}}{2} = (3/2)\ V_{1N} = (\sqrt{3}/2)V \qquad (5)$$

also

$$V_{30} = V_c \sin \phi \qquad (6)$$

Therefore, from Equations 5 and 6

$$V_c = (\sqrt{3}/2)\ \frac{V}{\sin\phi} \tag{7}$$

and the voltage drop across the capacitor is

$$V_c = I_3\ X_c = I_3\ (\frac{1}{2\pi fC})$$

and $$C = (\frac{I_3}{V_c})\ (\frac{1}{2\pi f}) \tag{8}$$

Under balanced conditions, the currents in the three windings of the motor are equal.

$$I_1 = I_2 = I_3 = I$$

where I is nameplate current. Substituting the value of V_c from Equation 7 in Equation 8

$$C = (\frac{I}{V})\ (\frac{2\ \sin\phi}{\sqrt{3}})\ (\frac{1}{2\pi f}) \tag{9}$$

For f = 60 H_z and C in microfarads (μF), solving Equation 9 gives the following relation for the capacitance

$$C = 3063\ \ (\frac{I}{V})\ \sin\phi \tag{10}$$

where V and I are the nameplate voltage and current of the motor, and ϕ is the power factor angle.

The transformer output voltage V_{T2} can be written in terms of primary voltage

$$V_{T2} = nV$$

where n is turns-ratio of the transformer. From Figure 30, V_{T2} can also be expressed as:

$$V_{T2} = (\frac{1}{2} V) + (\frac{\sqrt{3} \cdot V}{2 \sin \phi}) \cos \phi$$

$$nV = \frac{1}{2} V + \frac{\sqrt{3}}{2} V \cot \phi \qquad (11)$$

Equation 11 gives the output voltage from the transformer required for balanced operation of the motor. The transformer turns-ratio, n, from Equation 10 is

$$n = \frac{1}{2} + \frac{\sqrt{3}}{2} \cot \phi \qquad (12)$$

where ϕ is the power factor angle previously defined.

Symmetrical components method

The method of symmetrical components permits analysis of motor performance under unbalanced conditions. An unbalanced system of three related phasors can be resolved into three systems of balanced phasors, called symmetrical components of the original phasors (20, 21). The three systems of balanced phasors are: 1) positive-sequence components, 2) negative-sequence components and 3) zero-sequence components. The first two systems consist of three phasors, equal in magnitude and displaced from each other by 120 degrees. Negative-sequence components have a direction of rotation opposite to that of positive-sequence components. Zero-sequence components are equal in magnitude and are in phase with each other (16, 28, 61, 62, 71, 73, 75, 83).

In Figure 30, taking V_{1N} as reference, the phase voltages V_{1N}, V_{2N} and V_{3N} can be expressed by the matrix Equation 13. The voltages V_{1NO}, V_{1N1} and V_{1N2} are the zero, positive and negative sequence components of phase 1.

$$\begin{bmatrix} V_{1N} \\ V_{2N} \\ V_{3N} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{1NO} \\ V_{1N1} \\ V_{1N2} \end{bmatrix} \tag{13}$$

where a is an operator, commonly called the characteristic angle of the system (89, 101, 102). For a three-phase system, a is defined as

$$a = 1 \angle 120 = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

$$a^2 = 1 \angle 240 = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

Phase voltages obtained from Equation 13 are

$$V_{1N} = V_{1NO} + V_{1N1} + V_{1N2} \tag{14}$$

$$V_{2N} = V_{1NO} + a^2 V_{1N1} + a\, V_{1N2} \tag{15}$$

$$V_{3N} = V_{1NO} + a\, V_{1N1} + a^2 V_{1N2} \tag{16}$$

The voltage Equations 17 and 18 for the single-phase voltage, V, and the output voltage of the autotransformer, nV, are obtained by applying Kirchhof's voltage law to the phase converter-motor circuit of Figure 29.

$$V = V_{1N} - V_{2N} \tag{17}$$

$$nV = V_c + V_{3N} - V_{2N} \tag{18}$$

Substituting the values of V_{1N}, V_{2N} and V_{3N} from Equations 14, 15 and 16 in Equations 17 and 18, and solving for n, the transformer turns-ratio

$$n = \frac{V_{1N1}\ (a-a^2) + V_{1N2}\ (a^2-a) + V_c}{V_{1N1}(1-a^2) + V_{1N2}(1-a)} \tag{19}$$

For the balanced condition of a motor, the zero-sequence and negative-sequence voltages are zero; therefore, $V_{1N} = V_{1N1}$ in Equation 14. Taking V as a reference voltage and further simplification of Equation 19 gives

$$n = \frac{a}{1+a} + \frac{V_c \angle{-\phi}}{\frac{V}{\sqrt{3}} \angle{-30}\ (1-a^2)}$$

$$n = \left(\frac{1}{2} + j\ \frac{\sqrt{3}}{2}\right) + \frac{V_c}{V}\ (\cos\phi - j \sin\phi) \tag{20}$$

In Equation 20, n is a real number. Equating imaginary and real parts of Equation 20

$$0 = j\ \frac{\sqrt{3}}{2} - j\ \frac{V_c}{V}\ \sin\phi$$

therefore $V_c = \frac{\sqrt{3}}{2}\ \frac{V}{\sin\phi}$ (21)

and $n = \frac{1}{2} + \frac{V_c}{V}\cos\phi$ (22)

Replacing V_c in Equation 21 by IX_c and solving for the capitance C in microfarads

$$C = 3063\ (\frac{I}{V})\ \sin\phi \tag{23}$$

where I = Full load current of the motor (amps)

V = Rated voltage (volts)

ϕ = Power factor angle (degrees)

Substituting V_c from Equation 21 in Equation 22

$$n = \frac{1}{2} + \frac{\sqrt{3}}{2}\cot\phi \tag{24}$$

Equations 23 and 24 are identical to Equations 10 and 12 developed with the vector method.

Experimental Verification of the Equations

Equations 10, 11, and 12 were verified experimentally for a 5 hp, three-phase, T-frame motor and a 10 hp, three-phase, U-frame motor, both operating on single-phase power through autotransformer-capacitor phase converters. The output voltage of the autotransformer was varied by feeding its primary windings through a variac. Capacitors were connected in parallel to obtain a capacitance value as close as possible to that predicted with the analytical equation. Test motors were loaded with the reaction-torque-table dynamometer shown in Figure 18.

Tests were conducted only at the full-load horsepower rating of the motors. Voltages, currents and power factors of the motors under full load were measured with the switching and metering arrangement shown in Figure 19. Data were obtained with motors operating on both three-phase power and phase converters. This provided a comparison of voltages, currents and power factors of the motors operated on both power sources.

The current and voltage value from the motor nameplate and the power factor from the manufacturer's literature for the 5 hp and 10 hp test motors are given in Table 4.

Table 4. Rated voltage, current and power factor of test motors.

Motor horsepower	I amps	V volts	P.F.	Phase angle ϕ	Insulation class
5, T-Frame	14.4	230	0.80	36° 52'	B
10, U-Frame	27.0	220	0.84	32° 52'	A

The predicted value of capacitance for balanced operation of the 5 hp motor can be calculated from the data in Table 4 and Equation 10 in the following manner.

$$C = 3063 \left(\frac{14.4}{230}\right) \sin (36^{\circ}\ 52')$$

$$= 115.0\ \mu F$$

The autotransformer secondary voltage required for balanced operation is obtained from Equation 11

$$nV = \frac{1}{2}(230) + \frac{\sqrt{3}}{2}(230) \cot (36^{\circ}\ 52')$$

$$= 380.6 \text{ volts}$$

Equation 12 gives the transformer turns-ratio

$$n = \frac{1}{2} + \frac{\sqrt{3}}{2} \cot (36^{\circ}\ 52')$$

$$= 1.65$$

The autotransformer-capacitor phase converter parameters are calculated for the 10 hp, U-frame motor by using Equations 10, 11 and 12 in a manner identical to that used for the 5 hp motor.

$$C = 3063 \left(\frac{27.0}{220}\right) \sin (32^{\circ}\ 52')$$

$$= 204.0\ \mu F$$

$$nV = \frac{1}{2}(220) + \frac{\sqrt{3}}{2}(220)\cot(32^{\circ}\ 52')$$

$$= 405 \text{ volts}$$

and $$n = \frac{1}{2} + \frac{\sqrt{3}}{2}\cot(32^{\circ}\ 52')$$

$$= 1.84$$

The predicted and experimental values of capacitor size, autotransformer voltage and turns-ratio are summarized in Table 5. The values of capacitance used in the experimental verification could not be set exactly equal to the predicted values because of the sizes of capacitors available. The voltages determined experimentally for balanced operation of the motors were slightly lower than the predicted values. This is attributed to the use of capacitance values slightly larger than those predicted by the analytical equation.

Table 5. Predicted and experimental values of autotransformer-capacitor phase converter parameters.

hp	Parameters	Predicted values for balanced operation	Experimental values for balanced operation
5	C	115.0 µF	119.8 µF
	nV	380.6 volts	375.0 volts
	n	1.65	1.63
10	C	204.0 µF	206.0 µF
	nV	405.0 volts	403.0 volts
	n	1.84	1.85

The performance of motors operating on three-phase line power and single-phase power through the phase converter is shown in Table 6. There were no significant differences between the voltages, currents, and power input.

Table 6. Voltages, currents, power input and power factor of three-phase motors operated at rated horsepower on three-phase power and single-phase power thru a phase converter.

Motor size	5 hp, T-frame		10 hp, U-frame	
Power source	Three-phase	Single phase thru converter	Three-phase	Single phase thru converter
I_1 (Amp)	14.8	14.4	28.0	28.6
I_2 "	14.6	14.4	27.6	26.0
I_3 "	14.2	14.6	27.0	26.4
V_{12} (Volt)	230	230	220	220
V_{23} "	230	230	220	220
V_{13} "	230	230	220	220
V_{1N} "	133	132	127	128
V_{2N} "	133	132	127	127
V_{3N} "	133	132	126.5	128
Power (kW)	4.52	4.54	8.84	8.60
Power factor	0.78	.88	0.84	0.96

The close agreement of the operating conditions of the motors on three-phase power and on the phase converter verifies that the equations developed in this study can be applied to determine analytically the capacitor size and autotransformer setting for balanced voltages and currents in a three-phase motor with an autotransformer-capacitor phase converter.

OPTIMIZATION OF PARAMETERS FOR THE PRACTICAL APPLICATIONS

With changes in load on a general purpose 3-phase motor operated on three-phase line power, the power factor of the motor changes. Power factor of a lightly loaded motor is less than that of a motor under full load. In a lightly loaded motor, currents in the three-phases are equal but smaller in magnitude than the full load current.

An autotransformer-capacitor phase converter adjusted to parameter values determined by Equations 10 and 11 provide balanced voltages and currents to a three-phase motor but for a given load only. The effect of line current and phase angle changes for the motor with different loads can be shown with vectors V_c and V_{T2} in Figure 31. As the load on the motor is reduced, the lengths of vectors V_c and V_{T2} are also reduced. Knowing the values of ϕ and I for the load on the motor, the size of capacitors, C, and transformer turns-ratio, n, can be determined from Equations 10 and 11. These parameter values would provide balanced operation of three-phase motor for the particular value of load on the motor. For loads where the power required is constant, the running performance of a three-phase motor with an autotransformer-capacitor phase converter is nearly equal to the performance of the motor on three-phase power line. In many applications on farms, however, the loads are variable.

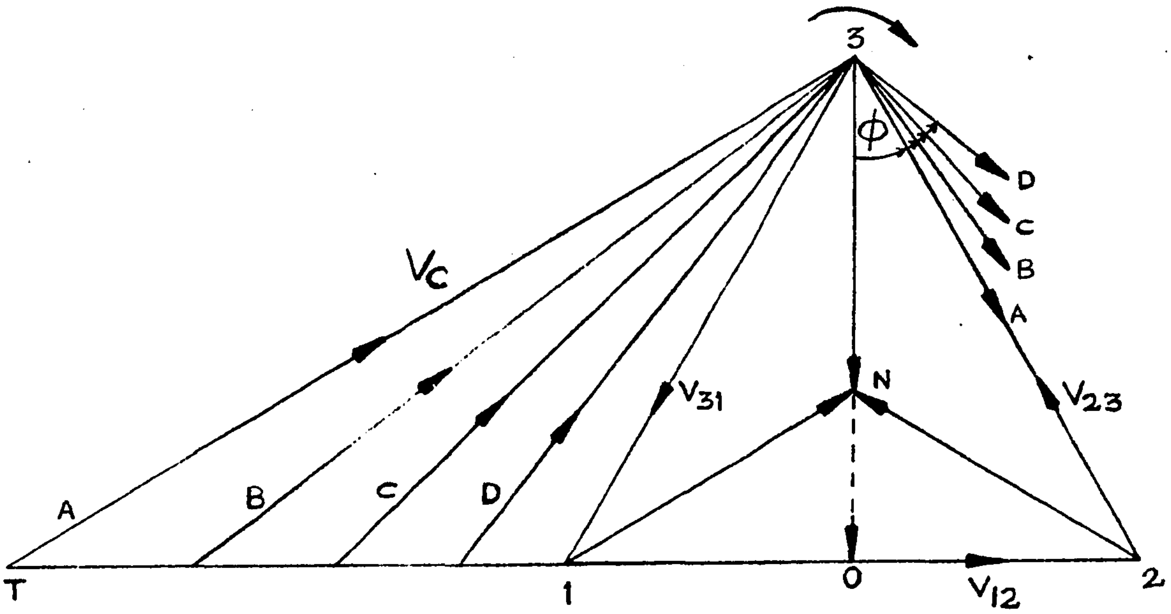


Figure 31. Vector diagram for the balanced operation of a phase converter operated three-phase motor at various loads.

An autotransformer-capacitor phase converter adjusted for the maximum load may not operate a motor satisfactorily over a range of loads. To avoid poor performance, manufacturers of farm equipment sometimes install oversized motors. These motors do not draw rated currents when operating lighter loads. A phase converter with parameters selected for the nameplate current and full load power factor will not provide balanced currents and voltage.

An attempt was made in this study to find the optimum adjustment on an autotransformer-capacitor converter that would provide satisfactory performance of a three-phase motor for moderately variable loads. Tests were conducted on a 10-hp, U-frame, 220 volts, three-phase motor and a 5-hp, T-frame, 230 volts three-phase motor. To find the phase angle and current requirement for various loads, the test motors were first operated on three-phase power. The performance characteristics curves for the two motors are shown in Figures 32 and 33. The experimental data for these curves are given in Tables 19 and 20 in Appendix C.

The design parameters for the 10-hp and 5-hp motors were calculated using Equations 10 and 11, for the balanced operation of the motors at 80, 90, and 100% of rated load. Equations 10 and 11 are reproduced below.

$$C = 3063\ (\frac{I}{V})\ \mathrm{Sin}\ \phi$$

$$nV = \frac{1}{2}V + \frac{\sqrt{3}}{2}\,\mathrm{Cot}\ \phi$$

Table 7 shows the values of C and nV for the three loads. The 5-hp, T-frame motor used for this study was a different brand than the motor used in the previous section, experimental verification of design equations.

Performance Characteristics

The autotransformer-capacitor phase converter parameters were adjusted for balanced voltages and currents with a 80% load on the 10-hp motor. To illustrate the effect of

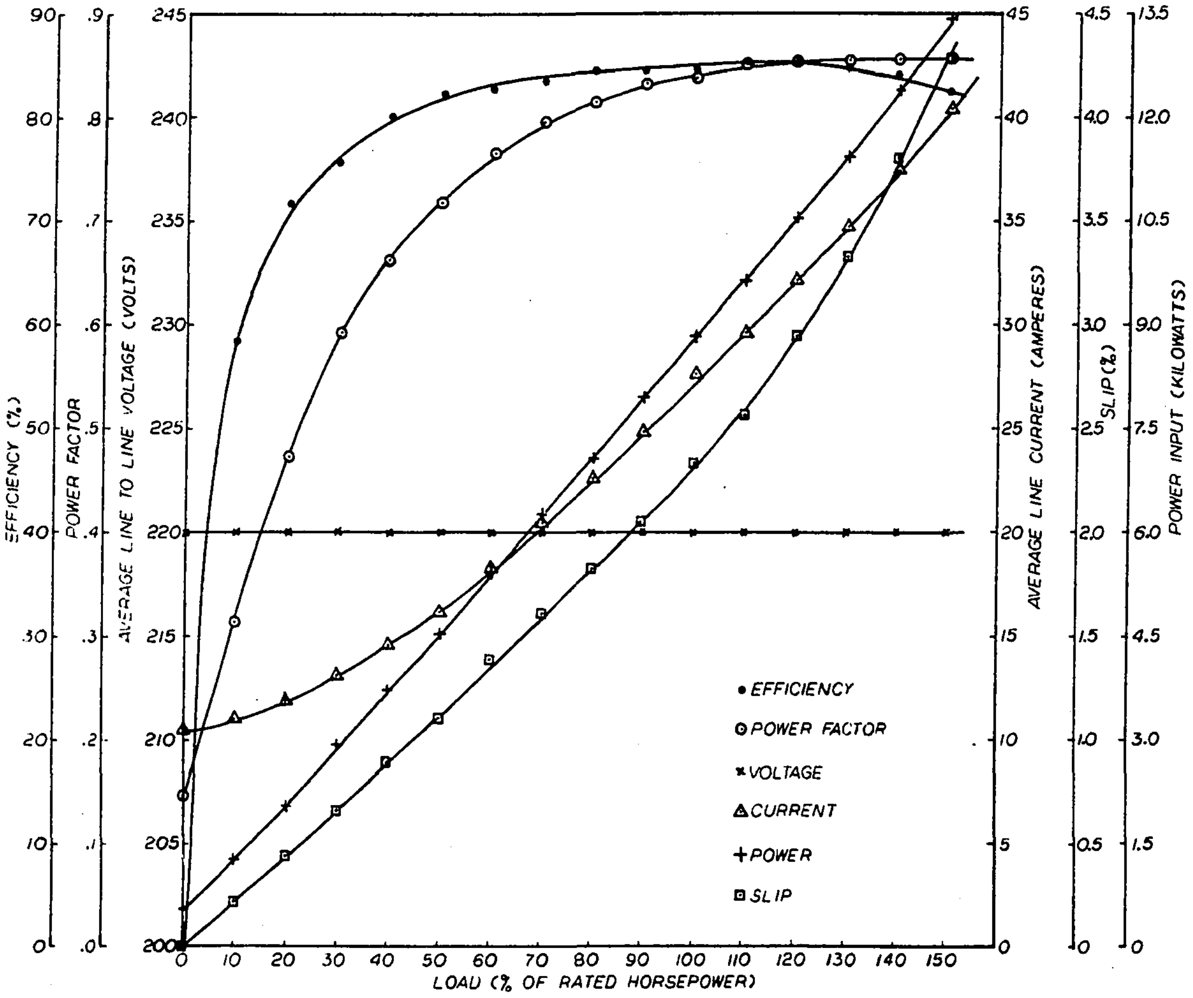


Figure 32. Performance curves of a 10-hp, U-frame, 220 volts, three-phase motor operated on three-phase line power.

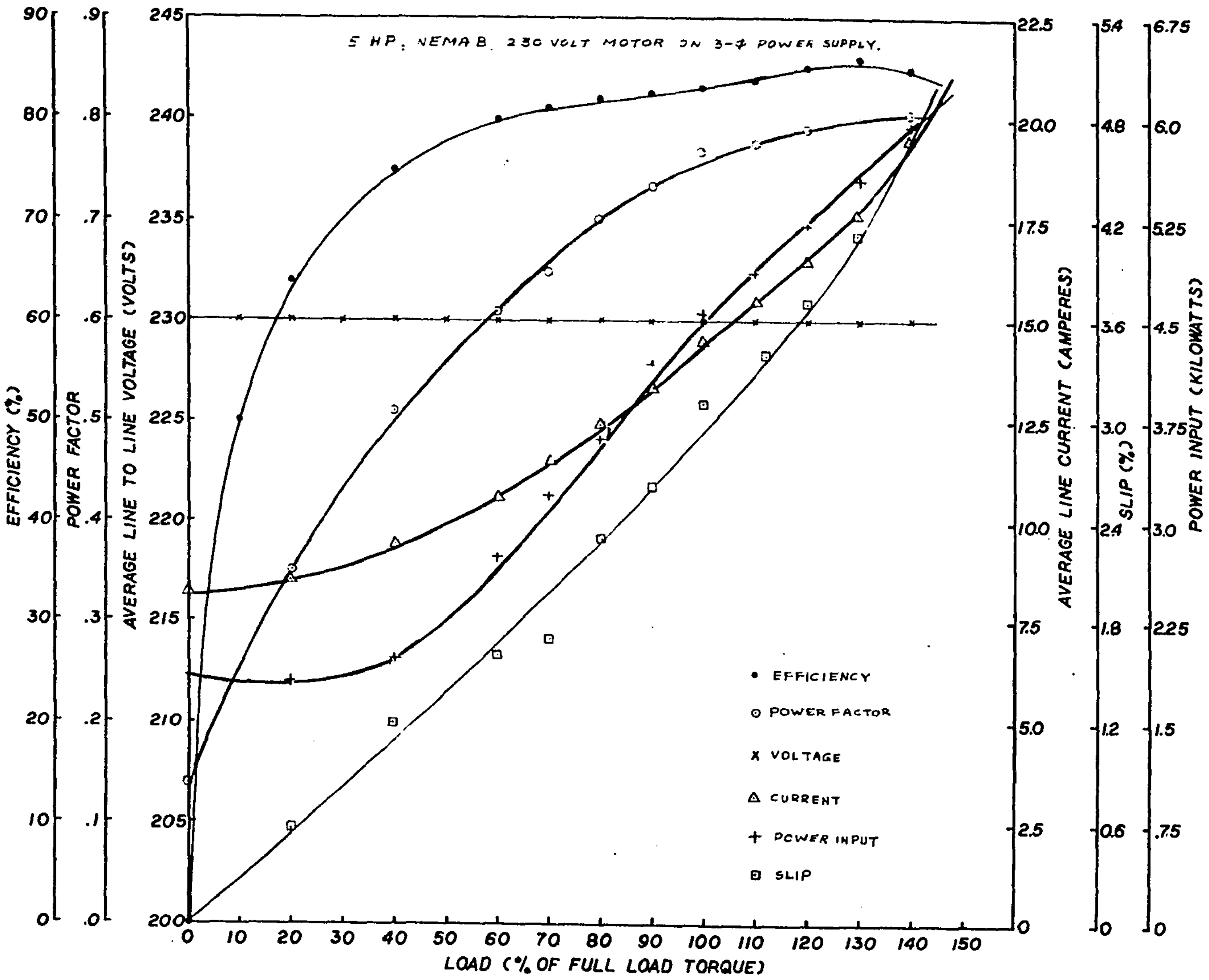


Figure 33. Performance curves of a 5-hp, T-frame, 230 volts, three-phase motor operated on three-phase line power.

loads other than that for which the converter was adjusted the test motor was loaded from 60 to 120% of the full load. For each load on the motor, information was obtained on line currents, line to line voltages at the motor terminals, power input, efficiency of the motor converter combination, slip of the motor, and temperature rise of the motor windings.

Table 7. Parameters of an autotransformer-capacitor phase converter for balanced operation of the 10-hp, U-frame, 220 volts motor and the 5-hp, T-frame, 230 volts motor at various loads.

Test Motors	Parameters for balanced operation at								
	80% load			90% load			100% load		
	C	nV	n	C	nV	n	C	nV	n
5-hp, T brand (2)	111	331	1.44	115	351	1.53	121	363	1.58
10-hp, U	180	383	1.74	193	394	1.79	204	405	1.84

The experiment was repeated with the converter adjusted for balanced operation at 90% and 100% of the load.

Voltages and currents

With the converter adjusted for 80% motor load, the line currents and voltages as shown in Figures 34 and 35 are closely balanced when the motor was loaded to 80% of its rated horsepower. Motor terminal voltages and line currents became unbalanced, however, with the load on the motor other than 80%. For example the percentage unbalance in line currents was 12% at 70% and 90% loads. The unbalance at ± 20% load increased to 24%. The percentage of unbalance was computed from the maximum difference in current or voltage from the average of the three line currents or the three line to line voltages.

The maximum unbalance in terminal voltages was 2% at ± 10% load and 4% at ± 20% load. As the load on the motor deviated further from 80%, the unbalance in both current and voltage increased rapidly.

The average line current of the motor operated at various loads from the three-phase power line is also graphed in Figure 34 for comparison. This illustrates the spread of three unbalanced line currents of the motor operated from an autotransformer-capacitor converter in relation to the average line current with three-phase power.

Figures 36 and 37 are line currents and voltages of the 10-hp U-frame motor with the converter adjusted for balanced operation at 90% of the load. The maximum unbalance in line current was 8% at -10% load and 16% at +10% load. At -20% load the current unbalance increased to 22% and at +20% load the unbalance was 27%. The maximum voltage unbalance was 3.2% at -20% load, 1.9% at -10% load,

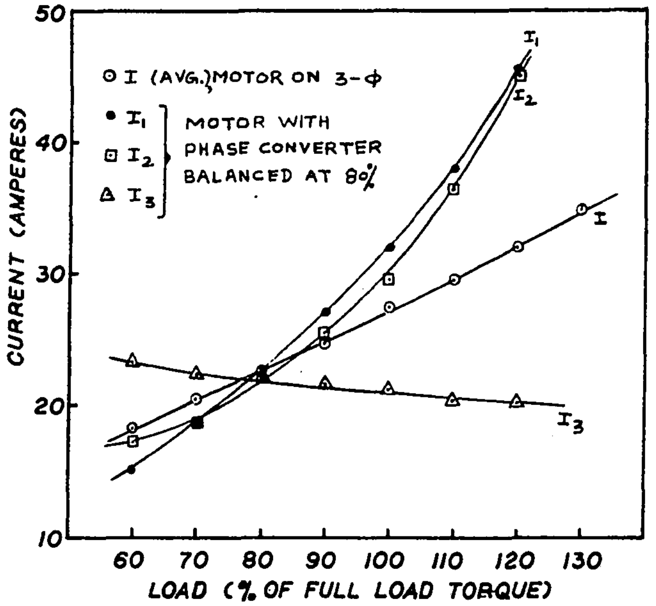


Figure 34. Current vs. load of a 10-hp U-frame, 220 volts motor with the converter adjusted for balanced operation at 80% of rated load.

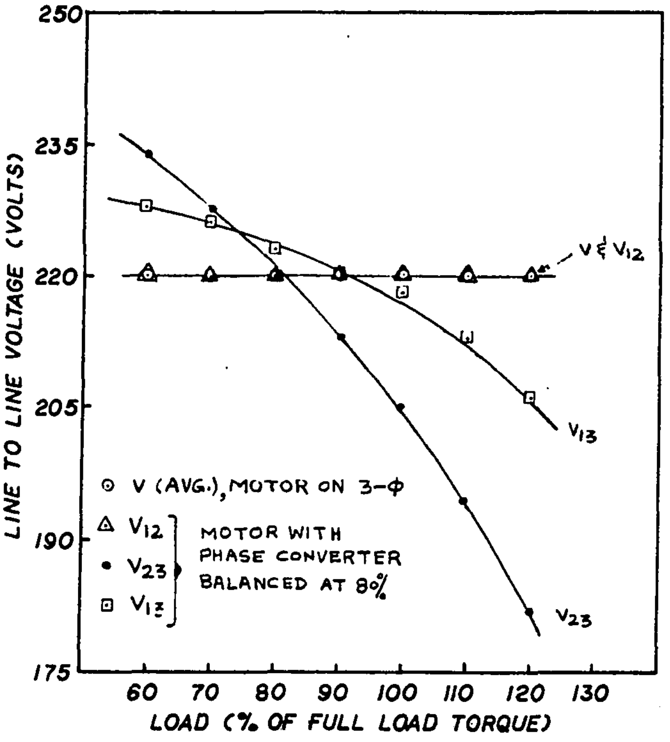


Figure 35. Voltage vs. load of a 10-hp U-frame, 220 volts motor with the converter adjusted for balanced operation at 80% of rated load.

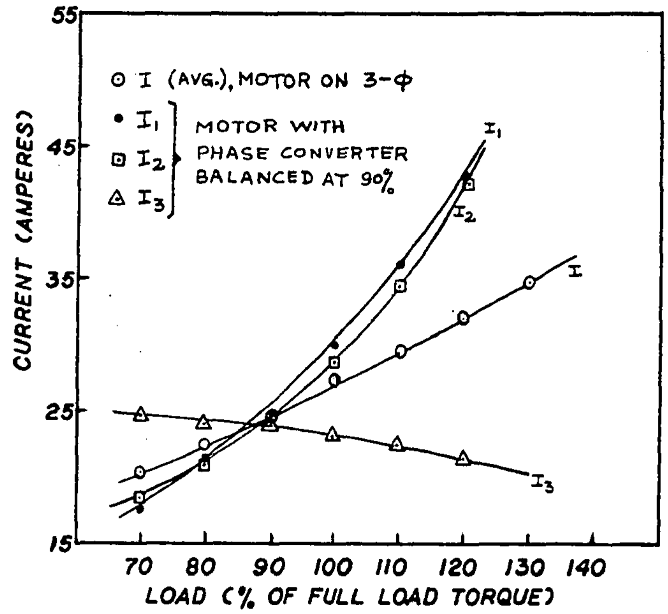


Figure 36. Current vs. load of 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 90% of rated load.

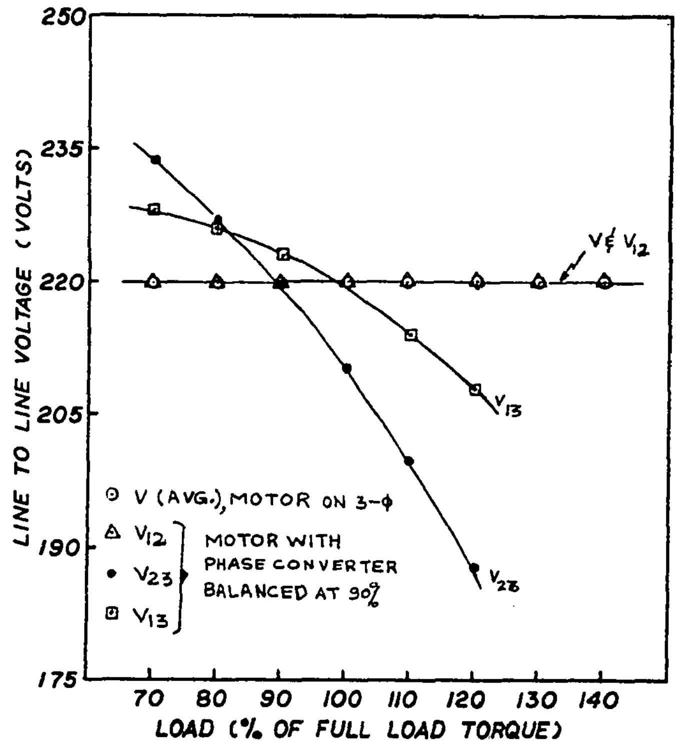


Figure 37. Voltage vs. load of a 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 90% of rated load.

3.1% at +10% load, and 5.4% at +20% load. Line currents and voltage of motor with the converter adjusted for 100% load are shown in Figures 38 and 39.

The data on percentage unbalance of currents and voltages of a 10-hp U-frame, 220 volts motor with the three adjustments of converter parameters are summarized in Table 8. Deviation in loads is the difference between the actual load on the motor and the load for which the converter was adjusted.

Table 8. Percentage of maximum unbalance in line currents and terminal voltages of a 10-hp U-frame, 220 volts motor under various loads.

I and V	Converter adjusted for % rated load	Percentage maximum unbalance						
		Deviation in load, % of rated						
		-30	-20	-10	0	+10	+20	+30
I	80	40	25	12	2	12	23	35
	90	33	22	8	3	16	27	39
	100	30	21	10	4	15	27	42
V	80	4.3	3.2	2.1	0.9	2.0	4.3	6.8
	90	4.5	3.2	1.9	0.9	3.1	5.4	8.4
	100	4.8	3.6	2.1	1.2	2.6	5.9	9.5

The experimental data pertaining to Figures 34 through 39 are given in Tables 21, 22, and 23 in Appendix C.

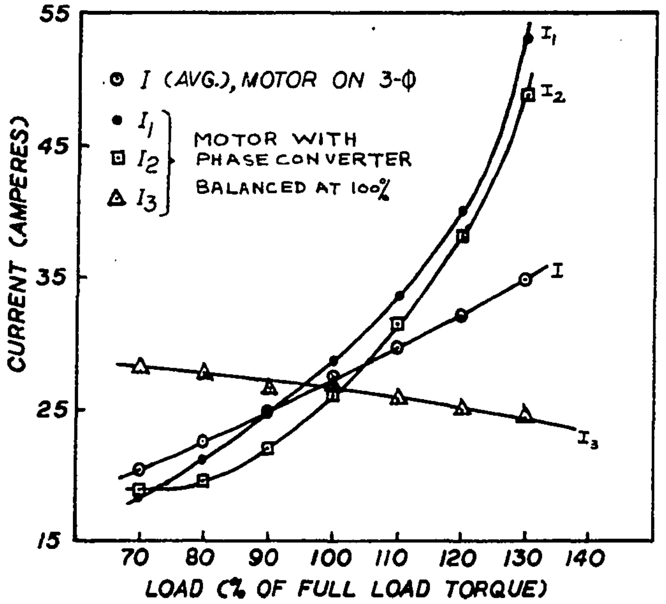


Figure 38. Current vs. load of a 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 100% of rated load.

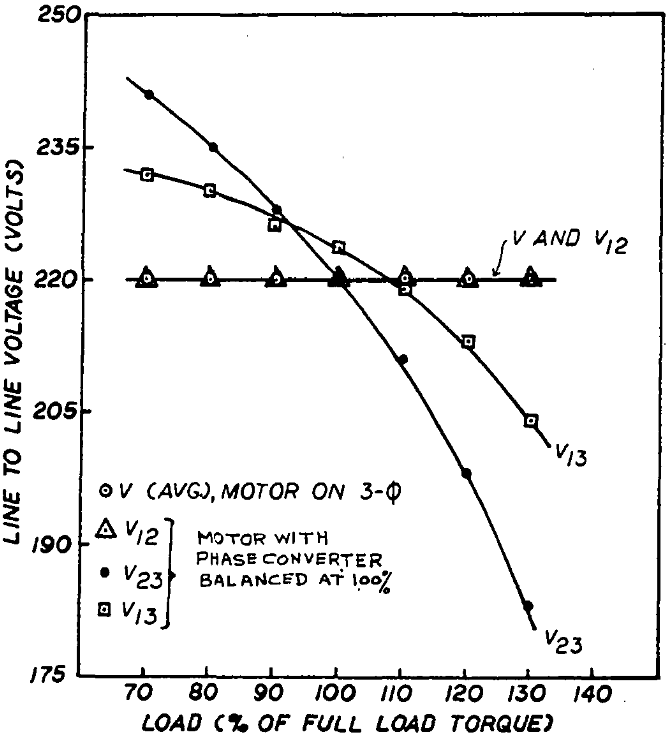


Figure 39. Voltage vs. load of a 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 100% of rated load.

Power input and efficiency

Power input and efficiency curves for the motor operating on a three-phase power line and on an autotransformer-capacitor converter with parameters adjusted for the balanced operation at 80, 90, and 100% load are shown in Figures 40 and 41. Power input to the motor, over the range of loads, was minimum with the three-phase power line. Power drawn by the motor-converter combination, for the three settings of parameters, was about the same. A slightly higher power was drawn by the motor operating with the converter adjusted for balanced currents at 80%, 90%, and 100% of the rated load than that with three-phase operation.

Efficiency of the motor operated on a three-phase power line was greater than with the phase converter. This was due to the additional power lost, I^2R and eddy current losses in the transformer winding of the phase converter. The motor phase converter combination had about the same maximum efficiency for the three adjustments of capacitors and transformers. For all the three settings, the maximum efficiency resulted at a load 10% above that for which the parameters were adjusted. For example, with the parameters adjusted for 80% load, the maximum efficiency occurred at 90% of the rated load.

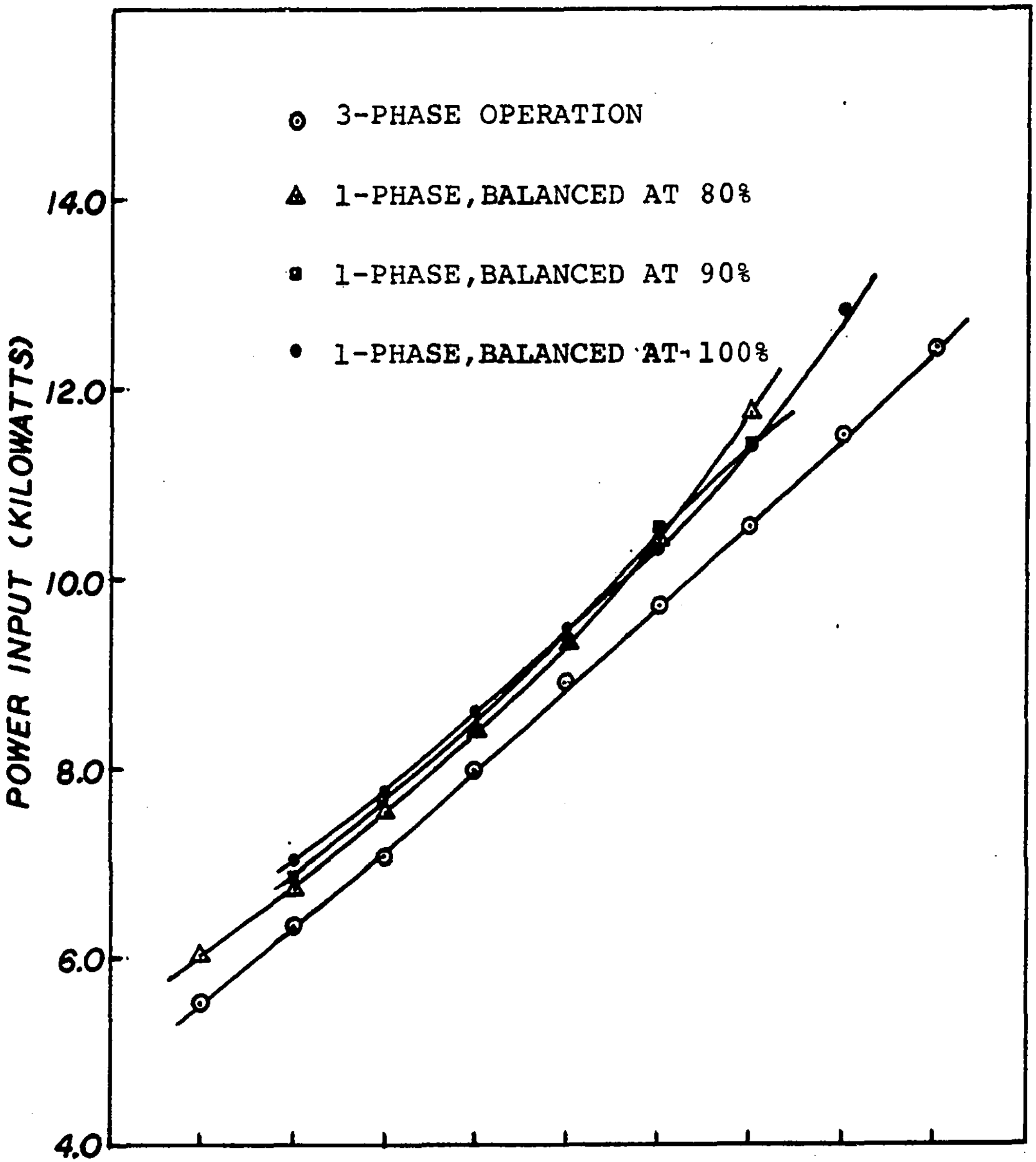


Figure 40. Power input vs. load of a 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 80, 90, and 100% of rated load.

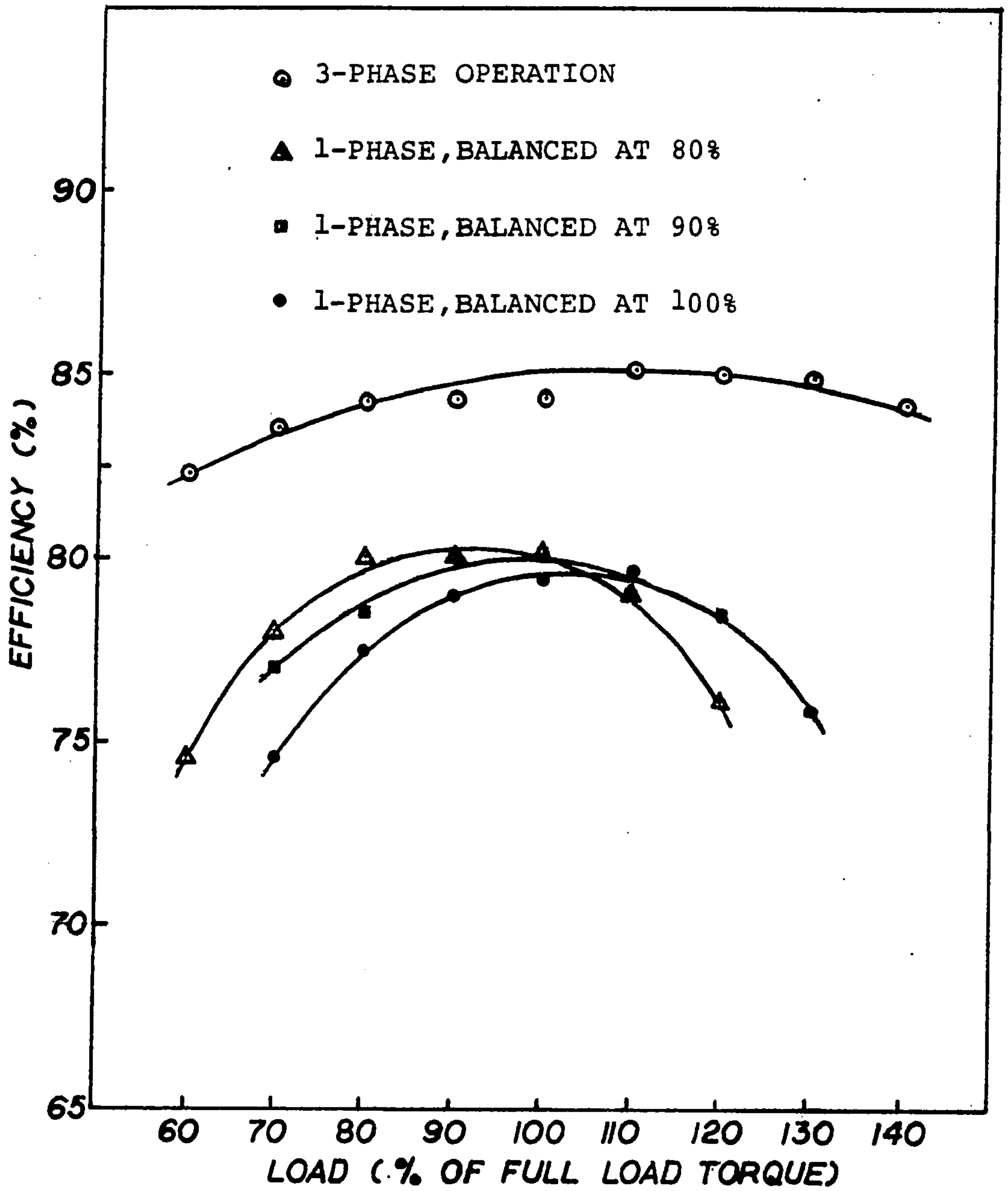


Figure 41. Efficiency vs. load of a 10 hp U-frame 220 volts motor with the converter adjusted for balanced operation at 80, 90, and 100% of rated load.

Power factor

The power factor of the motor is improved when operated from a phase converter. As shown in Figure 42, the power factor of the three-phase line supplying power to the test motor is less than that of the single-phase line connected to the phase converter-motor combination. Power factor of the system improved as the load on the motor was increased. At 120% of the rated load, power factor of the three-phase motor is 0.85 and nearly unity for the three settings of the phase converter.

Slip

Slip of the motor, at various loads, operating from a three-phase power line and a phase converter is shown in Figure 43. The speed of an induction motor is reduced with an increased load. The difference in slip of the motor at 60 to 90% of the rated load, operating on the three-phase line and the three settings of the phase converter is very small. At loads above 90%, however, slip of the motor operated from a phase converter is higher than that with the three-phase power source. Slip was highest for balanced operation at 80% load and least with the adjustment for balanced currents at 100% load.

Temperature rise

The temperature rise of the motor winding measured with embedded thermocouples is shown in Figure 44. For the

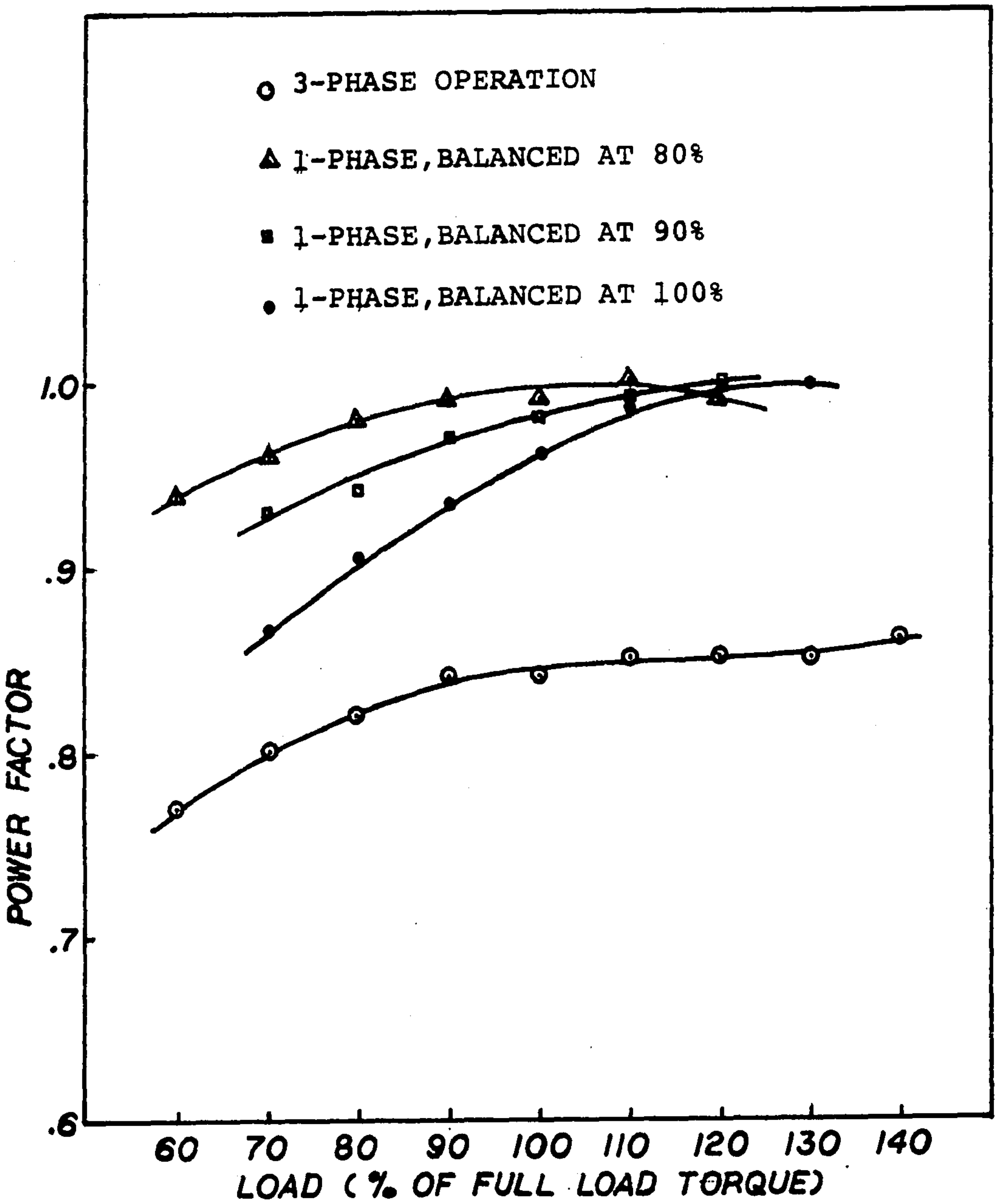


Figure 42. Power factor vs. load of a 10-hp U-frame 220 volts motor with the converter adjusted for balanced operation at 80, 90, 100% of rated load.

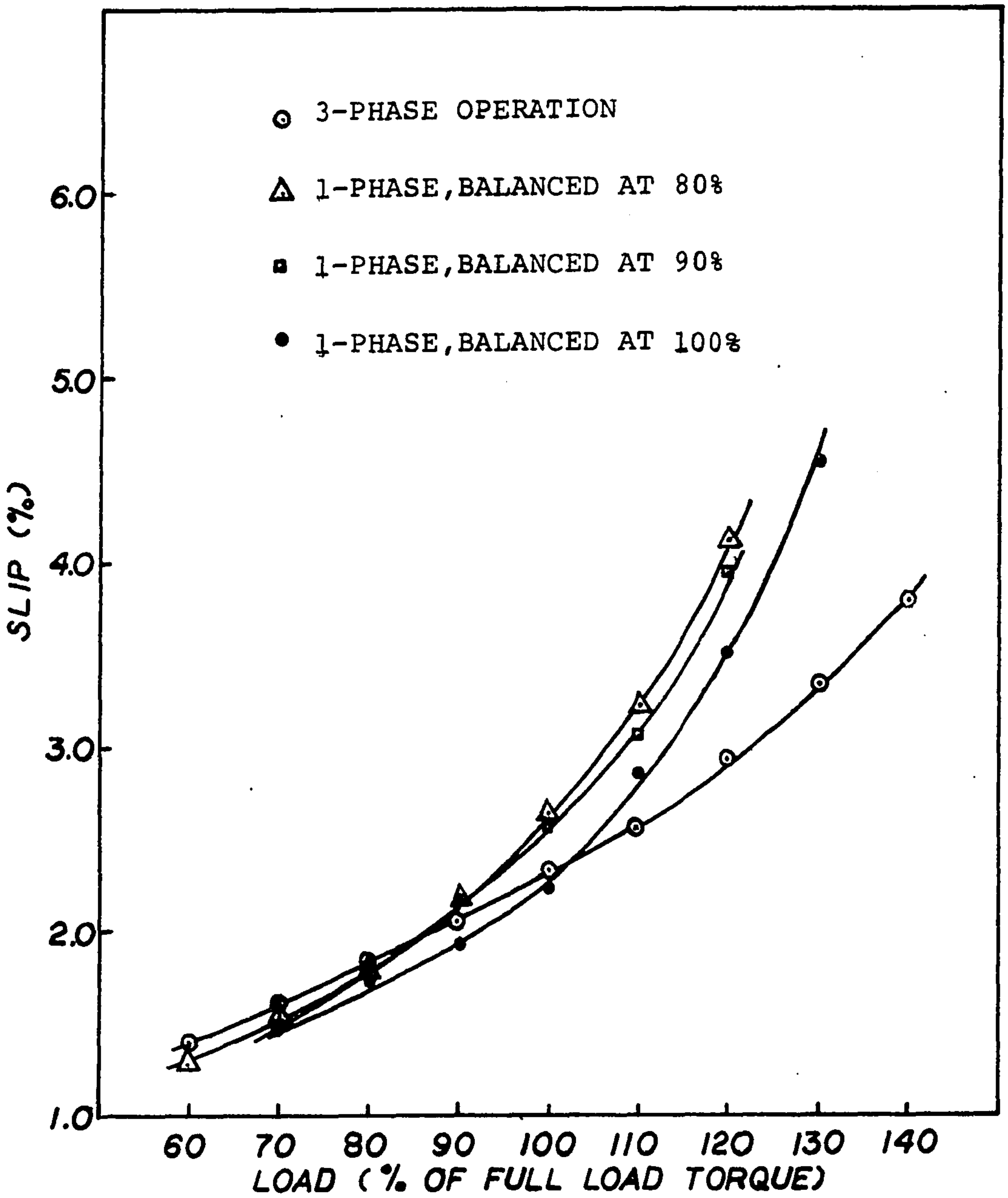


Figure 43. Slip vs. load of a 10 hp U-frame 220 volts motor with the converter adjusted for balanced operation at 80, 90, and 100% of rated load.

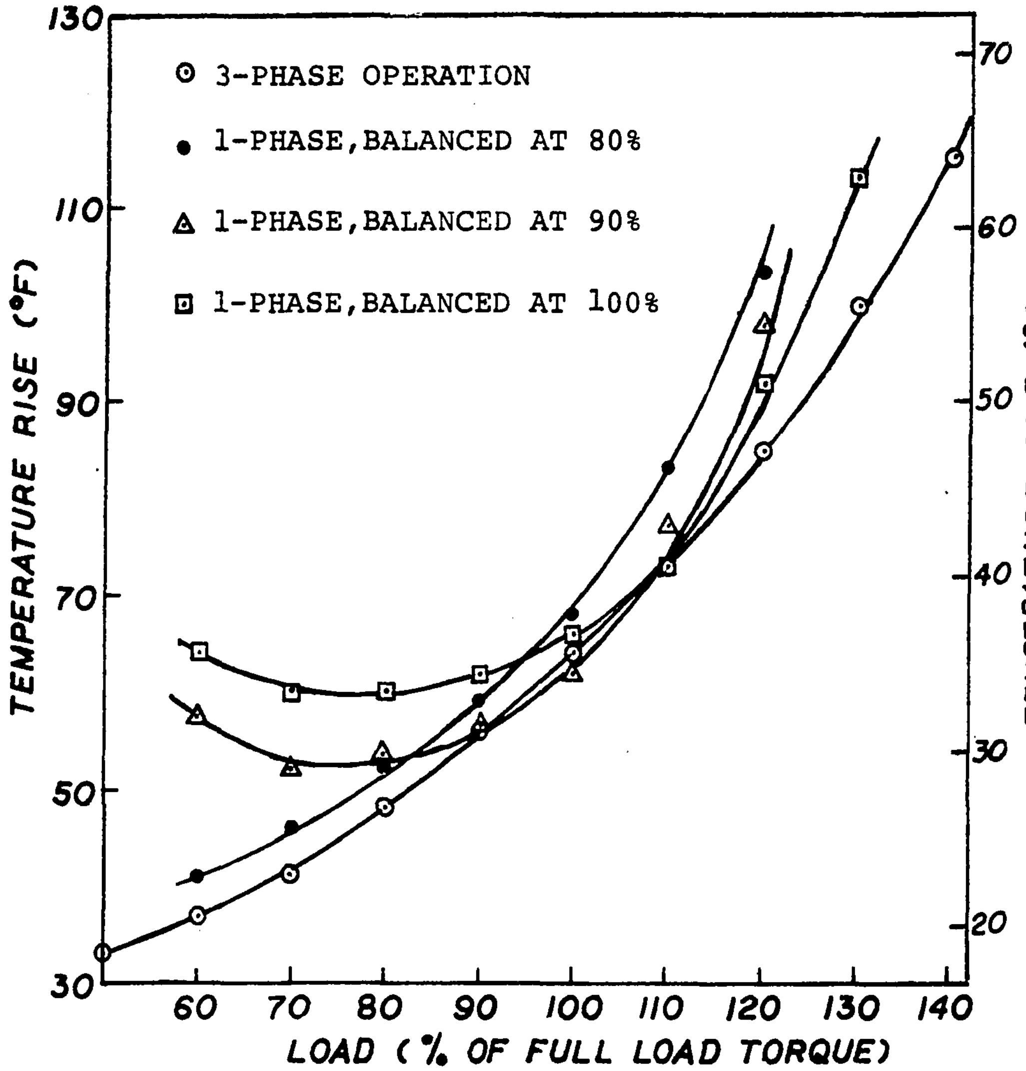


Figure 44. Temperature rise vs. load of a 10 hp U-frame 220 volts motor with the converter adjusted for balanced operation at 80, 90, and 100% of rated load.

same load on the motor, the motor ran cooler, in general, on the three-phase supply than on single-phase line through a phase converter. Temperature of the winding is related to motor current, thus temperature rise is greater at higher loads. Temperature rise in the motor windings under all test conditions did not exceed the design limits of the insulation.

The experiment conducted on the 10-hp U-frame motor was repeated for a 5-hp T-frame, design B, 230 volts motor. The values of parameters for balanced operation at 80, 90 and 100% of rated load are given in Table 7. The difference in capacitor sizes for balanced operation at 80 and 90%, was very small. The capacitors available for this study did not permit fine adjustment. Therefore, tests for the 5-hp motor were conducted for two settings only, i.e., balanced operation adjustments at 80 and 100% of the rated motor load.

The performance characteristics curves of currents, voltages, power input, efficiency, power factor, slip, and temperature rise, for a 5-hp, design B, 230 volts, three-phase test motor are shown in Figures 92 through 100 in Appendix C. The experimental data related to these figures are given in Tables 24 and 25, also in Appendix C.

The effects of loads other than the load, for which the converter was adjusted, on the performance of a 5-hp T-frame 230 volts test motor are very similar to those explained for the 10-hp, U-frame, 220 volts test motor.

The experimental results in this section of the study show that in the applications where the motor supplied with the machine is oversized, for better performance of the motor, parameters in the autotransformer-capacitor phase converter should be adjusted for the actual load on the motor and not for its nameplate horsepower. This will require measurement of the current drawn by the motor and determination of the corresponding power factor from the performance characteristics curves obtained with the motor operating on three-phase power. Figures 32 and 33 are two examples of such curves.

In applications where load fluctuates often over a moderate range, the autotransformer-capacitor converter should be adjusted for the average value of the load. For example, with the motor load varying between 80 to 100% of the rated, parameters adjusted for 90% of the rated load may give the best results. On applications where only infrequent variations in load are expected, the converter should be adjusted for the most frequently encountered load.

VOLTAGE EFFECTS ON PHASE CONVERTER OPERATED THREE-PHASE MOTORS

The increased use of phase converter operated three-phase motors has made desirable the study of the effects of input line voltage variation on motor performance. Present phase converter designs do not provide identical terminal voltages at each phase of the motor when the single-phase input voltage to the phase converter varies. When the phase voltages are not equal, unbalanced currents flow in the motor stator windings. The magnitude of current unbalance is dependent on the voltage unbalance. Even a small amount of voltage unbalance may increase currents and excessive motor heating, because phase current unbalance is several times the voltage unbalance.

Most general purpose poly-phase induction motors are designed to operate within a voltage range of 10 per cent above or below a nominal voltage (3, 69). This allowable operating range is based on the assumption that the voltages applied to the motor are equal. Performance of a three-phase motor operating on unbalanced voltage can be undesirably different from that given by motor manufacturers (33, 34). For this reason, some manufacturers often have refused to guarantee three-phase motors operated on single-phase power through a phase converter.

Test Outline

In this study, the effects were investigated of input line voltage variation on the performance of a 5-hp, three-phase, T-frame, 230-volts, NEMA design B motor. The motor was operated on a three-phase power supply and on autotransformer-capacitor and rotary converters. Input voltage was varied over the range of 85 to 115 per cent of the rated voltage of the motor.

The block diagram shown in Figure 45 outlines the tests performed and parameters studied. Motor terminal voltage, line currents, winding temperature, power input, and slip were recorded with load on the motor held constant at rated full-load torque (15 lb.-ft.).

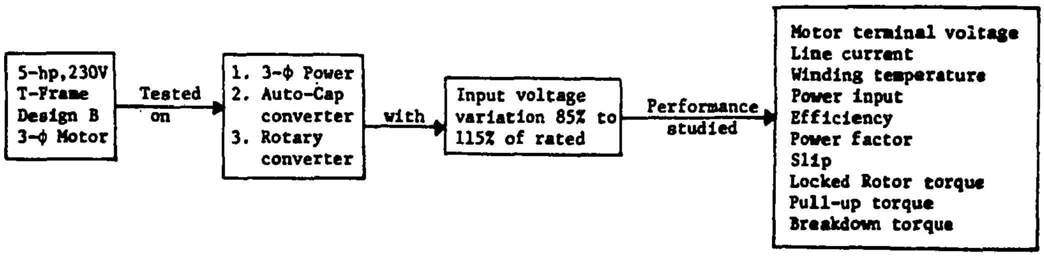


Figure 45. Outline of motor tests and parameters studied.

Three-Phase Power

The motor was operated from a three-phase power line, and line-to-line voltages V_{12}, V_{13}, and V_{23} were kept in balance as the applied voltage was varied. This contrasts with the phase converter tests where the balance of voltages at the motor terminals were dependent on the magnitude of the single-phase input line voltage to the phase converter.

Autotransformer-Capacitor Converter

This converter provides balanced operation of a three-phase motor with proper capacitor size and autotransformer output voltage for a given load. For these tests, the capacitor value and autotransformer voltage were adjusted to give balanced voltages and currents at the motor terminals with the motor operating at full load and rated voltage. A simplified diagram of an autotransformer-capacitor phase converter, and three phase motor combination is shown in Figure 46.

The capacitor size and transformer output voltage were determined by using design Equations 10 and 11 developed by the author and described previously on pages 65 and 66. Equations are repeated below.

$$C = 3063 \left(\frac{I}{V}\right) \sin \phi$$

$$V_{T2} = \frac{1}{2} (V) + \frac{\sqrt{3}}{2} (V) \cot \phi$$

C = capacitor size (microfarads)

I = full-load current of motor (amps)

V = rated voltage (volts)

ϕ = power factor angle (degrees)

V_{T2} = transformer output voltage (volts)

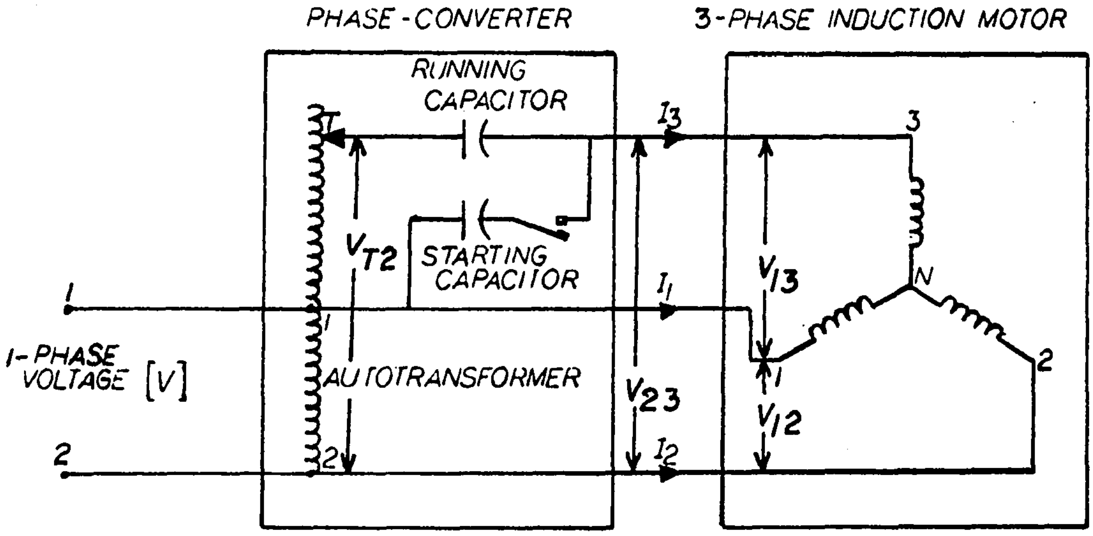


Figure 46. Schematic diagram of an autotransformer-capacitor phase converter and three-phase motor combination.

Rated current of the motor was 14.5 amps, and power factor at full load and rated voltage was 0.78(38° 40'). Values of C and V_{T2} were computed as:

$$C = 3063 \left(\frac{14.5}{230}\right) \text{Sin } (38^{\circ}\ 40')$$

$$= 120.6\ \mu F$$

$$V_{T2} = \frac{1}{2}(230) + \frac{\sqrt{3}}{2}(230)\,\mathrm{Cot}\,(38^{\circ}\,40')$$

$$= 364 \text{ volts}$$

Rotary Phase Converter

A diagram of a rotary phase converter and three-phase motor combination is shown in Figure 47. The rotating transformer base unit was rated at 10.5 KVA, 230 volts and a total motor load of 10.5 hp. The value of capacitance in the capacitor panel was 365 μF.

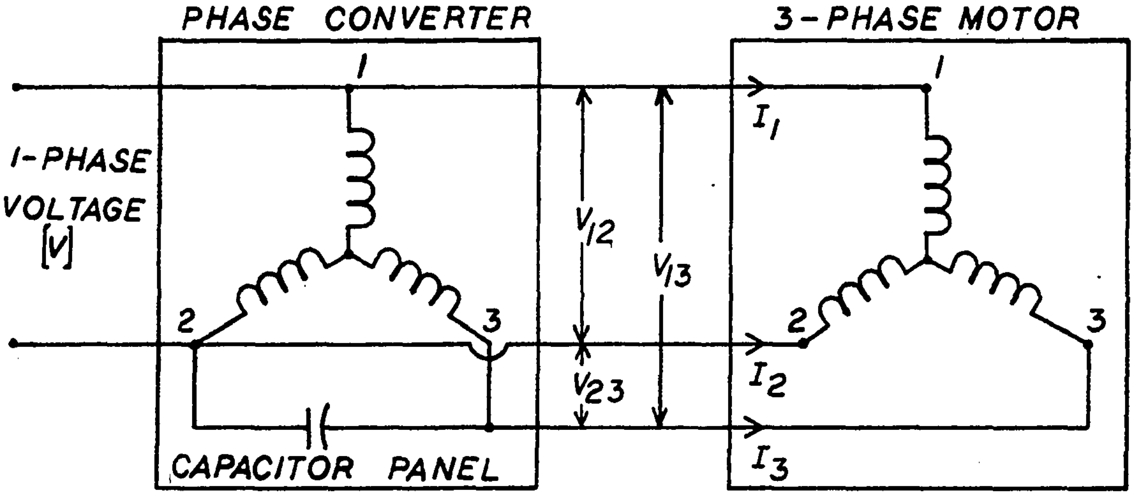


Figure 47. Schematic diagram of a rotary phase converter and three-phase motor combination.

Performance Characteristics

Electrical and mechanical characteristics of the test motor are illustrated in Figures 48 through 59. Comparisons are shown for the motor operating on three-phase power and on single-phase power through phase converters. Phase voltages and currents, motor temperature rise, power input, efficiency, power factor, slip, and locked-rotor, pull-up, and breakdown torques are given for a variation of input line voltage of ± 15 per cent of nominal motor voltage. Experimental data pertaining to these tests is given in Tables 26 through 32 in Appendix C.

Voltages and currents

Motor terminal voltages for the motor operating on an autotransformer-capacitor phase converter are shown in Figure 48. With the calculated values of capacitance, autotransformer output voltage and an input voltage of 230 volts, the line-to-line voltages V_{12}, V_{13}, and V_{23} at the motor terminals were equal. Motor terminal voltages became unbalanced, however, with the variation of input voltage above and below rated motor voltage. The percentage unbalance as computed from the maximum deviation in voltage from the average of the three voltages was 4.5 and 2.5 per cent at an input voltage 10 per cent below and above rated voltage, respectively.

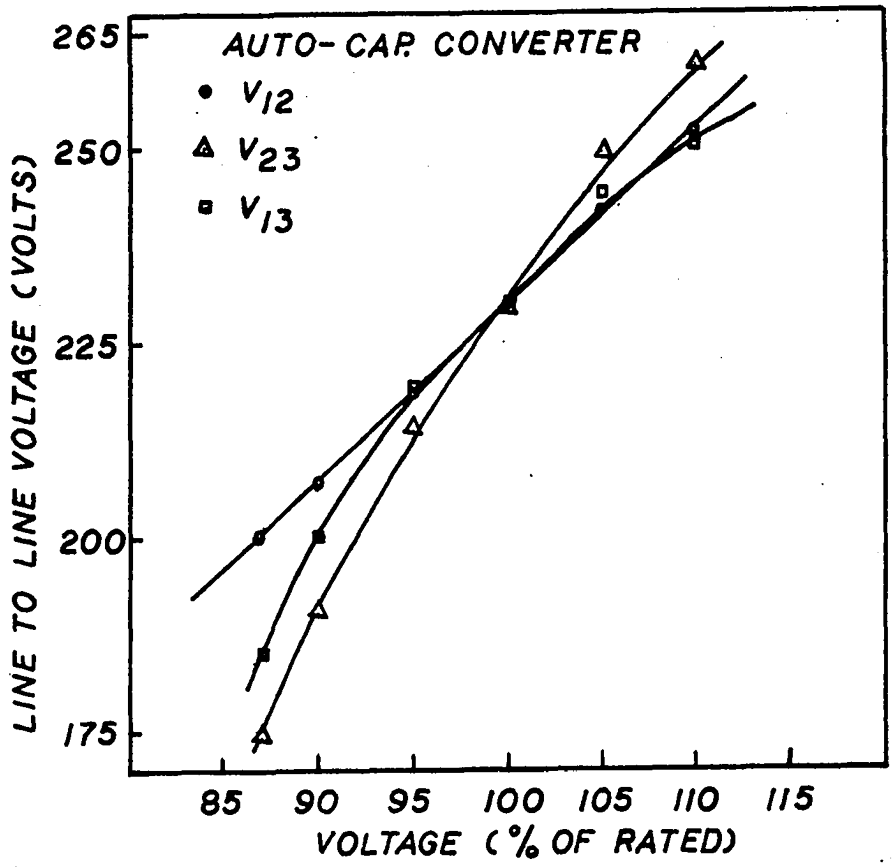


Figure 48. Voltage at terminals of a 5-hp, T-frame, 230 volts, design B test motor vs. single-phase input line voltage to autotransformer-capacitor phase converter.

Figure 49 shows the effect of voltage variation on currents in the motor operated on three-phase power and on the autotransformer-capacitor converter. With the motor on three-phase power, line currents increased with input voltage above or below nominal, but remained approximately balanced. The average of the three line currents shown in Figure 49 was 8 and 10 per cent higher than rated at 85 and 115

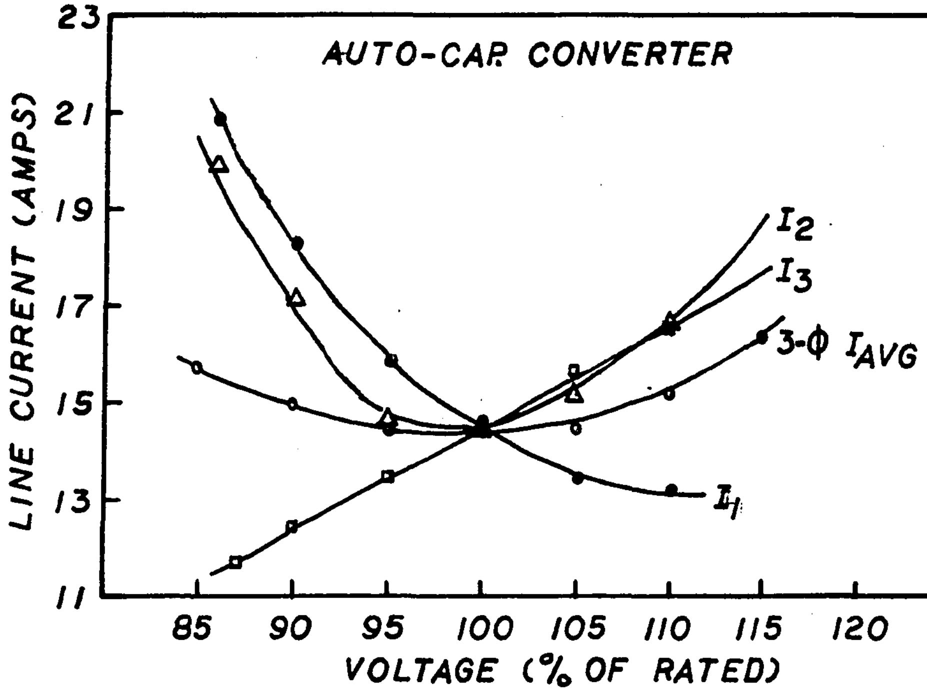


Figure 49. Line current of a 5-hp, T-frame, 230 volts test motor operated on three-phase power and on autotransformer-capacitor converter vs. input line voltage.

per cent of rated voltage, respectively. With the motor operating on the autotransformer-capacitor phase converter, line currents were balanced at nameplate value at rated voltage and became unbalanced as the voltage varied. Currents I_1 and I_2 were about 50 per cent higher, and I_3 was 21 per cent lower, than rated current at 85 per cent voltage. At 110 per cent of rated voltage, I_2 and I_3 were 14 per cent above, and I_1 was 8 per cent below rated voltage.

Terminal voltages of the motor operating on the rotary phase converter are shown in Figure 50. With the rotary

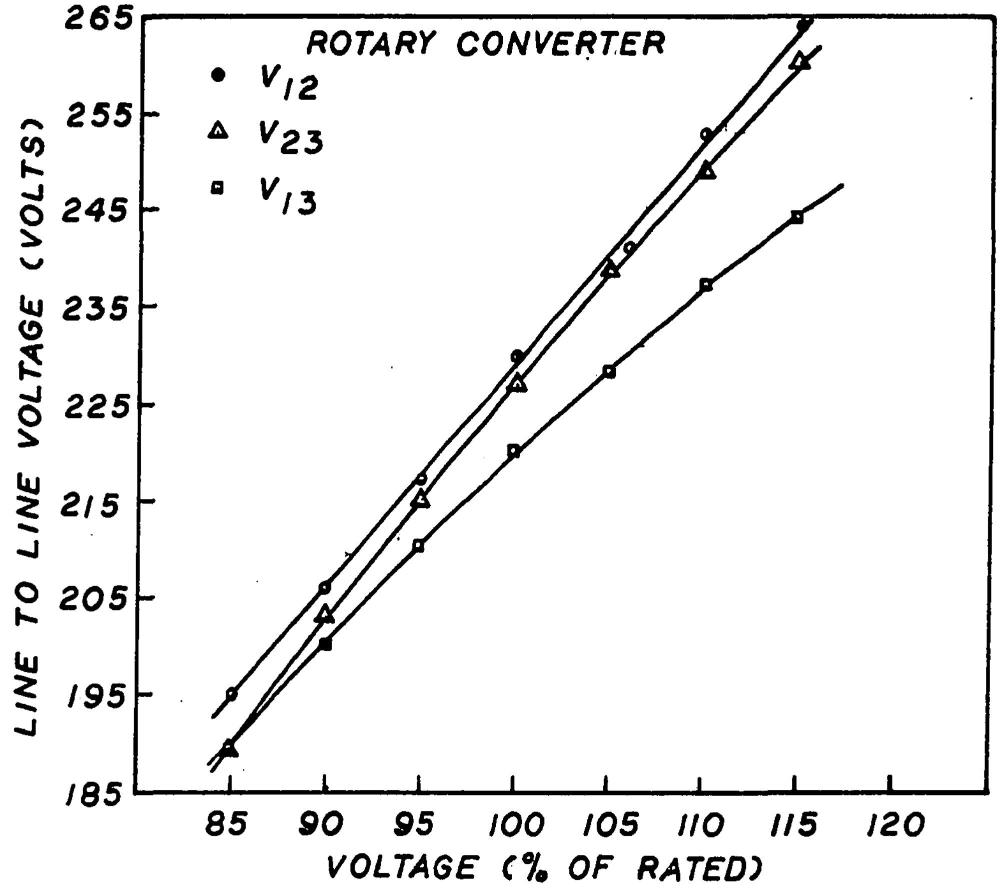


Figure 50. Voltage at terminals of a 5-hp, T-frame, 230 volts, design B test motor vs. single-phase input line voltage to rotary phase converter.

converter, the change in single-phase input line voltage has slightly less effect on terminal voltage as compared with that which occurred with the autotransformer-capacitor converter, but the percentage unbalance was greater at over voltage.

The effects of voltage variation on phase currents for the motor operated on the rotary converter are illustrated in Figure 51. The artificial phase current, I_3, remained

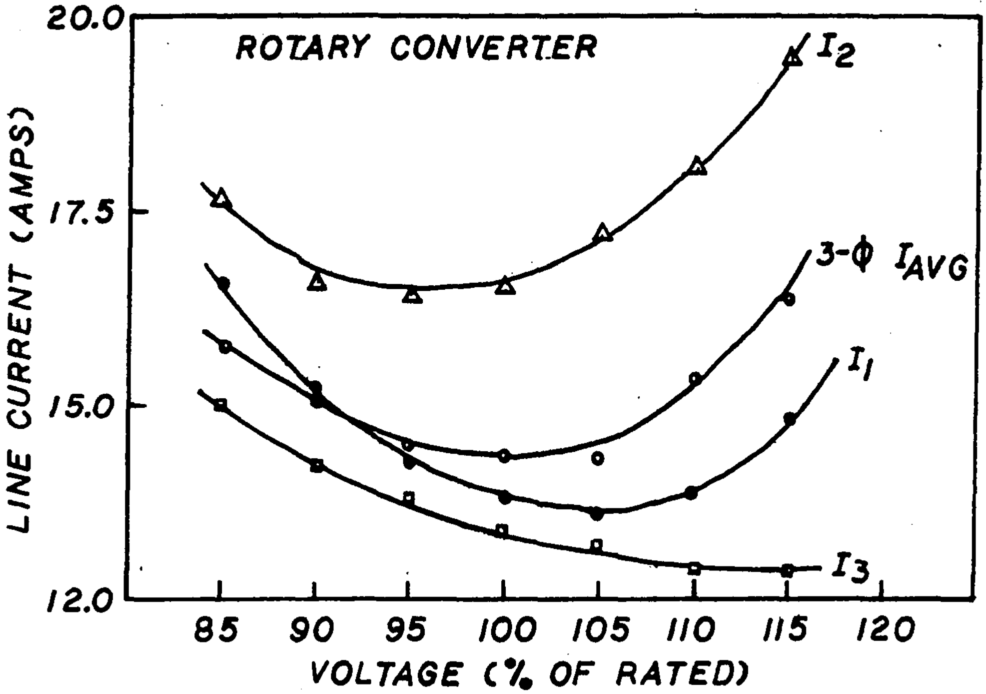


Figure 51. Line current of a 5-hp, T-frame, 230 volts test motor operated on three-phase power and on rotary converter vs. input line voltage.

below, and I_2 above, the three-phase average line current over the entire range of voltage. The percentage unbalance in phase currents was greater at the higher voltages with the rotary converter in contrast to the greater unbalance that occurred with the autotransformer-capacitor converter at voltages lower than rated. The highest current, I_2, was 22 and 35 per cent above the rated value at 85 and 115 per cent of the rated voltage, respectively.

Winding temperature

Because one or more of the motor phase currents increase at under and over voltage, temperature of the motor windings will be higher than at rated voltage. High winding temperature may cause insulation deterioration and reduction of motor life.

Figure 52 shows the highest temperature rise of the motor windings as measured with embedded thermocouples, with the motor operating on three-phase power and on the two types of phase converters. Temperature rise was lowest at rated voltage and increased at under and over voltages. A ± 15 per cent variation of the rated three-phase voltage increased the temperature rise by 15° C (27° F) above the temperature rise of 66° C (119° F) at rated voltage. The highest temperature rise recorded for the motor operating on the autotransformer-capacitor converter was 97° C (175° F) at 90 per cent voltage. With the rotary converter, the highest winding temperatures recorded were 83° C (149° F) and 98° C (176° F) at an input line voltage of 110 and 115 per cent, respectively.

Class B insulation used in NEMA T-frame motors is rated for a total allowable temperature of 130° C (266° F). The allowable temperature rise is 90° C (162° F) on the basis of a 40° C (104° F) ambient temperature. As illustrated in Figure 61, input voltage to the autotransformer-capacitor

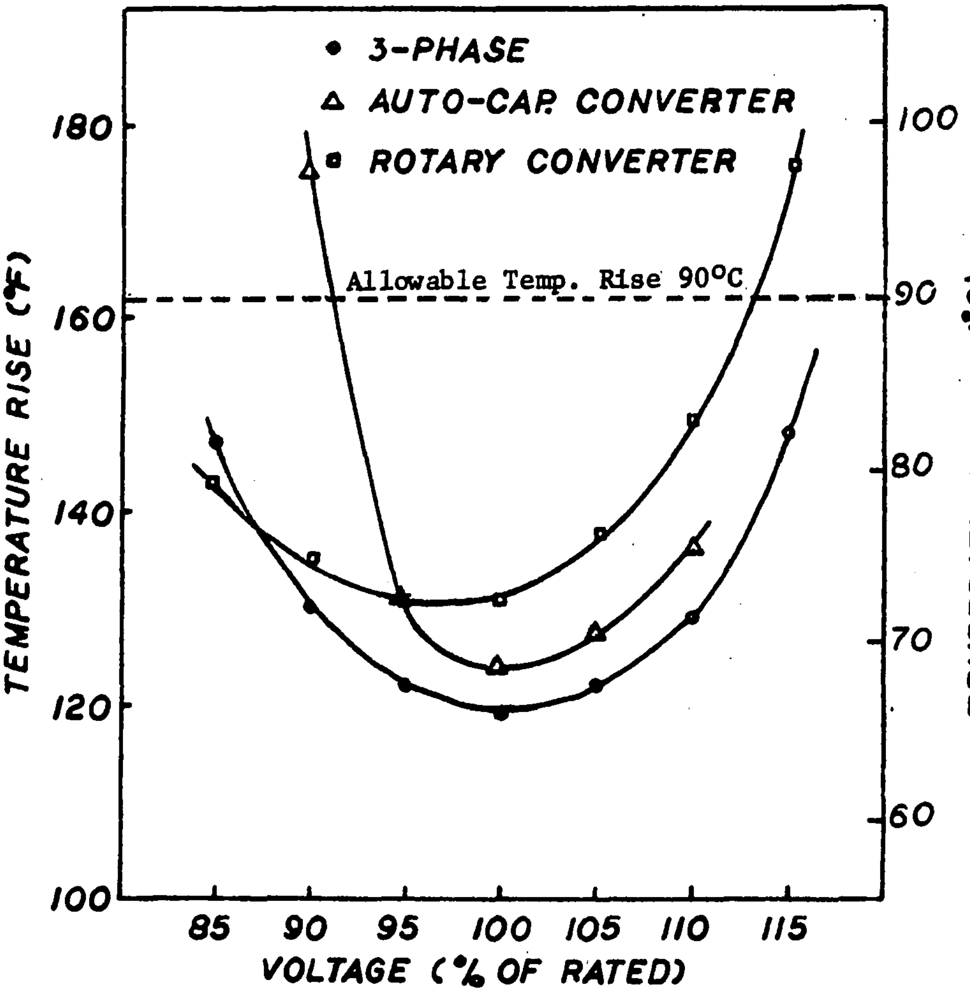


Figure 52. Temperature rise of a 5-hp T-frame, 230 volts, design B motor vs. input line voltage.

converter below 90 per cent of rated and input voltage to the rotary converter above 115 per cent of rated may cause excessive temperature rise and thus insulation damage, particularly with ambient temperatures of 40° C (104° F) or higher.

Power input and efficiency

Power input to the test motor and efficiency of the motor on three-phase power and on the two types of phase converters are shown in Figures 53 and 54, respectively. For the entire range of line voltage, the power input was highest for the rotary converter and lowest for the three-phase line power operation. Power input to the motor on three-phase line power was almost constant up to 105 per cent of rated voltage and increased slightly at higher voltages. Power input to the autotransformer-capacitor converter operating the test motor was lowest at rated voltage and slightly higher at voltages of 85 and 110 per cent of rated. With the rotary phase converter, power input was approximately constant from 85 to 100 per cent of rated voltage, but increased by 18 per cent at 115 per cent of rated voltage.

Efficiency of the motor operating on three-phase line power was nearly constant up to 105 per cent of rated voltage and decreased slightly at higher voltage. For the motor operating on phase converters, the curves represent the combined efficiency of the phase converter and motor. With ± 10 per cent variation in input voltage, efficiency of the autotransformer-capacitor converter and motor combination dropped by only 3 per cent from a nominal value of 78 per cent. Efficiency of the rotary phase converter and motor

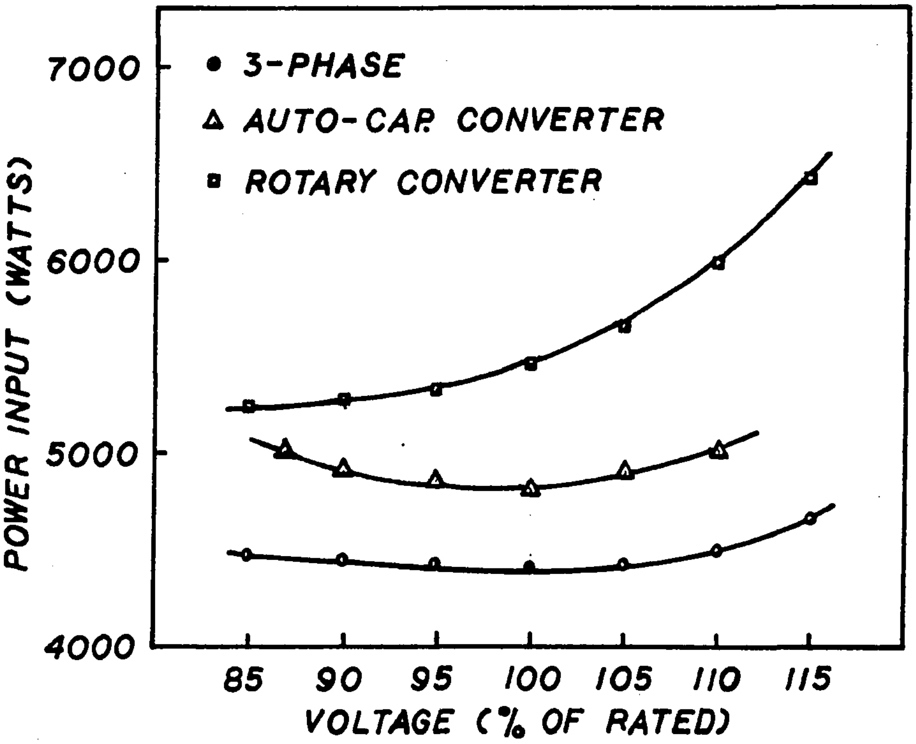


Figure 53. Power input of a 5 hp T-frame, 230 volts, design B motor vs. input line voltage.

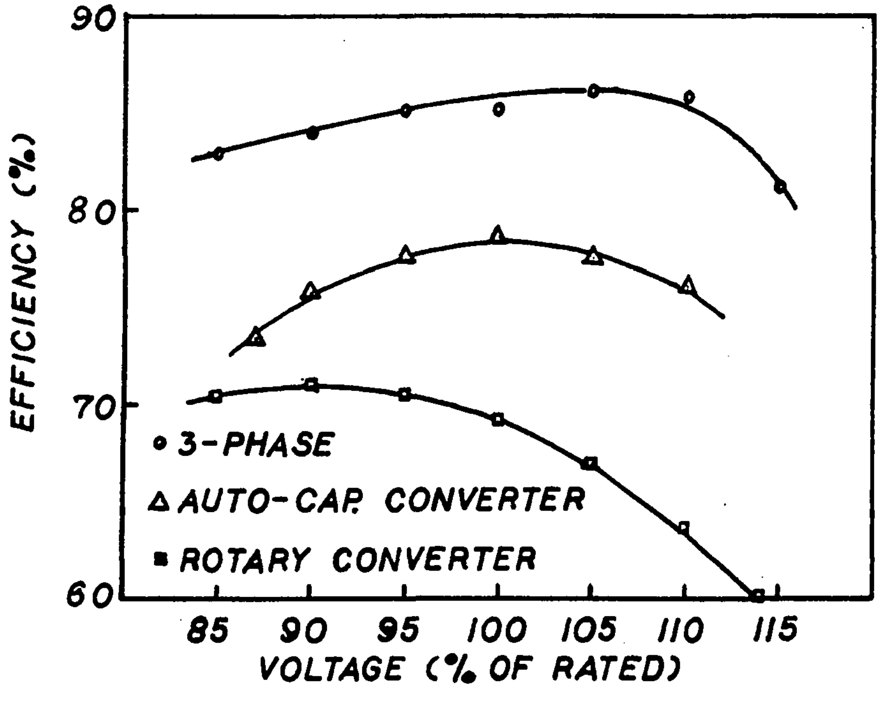


Figure 54. Efficiency of a 5 hp T-frame, 230 volts, design B motor vs. input line voltage.

combination was approximately 70 per cent from 85 to 95 per cent of rated voltage, but dropped sharply to a value of 59 per cent at 115 per cent of rated voltage.

Power factor

Power factor of the test motor operating on three-phase line power and phase converters is shown in Figure 55. On three-phase line power, power factor increased slightly with decreasing voltage (0.8 at 100% and 0.82 at 90%) and decreased rapidly with voltage above rated (0.69 at 110%). With the autotransformer-capacitor converter, power factor of the system was 0.9 at rated voltage and increased to approximately 1.0 at 90 and 110 per cent of rated voltage. Power factor of the system with the motor operating on the rotary converter was lower than that with three-phase and decreased linearly as input line voltage was increased (0.70 at 90 per cent and 0.48 at 100 per cent).

Slip

Figure 56 shows slip of the test motor in relation to input line voltage. At rated voltage, slip was approximately 3 per cent for operation on three-phase power and on both phase converters. At 90 per cent of rated voltage, slip increased to approximatley 4 per cent and was greater with both phase converters than with three-phase power. At 110 per cent of rated voltage, slip decreased to approximately 2.5 per cent. At the higher voltage, slip was

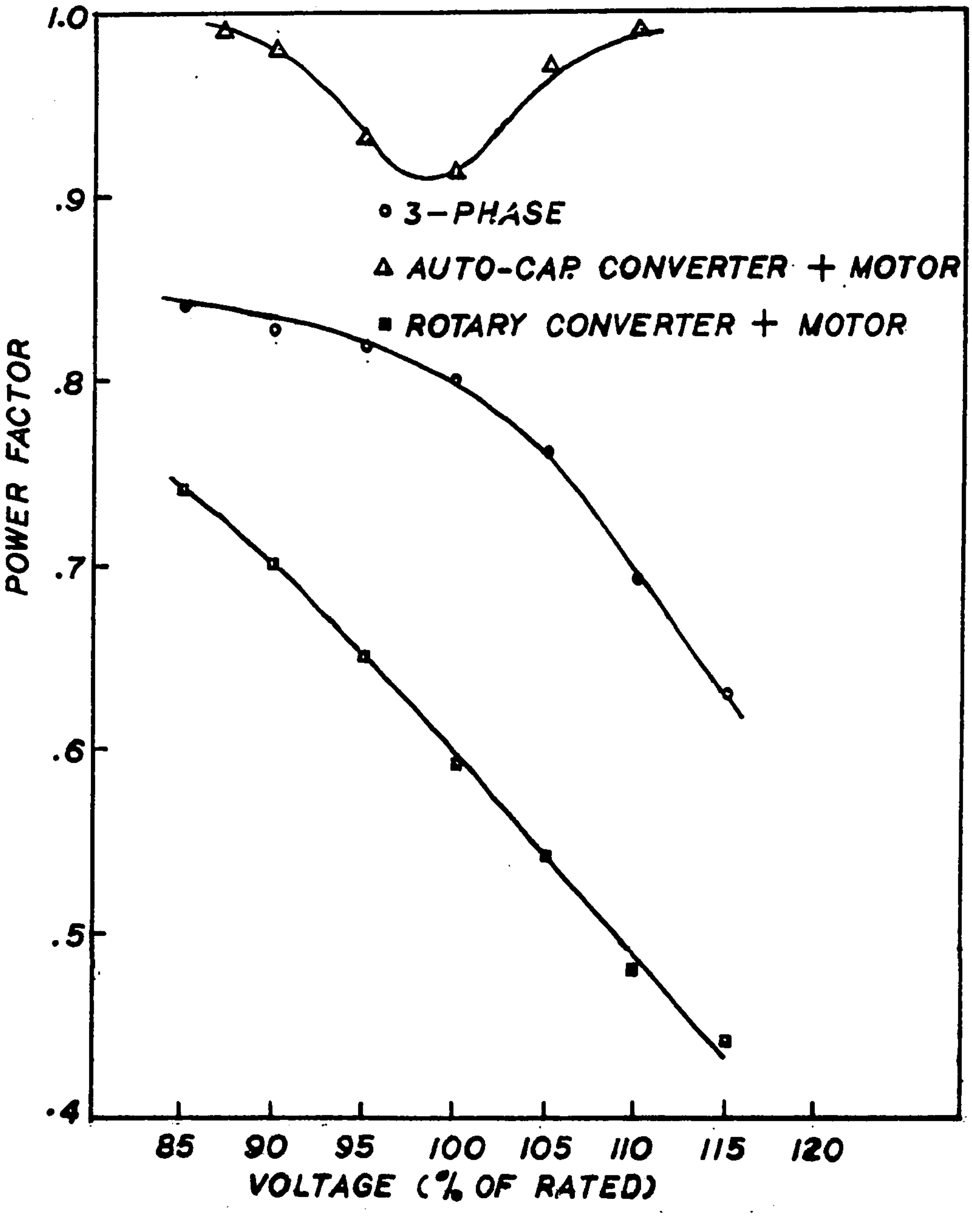


Figure 55. Power factor of a 5-hp, 230 volts, T-frame, design B motor vs. input line voltage.

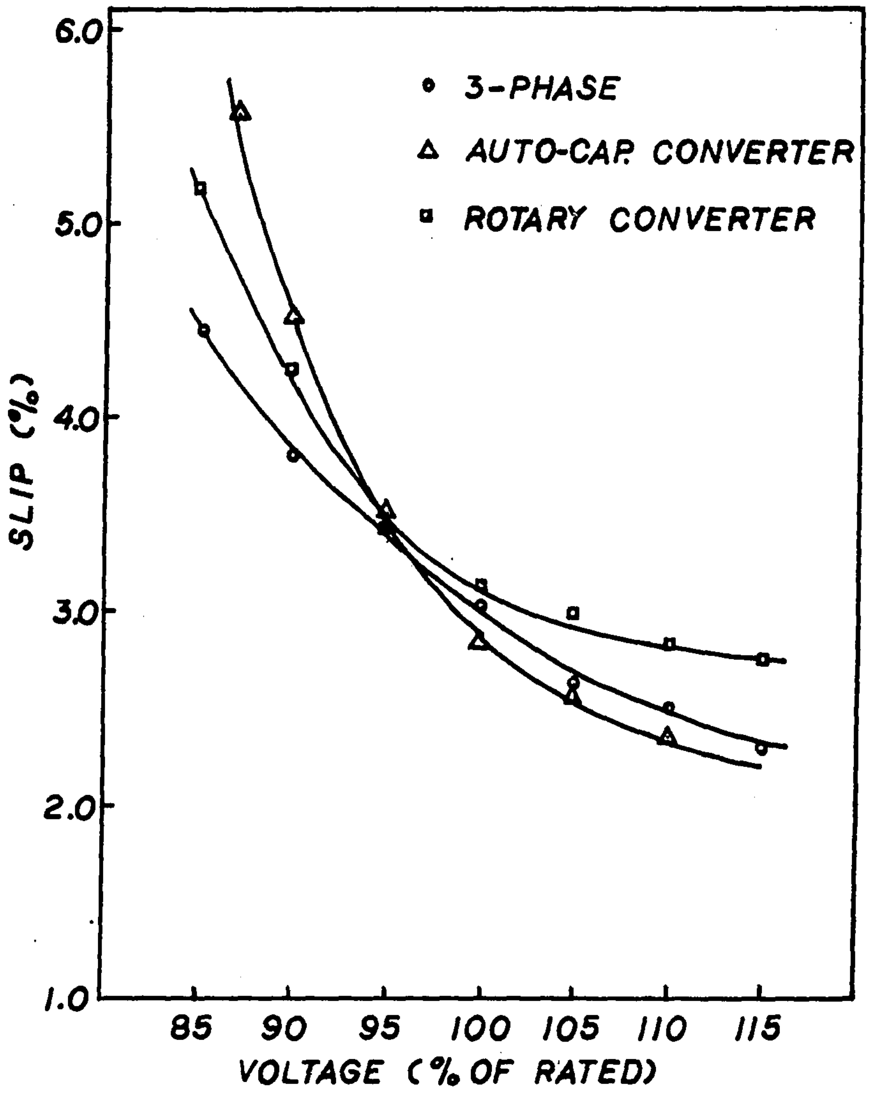


Figure 56. Slip of a 5-hp, 230 volts, T-frame, design B test motor vs. input line voltage.

greatest with the rotary converter and lowest with the autotransformer-capacitor converter.

Torque

When a motor is started on other than normal voltage, the locked-rotor, pull-up, and breakdown torques must be considered carefully. An approximation is frequently made that torque varies as the square of the applied voltage (7). According to standards on motors (33, 72), this assumption does not apply when the motor terminal voltages are other than balanced.

Data on locked-rotor, pull-up, and breakdown torques of the test motor operating on three-phase line power and phase converters are graphed in Figures 57, 58, and 59. With three-phase line power, torques were consistently higher than those with phase converters. Locked-rotor and pull-up torques of the motor operated on the autotransformer-capacitor converter were higher than on the rotary converter. However, breakdown torque was higher with the motor operating on the rotary converter than on the autotransformer-capacitor converter.

Locked-rotor, pull-up, and breakdown torques of the motor operating on three-phase line power and on phase converters, over the input voltage range of 85 to 115 per cent of rated are summarized in Table 9. Torque values are given as a percentage of rated full-load torque of the test motor. Breakdown torque of the motor operating on the autotransformer-capacitor phase converter is the maximum torque on that portion of the torque-speed curve with the starting capacitor switched out of the circuit.

Although locked-rotor and pull-up torques of the motor with phase converters are lower than those obtained on

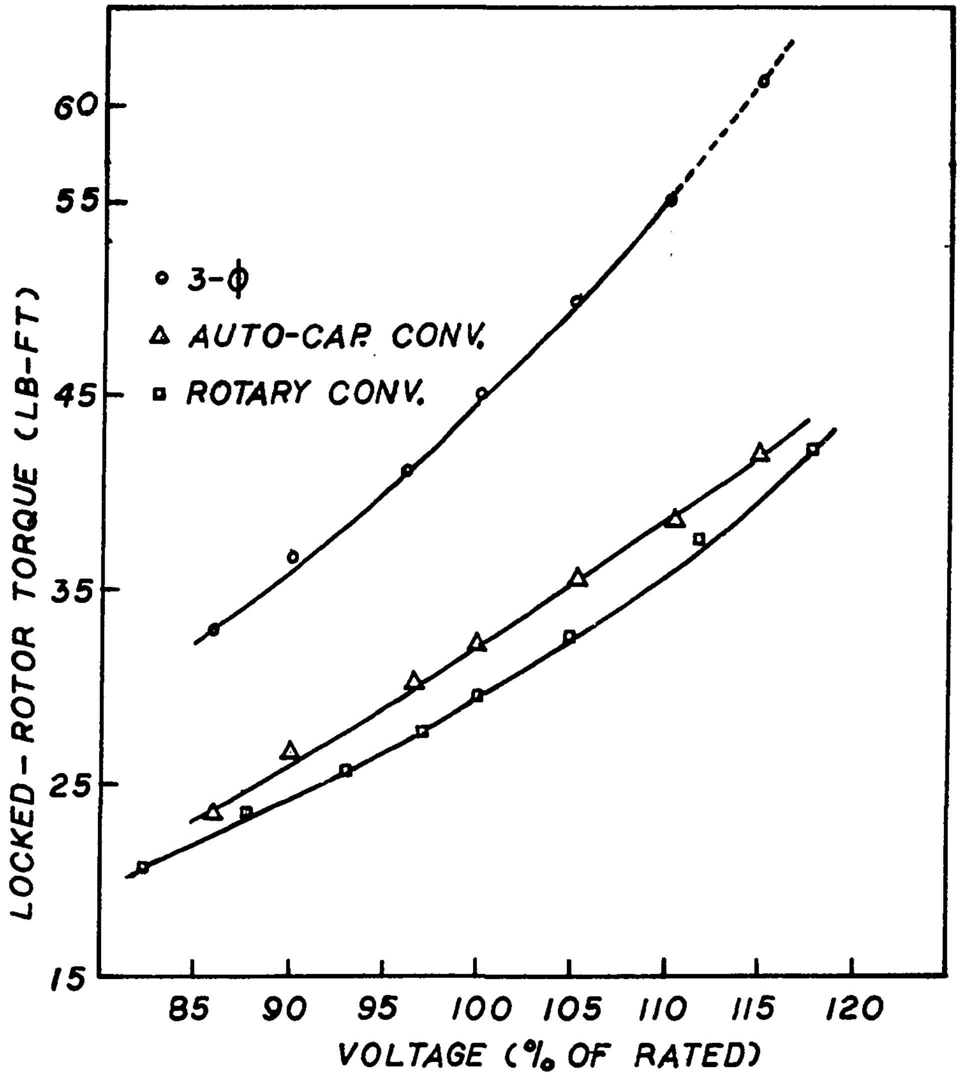


Figure 57. Locked-rotor torque of a 5-hp, T-frame, 230 volts test motor vs. input line voltage.

three-phase line power, they may be sufficient to start a majority of farm loads. Load torque at operating speed, in most applications, is much lower than the breakdown torque. The lower values of breakdown torque with phase converters may not be a serious problem as long as the reduction in

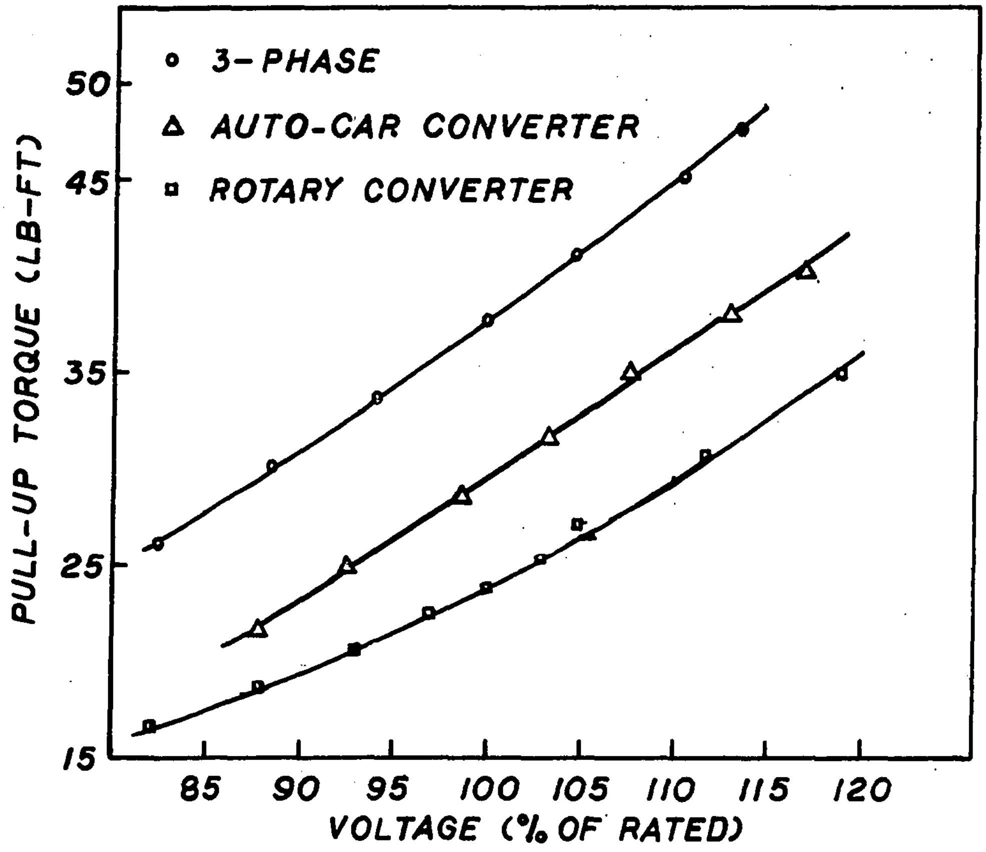


Figure 58. Pull-up torque of a 5-hp, T-frame, 230 volts, design B test motor vs. input line voltage.

torque is minimized by holding the input line voltage close to the rated value.

To show the effect of voltage variation, dynamic torque-speed curves of the motor, operated on three-phase line power and both types of phase converters, were plotted. Figures 86, 87, and 88 in Appendix C are torque-speed curves for a 5-hp, design B, 230 volts, brand 1, three-phase motor.

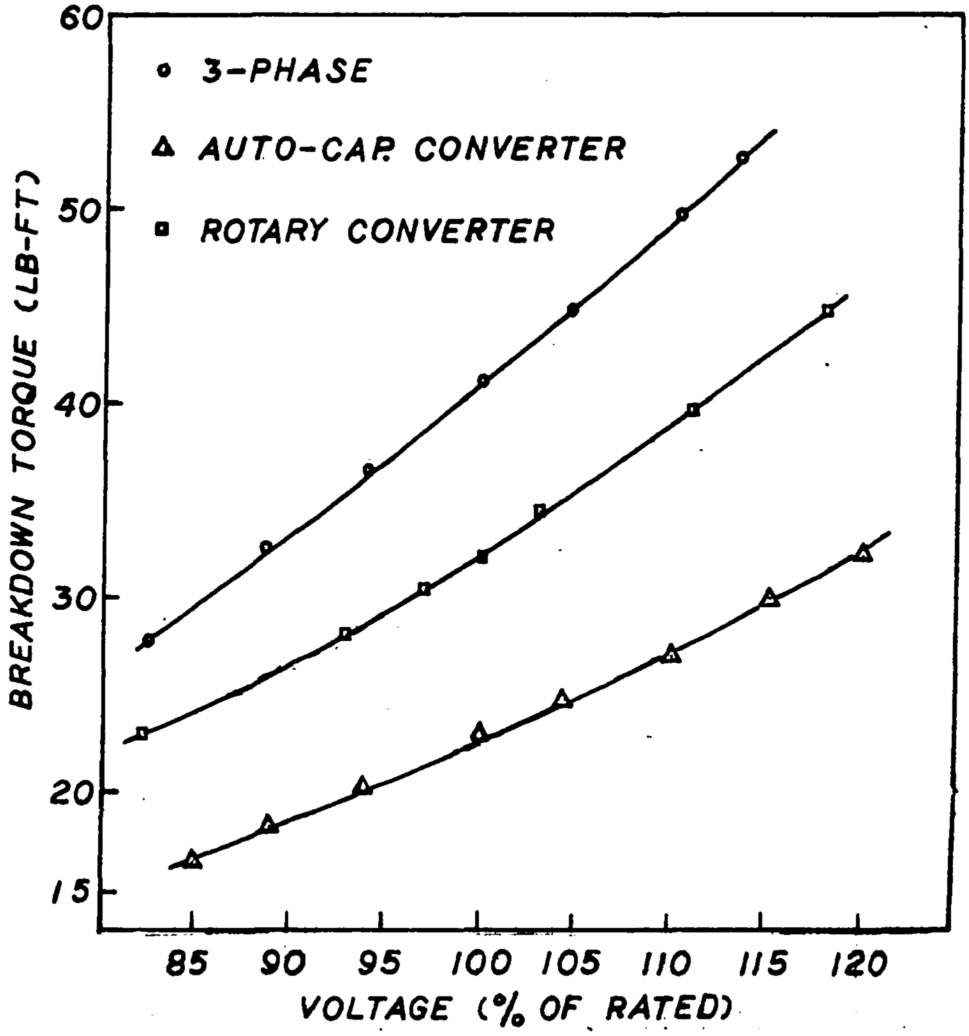


Figure 59. Breakdown torque of a 5-hp, T-frame, 230 volts, design B test motor vs. input line voltage.

Table 9. 5-hp, T-frame, design B, 230 volt motor torque characteristics with variations in input line voltage.

Input line voltage % of rated	Locked-rotor torque[a]			Pull-up torque			Breakdown torque		
	3-ϕ power	Auto-cap. conv.	Rotary conv.	3-ϕ power	Auto-cap. conv.	Rotary conv.	3-ϕ power	Auto-cap. conv.	Rotary conv.
85	213	153	147	185	133	117	197	110	160
90	240	173	160	206	153	128	220	123	177
100	300	213	197	253	200	160	273	153	213
110	367	257	237	300	240	197	330	180	260
115	406	280	263	327	261	217	360	200	283

[a] All torque values are given as a percentage of rated full-load torque.

EFFECTS OF UNBALANCED VOLTAGE ON MOTOR PERFORMANCE

When three-phase motors are operated from a single-phase power line through phase converters, the voltage at the motor terminals are not always balanced. The effects of unbalanced voltage on the performance of three-phase induction motors have been disucssed in various technical reports (8, 54, 63, 65, 84, 110). Most of these reports deal with the unbalance conditions of voltage on three-phase line power. They do not include the voltage unbalance that is typical of the three-phase voltage output of phase converters. Because of this difference a study was made of the effects of unbalanced voltage on the performance of a three-phase motor operating on a phase converter.

Unbalance in the voltage output of a phase converter is caused mainly by two conditions, the load on the motor-converter combination is above or below the motor rating and the single-phase voltage input to the phase converter is different than the rated voltage. In both conditions the nature of unbalance, usually, is such that the two voltages V_{13} and V_{23} are either higher than V_{12} or both are lower than V_{12}. This is shown in Figures 35, 37, 39, 48, and 50 and also verified by Knight et al. (57).

Unbalance with Three-Phase Power

To study the effects of unbalanced voltage on the three line currents and winding temperature, the test motors were operated at various percentages of unbalance in motor terminal voltages. The voltage unbalance similar to that which occurred with the motors operating from phase converters, was simulated from the three-phase line power supply. The voltage V_{12} was held constant and the magnitude of the two voltages V_{13} and V_{23} were maintained at various values above and below V_{12}. The circuit used to obtain the various values of V_{13} and V_{23} is shown in Figure 15.

A 10 hp U-frame and a 10 hp T-frame motor were tested at 80 and 100 per cent of the rated load, with voltage unbalance up to a maximum of 6 per cent. The unbalances in voltage and current were computed according to the following definition given in the application data section MG1-14.33 of NEMA Standards (72).

$$\begin{array}{l}\text{Per cent}\\ \text{voltage}\\ \text{unbalance}\end{array} = 100 \times \frac{\text{Maximum deviation from avg. voltage}}{\text{avg. voltage}} \qquad (25)$$

For example, if three line to line voltages are 220, 241, and 232, the average voltage is 231, the maximum deviation from the average is (231-220) = 11 volts, and the percentage unbalance is (11/231) x 100 = 4.76.

Current unbalance

Figure 60 shows the percentage unbalance in three line currents of the two test motors with respect to the percentage unbalance in voltages. The zero on the X-axis represents perfect balance. The curves to right of zero are for voltages V_{13} and V_{23} exceeding the single-phase voltage, V_{12}, and the curves on the left of the zero are for V_{13} and V_{23} less than V_{12}. The experimental data and computed unbalance in voltages and currents of 10 hp U and T-frame motors, corresponding to Figure 60 are given in Tables 33 through 37 in Appendix C.

As shown in Figure 60, the current unbalance was slightly higher at 80 and 100% load for U-frame motors than for T-frame motors. This was found to be true for the voltage unbalance, range shown in Figure 60. For both motors, the unbalance in line currents was about 5 to 7 times greater than voltage unbalance. For example at 3% voltage unbalance, the unbalance in currents varied from 17% to 21%.

For the two test motors, under both conditions of voltage unbalance, i.e. V_{13} and V_{23} above and below V_{12}, the current unbalance was higher at 80% than at 100% of the rated load for the same percentage of unbalance in voltage. This is because of the greater spread and lower average value of currents at lighter load.

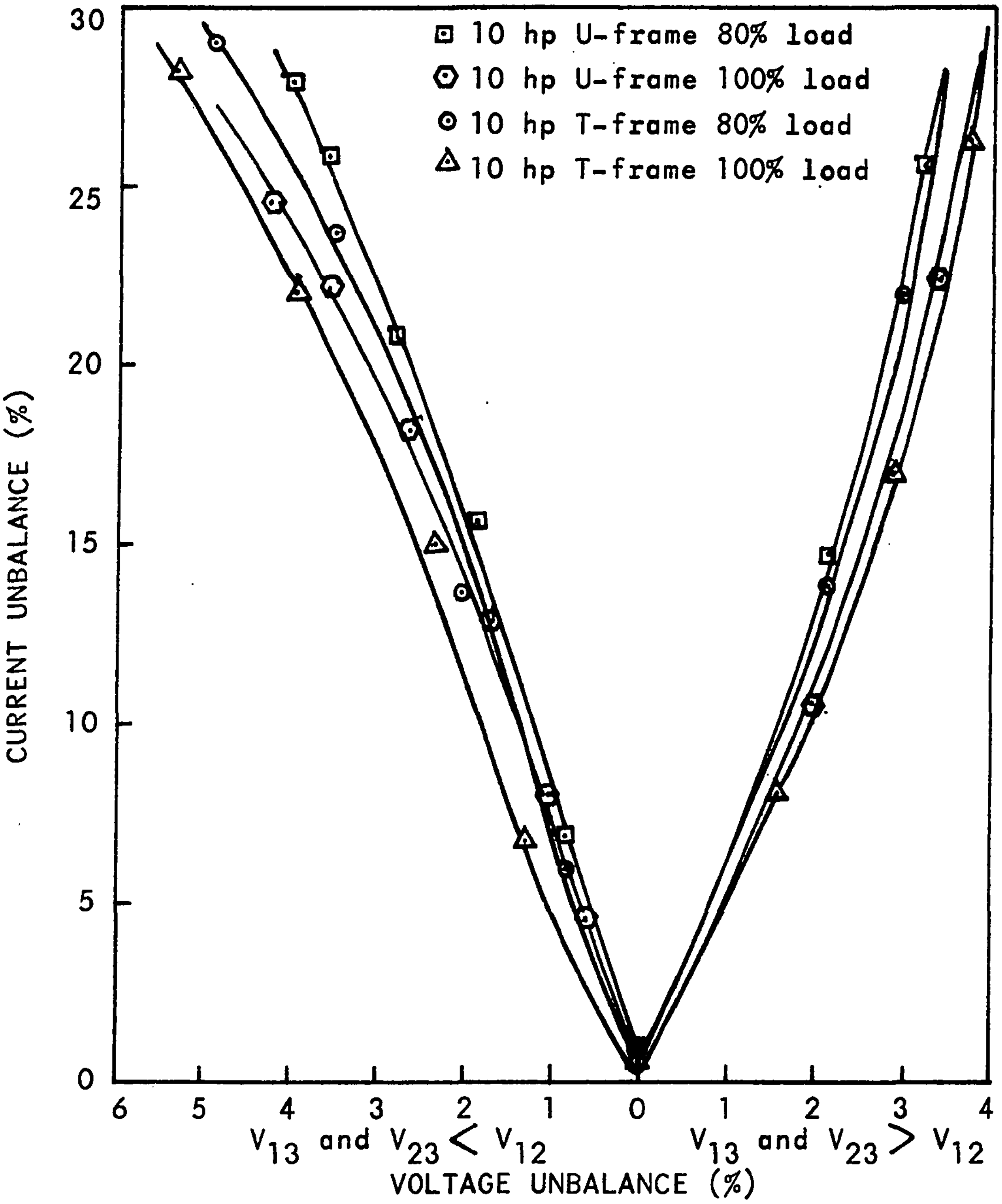


Figure 60. Voltage unbalance vs. current unbalance of 10 hp U-frame, 220 volts and T-frame, 230 volts test motors operated on three-phase power supply.

Winding temperature

Figure 61 shows the temperature rise in the windings of motors at 80 and 100% of the rated load for various percentage unbalance in voltages. The temperature rise was a minimum with the motor operated with balanced voltages and increased with the increase in voltage unbalance. An unbalance in line voltages produced circulating currents in the motor winding and thus higher copper losses, I^2R, in the stator and rotor. Unbalanced voltage can also cause nonuniform distribution of stator I^2R losses. William (110) found in an experiment with a 10 hp three-phase motor that a 11% unbalance in voltage caused 59% of the total stator copper losses to occur in one phase of the motor.

The U-frame and T-frame motors used in the study had class A and class B insulation, respectively. The insulation temperature and life differences between the two motors are explained in Figure 62. Insulation life of a motor is reduced to half when operated continuously at 10°C higher temperature. The T-frame motor had a higher temperature rating per frame size than the U-frame motor. A given change in load caused a greater change in temperature rise for the higher temperature T-frame, class B motor. This effect is shown in Figure 61. For the same unbalance in voltage, the increment in temperature rise in the T-frame motor windings with increase in load from 80 to 100% of the rated, was twice the value in the U-frame motor.

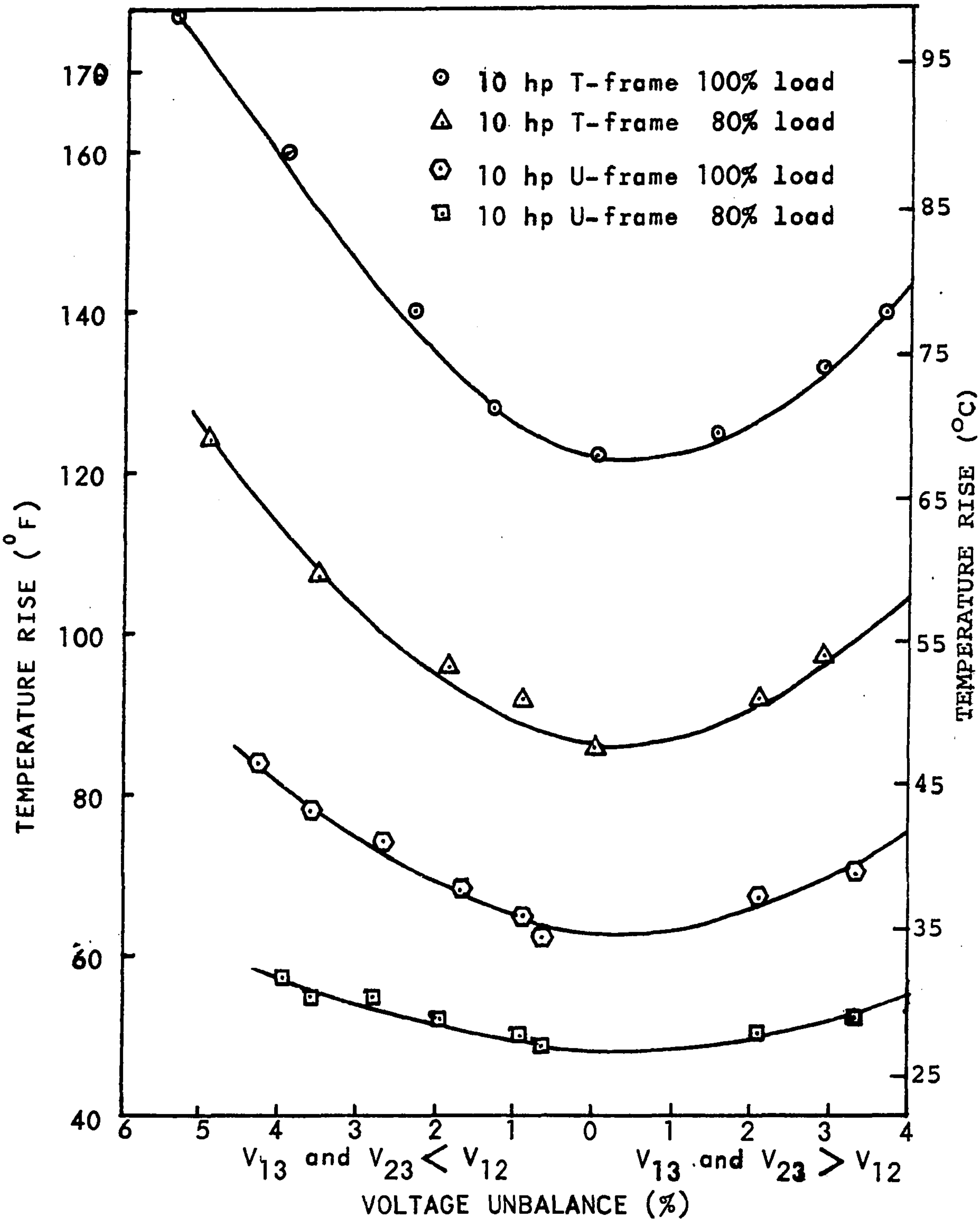


Figure 61. Temperature rise vs. voltage unbalance of two test motors operated on three-phase line power.

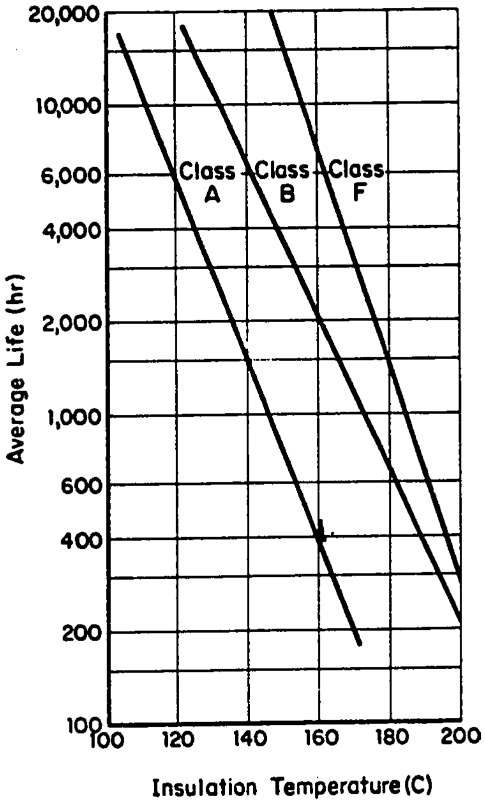


Figure 62. Typical motor winding life vs. temperature for commonly used classes of insulation.

Unbalance with Phase Converter

Current unbalance and temperature rise

Figures 63 and 64 show the effects of voltage unbalance on the unbalance in line currents and temperature rise of a three-phase motor operated from an autotransformer-capacitor phase converter and rotary phase converter, respectively. The experimental data corresponding to these figures are given in Tables 10 and 11.

As shown in Figure 63, the curves for the current unbalance and temperature rise of a 10 hp, U-frame 220 volt motor operated from an autotransformer-capacitor phase converter are very similar to those obtained with the motor operated from three-phase line power, Figure 60. With the capacitor size and transformer output voltage adjusted for 100% motor load, the three-phase voltage output is very nearly balanced with the motor loaded to its rated horsepower. An overload on the motor causes unbalance due to voltage V_{13} and V_{23} being less than the single-phase voltage, V_{12}. A lighter load increases V_{13} and V_{23} above the value of V_{12} and thus results in an unbalance in three-phase voltages.

The type of unbalance due to overload on the motor, i.e. V_{13} and V_{23} less than V_{12}, had a more severe effect on winding temperature than the unbalance due to lighter load on the motor. This is because of the higher line currents drawn by the motor to produce the rated horsepower with voltages V_{13} and V_{23} lower than nominal. The maximum temperature rise recorded was 90^{o}F which is less than the allowable rise 126^{o}F for class A insulation. Though, the maximum current unbalance was recorded with a lighter load on the motor, the motor ran cooler because of lower than rated line currents.

The current unbalance of the 10 hp, T-frame 230 volts motor operated from a rotary phase converter varied from

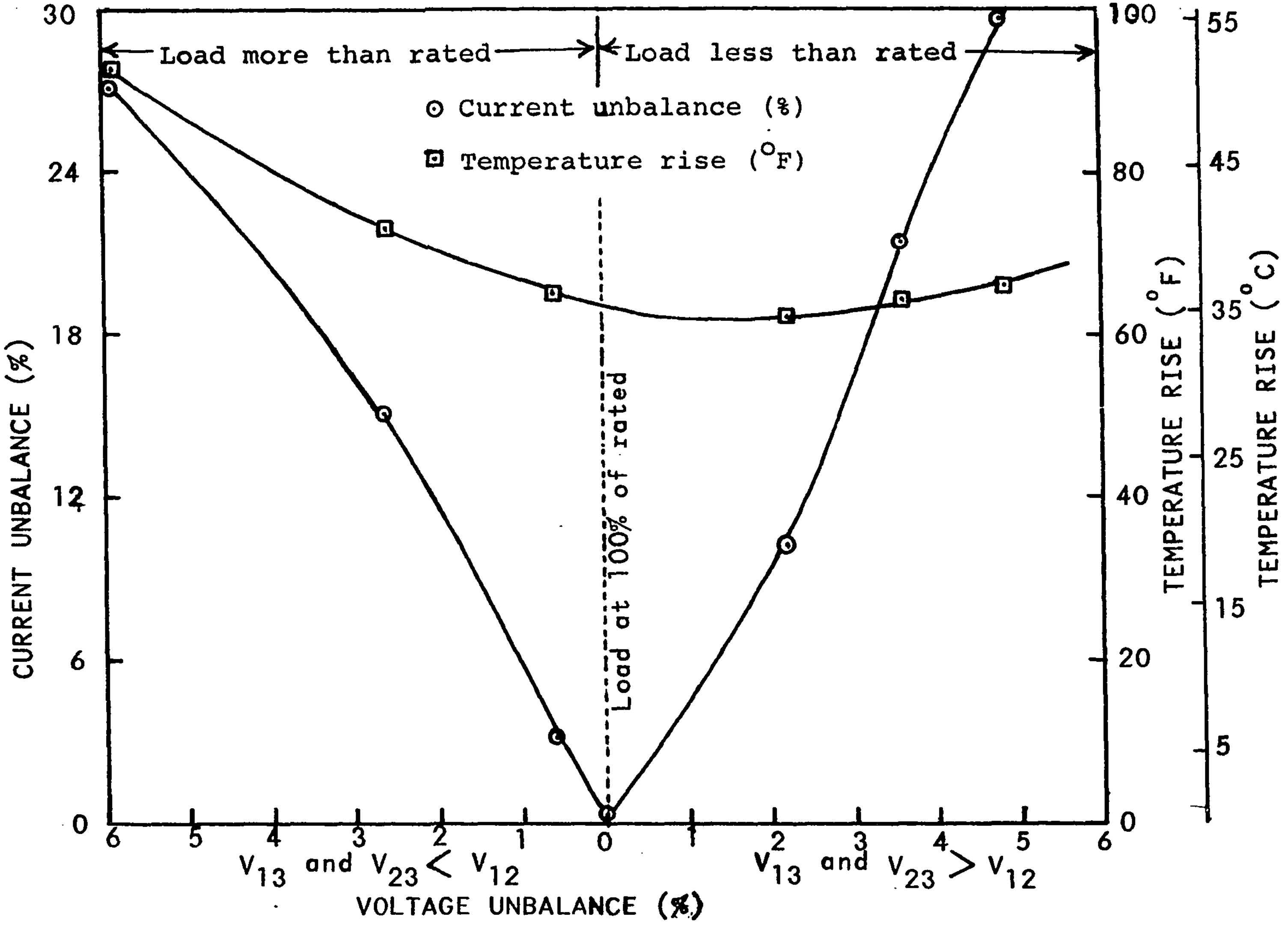


Figure 63. Voltage unbalance vs. current unbalance and temperature rise of a 10 hp, U-frame motor with an autotransformer-capacitor converter adjusted for balanced operation at 100% load.

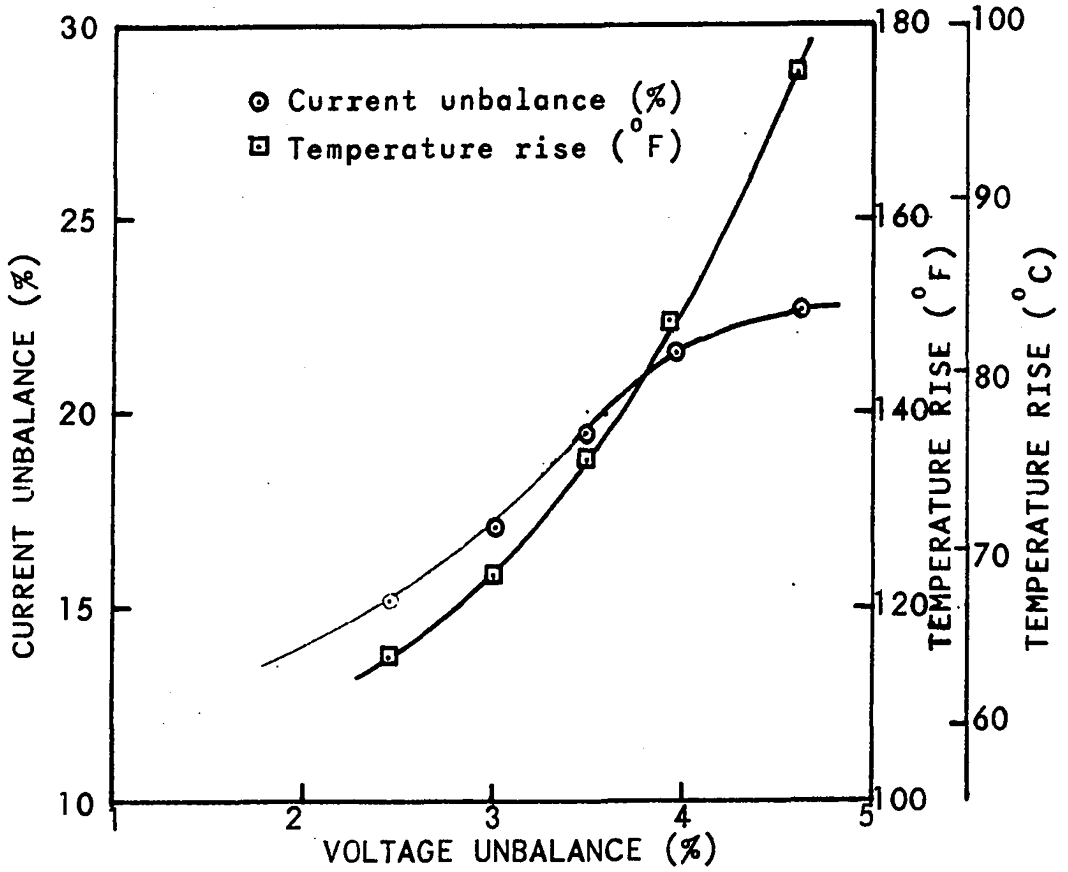


Figure 64. Current unbalance and temperature rise vs. voltage unbalance of a 10 hp T-frame 230 volts motor with a rotary phase converter.

13% to 23%. Because of the design of the newer T-frame motor, the unbalance in voltage due to overload on the motor increased the winding temperature rapidly. The maximum temperature rise of 175°F recorded at 4.5% voltage unbalance exceeded the allowable rise, 162°F, for class B insulation.

Experimental data showed that voltage unbalance in the three-phase output of phase converters caused by an overload

Table 10. Voltage and current unbalance and temperature rise of a 10 hp, U-frame motor operated from an auto-transformer-capacitor phase converter adjusted for balanced operation at 100% load.

Load % of rated	V_{12}	V_{23}	V_{13}	Voltage unbalance %	I_1	I_2	I_3	Current unbalance %	Temp. rise (°F)	(°C)
70	220	241	232	4.8	18.2	18.6	28.0	29.6	66	36.4
80	220	235	230	3.6	21.0	19.6	27.6	21.4	64	35.5
90	220	228	226	2.1	24.8	22.0	26.8	10.2	62	34.4
100	220	220	222	0.6	27.6	26.0	26.4	3.5	65	36.1
110	220	211	219	2.6	33.8	31.2	25.8	14.9	73	40.5
120	220	158	213	5.9	40.0	38.0	25.0	27.1	92	51.1

Table 11. Voltage and current unbalance and temperature rise of a 10 hp, T-frame, design B motor operated from a rotary phase converter.

Load % of rated	V_{12}	V_{23}	V_{13}	Voltage unbalance %	I_1	I_2	I_3	Current unbalance %	Temp. rise (°F)	(°C)
70	230	223	220	2.53	18.4	22.0	16.4	16.0	115	63.9
80	229	220	218	3.00	22.4	25.0	18.0	17.0	123	68.3
90	228	216	217	3.48	24.8	27.6	19.2	19.5	135	75.0
100	227	213	215	3.97	28.4	31.2	21.2	21.3	148	82.2
110	227	210	214	4.61	32.0	34.0	23.2	22.0	175	97.2

on the motor or because of lower single-phase input voltage may be detrimental to the motor life. The voltage unbalance caused by a load less than the full load and single-phase voltage higher than rated has less serious temperature rise and in many cases may be acceptable.

PERFORMANCE CHARACTERISTICS OF MOTORS OPERATING FROM OPEN-WYE TYPE PHASE CONVERTER

Open-wye type phase converters are usually recommended for use with single-speed, dual voltage wye connected three-phase motors. As illustrated in Figure 65, it is necessary to bring out three additional leads, 10, 11, and 12, on the motor for proper connection of the open-wye type phase conversion system. The phase shifting capacitor, C, is connected in series with phase c of the motor.

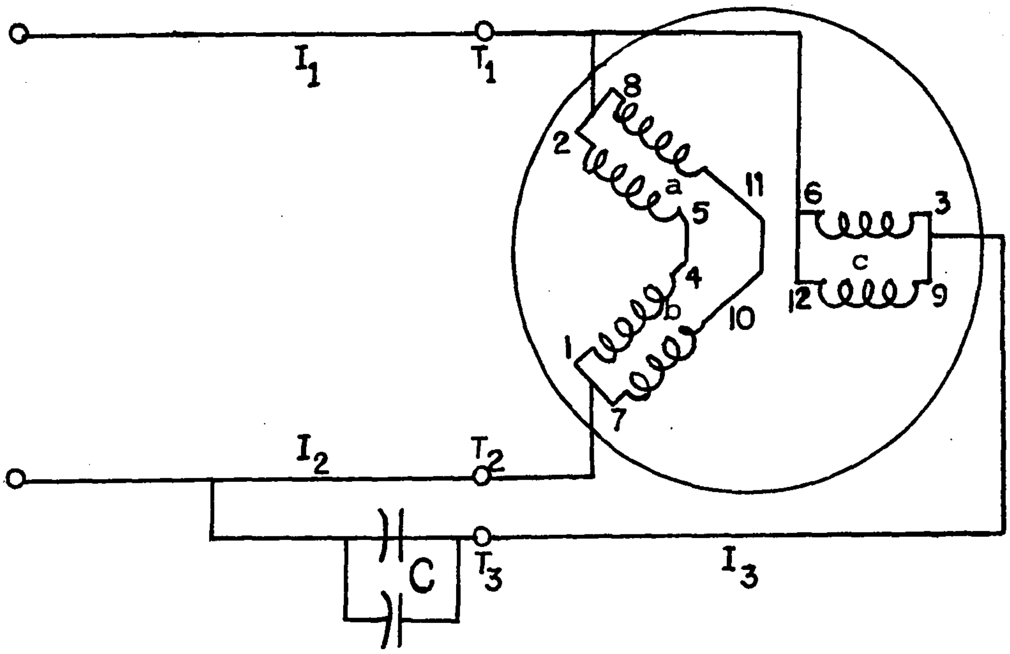


Figure 65. Modified winding connection of a three-phase motor connected to an open-wye type phase converter.

The purpose of this part of the study was to determine the size of capacitance C that would allow a three-phase motor to be loaded up to its rated horsepower when operated from a single-phase power supply. A 10-hp, 230 volts, T-frame and a 10-hp, 220 volts, U-frame motor were operated from an open-wye type phase converter. Both motors were tested with two different values of capacitance, 280 and 420 microfarads.

Figures 66 and 67 show line currents and line to line voltages of a 10-hp, 220 volts, U-frame motor loaded from 40 to 80% of the rated torque with C = 280 microfarads. Because of excessive vibration, the test motor could not be loaded beyond 80% of the rated capacity. The experiment was repeated on the same motor with a capacitance value of 420 microfarads. The graphs of line currents and line to line voltages for load range of 60 to 120 per cent of rated are shown in Figures 68 and 69 respectively. Experimental data corresponding to Figures 66 through 69 are given in Tables 40 and 41 in Appendix C.

The line currents appear to indicate severe unbalance. Because of the way the motor winding was connected, however, the three line currents can not be compared to that obtained with the usual operation from a three-phase power line. In reality, the test motor with modified winding connection operated as a two-phase motor.

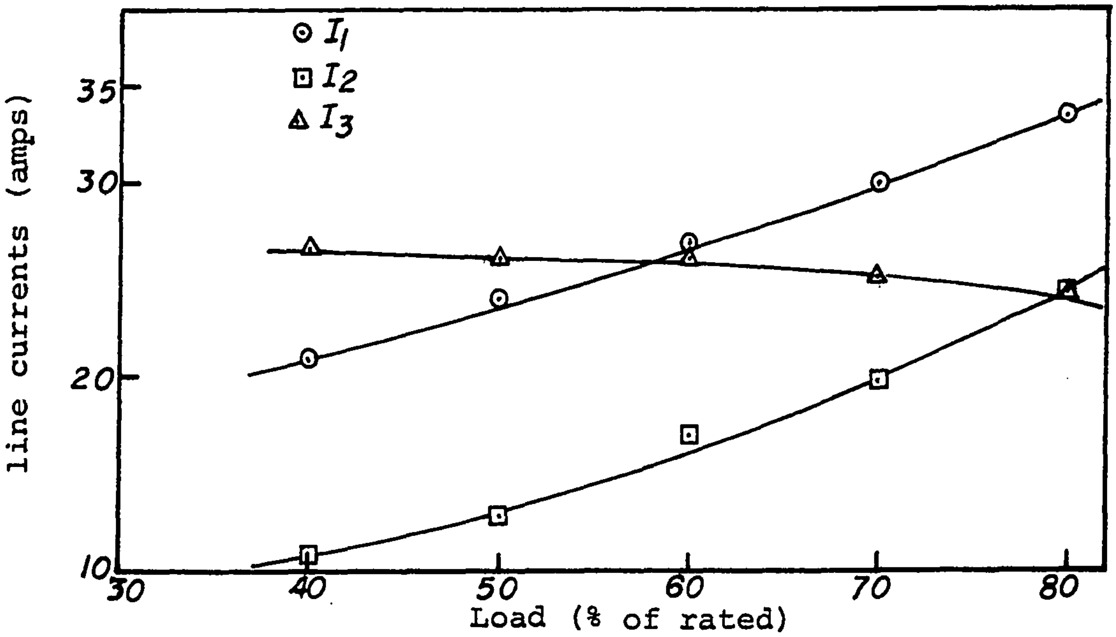


Figure 66. Line currents vs. load on a 10-hp, 220 volts, U-frame motor, C = 280 μF.

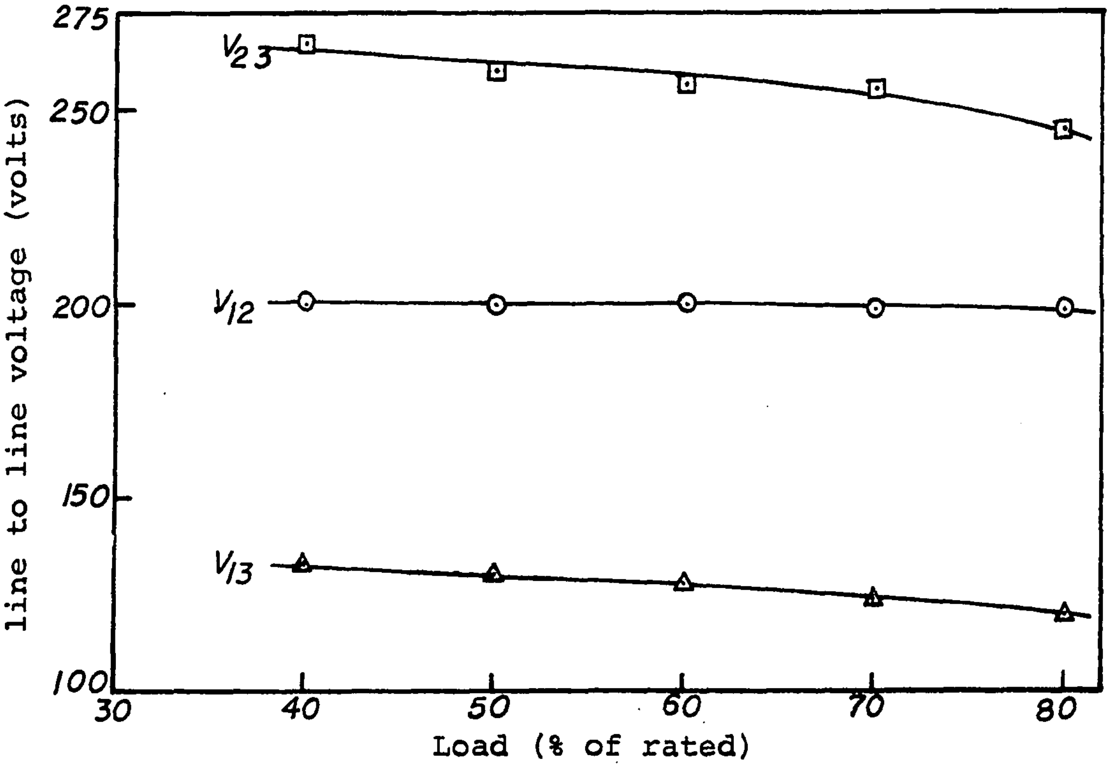


Figure 67. Line to line voltage vs. load on a 10 hp, 220 volts, U-frame motor, C = 280 μF.

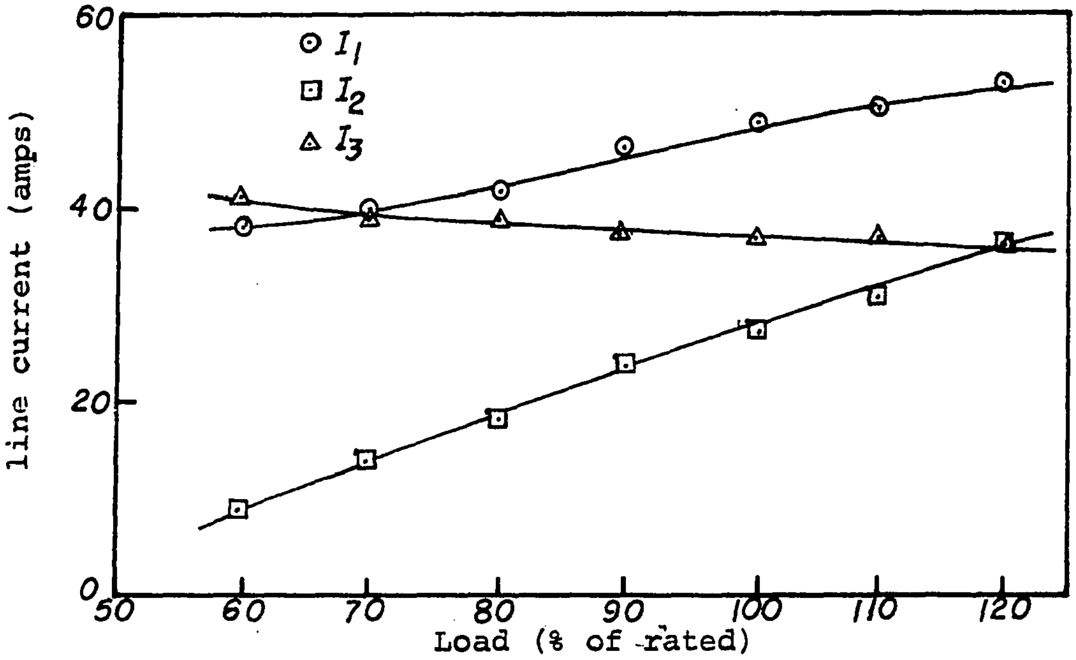


Figure 68. Line currents vs. load on a 10-hp, 220 volts, U-frame motor, C = 420 μF.

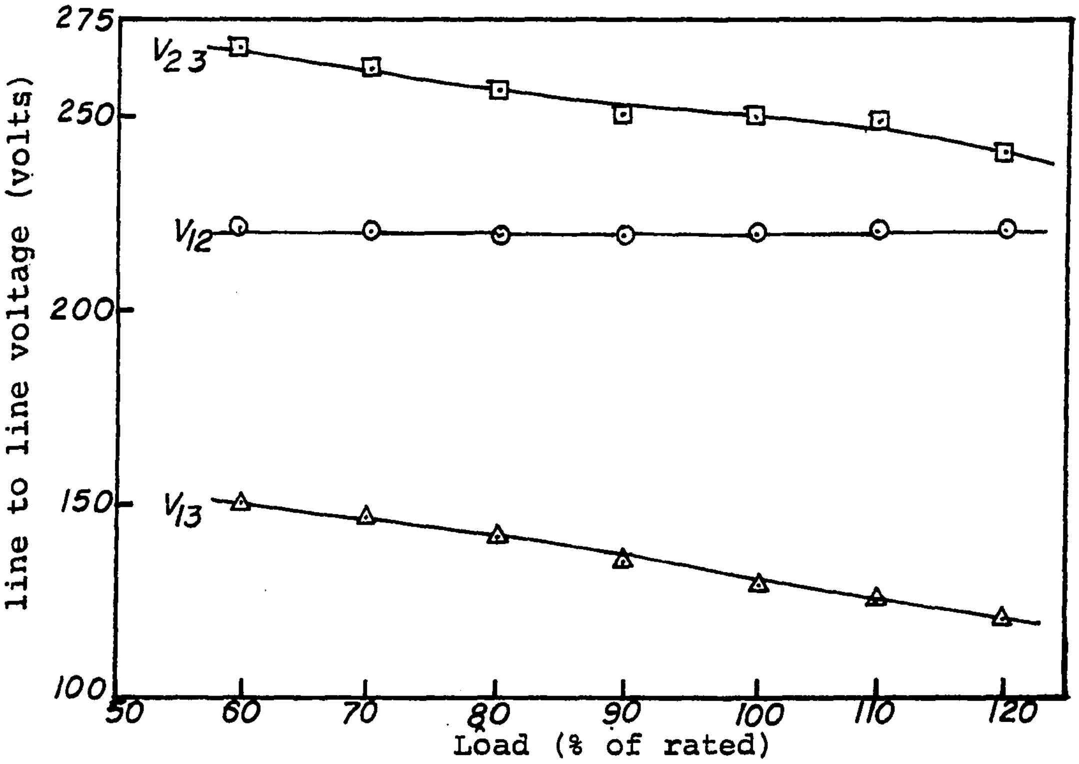


Figure 69. Line to line voltage vs. load on a 10-hp, 220 volts, U-frame motor, C = 420 μF.

The single-phase line current, I_1, in Figure 65 is vector sum of currents in phase ab and phase c. At no load, the current through the capacitor phase, I_3, was very high and produced severe vibrations in the motor. As the load on the motor was increased, I_3 showed slight variation. Current I_1 is considerably higher than I_2 because I_1 is vector sum of currents I_2 and I_3. Curves for I_1 and I_2 are nearly parallel for the range of load on the test motor. Both currents, however, increased with the load.

Voltage V_{23}, the voltage across capacitors C, was the highest. This voltage was the vector sum of voltage across winding c, V_{13}, and single-phase voltage V_{12} across phase ab of the motor.

By using the correct value of oil capacitor the current I_2 in phase ab as related to I_3 in phase c can be displaced by nearly 90°. The test motor will operate practically as though it was fed from a two-phase power line. Voltage across phase c is nearly in quadrature with the line voltage across phase ab.

Perfect two-phase operating conditions occur at only one value of load for a given value of capacitance. As the load changes, the magnitudes of current and phase angle deviates from a true two-phase operation. Tests showed that for a 10-hp, general purpose, U-frame, induction motor, capacitors sized at 40 microfarads per motor horsepower would provide nearly two-phase operating conditions of a three-phase motor loaded to its rated capacity.

The experimental data on a 10-hp, 230 volts, T-frame, NEMA design B motor operating from an open-wye type phase converter with C = 280 and 420 microfarads are given in Tables 42 and 43 in Appendix C. The efficiency of both motors was slightly lower than on three-phase line power through out the range of loads. Slip of the motors increased rapidly with overload.

To avoid stalling and overheating of a motor operated from an open-wye type phase converter, caution should be exercised not to exceed 100% of the nameplate horsepower.

The open-wye phase conversion system is less expensive than rotary and autotransformer-capacitor converters and, in applications where low starting torque is required and the load on the motor does not fluctuate, this system will operate three-phase motors from single-phase power.

EFFECTS OF STARTING CAPACITANCE ON LOCKED-ROTOR TORQUE

A typical torque-speed curve of a three-phase, squirrel cage, design B motor operated from three-phase power is shown in Figure 21. The locked-rotor, pull-up, and breakdown torques are identified on the curve. According to the ASA (3) and NEMA (72) specifications, a 5-hp, squirrel cage, 230 volts, three-phase, design B motor with rated voltage and frequency applied should produce locked-rotor, pull-up, and breakdown torques of 185, 225, and 130 per cent of the full-load torque respectively.

The torque characteristics of a three-phase motor operated from a phase converter usually are different in values than those obtained with three-phase line power. Starting torque is reduced considerably (22, 23) and breakdown torque is also lower (49).

Design Equations 10 and 11 for the autotransformer-capacitor phase converter give the optimum values of parameters i.e., size of the capacitors and transformer output voltage for the balanced steady state operation of a three-phase motor. These equations do not determine the capacitor size needed for starting conditions. If started with only the running capacitance in the circuit, the motor would have very little starting torque. For example, the torque-speed curve closest to the Y-axis in Figure 70, was obtained for a 5-hp, 230 volts, T-frame, NEMA design B, three-phase motor

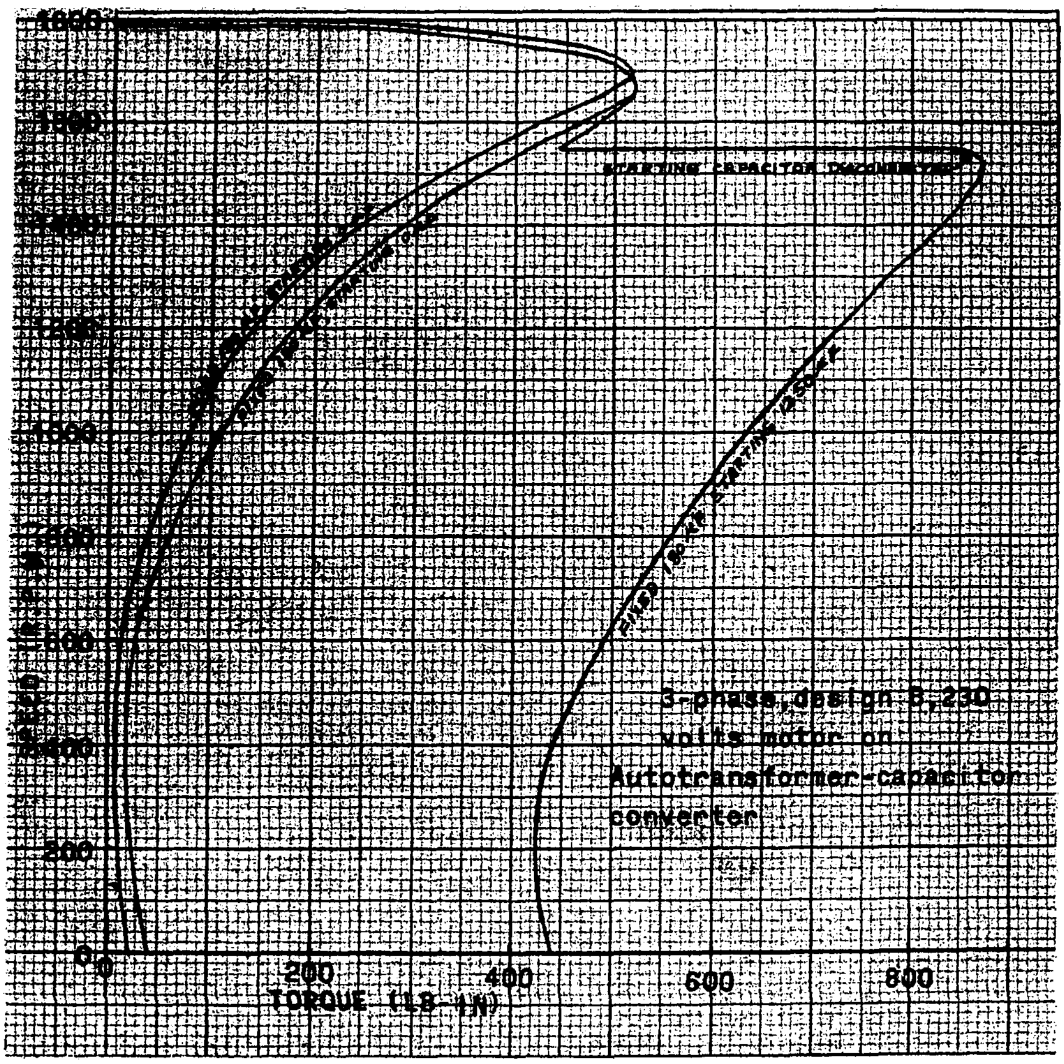


Figure 70. Dynamic torque-speed characteristics of a 5-hp, T-frame, design B, three-phase motor operated from an autotransformer-capacitor-phase converter.

operated from an autotransformer-capacitor phase converter with running capacitance of 150 microfarads. A similar curve for the same motor and converter but, with 180 microfarads of running capacitance shows a slight improvement in the locked rotor, pull-up and breakdown torque of the motor.

For a motor to perform properly, the locked-rotor and pull-up torques must exceed the load torque requirements by a margin great enough to accelerate the load to the operating point in a short period of time, generally no more than 10 seconds. The torques available from the test motor with capacitance of 150 or 180 μF would be insufficient to start a load that requires a 5-hp motor for steady state operation.

Locked-rotor and pull-up torques can be improved by placing more capacitance in the circuit for the duration of the starting cycle. Common practice has been to use electrolytic capacitors because of their lower cost, high capacitance, and smaller size. Electrolytic capacitors, however, have short duty cycles and should be disconnected at about 90% of the full load speed of the motor. Several switching arrangements to switch the electrolyte capacitors out of the circuit have been applied successfully (32, 86).

The effects of starting capacitance on the torque-speed curve of the test motor are shown in Figure 70. The locked-rotor torque of the 5-hp motor was improved to 36.6 pound-ft by adding 1250 microfarads of electrolytic capacitance to the starting circuit. This is about 240 per cent of the full load torque of the motor. The torque-speed curve beyond the point where electrolytic capacitors are removed from the circuit, overlaps the torque curve of motor obtained with 180 microfarads of running capacitance alone. The torque available with the running capacitance alone in most applications is sufficient to accelerate the load to the operating point.

To find the optimum size of electrolytic capacitors that would give a maximum possible locked-rotor and pull-up torque, tests were conducted on a 5-hp, 3-phase, 230 volts, T-frame, design B motor. The experimental data in graphical form are shown in Figures 71 and 72.

To improve the starting torque of the motor by using electrolytic capacitors, it is important for the single-phase line voltage to be at its rated value. Lower single-phase voltage would reduce the effect of starting capacitors on the locked-rotor torque. For example, at 100% of rated input single-phase voltage the locked rotor torque was 35 pound-feet with 700 microfarads and decreased to 31 pound-feet at 95% of rated voltage. When low voltage at starting of the motor is expected, the value of electrolytic capacitance should be increased to offset the reduction in locked rotor torque. At 95% of the rated voltage, it was possible to obtain 35 pound-feet of locked rotor torque by increasing

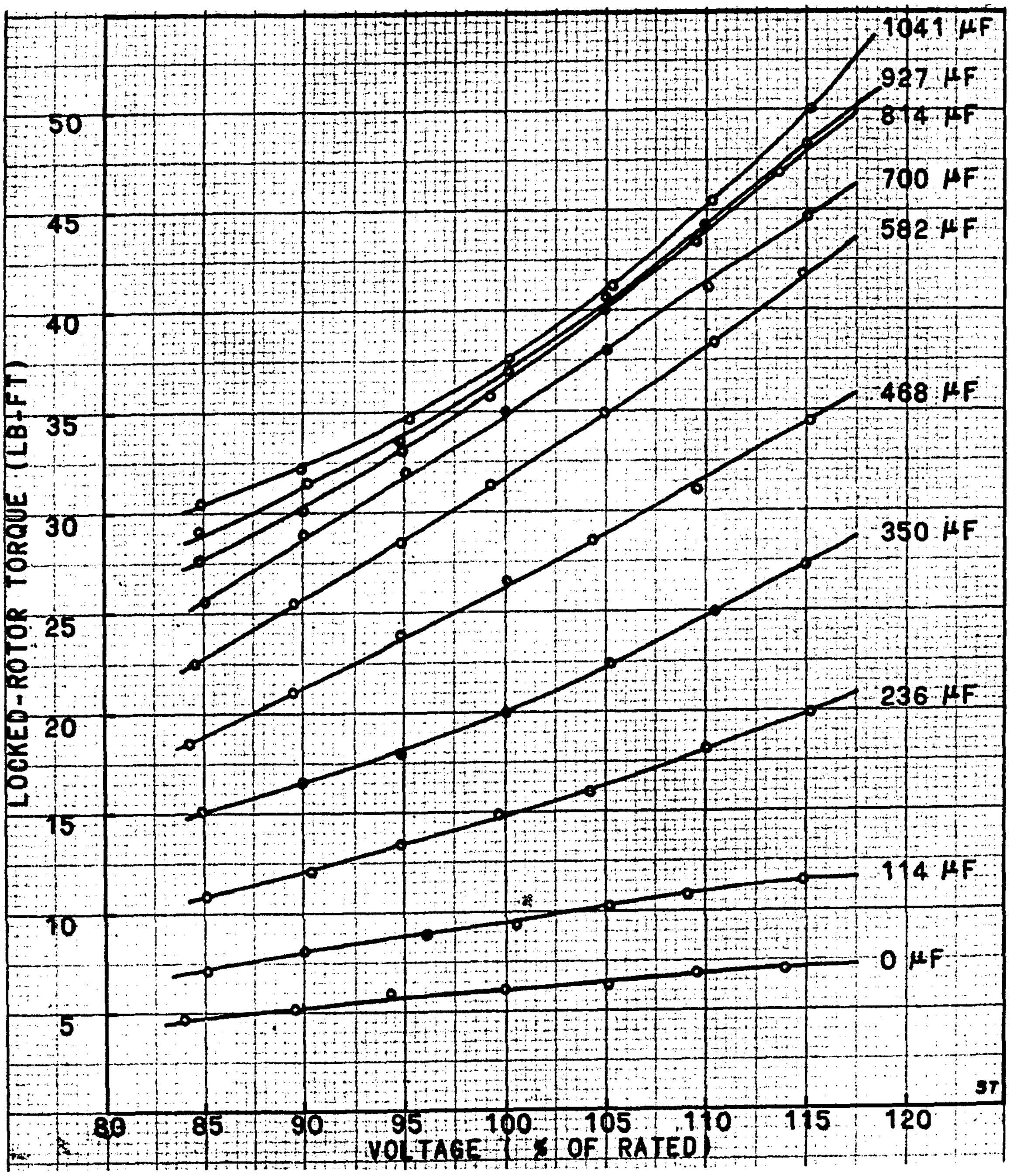


Figure 71. Locked-rotor torque vs. single-phase line voltage for a 5-hp, 230 volts, NEMA design B, three-phase motor operated with an autotransformer-capacitor phase converter.

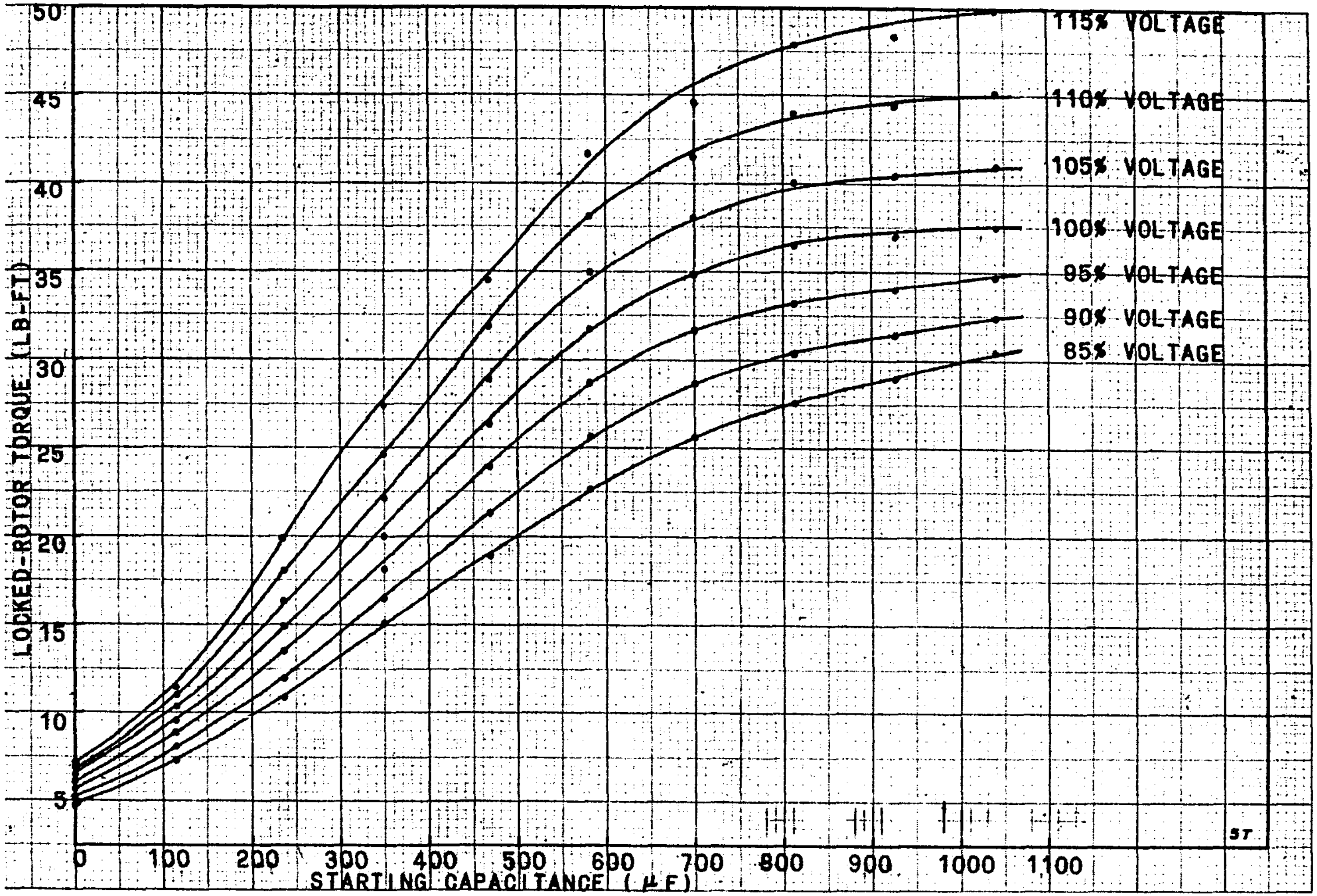


Figure 72. Locked-rotor torque vs. starting capacitance (μF) for a 5-hp, 230 volts NEMA design B, three-phase motor operated with an autotransformer-capacitor phase converter.

the starting capacitance from 700 to 1040 microfarads.

Graphs in Figure 72 show that holding single-phase input voltage constant, an increase in starting capacitance improved the motor locked-rotor torque. This is because of phase shift in the artificial phase voltage to about 120 electrical degrees apart from the other two phases, giving approximately three-phase conditions during the starting cycle. Beyond a certain value of capacitance, however, the effect of additional capacitors is relatively very small. For example, for rated line voltage, locked-rotor torque was 23 lb-ft with 400 μF, 32 lb-ft with 600 μF, and 36 lb-ft with 800 μF. An additional 200 μF in the circuit improved the locked-rotor torque to 37 lb-ft, an increase of 1 lb-ft over that obtained with 800 μF.

The test data on an autotransformer capacitor phase converter operated 5-hp three-phase motor with single-phase voltage at rated value showed that electrolytic capacitors sized at 180 μF per motor horsepower would give locked-rotor and pull-up torques slightly higher than NEMA specifications for the motor. The nearly maximum locked-rotor torque was obtained with 200 μF per horsepower. Starting capacitance larger than 200 μF per horsepower had a very little increase in the starting torque of the motor.

Starting capacitors have similar improvement in the locked-rotor and pull-up torques of a three-phase motor operated from various types of phase converters. The effects of starting capacitors on the dynamic torque-speed characteristics of motors operated from capacitor-only, open-wye type, and rotary phase converters are shown in Figures 89, 90, and 91 respectively in Appendix C.

POWER SERVICE DESIGN FOR PHASE CONVERTER AND ASSOCIATED THREE-PHASE MOTOR(S)

A majority of the problems encountered with phase converter applications have been due to improper installation and undersized wiring. In general, undersized wiring on any electric motor application will cause excessive voltage drop. This will reduce starting torque, and motors may not start or may start but take too long to accelerate the load, causing overheating of the motor in either case.

Problems arising from undersized wiring and excessive voltage drop are more severe when three-phase motors are supplied power from a single-phase source through a phase converter. In many cases, phase converters are adjusted to give balanced three-phase output at the rated input voltage and rated load on the motor. Any drop in the single-phase voltage at the input of the phase converter, therefore, will usually result in unbalanced three-phase voltage output (40).

Unbalanced voltage causes excessively high current in one or more phases of the fully loaded motor, and the average current often is higher than the nameplate rating. The consequences of higher than normal currents are excessive heating and premature deterioration of the motor. Low single-phase input voltage accompanied by an unbalanced three-phase output has a compound effect on the reduction of motor torque which impairs the performance of the phase converter, three-phase motor system.

Well designed services to phase converters can be achieved by selecting the proper transformer, conductor size, and overload protection.

Transformer Size

In the past, some of the commercially available rotary phase converters were rated by their motor starting capability. Commonly, rotary phase converters with a nameplate rating of 30 horsepower could be used to start and operate a maximum of a 30-hp single motor or several three-phase motors with a combined rating of 60 hp. However, there is a wide variation in recommendations on the maximum motor load that can be operated from a rotary phase converter. Following are a few examples:

> "The combined horsepower of all the motors to be operated simultaneously should not exceed 1.5 times horsepower rating of the converter." (51)

> "Loading on a rotary converter can not be more than twice its rated horsepower before recommended temperature rise is exceeded." (23)

> "The total horsepower load that can be connected to a rotary converter is two to four times the horsepower of the largest motor that may be started." (94)

> "Total horsepower of motors may be well in excess of the converter single motor rating. Generally a load four times the rating is acceptable, sometimes even more if voltage is maintained." (4)

> "Total motor load should not be greater than four times the size of converter." (12, 96)

With static phase converters, the rating problem did not usually arise because static converters were recommended for use with only one three-phase motor.

Power suppliers select and install stepdown transformers to serve farm loads. In many instances, transformers are sized on the basis of converter horsepower rating and not for their total motor horsepower capability.

In sizing a transformer for phase converter operated three-phase motors, the total horsepower of all the motors to be operated from the phase converter should be considered. Some manufacturers of phase converters recently have added the combined maximum horsepower capacity to the phase converter nameplate.

When selecting a transformer for three-phase motors operated on three-phase power or for a phase converter operated, three-phase motor on single-phase power, economics usually dictates the sizing of the transformer bank to provide loads beyond the transformer rating. Because transformers can withstand heating for short periods of time, seldom will obvious damage occur from overloading. If too small a transformer is used, the excessive voltage drop in the impedance of the transformer may give an unbalanced voltage output from the phase converter and thus reduce performance of the three-phase motor.

Often three-phase transformers sized by allowing 3/4 KVA for each horsepower motor load have performed satisfactorily. However, to provide for the losses in the phase converter as well as to avoid excessive voltage drop in the transformer winding, some of the electric power supply companies size a single-phase transformer for a phase-converter three-phase motor system at 1 KVA per horsepower motor load.

For applications where one transformer will supply a phase converter load as well as other loads, both loads should be considered. A transformer should be selected so that it provides one KVA per motor horsepower as well as the KVA requirements of the additional loads being served from it (11, 12, 40).

Conductor Size

Two different sizes of wires are required for the phase converter three-phase motor system: 1) those used to supply single-phase power from the meter pole to the phase converter and 2) those used to supply three-phase power from the phase converter to the three-phase motor(s).

To properly design an electrical wiring system, the following factors must be considered:

1. Load current amperes
2. Length of wires (distance between power source and load)
3. Permissible voltage drop on lines

4. Conductor insulation and material

5. Any national or local code requirements.

The ampere load on the wires supplying three-phase power from the phase converter to the motor is determined by the size and type of motor(s) being used. The motor nameplate is the best source for determining current requirements at full motor load. Full load current of three-phase motors can also be obtained from table 430-150 of the 1971 National Electric Code (NEC).

To determine the size of conductors required to serve single-phase power to a phase converter, knowledge of the current drawn by the phase converter at rated motor horsepower load is essential. Unlike motors, phase converters are not standardized, and such information is not readily available. Even the manufacturers of phase converters may not be able to furnish this information because the amperes drawn by a phase converter will depend upon the size, type, and voltage rating of the three-phase motor(s) to be used. The efficiency of a phase converter will also affect the single-phase ampere load.

The ampere load of phase converters supplying power to three-phase motors can be found by the following analytical method. Power requirements of a three-phase motor on three-phase service can be written

$$P_T = \frac{hp \times 746}{\eta_T} = \sqrt{3}\ V_T\ I_T \text{ Cos } \phi_T \qquad (26)$$

and the single-phase power drawn by a phase converter motor combination is

$$P_S = \frac{hp \times 746}{\eta_C \times \eta_T} = V_S\ I_S \text{ Cos } \phi_S \qquad (27)$$

where P_T = power from three-phase line

P_S = power from single-phase line

η_T = efficiency of three-phase

η_C = efficiency of phase converter

ϕ_T = phase angle of three-phase motor

ϕ_S = phase angle of single-phase power

The efficiency of a phase converter alone is not very meaningful; therefore, an overall efficiency η_S of a phase converter and its motor can be written as

$$\eta_S = \eta_C\ \eta_T$$

Equation 27 is rewritten

$$P_S = \frac{hp \times 746}{\eta_S} = V_S\ I_S \text{ Cos } \phi_S \qquad (28)$$

From Equations 26 and 28

$$V_S\ I_S\ \eta_S \text{ Cos } \phi_S = \sqrt{3}\ V_T\ I_T\ \eta_T \text{ Cos } \phi_T$$

Voltage ratings of a converter and associated motor are usually the same; therefore,

$$I_S \eta_S \cos \phi_S = \sqrt{3}\, I_T \eta_T \cos \phi_T \qquad (29)$$

Efficiency of a three-phase motor operating from three-phase lines is, usually, greater than the combined efficiciency of phase converter and three-phase motor, but the power factor of the single-phase service to phase converter is higher than the power factor of three-phase motors on the three-phase source. To determine the net effect of these two factors, the product of efficiency and power factor is defined by a constant K. Equation 29 can be rewritten as

$$I_S K_S = \sqrt{3}\, I_T K_T$$

$$I_S = \sqrt{3}\, \frac{K_T}{K_S}\, I_T \qquad (30)$$

When the values of K_S and K_T are known, I_S can be easily computed. Table 12 shows typical values of η_T and $\cos \phi_T$ obtained from manufacturers' data. The calculated value of K_T for 5 to 100 horsepower three-phase motors varies from 0.73 to 0.85.

Value of η_S and $\cos \phi_S$ for three brands of rotary phase converters obtained from experimental data are given in Table 13. The single-phase voltage was maintained at 230 volts and motors were loaded to their nameplate ratings.

Table 12. Typical efficiency, power factor, and a constant K_T value of three-phase squirrel cage, 1800 RPM, 230 volts, design B induction motors at rated load

hp	η_T	Cos ϕ_T	K_T
5	.83	.88	.73
7.5	.84	.88	.74
10	.85	.89	.75
15	.87	.89	.78
20	.88	.90	.79
30	.89	.90	.80
40	.89	.91	.81
50	.90	.91	.82
75	.91	.91	.83
100	.92	.92	.85

Values of η_S and Cos ϕ_S for static converters are summarized in Table 14. The source of data is listed in the first column of the table. The author conducted experiments for the data for which the source is not given. The ratios of K_T/K_S for rotary and static phase converters are given in Table 15. The ratio (K_T/K_S) varies between 1.01 and 1.30. The average of the 17 values of (K_T/K_S) reported in Table 14 is 1.14, and 11 out of these 17 values are 1.13 or larger. The constant 1.15 was, therefore, considered as a typical value for the ratio (K_T/K_S). From Equation 30

$$I_S = 1.732 \times 1.15 \times I_T$$

$$= 1.99\ I_T \approx 2\ I_T \text{ (approx.)} \qquad (31)$$

Table 13. Experimental data on efficiency and power factor of rotary phase converter three-phase, 230 volts, design B induction motor combinations

	Converter A			Converter B			Converter C		
Motor hp	η_S	Cos ϕ_S	K_S	η_S	Cos ϕ_S	K_S	η_S	Cos ϕ_S	K_S
15	.75	.93	.69	.75	.80	.60	.75	.93	.69
20	.76	.82	.70	.79	.82	.65	.79	.91	.72
30	.79	.91	.72	.79	.87	.68	.77	.91	.70
2-15	.76	.95	.72	.78	.89	.69	.73	.92	.68
2-20	.80	.99	.80	.83	.90	.74	.76	.88	.67

The conductor size serving phase converters can be designed by the relationship in Equation 31; i.e., ampere load of the single-phase line should be considered twice the full load ampere rating of the three-phase motor(s) being operated from it.

To verify Equation 31, a study was conducted of the current drawn by various brands of rotary and static phase converters. Test data on ampere load of phase converters

Table 14. Experimental data on efficiency, power factor, and K_S of static converter three-phase motor combinations, with the motor at rated load

Source	Motor hp	η_S	Cos ϕ_S	K_S
(59)[a]	5	.75	.89	.66
	7.5	.78	.77	.60
	10	.77	.85	.65
(108)	15	.81	.91	.73
(41)	20	.74	.94	.70

[a] Numbers refer to appended references.

Table 15. Ratios of (K_T/K_S)

Motor hp	K_T	Rotary Phase Converter						Static phase converter	
		Brand A		Brand B		Brand C			
		K_S	K_T/K_S	K_S	K_T/K_S	K_S	K_T/K_S	K_S	K_T/K_S
5	.73	--	---	--	---	--	---	.66	1.11
7.5	.74	--	---	--	---	--	---	.60	1.23
10	.75	--	---	--	---	--	---	.65	1.16
15	.78	.69	1.13	.60	1.30	.69	1.13	.73	1.06
20	.79	.70	1.13	.65	1.21	.72	1.10	.70	1.13
30	.80	.72	1.11	.68	1.18	.70	1.14	---	----
40	.81	.80	1.01	.74	1.10	.67	1.21	---	----

and current of associated three-phase motor(s) are given in Table 16. Data on rotary phase converters are in close agreement with Equation 31. Current drawn by static converters is slightly lower than twice the current of three-phase motors. This is because of the relatively lower losses in static phase converters.

Table 16. Test data on ampere load of phase converters serving three-phase fully loaded motor(s)

Motor hp	3-ϕ Current	Rotary Converter Brand A	Rotary Converter Brand B	Rotary Converter Brand C	Static Converter Brand D	Static Converter Brand E
5	14	24.0	29.8	----	21.4	23.0
7.5	20	----	----	----	35.4	42.0
10	28	46.0	58.0	48.0	47.6	44.5
15	41	70.0	81.0	70.0	69.0	67.0
20	52	92.0	100.0	90.0	----	----
30	77	134.0	142.0	138.0	----	----
40	100	163.0	161.0	194.0	----	----

The size of the conductor can be computed with the following equations:

For single-phase wiring

Copper conductor $$CM = \frac{22 \times I_S \times L}{V_D} \qquad (32)$$

Aluminum conductor $$CM = \frac{35 \times I_S \times L}{V_D} \quad (33)$$

For three phase wiring

Copper conductor $$CM = \frac{19 \times I_T \times L}{V_D} \quad (34)$$

Aluminum conductor $$CM = \frac{30 \times I_T \times L}{V_D} \quad (35)$$

where CM = area of conductor, circular mils

I = current of load, amperes

L = one way length of the conductor, feet

V_D = voltage drop, volts

In using the above Equations 32, 33, 34, and 35, the NEC requires that, for a single motor, the design value of I_S or I_T should be 125% of the amperes for three-phase motor(s) given in NEC Table 430-150. For a multi-motor application, I_S or I_T are determined by adding 125% of the largest motor's amperes to 100% amperes of all additional motors.

For satisfactory performance of phase converter operated motors, voltage drop on the branch circuit and feeders should be limited to 5%.

Motors driving varying or pulsating loads must be carefully matched to the phase converters. When sizing conductors for this type of load, it may be desirable to limit voltage drop to a maximum of 2%. For fluctuating loads, it is recommended that feeders and branch circuit should be designed to carry the intermittent inrush current of the phase converter rather than rated current. After the conductor area in CM is computed, its size in American wire gauge (AWG) can be found from a CM-AWG conversion table. Such conversion tables are given in the Handbook (33).

The wire size selected should be checked for its allowable ampacity from Tables 310-12 through 310-15 of the 1971 NEC. If the allowable ampacity is less than the value, I_S or I_T, used in computing CM from Equations 32, 33, 34, or 35, then the larger size conductors capable of carrying the current I_S or I_T should be used.

Overload Protection

Large horsepower motors, phase converters and their wiring represent a sizable investment. NEC requires that the system be protected against excessive currents because of the possibility of an overload on the motors or malfunctioning of either the motor or the phase converter.

As shown in Figure 73, a single-phase fused disconnect should be installed ahead of the phase converter. This disconnect is desirable even if the phase converter has its own circuit breaker. The size of single-phase disconnect is determined by the ampere load of the phase converter, I_S, used in sizing the single-phase conductors between the meter

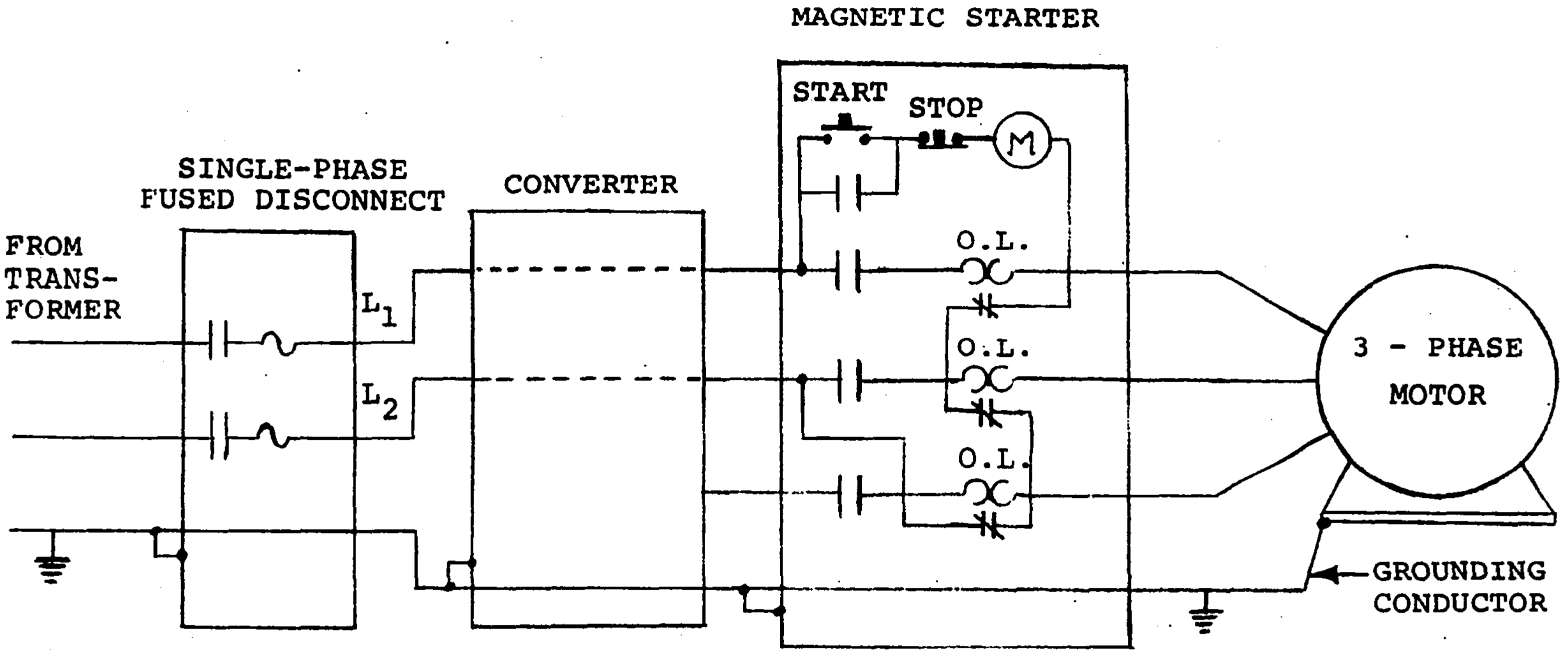


Figure 73. Diagram showing a single-phase fused disconnect for protection of the phase converter and a magnetic starter for protection of the three-phase motor.

pole and the phase converter. Fuses preferably should be of time-delay type to allow inrush current for starting the motors.

To protect the windings of the three-phase motor(s) from continuous excessive currents, a magnetic starter should be installed between the phase converter and the motor. If more than one motor is used, each motor should be provided with a magnetic starter.

The magnetic starter used with each three-phase motor is the same size and type regardless of whether the power source is a power line or a phase converter. Overload heaters in the magnetic starter should be sized according to the NEC recommendations. Overload current protection sensors require careful installation. A correct ambient compensated heater should be installed on each of the three lines from the phase converter to the motor. Very heavy current is drawn in the manufactured phase when a motor is running with an overload. This is particularly true on fluctuating loads like haylage filling applications. For example, a motor used on materials-handling blower may experience a wide variation of overload. Varying loads may cause instantaneous heavy current, which can result in unwanted tripping of the magnetic starter. Sometimes this is eliminated by bypassing the heater in the manufactured phase. This, however, may shorten the motor life. Also, bypassing of the overload heater is a violation of Code recommendations.

Because the voltage between the manufactured phase and one of the single-phase power line phase is not constant during starting or during any period of load variation this phase should not be used for the holding coil of the magnetic starter.

Grounding

For the safety of the operator it is important that a grounding conductor should be installed on all electrical equipment. For phase converter applications, the grounding conductors should be connected to the motor base, the phase converter enclosure, and the grounding provision on the meter pole. This will insure a continuous ground return to carry any fault current back to the transformer and minimize electrical shock hazard (109).

Installation

Figure 74 is a wiring diagram for a three-phase motor operated from an autotransformer-capacitor phase converter. The setting on a current limiting resistor in series with the coil of a relay number 2, a voltage sensitive relay, determines the time for which a bank of electrolytic capacitors is connected in the circuit for motor starting.

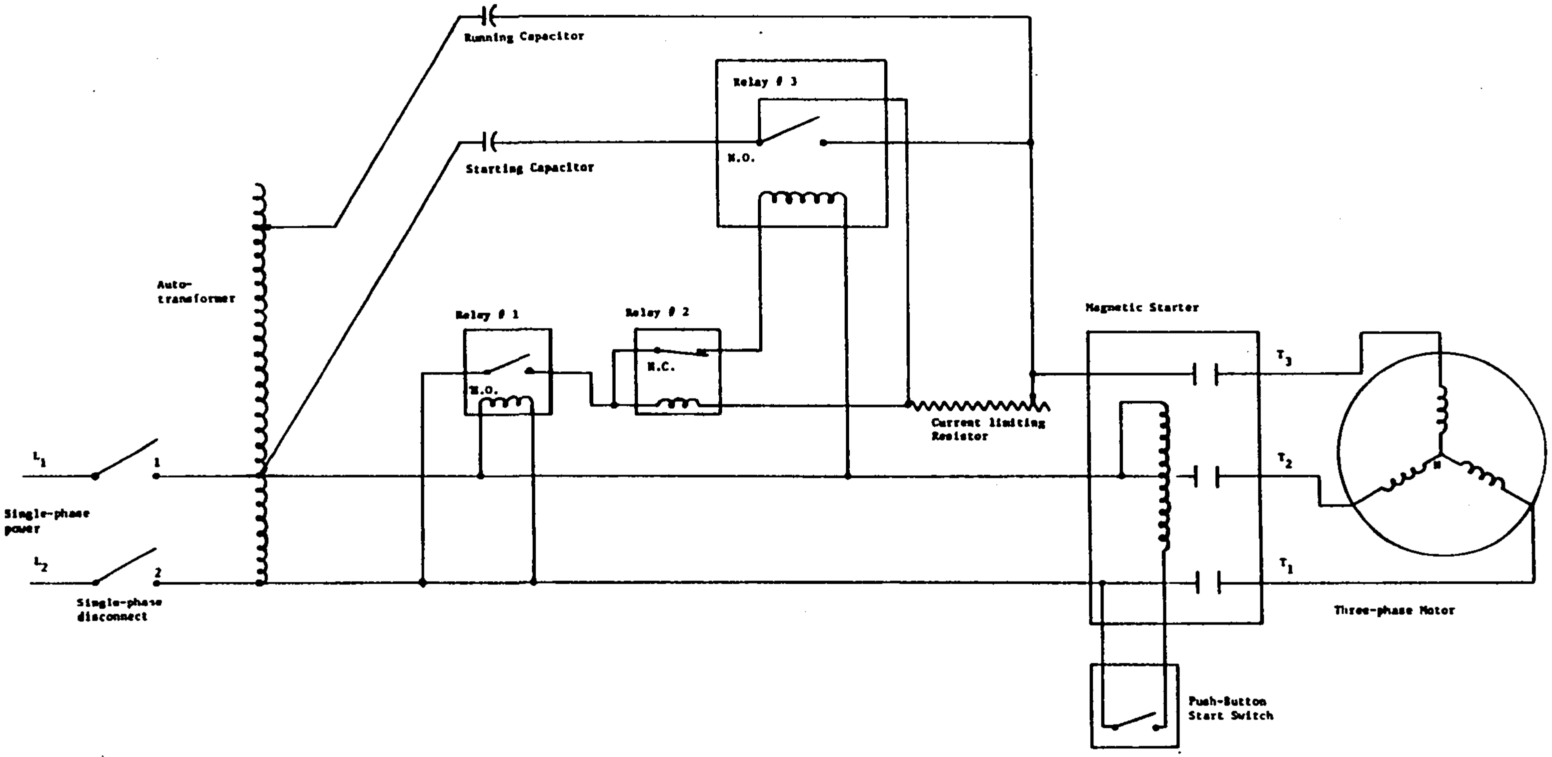


Figure 74. Wiring connections for an autotransformer-capacitor phase converter and three-phase motor with a current limiting resistor.

Figure 75 shows a wiring diagram for multimotor application from a single rotary phase converter. Each motor is protected by a magnetic starter. The capacitor bank associated with an individual motor is connected in parallel with the main capacitor bank of the rotary unit when the motor is started.

Figure 76 shows wiring connections of an open-wye type phase converter and a three-phase motor. Modified connections of the motor winding are illustrated. A current limiting resistor, similar to that used in an autotransformer capacitor converter, is connected in series with the voltage sensitive control relay to drop the electrolytic capacitors out of circuit at the proper speed of the motor.

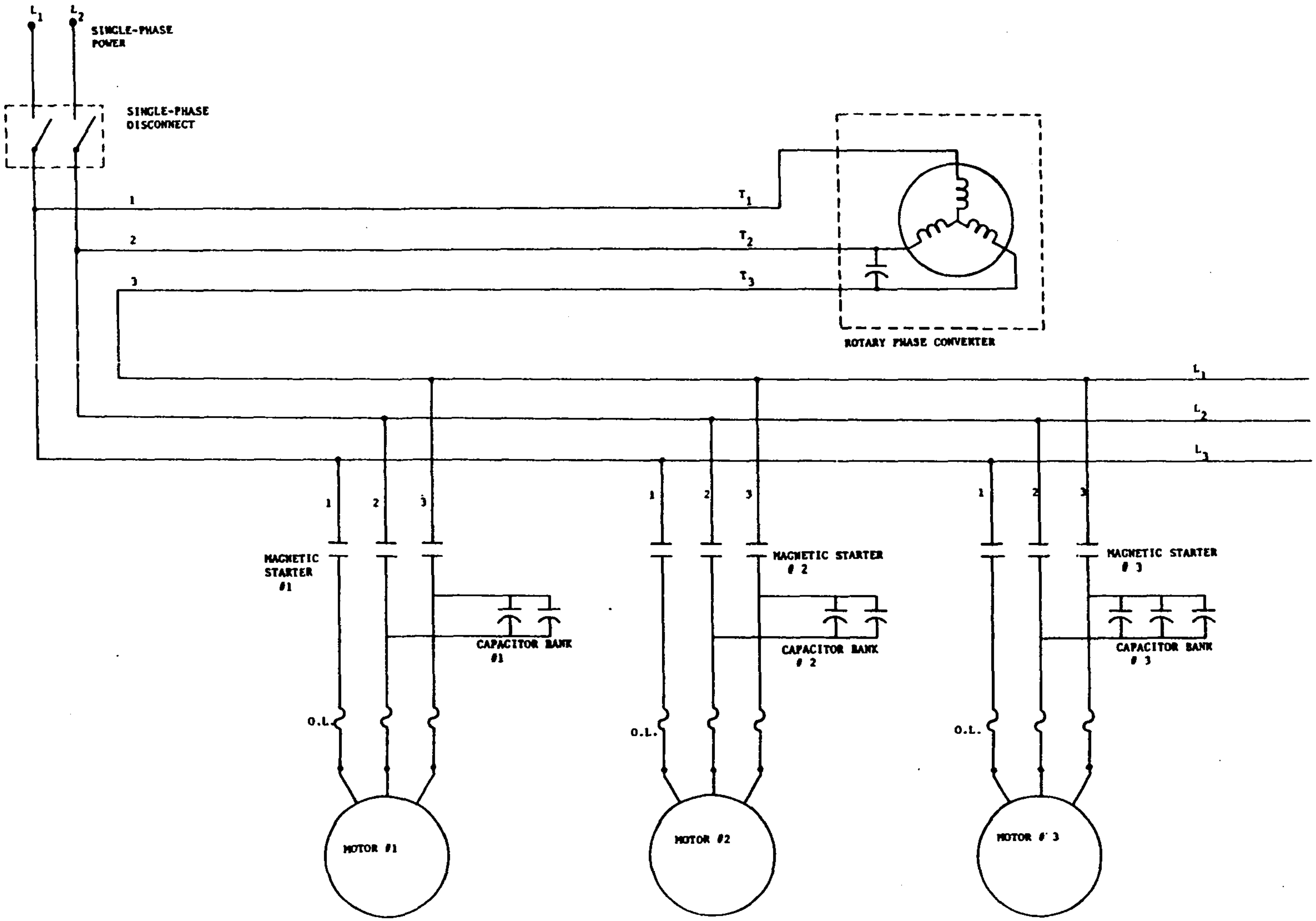


Figure 75. Wiring connections for a multimotor application from a single rotary phase converter.

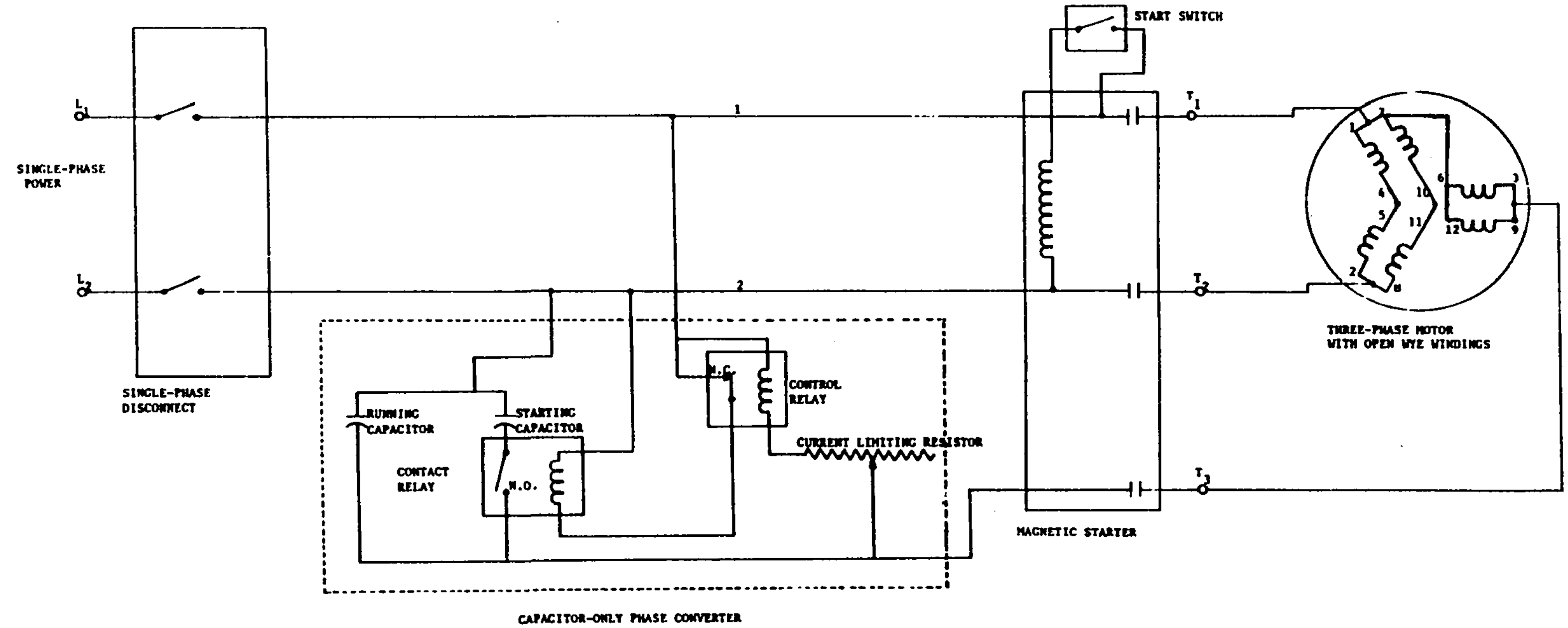


Figure 76. Wiring connections for an open-wye type phase converter and a three-phase motor with a current limiting resistor.

DISCUSSION

Static and rotary phase converters have made possible the satisfactory operation of many three-phase motors from single-phase power lines on farms. Usually, the cost for a phase converter system is lower than the cost of extending three-phase power to the farm. By no means, however, should phase converters be considered a replacement for commercial three-phase power.

Design Equations 10 and 12 eliminate the tedious empirical methods for determining capacitor size and transformer turns ratio of an autotransformer-capacitor phase converter to give the balanced voltages and currents in a three-phase motor. It must be admitted that the simplification of design does not make an autotransformer-capacitor phase converter the universal answer to all the applications of three-phase motors on farms with only single-phase power. Torque characteristics of a three-phase motor are changed when used with a phase converter.

Perhaps the greatest limitation of an autotransformer-capacitor phase converter is the need for electrolytic capacitors to obtain the desired starting torque. This is the only component used in autotransformer-capacitor converters that has low reliability. A majority of the problems encountered in the use of autotransformer-capacitor phase converter can be attributed to the failure of one or more electrolytic capacitors. The short duty cycle of electrolytic capacitors make the phase converter unsuitable for cyclical start-stop loads.

The taps on the secondary of the transformer winding and capacitor size can be adjusted in the field to obtain close balance in the voltages and currents of a three-phase motor. Taking all the facts into account, however, this may not be always an acceptable procedure to the user of autotransformer-capacitor phase converter.

A rotary phase converter has the advantage that it can be used for more than one three-phase motor. It also seems to be possible to obtain NEMA specified torques from a design B, general purpose induction motor operated from a rotary phase converter without the use of electrolytic capacitors (4).

The oil type capacitors, usually, have long duty cycle. Any possibility of failure of running capacitors because of over voltage can be eliminated by designing the rotary converter winding so that with the rotary converter idling, the voltage across the capacitor does not exceed the voltage ratings. The voltage output across terminals 2 and 3 in Figure 47 drops when the rotary converter is supplying power to a three-phase motor.

The author from his experiences of working with several rotary phase converters has found that oil type capacitors sized at 40 to 45 μF per motor horsepower give optimum balance in voltages and currents and fairly good dynamic torque-speed characteristics from the motor. More experimental study should be made, however, before this is accepted as a design criteria.

As a general rule, temperature rise of the three-phase motor windings has been found to be higher with phase converters than those with three-phase line power. In most cases the rise does not exceed the allowable rise for the class of insulation used in the motor.

Locked-rotor, pull-up, and breakdown torques of motors operated from phase converters are lower than that obtained with three-phase line power, although they may be sufficient to start and accelerate a majority of farm loads without affecting motor life.

The author believes that measurement techniques used in this study can be improved. For example, external current transformers were used to read the currents on 5 and 10 ampere full scale ammeters. Better accuracy of measurement can be obtained by using ammeters calibrated with built in internal current transformers.

The thermocouple method for measuring temperature was found to be quite reliable. The resistance method requires elaborate instrumentation. It is also time consuming and the machine has to be stopped after each test. Thermocouples were installed in the lab and could not be embedded deep inside the motor windings. Thermocouples installed at the factory at the time of winding the stator would give better estimates of the hot-spot.

SUMMARY

The need for three-phase motors on farms is discussed and the potential for phase converters is considered in meeting the demand to operate large motors from the existing single-phase power line. Technical literature on various types of phase converters is reviewed in some detail. Comparative limitations on the use of various types of phase converters are presented.

Design equations are developed for the capacitor size and transformer turns-ratio to give balanced operation of a three-phase motor operating from an autotransformer-capacitor phase converter. Recommendations are made on adjusting parameters for fluctuating and variable loads. The effects of variation in the single-phase line voltage are given on the performance of three-phase motors operating from rotary and autotransformer-capacitor phase converters.

Performance of three-phase motors are presented under various percentages of unbalance in their terminal voltage. This voltage unbalance was similar to the voltage unbalance that may occur with phase converters. Performance characteristics are discussed for a 10 hp U-frame motor and a 10 hp T-frame motor operated from an open-wye type phase converter. Effects of the size of starting capacitance are determined on the locked rotor torque of a three-phase motor operating from an autotransformer-capacitor phase converter

that has been adjusted for balanced condition at rated motor horsepower.

A method is developed for designing power distribution conductors for a phase converter and associated three-phase motor(s). The analytical equation developed for determining conductor size was verified experimentally.

RESULTS AND CONCLUSIONS

The author believes that the results from the various phases of this study have met the objectives of the research project. The following conclusions are drawn from these studies:

(1) Equations 10 and 12 $\{C = 3063\ (I/V)\ \sin \phi\}$, $\{n = (1/2) + (\sqrt{3}/2)\ \cot \phi\}$, are accurate and practical for determing capacitance value and transformer turns ratio in an autotransformer-capacitor phase converter to give balanced currents and voltages to a three-phase motor for a given load. These equations are in terms of nameplate data and phase angle of the three-phase motor and are of greater practical value than equations that require internal parameters like resistance and reactance of the motor.

(2) Capacitance value and transformer output voltage in an autotransformer-capacitor phase converter, in application where the three-phase motor is oversized, should be adjusted for the load on the motor and not for the nameplate horsepower. If the load varies moderately, the two parameters should be adjusted for the average load and not for the maximum or minimum load on the motor.

(3) Variations in single-phase voltage input to the phase converter results in unbalanced three-phase output voltages.

(4) Lower than nominal voltage will cause higher temperature rise of a motor on an autotransformer-capacitor phase converter. Higher temperature of the test motor operated from a rotary converter will be experienced with single-phase voltage higher than nominal.

(5) Locked rotor torque and pull-up torque of the general purpose, three-phase induction motor operating from the autotransformer-capacitor phase converter are higher than those obtained with the rotary phase converter. The breakdown torque, however, is higher with the motor operating on the rotary phase converter.

(6) The unbalance in currents due to overload on the motor at rated single-phase voltage or due to lower single-phase voltage accompanied with a rated load on the motor increases the winding temperature rapidly. An overload on motors operated from phase converter should be avoided and motor capacity must be derated when the single-phase voltage is lower than rated.

(7) The open-wye type phase conversion system is the least expensive for applications where low starting torque is required. The phase shifting capacitance sized at 40 µf per horsepower gives optimum steady state performance.

(8) To obtain maximum locked-rotor torque with a general purpose three-phase, induction motor operating from an autotransformer-capacitor phase converter, starting capacitance should be sized at 200 µf per horsepower of steady state load on the motor.

(9) Due to additional losses in the phase converter, the combined efficiency of motor-phase converter system is lower than the efficiency of the motor operating on three-phase line power. At no load or very light load on the motor, the motor losses and heating are greater with a phase converter than with balanced three-phase power.

(10) A single-phase transformer to supply the power to a phase converter and its associated motor(s) should be rated at 1 KVA per horsepower of motor load. Single-phase conductors serving phase converters should be designed according to Equation 31 $\{I_S \simeq 2\ I_T\}$, considering ampere load on the single-phase line to be twice that of full load amperes drawn by the three-phase motor(s).

SUGGESTIONS FOR FURTHER STUDY

Equations 10 and 12 for calculating the size of capacitors and transformer turns-ratio of an autotransformer-capacitor phase converter were found to be of a greater practical value than design equations requiring motor internal parameters. To further the usefulness of this study an attempt should be made to develop a similar equation to give the size of capacitors and rotating unit of the rotary phase converter for balanced operation of a given motor. This equation should be in terms of nameplate data of the converter and motor. The investigation probably should be extended to developing a general equation that may be applicable to one or multimotor applications.

Investigations should be made of a practical method of incorporating a feedback circuit in the design of autotransformer-capacitor phase converters. This would permit the control of output voltages V_{13} and V_{23} by the three-phase line currents which are representative of the load on the three-phase motor. It is believed that addition of the feedback loop to the autotransformer-capacitor phase converter circuit would allow use of a single motor, or a combination of motors, of various sizes within the rating of the phase converter.

The optimum size of starting capacitors used in the rotary phase converter should be determined to give the rated locked rotor torque of the three-phase motor. Further investigations should be made to determine the size of the starting capacitors needed for each of the additional motors to be used on a multimotor application of a rotary phase converter, preferably each motor should be capable of providing rated starting torque.

The possibility should be investigated of using a saturable core reactor in place of the capacitors in the rotary phase conversion system. Increasing the current through a reactor made of core metal with a very sharp limit of magnetization would cause no substantial rise of voltage, once the saturation point is reached. This arrangement, perhaps, may give better voltage balance than that obtained from a rotary phase converter with capacitive reactance.

The author studied the effects of voltage variations on the performance of phase converter operated three-phase motors, with the motor loaded to rated horsepower. It is suggested that investigations should be conducted to study the combined effects of voltage variations and motor operated at above and below the rated horsepower.

An investigation should be made on the performance of three-phase synchronous motors operated from a single-phase power source through the rotary as well as autotransformer-capacitor phase converters.

It would be useful to explore, by studying the voltage and current balance and temperature rise of three-phase motors, the application of the Voltano phase conversion system for farm loads.

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APPENDIX A: EQUIPMENT SPECIFICATIONS

Electric Motor Specifications

Manufacturer - Century Electric Company, St. Louis, Missouri.

Horsepower	5	Frame	184 T
Phase	3	Type	SC
RPM	1745	Locked KVA CODE	J
Amps	14.4/7.2	Ins. Class	B, Design B
Volts	230/460	Max. Amb.	40° C
Frequency	60 Hz	Service Factor	1.15
		Assigned Brand	(1)

Manufacturer - General Electric, Fort Wayne, Indiana.

Horsepower	5	Frame	184 T
Phase	3	Type	K
RPM	1745	Locked KVA Code	H
Amps	14.2/7.1	Ins. Class	B, Design B
Volts	230/460	Max. Amb.	40° C
Frequency	60 Hz	Service Factor	1.15
		Assigned Brand	(2)

Manufacturer - Century Electric, St. Louis, Missouri.

Horsepower	10	Frame	256 U
Phase	3	Type	SC
RPM	1750/1460	Locked KVA Code	G
Amps	27/13.5	Ins. Class	A
Volts	220/440	Max. Amb.	40° C
Frequency	60/50 Hz	Service Factor	1.15

Manufacturer - Century Electric, St. Louis, Missouri.

Horsepower	10	Frame	S215 T
Phase	3	Type	SC
RPM	1750	Locked KVA Code	H
Amps	25/12.5	Ins. Class	B, Design B
Volts	230/460	Max. Amb.	40° C
Frequency	60 Hz	Service Factor	1.15

Phase Converter Specifications

Manufacturer - Ronk Electrical Industries, Nokomis, Illinois.

Horsepower 15
Phase 3
RPM 1800
Amps 38
Volts 230
Frequency 60 Hz
Frame 254 T
Type RV (Rotary)
Ins. Class B
Max. Amb. 40° C

Manufacturer - Ronk Electrical Industries, Nokomis, Illinois.

Horsepower 10
Phase 1
Amps 40, 1-ϕ
Input Volts 220 V, 1-ϕ
Output Volts 220 V, 3-ϕ
Frequency 60 Hz
Type 25 (Auto - Cap)
Temp. Rise 40° C

Manufacturer - Ken Elliot Motors, Bossier City, Louisiana.

Horsepower 15
Phase 1
Amps 57/29, 1-ϕ
Volts 220/440, 1-ϕ
Frequency 60 Hz
Type Open Wye

Manufacturer - Arco Electric Products Corporation
Shelbyville, Indiana.

Horsepower 15
Phase 1
Input Volts 230 V, 1-ϕ
Output Volts 230, 3-ϕ
Frequency 60 Hz
Model C

Manufacturer - Spindler Supply Company, Plymouth, Indiana.

Horsepower 30
Phase 1
Input Volts 208/220, 1-ϕ
Output Volts 220, 3-ϕ
Frequency 60 Hz
Model 6

Dynamometer Specifications

Manufacturer - Reliance Electric Company, Cleveland, Ohio.

V-S Drive, Rotating Power Conversion

Horsepower	20	L.R. Amps	432 - 456/228
Phase	3	Frame	D 20 VS
RPM	3530	DC Amps	72
Amps	69.4 - 68/34	DC Volts	240
Volts	208 - 220/440	Excitation	120V, 2.24 Amps
Frequency	60 Hz		

Power Matched RPM - DC Motor

Horsepower	20	Field Amps	1.6/.325
RPM	1750/4000	Windings	Stab-Shunt
Amp	72	Frame	287AT
Volt	240	Type	TR
Field Volts	240	Insulation Class	F
Field Max. Amps	2.27	Max. Amb.	40° C

Ventilation Motor - Forced Ventilation

Horsepower	0.5	Frequency	60 Hz
Phase	3	Type	P
RPM	3450	Locked KVA Code	L
Amps	2.2	Ins. Class	A
Volts	200	Max. Amb.	40° C

Transducer and Recording Instruments Specifications

Strain Gage Reaction Torque Sensor
Manufacturer - Lebow Associates Inc., Oak Park, Michigan.

Model 2540-2K, SN-106
Rated Capacity 60 Lb-Ft.
Max. Load 50% Overload
Signal Sensor 4 arm strain gage bridge
Usable Temp. (-50°F to 200°F)
Linearity (0.1% of rated capacity)

X-Y Recorder
Manufacturer - Hewlett Packard, Mosley Division, California.

Model 7000A
Input DC 0.1 mv/inch - 20 v/inch
AC 5 mv/inch - 20 v/inch
Input Impedance 1,000,000 ohms
Accuracy DC 0.2% FS, AC 0.5% FS, Time Sweep 2% FS
Power 115/230 V, 50/60 Hz, 60 volt-Amp to 90 volt-Amp.

Signal Conditioner
Manufacturer - Lebow Associates Inc., Oak Park, Michigan.

Model 7703
Signal Output 60 Lb-Ft = 6 volt, 4000 RPM = 10 volt
Capacity 0 to 10 volt analog signal
Digital Panel Meter AN 2500
Power Input 117 V Ac

Universal EPut and Timer
Manufacturer - Berkeley Division, Beckman Inc., Richmond, Ca.

Model 7350
Volts 117 Ac
Frequency 50-60 Hz
Watts 270

Temperature Recorder
Manufacturer - Honeywell, Brown Instruments Division, Pa.

Model 153X60 P16-X-31 F1 Modified Range (75° F to 320° F)
Range (-40° F to 140° F) Volts 115V AC. 60 Hz

Metering Instruments Specification

Instrument Current Transformer
Manufacturer - General Electric, Schenectady, New York.

Type JP-1
Frequency 25-125
Amps 10/20/50/100/200/300/400/600/800:5
Ratio 2/4/10/20/40/60/80/120/160:1

Variable Transformers (Powerstat)
Manufacturer - Superior Electric Company, Bristol, Connecticut.

Type 1256-3P: 2312
Primary volts 115/230
Output Volts Range 0-270
Max. FVA Output 22.7 at 84 Amps
Frequency 50/60 Hz, 1-ϕ

Stepdown Transformer
Manufacturer - Marcus Transformer Company Inc., Hillside, N.J.

Type F
Primary Volts 480
KVA 200
Phase 1
Frequency 60 Hz

Secondary Volts 120/240
Temp. Rise 80° C
Percent Impedance 4.7
Polarity ADD

Voltmeters, Ammeters, Wattmeters, and Power Factor Meters
Manufacturer - Yokogawa Electric Works (YEW), Tokyo, Japan.

Accuracy 0.5% Full Scale
Frequency 50-70 Hz
External Temp. Influence 0.1% Full Scale
External Field Influence 0.3% Full Scale

APPENDIX B: TYPES OF PHASE CONVERTERS

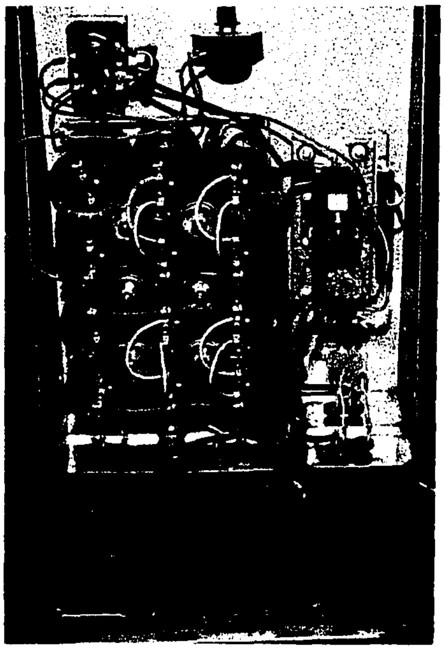


Figure 77. Capacitor type phase converter.

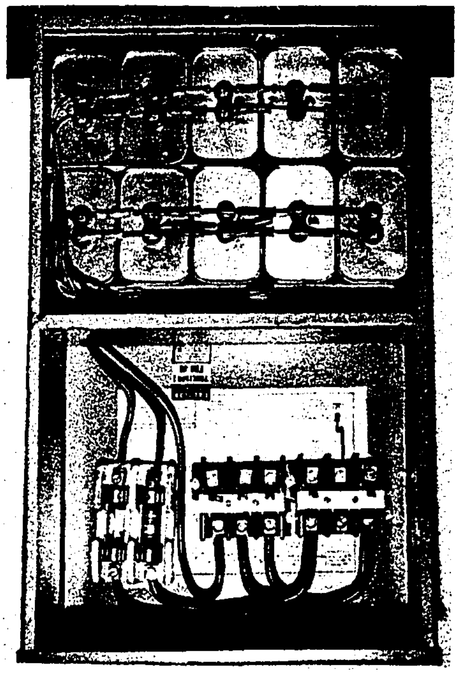


Figure 78. Capacitor type phase converter.

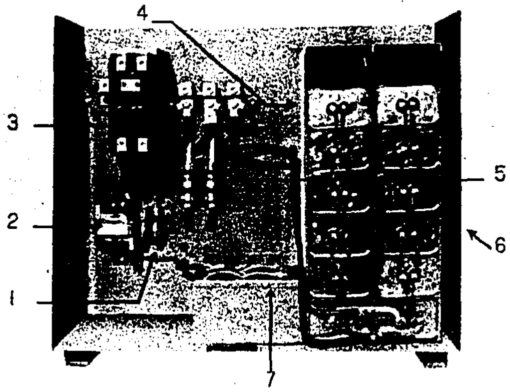


Figure 79. Capacitor type phase converter.

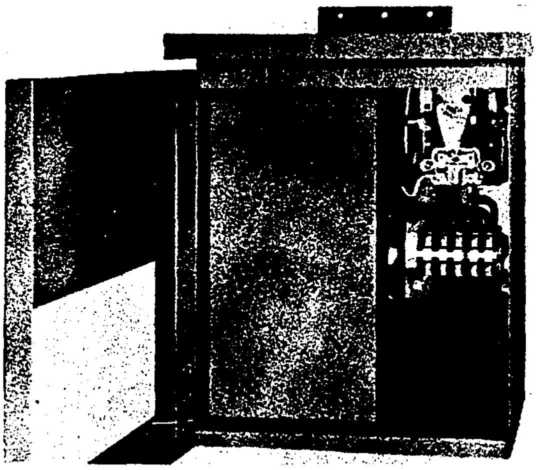


Figure 80. Capacitor type phase converter.

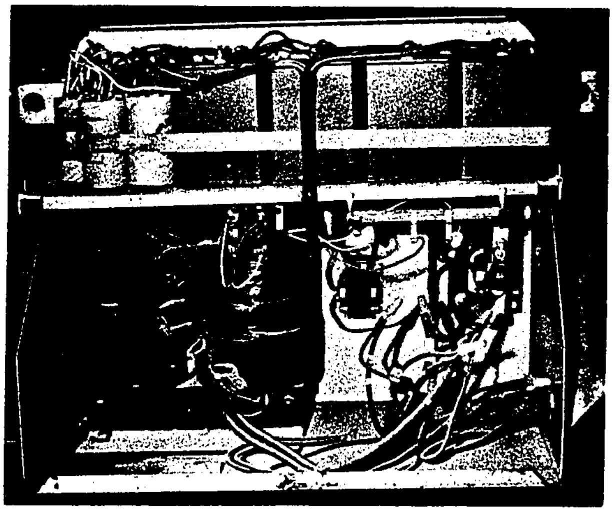


Figure 81. Autotransformer-capacitor phase converter.

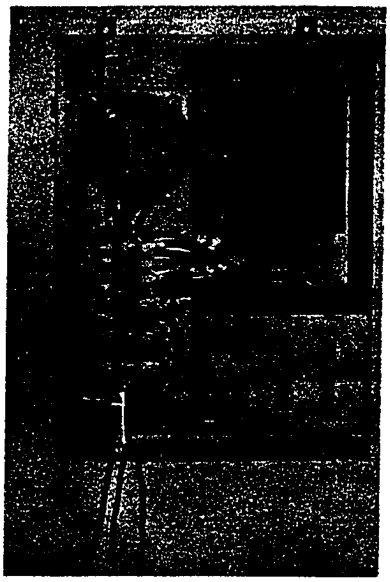
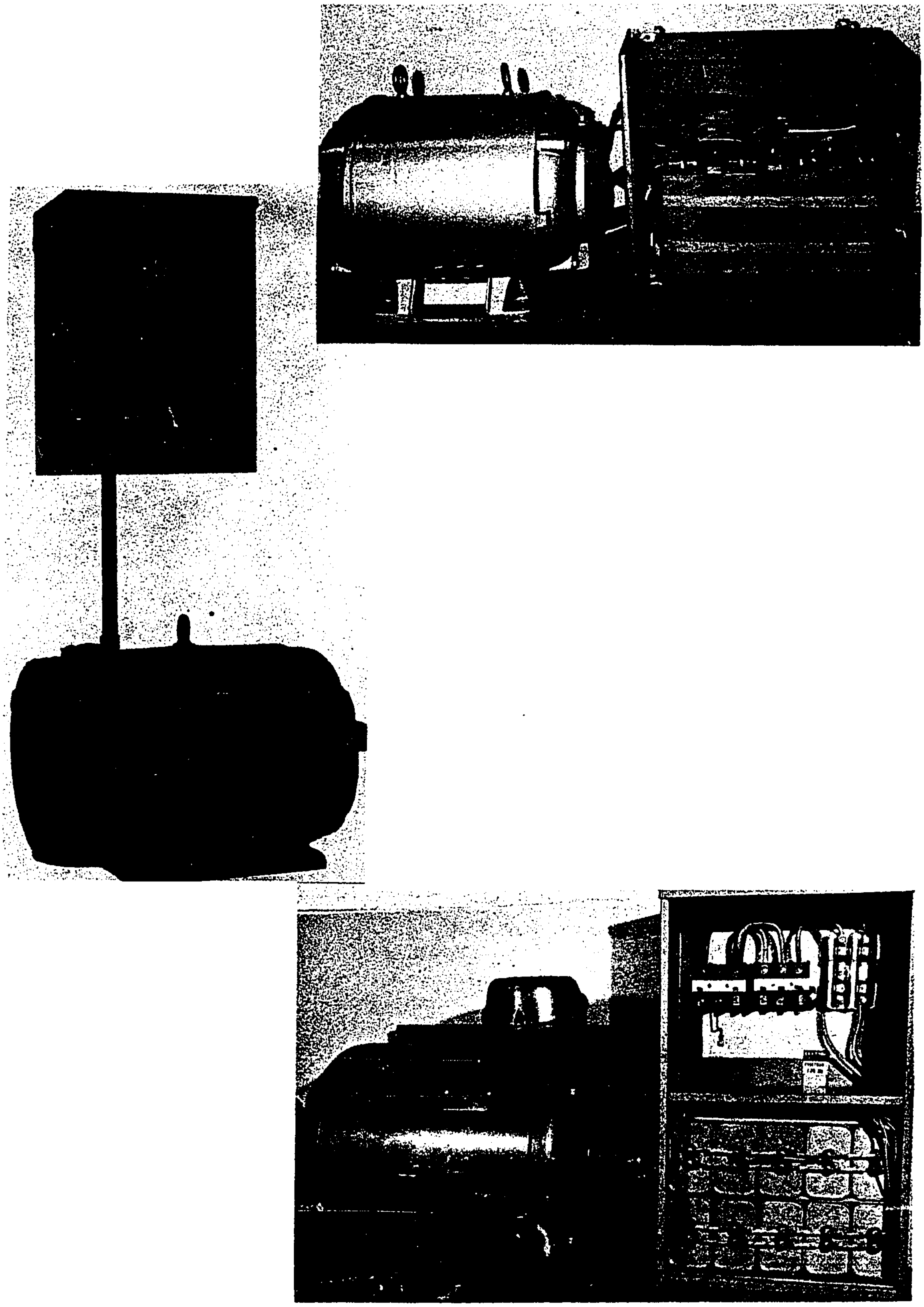


Figure 82. Autotransformer-capacitor phase converter.

Figure 83 (upper right). Rotary phase converter.

Figure 84 (center). Open-wye type phase converter.

Figure 85 (lower right). Rotary phase converter.



APPENDIX C: EXPERIMENTAL DATA

Table 17. Average cost of 3-ϕ motors, 1-ϕ motors, and phase converters (All figures are list price in dollars)

HP	3-ϕ Motor[a] Design B GP, DP 1800 RPM	1-ϕ Motor[b] Capacitor Start general purpose 1800 RPM	Static Converter			Rotary Converter		
				Identification letters				
			A	B	C	D	E	F
5	88	250	160	224	434	389	489	408
7-1/2	111	350	264	284	568	621	---	590
10	135	450[c]	319	340	678	707	789	684
15	180	900	434	469	886	945	997	908
20	226	1000	534	575	1124	1209	1249	1136
25	268	1170	671	716	1378	1540	1395	1504
30	314	1300	764	820	1536	1548	1495	1668
40	395	1600	962	1025	2134	1722	----	2218
50	477	2000	1150	1230	2588	2521	----	2686

[a] Average estimated cost from price list of 5 major manufacturers.

[b] Average estimated cost from price list of 3 major manufacturers.

[c] Many manufacturers do not make 1-ϕ motors larger than 10 HP.

Table 18. Locked-rotor torque of a 5-hp, T-frame, 230 volts, design B, three-phase motor vs. input line voltage at various values of starting capacitors used in an autotransformer-capacitor phase converter

1-ϕ V	V % of Rated	LRT Lb-Ft	1-ϕ V	V % of Rated	LRT Lb-Ft
Starting Capacitance = 0 μF			Starting Capacitance = 350 μF		
193	83.9	4.7	195	84.8	15.2
206	89.6	5.2	207	90.0	16.5
217	94.3	5.8	218	94.8	17.9
230	100.0	6.1	230	100.0	20.0
242	105.2	6.3	240	104.3	22.4
252	109.6	6.8	254	110.4	24.9
262	113.9	7.0	263	114.3	26.8
Starting Capacitance = 114 μF			Starting Capacitance = 468 μF		
196	85.2	7.1	194	84.3	18.5
207	90.0	8.1	206	89.6	21.0
221	96.1	8.8	218	94.8	24.0
231	100.4	9.3	230	100.0	26.5
242	105.2	10.2	240	104.3	28.5
251	109.1	10.8	252	109.6	31.0
264	114.8	11.5	265	115.2	34.4
Starting Capacitance = 236 μF			Starting Capacitance = 582 μF		
196	85.2	11.0	195	84.8	22.5
208	90.4	12.0	206	89.6	25.5
218	94.8	13.4	218	94.8	28.5
229	99.6	15.0	228	99.1	31.5
240	104.3	16.0	241	104.8	34.9
253	110.0	18.0	254	110.4	38.2
265	115.2	19.8	264	114.8	41.8

Table 18. Continued.

1-ϕ V	V % of Rated	LRT Lb-Ft	1-ϕ V	V % of Rated	LRT Lb-Ft
Starting Capacitance = 700 μF			Starting Capacitance = 927 μF		
196	85.2	25.7	195	84.8	29.1
207	90.0	29.0	207.5	90.2	31.5
218	94.8	32.0	218	94.8	33.5
230	100.0	35.0	231	100.4	36.5
242	105.2	38.0	241	104.8	41.0
253	110.0	41.0	253	110.0	44.0
264	114.8	44.7	264	114.8	48.0
Starting Capacitance = 814 μF			Starting Capacitance = 1041μF		
195	84.8	27.5	195	84.8	30.7
207	90.0	30.0	206	89.6	32.2
218	94.8	33.0	219	95.2	34.6
228	99.1	36.0	231	100.4	37.5
241	104.8	40.0	243	105.6	41.6
252	109.6	43.2	254	110.4	45.5
261	113.5	47.0	265	115.2	50.0

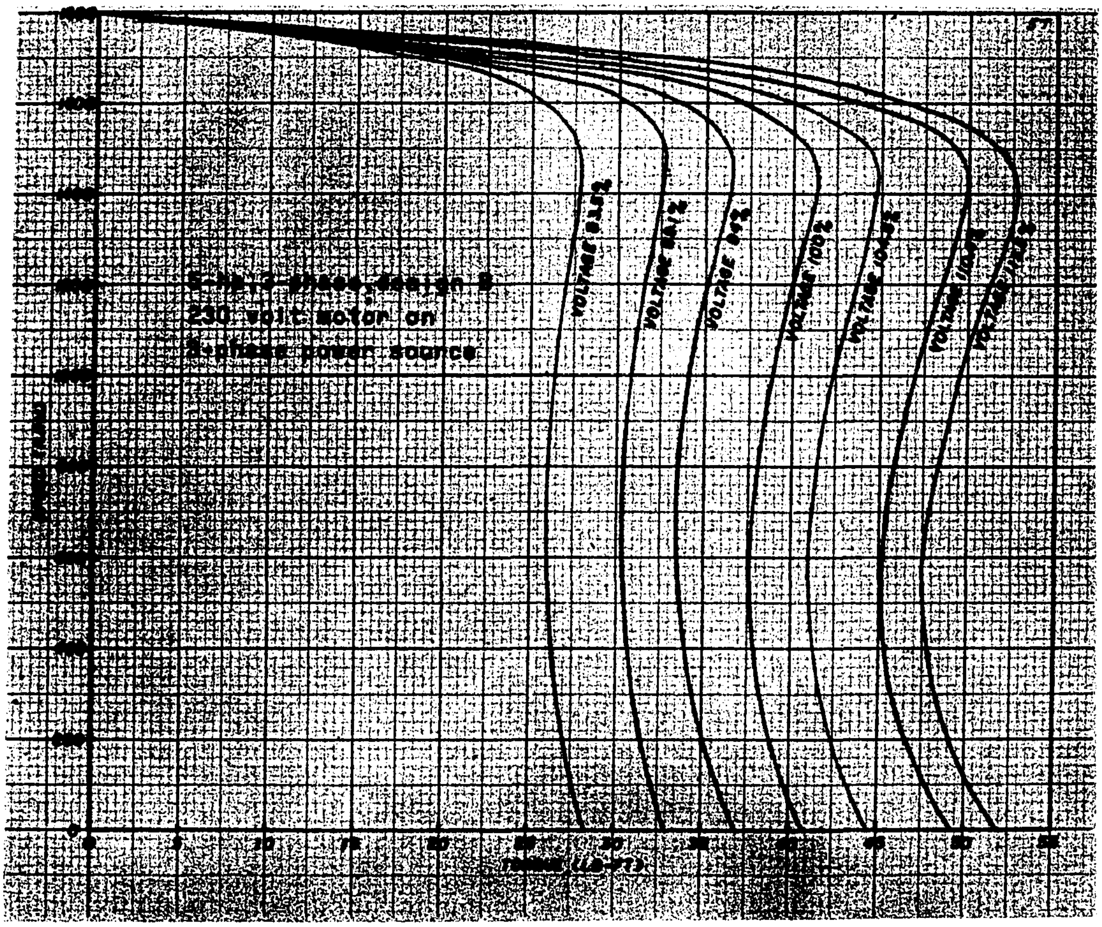


Figure 86. Torque-speed curve of a 5-hp, design B, 230 volts, three-phase motor at various three-phase line voltages.

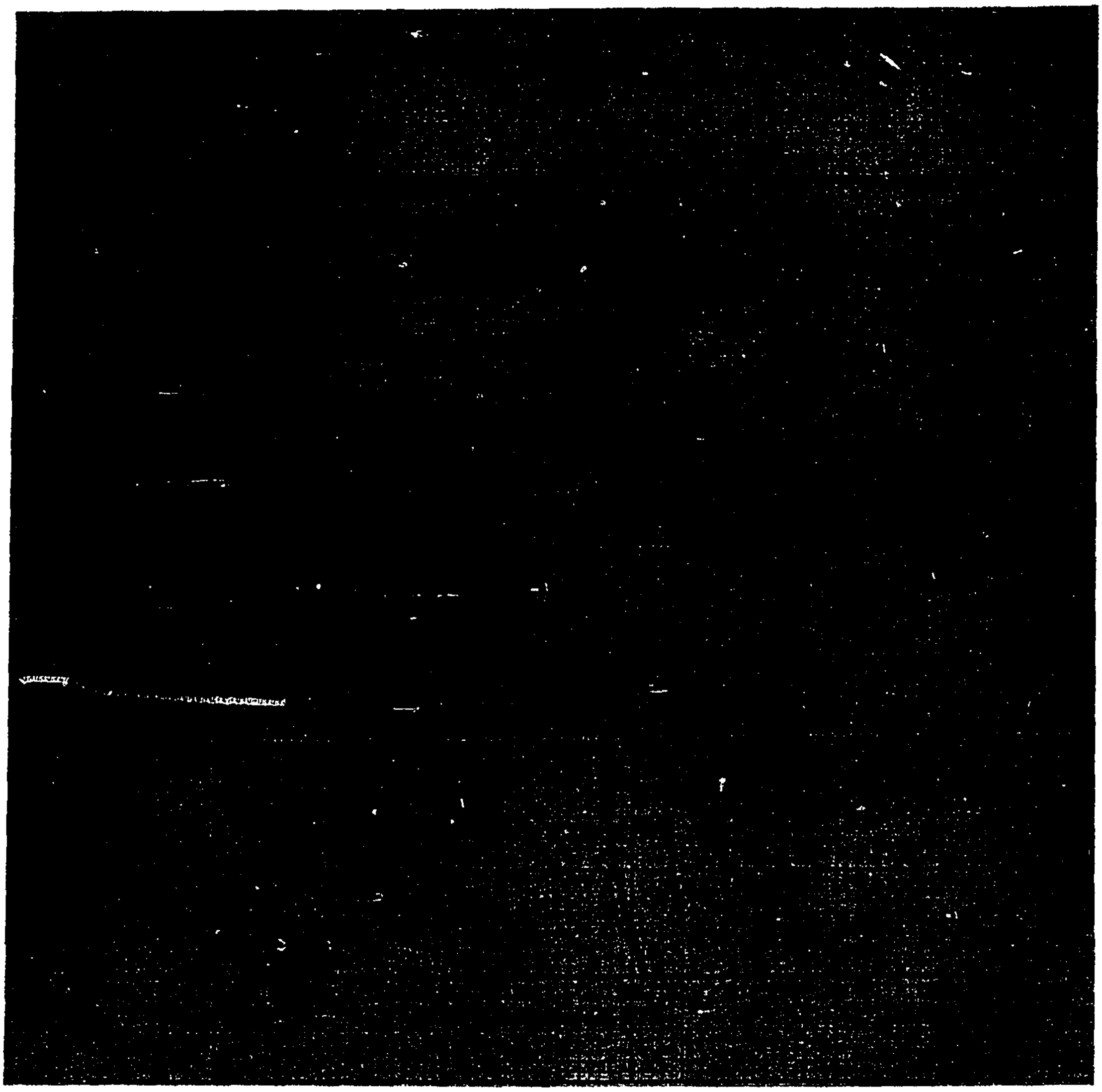


Figure 87. Torque-speed curves of an autotransformer phase converter operated 5-hp, design B, 230 volts, three-phase motor at various single-phase line voltages.

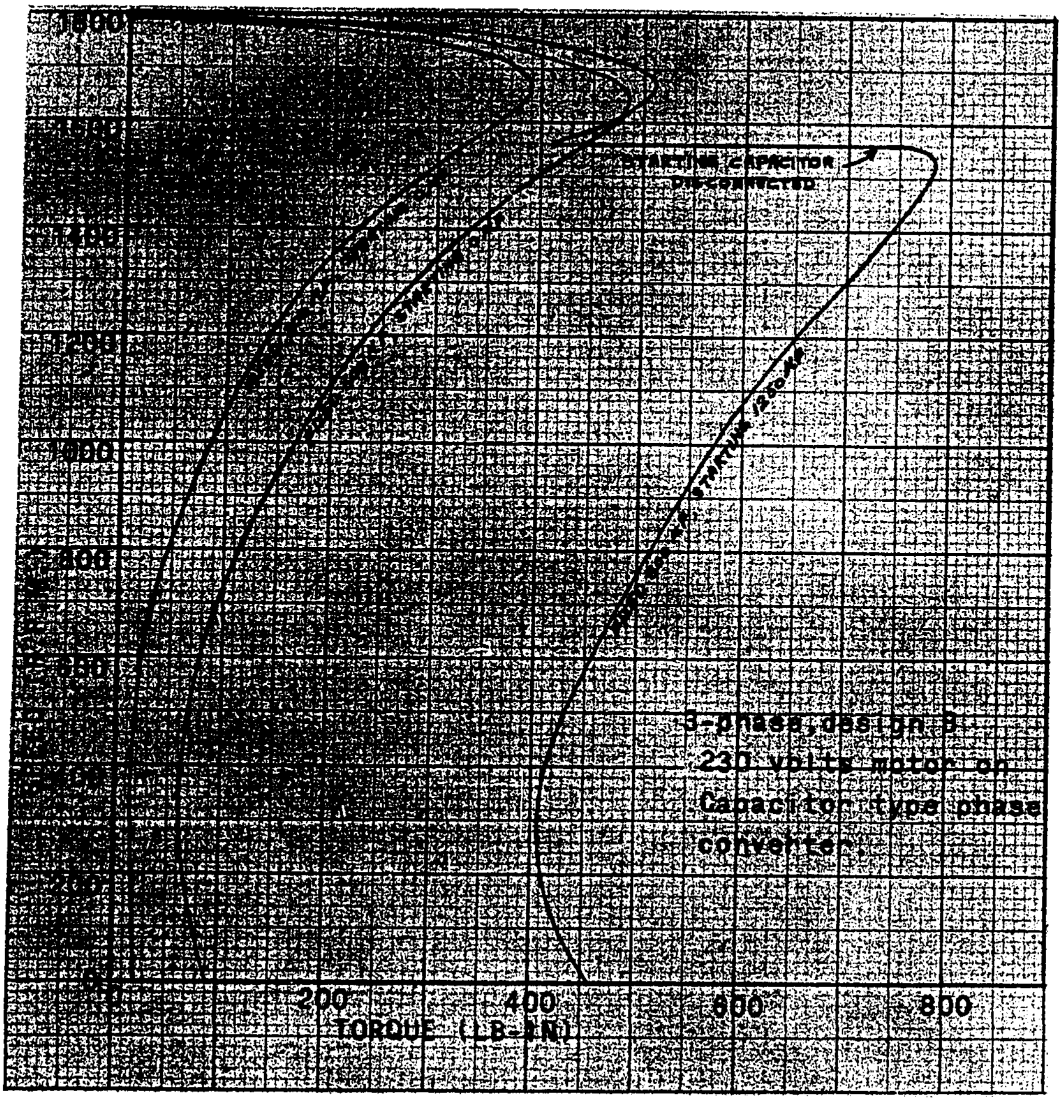


Figure 88. Torque-speed curves of a rotary phase converter operated 5-hp, design B, 230 volts, three-phase motor at various single-phase line voltages.

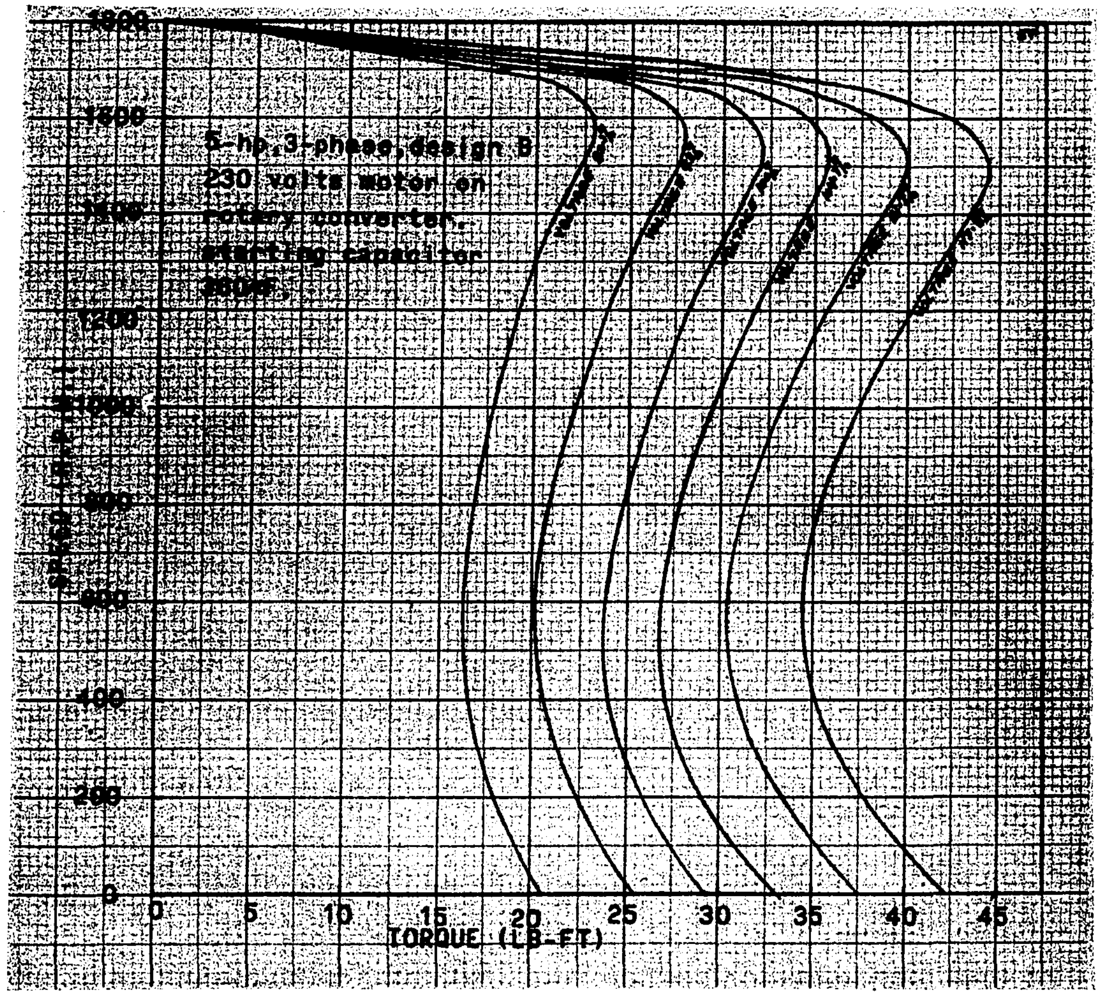


Figure 89. Dynamic torque-speed characteristics of a 10-hp, three-phase motor operated from a capacitor type phase converter.

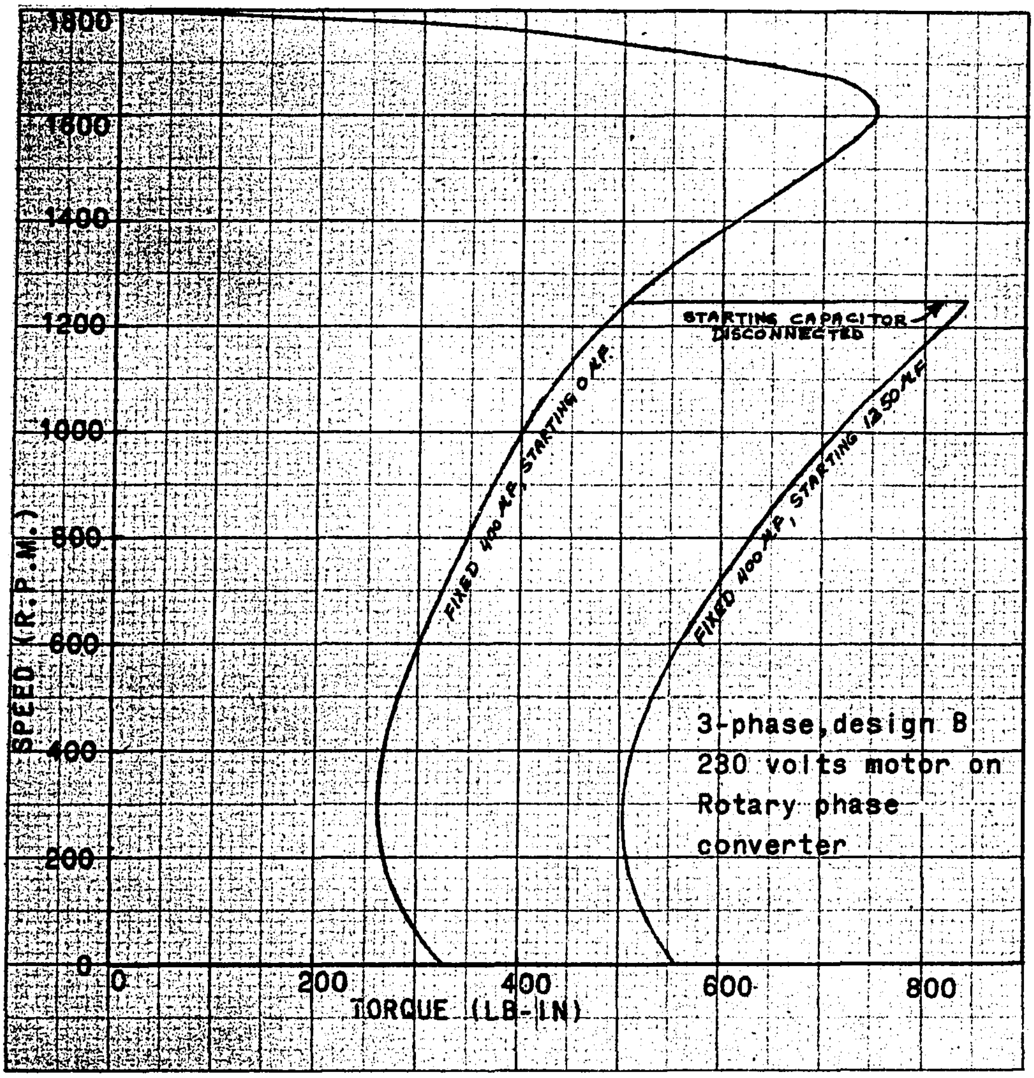


Figure 90. Dynamic torque-speed characteristics of a 10-hp, three-phase motor operated from a rotary phase converter.

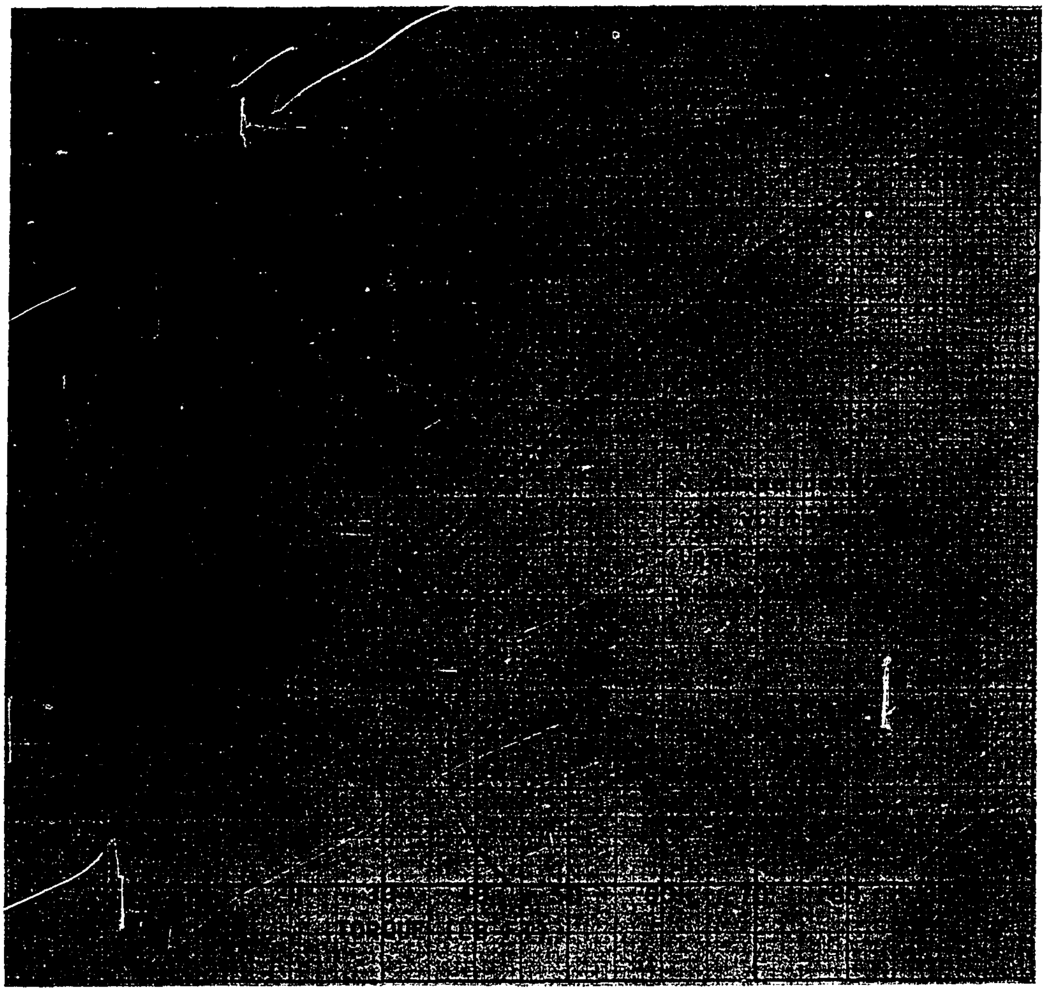


Figure 91. Dynamic torque-speed characteristics of a 10-hp, three-phase motor operated from an open wye type phase converter.

Table 19. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor on three-phase power supply.

LOAD LB-FT	LOAD % OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-ϕ PF(1)	3-ϕ PF(2)	SLIP %	EFFICIENCY %
0	0	1800	11.0	10.8	9.6	220	220	220	1.36	-.80	127	127	126.5	7.1	.12	.28	.16	.14	.15	0	0
3	10	1796	11.4	11.4	10.2	220	220	220	1.76	-.48	127	127	126.5	7.0	.36	.52	.40	.31	.31	.22	58.3
6	20	1792	12.4	12.4	11.2	220	220	220	2.16	-.08	127	127	126.5	7.3	.68	.80	.64	.45	.47	.44	71.7
9	30	1788	13.4	13.6	12.6	220	220	220	2.64	.32	127	127	126.5	7.2	.96	1.02	.96	.59	.59	.67	75.6
12	40	1784	14.8	14.8	14.0	220	220	220	3.08	.64	127	127	126.5	7.2	1.20	1.36	1.20	.67	.66	.89	80.2
15	50	1780	16.6	16.6	15.6	220	220	220	3.52	1.00	127	127	126.5	7.2	1.48	1.60	1.48	.73	.72	1.11	82.5
18	60	1775	18.8	18.8	17.6	220	220	220	4.04	1.40	127	127	126.5	7.3	1.76	1.88	1.84	.77	.76	1.39	82.3
21	70	1771	20.8	20.8	19.6	220	220	220	4.48	1.76	127	127	126.5	7.0	2.08	2.20	2.00	.80	.80	1.61	83.6
24	80	1767	23.0	22.8	22.0	220	220	220	5.00	2.08	127	127	126.5	7.2	2.32	2.48	2.32	.82	.81	1.83	84.3
27	90	1763	25.2	25.2	24.4	220	220	220	5.52	2.44	127	127	126.5	7.6	2.64	2.72	2.64	.84	.83	2.05	84.3
30	100	1758	28.0	27.6	27.0	220	220	220	6.12	2.72	127	127	126.5	7.5	2.96	2.96	2.96	.84	.84	2.33	84.4
33	110	1754	30.0	30.0	28.8	220	220	220	6.56	3.08	127	127	126.5	7.8	3.20	3.36	3.20	.85	.85	2.55	85.1
36	120	1747	32.4	32.4	31.2	220	220	220	7.12	3.40	127	127	126.5	7.8	3.52	3.60	3.48	.86	.85	2.94	85.1
39	130	1740	35.4	35.0	34.0	220	220	220	7.72	3.72	127	127	126.5	8.2	3.80	3.92	3.80	.86	.85	3.33	84.8
42	140	1732	38.2	38.0	36.4	220	220	220	8.36	4.04	127	127	126.5	8.4	4.12	4.24	4.08	.87	.86	3.78	84.2
45	150	1723	41.6	41.2	38.6	220	220	220	9.08	4.36	127	127	126.5	8.2	4.48	4.60	4.40	.87	.86	4.28	83.3

Table 20. Performance characteristics data of a 5-hp, T-frame, 230 volts, three-phase motor on three-phase supply.

LOAD LBFT	LOAD %OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP %	EFFICIENCY %
0	0	1800	8.4	8.3	8.0	230	230	230	1.14	-.70	133	133	133	.13	.17	.13	.14	0	0
3	20	1790	8.6	8.6	8.3	230	230	230	1.48	-.32	133	133	133	.35	.37	.35	.35	.56	64
6	40	1781	9.6	9.4	9.3	230	230	230	1.96	.02	133	133	133	.65	.67	.63	.51	1.8	75
9	60	1772	11.0	10.4	10.4	230	230	230	2.38	.36	133	133	133	.93	.91	.84	.61	1.6	80
10.5	70	1769	11.6	11.6	11.2	230	230	230	2.68	.52	133	133	133	1.08	1.05	1.00	.65	1.7	81
12.0	80	1758	12.6	12.4	12.0	230	230	230	2.86	.76	133	133	133	1.18	1.24	1.16	.706	2.3	82
13.5	90	1753	13.6	13.6	13.0	230	230	230	3.12	.96	133	133	133	1.34	1.40	1.31	.734	2.6	82.5
15.0	100	1745	14.8	14.6	14.2	230	230	230	3.32	1.20	133	133	133	1.50	1.56	1.48	.775	3.1	83
16.5	110	1739	15.6	15.6	15.0	230	230	230	3.58	1.28	133	133	133	1.62	1.66	1.60	.774	3.4	83.8
18.0	120	1734	16.4	16.4	15.8	230	230	230	3.78	1.42	133	133	133	1.73	1.77	1.70	.79	3.7	85
19.5	130	1727	17.2	17.2	16.6	230	230	230	3.98	1.56	133	133	133	1.84	1.88	1.82	.80	4.1	86
21.0	140	1714	19.4	19.2	18.6	230	230	230	4.12	1.84	133	133	133	2.00	2.04	1.98	.83	4.8	85

Table 21. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 80% of the rated load.

LOAD LB-FT	LOAD % OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP (%)	V_{T2} VOLT	V_C VOLT	1-Φ I AMP	1-Φ V VOLT	1-Φ KW	1-Φ PF(1)	1-Φ PF(2)	EFFICIENCY %
18	60	1777	15.2	17.2	23.2	220	234	228	3.48	2.04	134	131	125	68	.96	1.36	2.46	.91	1.28	384	355	29.5	220	6.00	.94	.93	74.6
21	70	1772	18.8	18.8	22.4	220	228	226	4.24	2.00	130	128	126	66	2.08	1.80	2.40	.85	1.56	384	347	32.0	220	6.70	.96	.95	78.0
24	80	1768	22.8	22.0	22.4	220	220	223	5.12	1.96	128	126	126	64	2.44	2.36	2.32	.79	1.78	384	340	35.2	220	7.50	.98	.97	80.0
27	90	1761	27.2	25.2	21.6	220	213	220	6.00	1.88	123	123	126	62	2.80	2.84	2.26	.74	2.17	384	332	38.0	220	8.40	.99	1.0	80.0
30	100	1753	32.0	29.6	21.2	220	205	218	6.96	1.84	120	121	126	59	3.20	3.60	2.18	.70	2.61	384	325	43.0	220	9.30	.99	.98	80.2
33	110	1742	38.0	36.4	20.4	220	195	213	8.16	1.76	114	118	127	56	3.70	4.16	2.08	.67	3.22	384	316	47.0	220	10.40	1.0	1.0	79.0
36	120	1726	45.6	45.2	20.0	220	182	206	9.60	1.64	105	114	126	51	4.30	5.00	1.92	.63	4.11	384	305	53.5	220	11.74	.99	.99	76.2

Table 22. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 90% of the rated load.

LOAD LB-FT	LOAD % OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP %	V_{T2} VOLT	V_C VOLT	1-Φ I AMP	1-Φ V VOLT	1-Φ KW	1-Φ PF(1)	1-Φ PF(2)	EFFICIENCY %
21	70	1773	17.6	18.4	24.8	220	234	228	4.04	2.24	133	130	127	68	2.04	1.62	2.62	.90	1.5	394	344	33.0	220	6.8	.93	.93	77.0
24	80	1768	21.6	21.0	24.0	220	227	226	4.84	2.24	130	128	126	66	240	2.12	2.58	.84	1.78	393	340	36.5	220	7.6	.94	.94	78.5
27	90	1761	25.0	24.0	24.0	220	220	223	5.84	2.16	126	125	126	64	2.80	2.72	2.48	.78	2.17	393	337	39.5	220	8.4	.97	.96	80.0
30	100	1754	30.0	28.8	23.0	220	210	220	6.80	2.08	122	123	127	61	3.20	3.28	2.42	.74	2.55	393	335	44.0	220	9.3	.98	.96	80.2
33	110	1745	36.0	34.4	22.4	220	200	214	7.84	2.00	116	120	126	57	3.64	3.92	2.26	.70	3.05	392	327	48.0	220	10.4	.99	.98	79.0
36	120	1729	42.8	42.4	21.6	220	188	208	9.12	1.84	110	118	127	53	4.14	4.74	2.10	.65	3.94	392	317	52.5	220	11.4	1.0	.99	78.5

Table 23. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 100% of the rated load.

LOAD LB-FT	LOAD % OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP %	V_{T2} VOLT	V_C VOLT	1-Φ I AMP	1-Φ V VOLT	1-Φ KW	1-Φ PF(1)	1-Φ PF(2)	EFFICIENCY %
21	70	1773	18.2	18.6	28.0	220	241	232	3.76	2.72	138	134	126	71	2.08	1.32	3.04	.96	1.50	403	358	37	220	7.0	.866	.860	74.6
24	80	1769	21.0	19.6	27.6	220	235	230	4.56	2.64	135	131	126	68	2.40	1.80	3.00	.90	1.72	403	355	39	220	7.7	.906	.897	77.5
27	90	1765	24.8	22.0	26.8	220	228	226	5.36	2.56	131	128	126	67	2.70	2.32	2.92	.86	1.94	400	355	41.5	220	8.5	.934	.931	79.0
30	100	1760	28.6	26.0	26.4	220	220	224	6.08	2.52	128	127	128	68	3.00	2.80	2.80	.81	2.22	403	353	44.5	220	9.4	.961	.960	79.4
33	110	1749	33.8	31.2	25.8	220	211	219	7.36	2.40	122	127	126	62	3.52	3.52	2.72	.75	2.83	402	340	48.0	220	10.3	.985	.975	79.7
36	120	1737	40.0	38.0	25.0	220	198	213	8.64	2.24	118	122	123	57	4.00	4.24	2.60	.70	3.50	403	332	52.0	220	11.4	.996	.996	78.5
39	130	1718	53.0	48.8	24.4	220	183	204	10.08	2.04	104	113	126	52	4.56	5.32	2.32	.66	4.56	402	317	58.2	220	12.8	.998	.999	75.8

Table 24. Performance characteristics data of a 5-hp, T-frame, 230 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 80% of the rated load.

LOAD LBFT	LOAD % OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP (%)	V_{T2} VOLT	V_C VOLT	1-Φ I AMP	1-Φ V VOLT	1-Φ KW	1-Φ PF(1)	1-Φ PF(2)	EFFICIENCY %
9	60	1773	9.4	11.2	13.0	230	242	237	2.08	.68	139	136	132	71.5	.86	.73	1.22	.75	1.5	316	302	14.0	230	3.12	.975	.97	72.7
10.5	70	1767	11.2	11.2	12.6	230	235	235	2.52	.68	135	134	132	69	1.08	.95	1.20	.71	1.83	315	295	15.8	230	3.56	.980	.980	74.0
12.0	80	1762	13.2	12.2	12.4	230	230	232	2.96	.66	132	131	132	67	1.30	1.20	1.16	.67	2.11	350	286	17.8	230	3.96	.980	.97	76.0
13.5	90	1754	14.8	13.0	12.2	230	224	230	3.34	.66	129	129	132	64.5	1.47	1.39	1.14	.65	2.56	350	282	20.2	230	4.36	.980	.95	77.2
15.0	100	1744	17.2	14.8	11.8	230	215	226	3.84	.62	124	126	132	62	1.72	1.67	1.09	.63	3.11	315	275	23.2	230	4.80	.975	.90	78.0
16.5	110	1733	19.4	17.0	11.4	230	207	221	4.32	.60	120	124	132	59	1.94	1.94	1.04	.61	3.72	315	265	25.0	230	5.28	.965	.973	77.0

Table 25. Performance characteristics data of a 5-hp, T-frame, 230 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 100% of the rated load.

LOAD LB-FT	LOAD %OF RATED	RPM	I_1 AMP	I_2 AMP	I_3 AMP	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-ϕ PF	SLIP (%)	V_{T2} VOLT	V_C VOLT	1-ϕ I AMP	1-ϕ V VOLT	1-ϕ KW	1-ϕ PF(1)	1-ϕ PF(2)	EFFICIENCY %
10.5	70	1766	9.2	12.8	15.4	230	248	239	2.12	1.22	142.0	138.0	130.0	73.5	.94	.82	.162	.9062	1.89	365	345	16.4	230	3.72	.990	.99	70.8
12.0	80	1761	10.8	12.8	15.0	230	243	236	2.50	1.20	139	136	131	71.5	.112	.101	.159	.8543	2.17	365	340	17.92	230	4.08	.992	.99	73.7
13.5	90	1759	11.8	13.2	14.84	230	240	235	2.70	1.20	138	135	132	70.0	.120	.113	.157	.8322	2.28	365	335	18.70	230	4.42	.995	1.0	76.3
15.0	100	1752	14.4	14.4	14.6	230	230	230	3.38	1.16	132	132	132	67	.152	.152	.151	.7631	2.67	365	325	21.4	230	4.80	.999	.98	78.0
16.5	110	1741	15.8	15.2	14.4	230	227	229	3.60	1.14	130	130	132	65.5	.163	.162	.148	.7438	3.28	365	324	22.24	230	5.12	1.00	1.0	79.7
18.0	120	1731	17.8	16.8	14.0	230	220	225	4.04	1.05	126	128	132	63.0	.182	.188	.143	.7014	3.83	365	316	24.0	230	5.52	.999	1.0	80.3
19.5	130	1715	20.86	19.7	13.6	230	208	217	4.68	1.04	119	125	130	59.0	.211	.227	.135	.6720	4.72	365	307	26.8	230	6.14	.995	.997	77.3

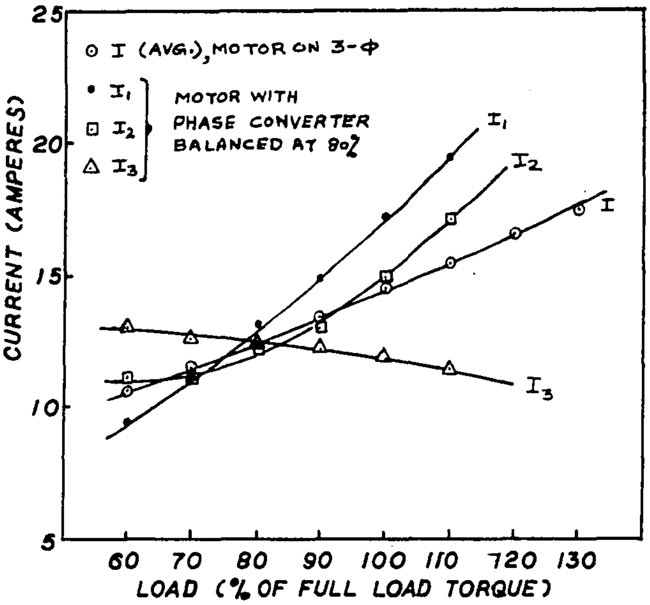


Figure 92. Current vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80% of the rated load.

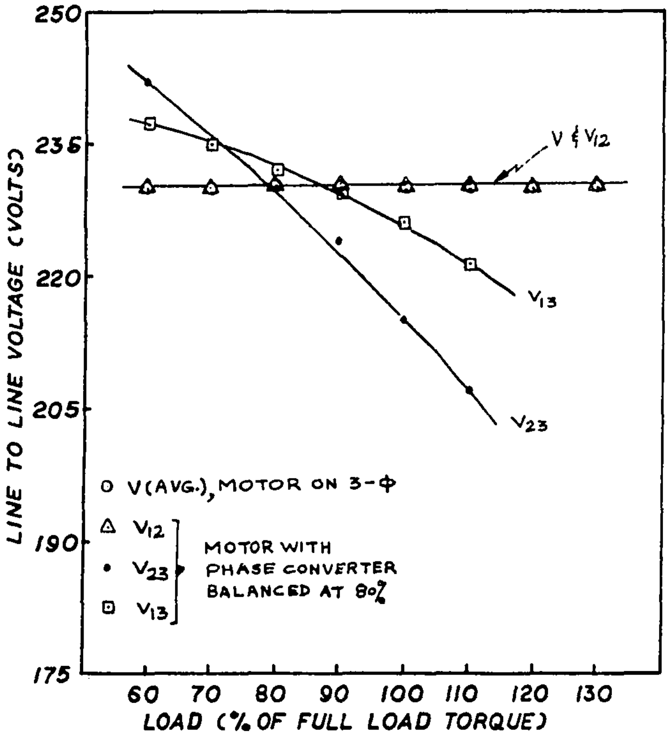


Figure 93. Voltage vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80% of the rated load.

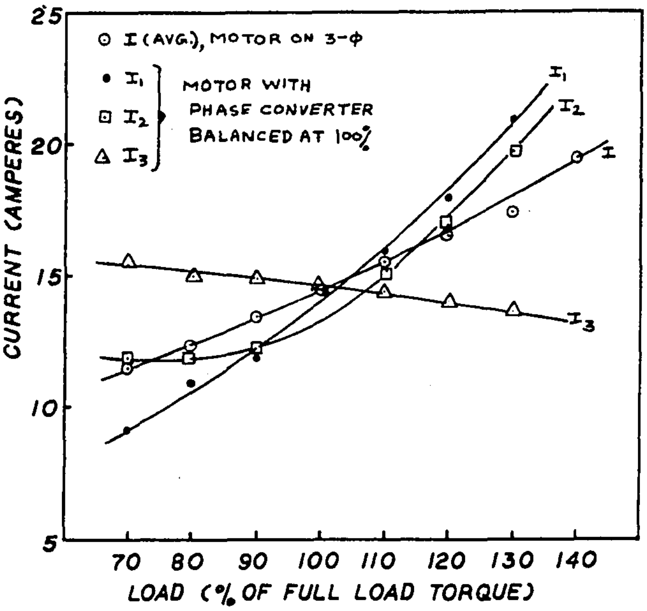


Figure 94. Current vs. load of a 5-hp motor with the converter adjusted for balanced operation at 100% of the rated load.

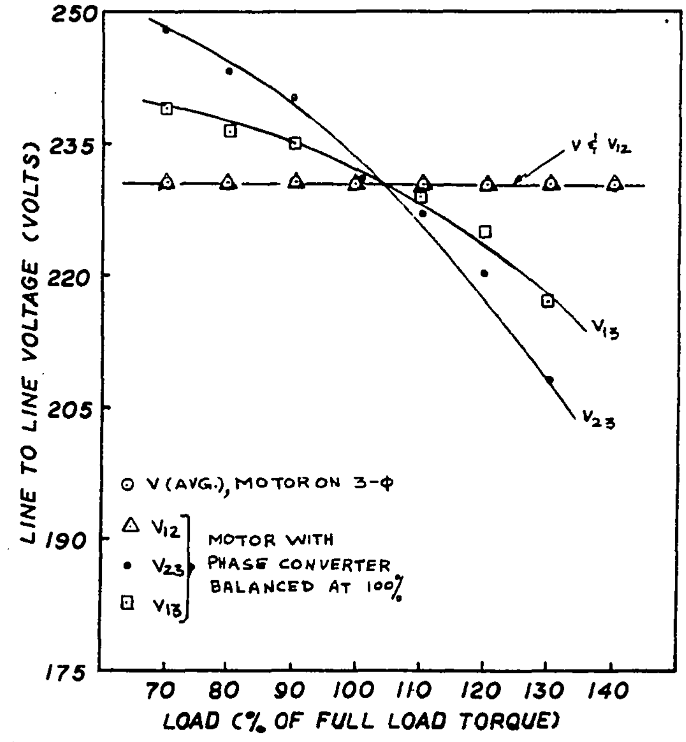


Figure 95. Voltage vs. load of a 5-hp motor with the converter adjusted for balanced operation at 100% of the rated load.

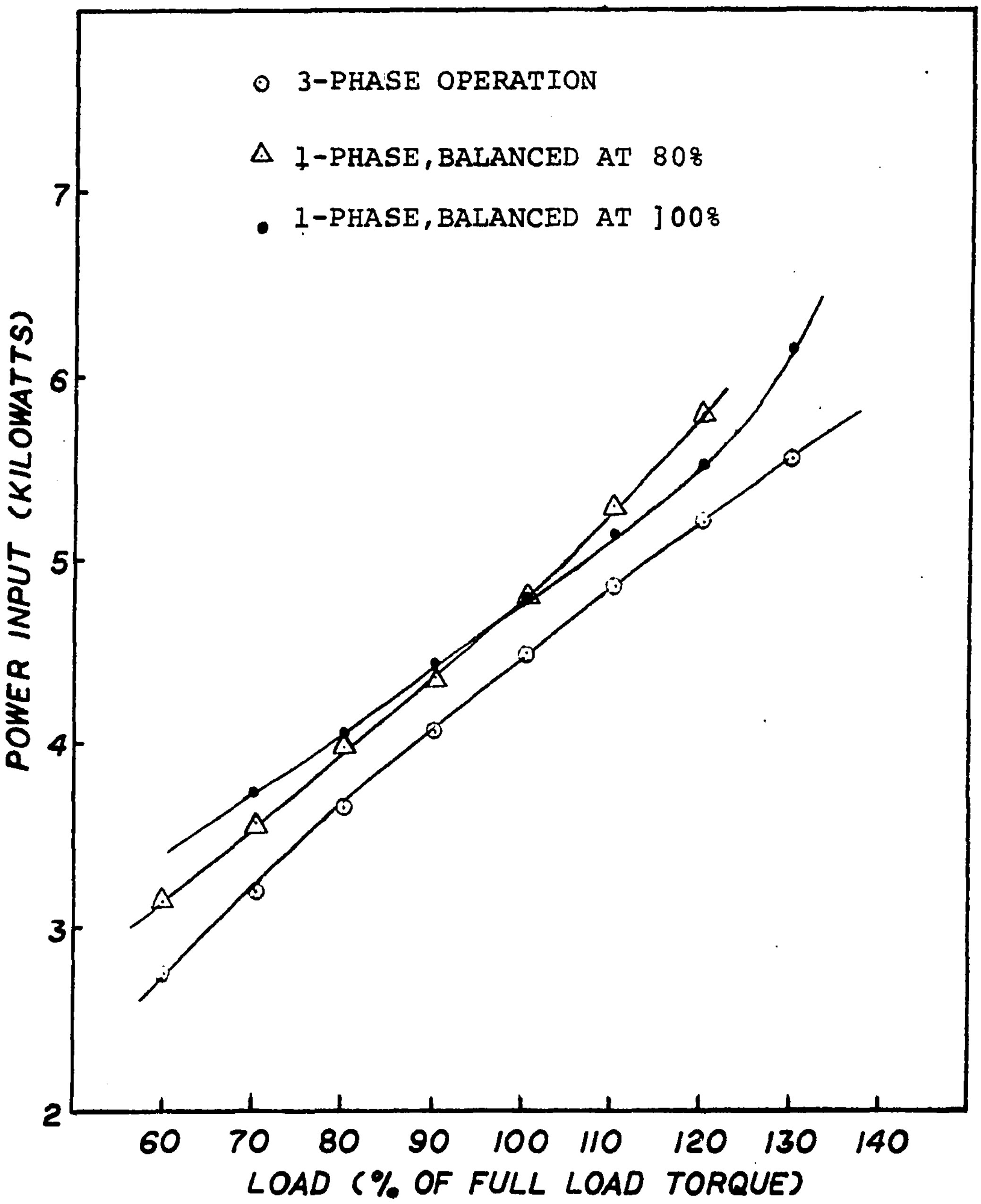


Figure 96. Power input vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80, and 100% of the rated load.

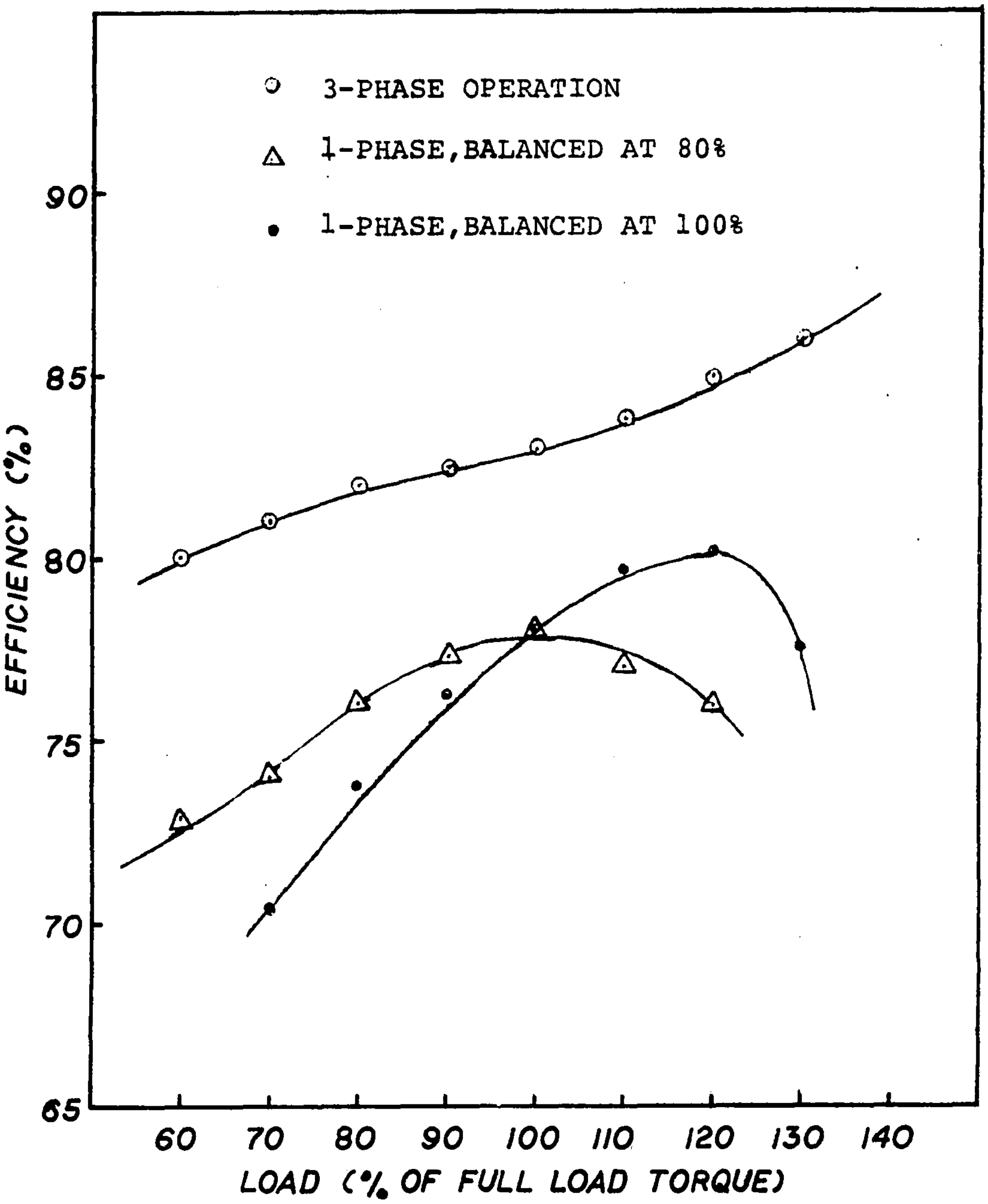


Figure 97. Efficiency vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80, and 100% of the rated load.

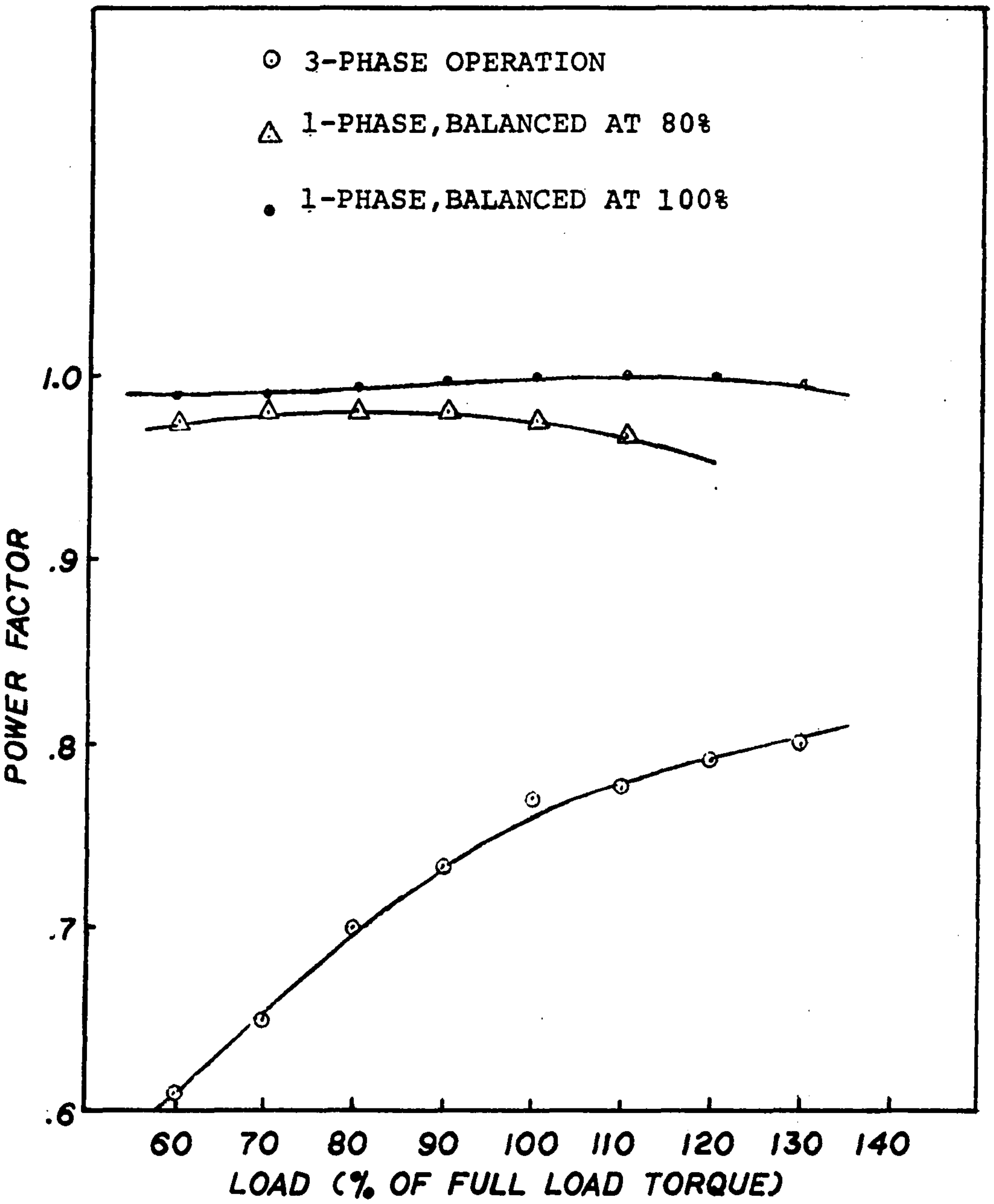


Figure 98. Power factor vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80, and 100% of the rated load.

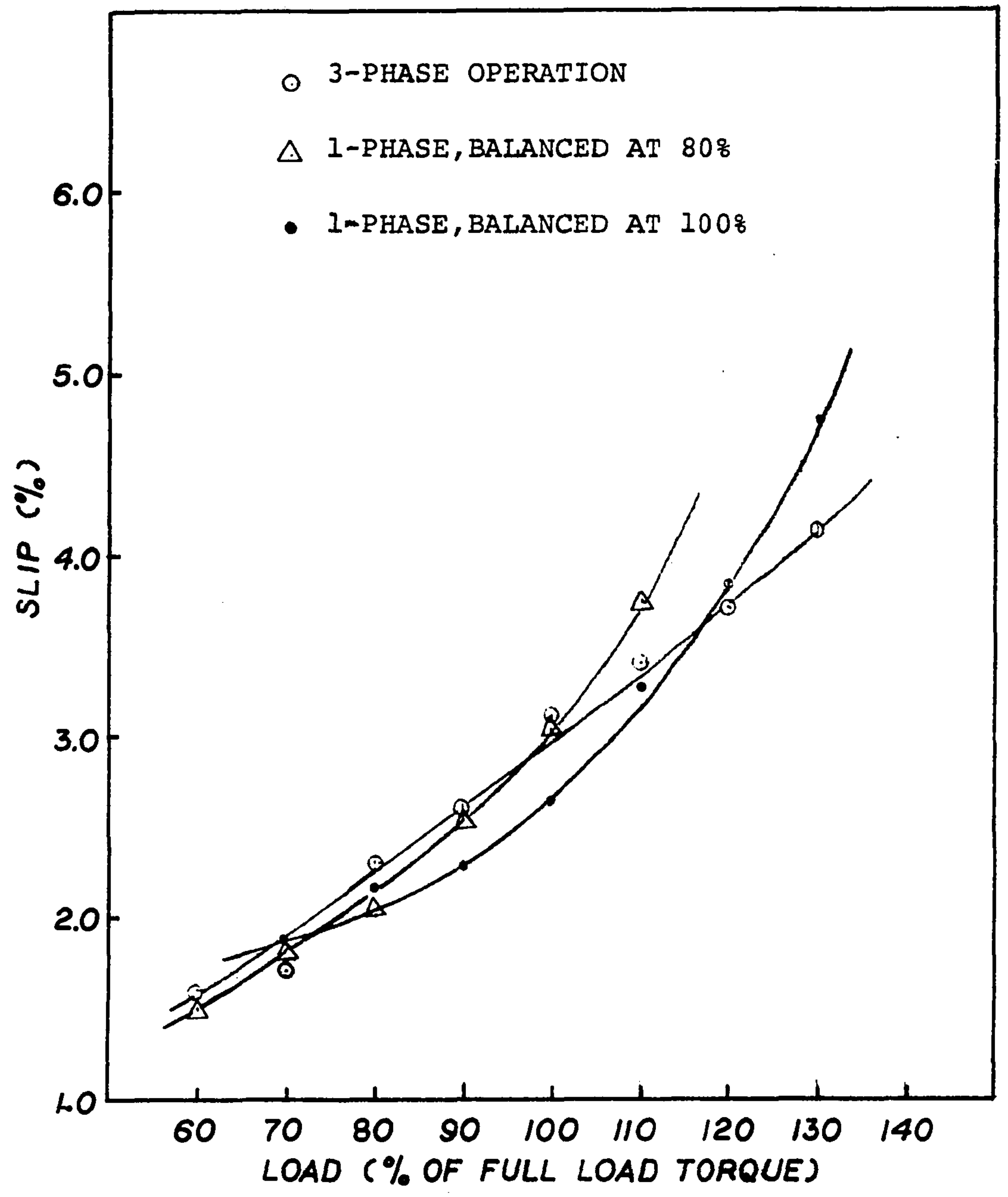


Figure 99. Slip vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80, and 100% of the rated load.

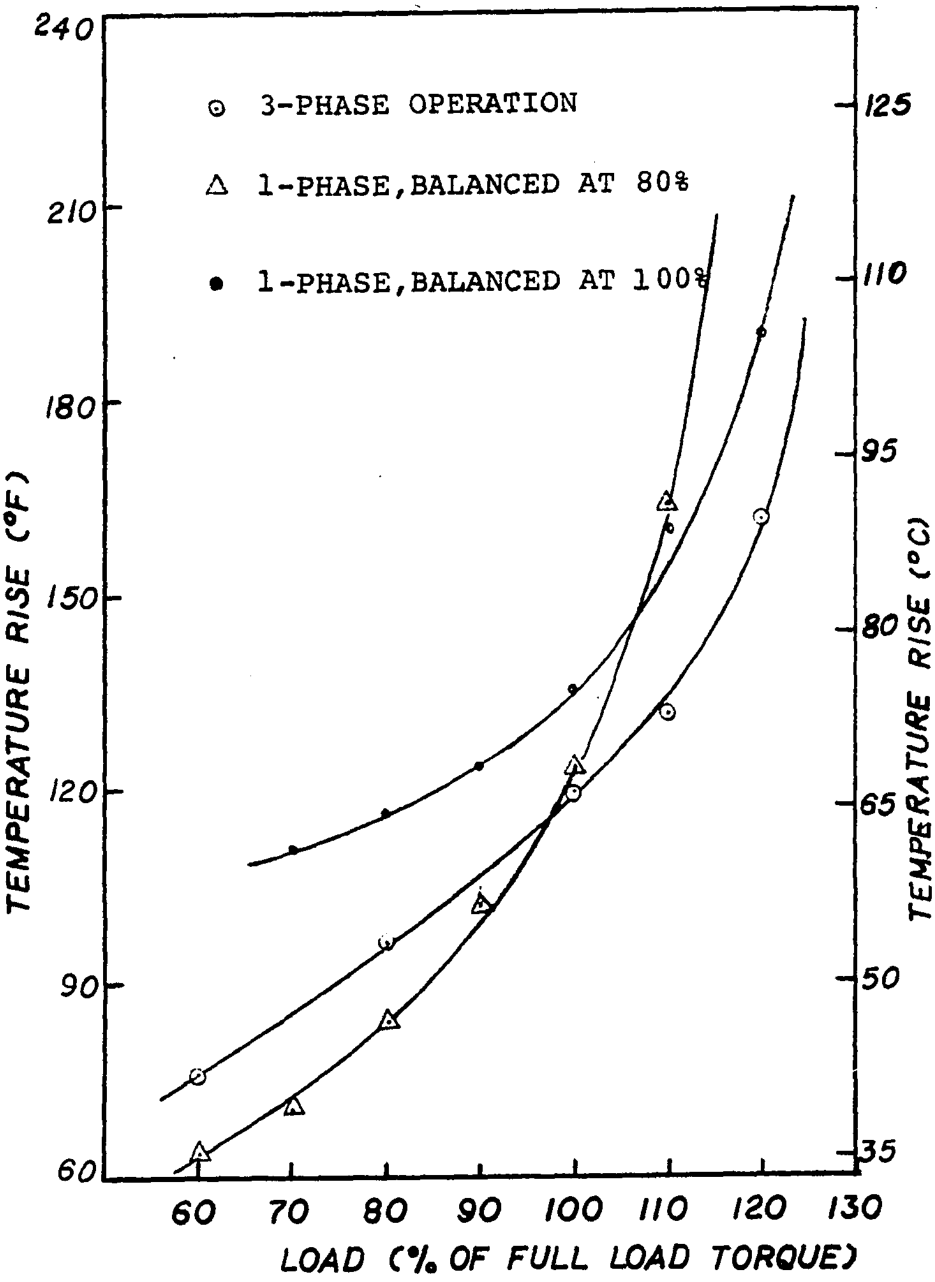


Figure 100. Temperature rise vs. load of a 5-hp motor with the converter adjusted for balanced operation at 80, and 100% of the rated load.

Table 26. Effects of three-phase voltage variation on the performance of 5-hp, T-frame, 230 volts, three-phase motor.

V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	V_{AVG} VOLT	V % OF RATED	LOAD LBFT	RPM	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	PF	SLIP %	EFFICIENCY %	TEMP RISE °F
196	196	196	196	85.2	15.2	1720	16.0	15.8	15.4	3.14	1.34	112	112	112	1.5	1.52	1.48	.84	4.44	83	147
208	208	208	208	90	15.2	1732	15.2	15.0	14.8	3.16	1.28	119	119	119	1.5	1.5	1.48	.82	3.78	84	130
218.5	218.5	218.5	218.5	95	15.2	1738	14.6	14.6	14.0	3.24	1.18	126	126	126	1.49	1.51	1.46	.82	3.44	85	122
230	230	230	230	100	15.2	1745	14.6	14.4	14.4	3.36	1.06	132	132	132	1.52	1.48	1.50	.80	3.05	85	119
241.5	241.5	241.5	241.5	105	15.2	1753	14.6	14.4	14.4	3.46	.96	139	139	139	1.53	1.54	1.50	.76	2.61	86	122
253	253	253	253	110	15.2	1755	15.4	15.2	15.2	3.72	.76	146	146	146	1.56	1.54	1.52	.69	2.50	86	129
264.5	264.5	264.5	264.5	115	15.2	1759	16.6	16.4	16.0	4.04	.60	152	152	152	1.58	1.61	1.53	.63	2.28	81	148

Table 27. Pull-up and break-down torque.

V_{AVG} VOLT	V % OF RATED	P.U.T. LB-FT	B.D.T. LB-FT
190	82.5	26.0	27.75
204	88.7	30.0	32.5
216	94.0	33.5	36.5
230	100	37.5	41.0
241	104.8	41.0	44.75
254	110.4	45.0	49.75
261	113.5	47.5	52.5

Table 28. Locked-rotor torque and current.

V_{AVG} VOLT	V % OF RATED	I_1 AMP	I_2 AMP	I_3 AMP	I_{AVG} AMP	LRT LB-FT
200	87	77	79	79	78.3	32
208	90.4	80	82	82	81.3	37
217	94.3	82	84	84	83.3	37.4
225	97.8	84	86	86	85.3	39
230	100	87	89	89	88.3	45
236	102.6	89	90	90	89.6	43
244	106.1	91	94	94	93	46
254	110	92	96	96	94.6	55

Table 29. Effects of single-phase voltage variation on the performance of a 5-hp, T-frame, 230 volts, three-phase motor with autotransformer-capacitor converter adjusted for balanced operation at 100% of the rated load.

1-Φ V VOLT	V % OF RATED	1-Φ I AMP	1-Φ KW	1-Φ PF(1)	1-Φ PF(2)	LOAD LBFT	RPN	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	3-Φ PF	SLIP %	EFFICIENCY %	TEMP RISE °F
200	86.9	25.0	5.0	.995	1.0	15.2	1700	200	174	185	20.8	19.8	11.6	4.04	.76	100	107	114	1.82	2.0	.99	.65	5.56	73.4	—
207	90	24.2	4.9	.999	.98	15.2	1719	207	190	200	18.2	17.0	12.4	3.70	.86	109	113	118	1.70	1.74	1.12	.68	4.5	75.8	175
218.5	95	24.0	4.85	.999	.93	15.2	1737	218	213	218	15.8	14.6	13.4	3.44	1.02	123	123	125	1.59	1.54	1.54	.73	3.5	77.4	130
230	100	23.0	4.8	1.0	.91	15.2	1749	230	229	230	14.6	14.4	14.6	3.32	1.16	133	133	132	1.49	1.47	1.53	.77	2.83	78.6	123
241.5	105	21.0	4.9	.999	.97	15.2	1754	242	249	244	13.4	15.2	15.6	3.22	1.32	142	141	138	1.37	1.46	1.70	.81	2.56	77.3	127
252.5	110	20.0	5.0	.995	.99	15.2	1758	252	261	251	13.2	16.6	16.4	3.20	1.40	148	148	142	1.26	1.41	1.84	.83	2.33	76.0	136

Table 30. Pull-up, breakdown, and locked rotor torque vs. single-phase voltage.

1-Φ V VOLT	V % OF RATED	P.U.T. LBFT	B.D.T. LBFT	L.R.T. LBFT
200	86.9	18.5	25.2	20
207	90.0	20.0	26.5	21.5
216	94.0	22.0	28.4	23.5
226	98.3	23.5	30.2	25.5
242	105.2	26.5	33.0	28.0
253	110.0	29.0	36.4	30.5
266	115.6	32.0	40.7	34.0

Table 31. Effects of single-phase voltage variation on the performance of a 5-hp, T-frame, 230 volts, three-phase motor with a 10-hp rotary converter.

$1-\phi$ V VOLT	V %OF RATED	$1-\phi$ I AMP	$1-\phi$ KW	$1-\phi$ PF(1)	$1-\phi$ PF(2)	LOAD LB-FT	RPM	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	$3-\phi$ PF	SLIP %	EFFICIENCY %	TEMP RISE °F
195.5	85	36.0	5.24	0.73	0.74	15.2	1707	195	189	189	16.6	17.6	15.0	3.24	1.36	107	111	110	1.50	1.70	1.43	0.816	5.17	70.3	143
207	90	36.0	5.24	0.69	0.70	15.2	1724	206	203	200	15.2	16.6	14.2	3.12	1.40	114	118	116	1.42	1.68	1.44	0.835	4.22	71.0	135
218.5	95	37.2	5.32	0.64	0.65	15.2	1739	217	215	210	14.2	16.4	13.8	3.08	1.40	120	125	122	1.35	1.70	1.46	0.838	3.39	70.5	131
230	100	39.8	5.44	0.58	0.59	15.2	1743	230	227	220	13.8	16.6	13.4	3.06	1.42	126	132	128	1.26	1.76	1.47	0.844	3.17	69.1	131
241.5	105	43.6	5.72	0.53	0.54	15.2	1746	241	239	228	13.6	17.2	13.2	3.16	1.42	131	140	133	1.23	1.87	1.49	0.835	3.00	65.8	138
253	110	48.8	5.96	0.47	0.48	15.2	1749	253	249	237	13.8	18.0	12.8	3.20	1.36	136	146	139	1.12	1.96	1.48	0.819	2.80	63.3	149
264.5	115	54.8	6.40	0.43	0.44	15.2	1751	264	258	244	14.8	19.4	12.8	3.36	1.32	140	153	144	1.06	2.14	1.48	0.800	2.75	59.0	176

Table 32. Pull-up, breakdown, and locked rotor torque of a 5-hp, T-frame, 230 volts, three-phase motor vs. single-phase line voltage with a 10 hp rotary converter.

1—φ V VOLT	V % OF RATED	P.U.T. LB-FT	B.D.T. LB-FT	L.R.T. LB-FT
189	82.2	16.5	23.0	20.5
202	87.8	18.5	25.3	23.5
214	93.0	20.2	28.0	25.5
223	97.0	22.2	30.2	27.5
230	100.0	23.7	32.0	29.3
241	104.8	27.2	35.7	32.5
257	111.7	30.5	39.7	37.5
271	117.8	34.5	44.4	42.0

Table 33. Performance characteristics data of a 10-hp, T-frame, design B, 230 volts, three-phase motor on three-phase power supply.

LOAD LB-FT	LOAD %OF RATED	RPM	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	PF	SLIP %	EFFICIENCY %	TEMP RISE °F
0	0	1800	230	230	230	10.4	10.0	10.0	1.28	-1.00	132	133	131	16.7	0.08	0.12	0.11	0.071	0	0	—
3	10	1796	230	230	230	10.4	10.4	10.4	1.68	-0.60	132	132	130	16.6	0.30	0.38	0.34	0.264	0.22	73.13	—
6	20	1792	230	230	230	11.2	11.2	10.8	2.08	-0.32	131	132	130	16.6	0.56	0.60	0.60	0.390	0.44	84.77	—
9	30	1789	230	230	230	12.4	12.4	12.0	2.48	0.08	132	132	130	16.6	0.80	0.92	0.86	0.524	0.61	86.74	—
12	40	1785	230	230	230	13.6	13.6	13.6	2.96	0.40	132	132	131	16.6	1.10	1.14	1.12	0.604	0.833	88.81	—
15	50	1780	230	230	230	15.2	15.2	14.8	3.40	0.80	132	132	131	16.6	1.36	1.42	1.38	0.682	1.11	89.66	55
18	60	1777	230	230	230	17.0	17.0	16.8	3.84	1.12	132	132	131	16.5	1.62	1.70	1.64	0.725	1.28	90.24	58
21	70	1772	230	230	230	18.8	18.6	18.4	4.32	1.48	132	132	131	16.5	1.92	1.98	1.92	0.763	1.56	89.72	71
24	80	1767	230	230	230	20.8	20.8	20.0	4.80	1.92	131	132	130	16.4	2.16	2.32	2.20	0.803	1.83	89.34	85
27	90	1761	230	230	230	23.2	23.0	22.8	5.40	2.28	131	132	130	16.4	2.52	2.60	2.52	0.818	2.17	87.88	99
30	100	1756	230	230	230	25.6	25.6	25.2	5.96	2.64	131	132	130	16.5	2.86	2.88	2.86	0.831	2.44	86.74	122
33	110	1749	230	230	230	28.0	28.0	27.6	6.56	3.04	131	132	131	16.6	3.18	3.20	3.16	0.844	2.83	86.02	145
36	120	1742	230	230	230	30.8	30.4	30.0	7.20	3.36	131	132	130	16.9	3.52	3.54	3.54	0.846	3.22	84.45	167
39	130	1734	230	230	230	33.6	33.2	32.8	7.80	3.80	132	132	131	17.1	3.84	3.90	3.80	0.858	3.67	84.03	—
42	140	1725	230	230	230	36.4	36.0	35.6	8.44	4.12	132	133	130	17.5	4.20	4.26	4.16	0.859	4.17	82.75	—
45	150	1716	230	230	230	39.2	38.8	38.4	9.20	4.52	131	132	130	18.0	4.60	4.62	4.52	0.861	4.67	81.44	—

Table 34. Effects of unbalanced voltage on the performance of a 10-hp, T-frame, 230 volts, three-phase motor loaded at 80% of the rated horsepower on three-phase line.

V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	UNBALANCE %	RPM	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
230	218	210	4.863	1759	20.0	28.4	17.6	4.36	2.52	126	131	117	9.5	1.64	3.20	2.04	2.277	86.74	124
230	221	216	3.448	1760	20.0	26.4	17.6	4.48	2.28	128	132	121	11.0	1.78	3.00	2.04	2.222	87.50	107
230	224	222	2.071	1761	20.4	23.6	18.4	4.68	2.04	129	132	125	12.1	1.98	2.68	2.08	2.166	88.54	96
230	227	227	0.8771	1763	20.8	21.2	19.2	4.84	1.88	130	132	128	13.5	2.14	2.44	2.12	2.055	89.07	92
230	233	239	2.136	1765	22.0	17.6	21.6	5.16	1.60	134	132	137	17.6	2.48	1.92	2.24	1.944	89.87	92
230	237	244	2.953	1769	22.4	16.0	23.2	5.24	1.48	135	133	138	19.0	2.68	1.70	2.34	1.722	88.81	97

Table 35. Effects of unbalanced voltage on the performance of a 10-hp, T-frame, 230 volts, three-phase motor loaded at 100% of the rated horsepower on three-phase line.

V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	UNBALANCE %	RPM	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
230	218	207	5.344	1750	24.4	35.6	23.2	5.44	3.48	125	132	116	8.2	2.18	4.12	2.68	2.777	83.07	178
230	221	213	3.916	1750	24.8	33.2	23.6	5.60	3.24	127	132	120	9.0	2.34	3.84	2.70	2.777	84.01	160
230	224	220	2.374	1751	25.2	30.4	23.6	5.80	3.00	128	132	123	10.3	2.54	3.58	2.74	2.722	84.19	140
230	226	225	1.321	1751	25.6	27.6	24.4	5.96	2.76	130	132	127	11.3	2.74	3.20	2.76	2.722	85.74	128
230	233	237	1.571	1754	26.4	23.2	26.0	6.20	2.48	133	132	134	13.9	3.08	2.68	2.92	2.555	85.94	125
230	236	243	2821	1754	27.2	20.8	27.2	6.36	2.36	134	132	138	17.0	3.28	2.40	3.00	2.555	85.94	133
230	238	247	3.636	1756	27.6	18.4	28.8	6.40	2.20	135	132	140	19.3	3.44	2.08	3.04	2444	87.14	140

Table 36. Effects of unbalanced voltage on the performance of a 10-hp, U-frame 220 volts, three-phase motor loaded at 80% of the rated horsepower on three-phase line.

V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	UNBALANCE %	RPM	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
220	211	204	3.969	1763	20.0	28.8	18.8	4.20	2.68	120	126	115	5.0	1.62	3.12	2.12	2.055	87.12	57
220	211	206	3.611	1763	20.0	28.0	18.8	4.28	2.56	121	126	116	5.2	1.70	3.04	2.12	2.055	86.99	55
220	213	209	2.804	1764	20.4	26.4	18.8	4.40	2.48	122	126	118	5.3	1.78	2.90	2.14	2.000	87.50	55
220	215	213	1.852	1765	20.4	24.8	19.2	4.48	2.28	123	126	120	6.1	1.92	2.72	2.16	1.944	87.76	51
220	217	217	0.917	1765	21.2	22.8	20.0	4.68	2.08	124	126	123	7.2	2.08	2.48	2.20	1.944	88.28	50
220	221	223	0.753	1766	22.0	20.4	20.8	4.88	1.88	126	126	126	8.5	2.28	2.24	2.20	1.888	88.80	49
220	224	229	2.080	1767	22.8	18.0	22.4	5.16	1.68	128	126	130	10.5	2.52	1.96	2.28	1.833	88.28	50
220	228	235	3.367	1768	24.0	16.0	24.4	5.32	1.48	130	126	134	12.0	2.78	1.70	2.36	1.777	87.25	52

Table 37. Effects of unbalanced voltage on the performance of a 10-hp, U-frame, 220 volts, three-phase motor loaded at 100% of the rated horsepower on three-phase line.

V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	UNBALANCE %	RPM	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
220	210	203	4.265	1751	24.4	34.4	24.0	5.36	3.44	120	126	116	5.1	2.24	3.78	2.74	2.722	85.15	84
220	211	206	3.611	1751	24.4	33.2	24.0	5.36	3.38	121	126	117	5.3	2.36	3.66	2.72	2.722	86.14	78
220	213	210	2.644	1752	24.8	32.0	24.4	5.52	3.20	122	126	118	5.3	2.42	3.54	2.76	2.666	85.55	72
220	215	214	1.695	1752	25.2	30.0	24.4	5.60	3.00	123	126	120	6.0	2.52	3.32	2.76	2.666	86.74	68
220	217	217	0.9174	1754	25.6	28.4	24.8	5.72	2.84	124	126	122	7.0	2.64	3.16	2.76	2.555	87.14	65
220	221	223	0.753	1757	26.4	25.6	25.2	5.96	2.60	126	126	127	8.6	2.90	2.88	2.84	2.388	86.54	62
220	224	229	2.080	1757	27.6	23.2	26.8	6.16	2.44	127	126	130	10.3	3.12	2.60	2.92	2.388	86.74	67
220	228	235	3.367	1758	28.8	20.0	28.4	6.40	2.24	130	126	134	12.0	3.52	2.24	2.96	2.333	85.16	70

Table 38. Performance characteristics data of a 10-hp, T-frame, 230 volts, three-phase motor operated from a 10-hp rotary converter.

LOAD LB-FT	LOAD % OF RATED	1–ϕ V	1–ϕ I	1–ϕ KW	1–ϕ P.F.	RPM	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %
21	70	230	47.2	6.96	0.62	1768	230	223	220	18.4	22.4	16.4	4.16	1.80	129	132	124	62.5	1.64	2.48	1.80	1.78	75.03
24	80	230	50.0	7.84	0.67	1764	229	220	218	22.4	25.0	18.0	4.88	2.00	128	130	122	62.0	2.00	2.80	2.00	2.00	76.12
27	90	230	53.6	8.80	0.70	1758	228	216	217	24.8	27.6	19.2	5.60	2.18	128	129	121	61.5	2.40	3.20	2.16	2.33	76.30
30	100	230	58.0	9.84	0.71	1750	227	213	215	28.4	31.2	21.2	6.40	2.39	128	128	119	60.0	2.80	3.64	2.32	2.78	75.81
33	110	230	62.4	10.96	0.74	1740	227	210	214	32.0	34.0	23.2	7.28	2.54	128	126	117	59.5	3.24	4.00	2.52	3.33	74.87

Table 39. Effects of single-phase voltage variation on the performance of a 10-hp, T-frame, 230 volts, three-phase motor loaded to 100% of the rated horsepower on a 10-hp rotary converter.

LOAD LB-FT	LOAD % OF RATED	1–ϕ V VOLT	V % OF RATED	1–ϕ I AMP	1–ϕ KW	1–ϕ PF	RPM	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	UNBALANCE %	I_1 AMP	I_2 AMP	I_3 AMP	KW_1	KW_2	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	V_{NG} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %
30	100	207.0	90	60.4	10.00	0.78	1724	204	186	193	4.97	33.6	34.4	23.2	6.88	2.20	116	112	104	55.5	3.12	3.64	2.24	4.22	74.60
30	100	218.5	95	58.4	9.92	0.74	1736	216	200	205	4.35	30.8	32.0	22.0	6.64	2.32	120	120.5	112	58.0	2.96	3.60	2.31	3.56	75.20
30	100	230.0	100	58	9.84	0.71	1750	227	213	215	3.97	28.4	31.2	21.2	6.40	2.39	128	128	119	60	2.80	3.64	2.32	2.78	75.81
30	100	241.5	105	59.2	10.0	0.69	1750	238	225	225	3.78	26.8	30.0	20.4	6.40	2.48	134	134	124	62	2.72	3.68	2.40	2.78	74.60
30	100	248.0	108	60.4	10.16	0.66	1753	244	230	230	3.68	26.0	30.0	20.0	6.32	2.60	137	138	128	64	2.64	3.76	2.40	2.61	73.43

Table 40. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor operated from an open-wye type phase converter with C = 280 microfarads.

LOAD LB-FT	LOAD % OF RATED	RPM	1-Φ V VOLT	1-Φ I AMP	1-Φ KW	1-Φ PF	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
12	40	1784	220	21.2	3.76	.82	220	267	133	20.8	10.4	26.4	82	155	118	1.76	0.92	0.92	0.88	79.36	33
15	50	1780	220	24.0	4.56	.88	220	260	130	24.0	12.8	26.0	82	153	114	2.00	1.58	0.92	1.11	81.80	33
18	60	1775	220	27.0	5.44	.95	219	256	127	26.8	17.0	27.0	83	152	111	2.24	2.24	0.88	1.39	82.23	38
21	70	1770	220	30.0	6.24	.96	219	251	124	29.4	19.6	25.0	83	150	108	2.44	2.80	0.87	1.67	83.70	43
24	80	1762	220	34.8	7.12	.98	218	245	120	33.2	24.4	24.4	83	148	104	2.72	3.52	0.84	2.11	83.82	74

Table 41. Performance characteristics data of a 10-hp, U-frame, 220 volts, three-phase motor operated from an open-wye type phase converter with C = 420 microfarads.

LOAD LB-FT	LOAD % OF RATED	RPM	1-Φ V VOLT	1-Φ I AMP	1-Φ KW	1-Φ PF	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
18	60	1775	220	38.8	6.24	.73	220	268	150	38.0	8.8	40.4	88	154	122	3.32	1.12	1.60	1.39	71.73	69
21	70	1770	220	40.4	6.96	.80	220	262	146	40.0	12.0	39.6	88	152	119	3.48	1.76	1.56	1.67	75.03	69
24	80	1764	220	42.0	7.76	.84	219	256	141	41.6	16.0	38.6	87	150	114	3.68	2.36	1.50	2.00	76.91	70
27	90	1755	220	44.4	8.64	.90	219	250	135	44.0	21.6	37.6	88	148	110	3.88	3.16	1.44	2.50	77.71	70
30	100	1749	220	47.0	9.60	.94	218	249	129	46.4	27.4	36.6	87	147	105	4.04	3.96	1.36	2.83	77.71	73
33	110	1744	220	48.8	10.18	.95	220	248	125	48.0	30.8	37.2	86	150	106	4.12	4.60	1.30	3.11	80.61	81
36	120	1731	220	52.0	11.02	.98	220	240	120	50.4	36.0	36.4	86	149	104	4.24	5.20	1.24	3.83	81.23	102

Table 42. Performance characteristics data of a 10-hp, T-frame, 230 volts, three-phase motor operated from an open-wye type phase converter with C = 280 microfarads.

LOAD LB-FT	LOAD % OF RATED	RPM	1-Φ V VOLT	1-Φ I AMP	1-Φ KW	1-Φ PF	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
18	60	1772	230	27.4	5.44	.90	229	276	143	27.2	14.4	28.0	87	161	123	2.32	1.92	1.00	1.55	82.28	115
21	70	1766	230	30.0	6.32	.95	229	270	137	29.6	17.6	27.6	87	159	119	2.52	2.60	1.00	1.89	82.62	117
24	80	1759	230	33.2	7.20	.97	228	265	133	32.4	22.0	26.8	87	158	116	2.76	3.32	.96	2.28	82.90	124
27	90	1749	230	37.2	8.32	.99	228	260	127	36.4	28.0	26.0	87	156	110	3.04	4.16	.92	2.83	80.70	149

Table 43. Performance characteristics of a 10-hp, T-frame, 230 volts, three-phase motor operated from an open-wye type phase converter with C = 420 microfarads.

LOAD LB-FT	LOAD % OF RATED	RPM	1-Φ V VOLT	1-Φ I AMP	1-Φ KW	1-Φ PF	V_{12} VOLT	V_{23} VOLT	V_{13} VOLT	I_1 AMP	I_2 AMP	I_3 AMP	V_{1N} VOLT	V_{2N} VOLT	V_{3N} VOLT	KW_{1N}	KW_{2N}	KW_{3N}	SLIP %	EFFICIENCY %	TEMP RISE °F
24	80	1767	230	43.6	7.84	.77	229	284	160	43.6	8.8	43.6	90	160	130	3.84	1.88	1.72	1.83	76.12	208
27	90	1761	230	45.2	8.40	.81	229	280	156	44.8	16.0	43.2	90	161	128	4.00	2.40	1.72	2.17	79.93	209
30	100	1754	230	47.6	9.44	.89	228	272	149	47.2	20.0	41.6	90	158	122	4.20	3.36	1.60	2.55	79.02	219
33	110	1742	230	50.0	10.48	.93	227	265	141	49.6	28.0	40.4	89	156	117	4.40	4.24	1.52	3.22	78.30	222
36	120	1721	230	54.0	11.92	.97	227	258	131	53.6	36.4	39.2	88	154	111	4.60	5.56	1.40	4.39	75.10	—