1974

High Efficiency Single Phase Motors

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HIGH EFFICIENCY SINGLE PHASE MOTORS

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ABSTRACT

Since the energy efficiency ratio (EER) of the air conditioning system is dependent on the efficiency of the motor in addition to the performance of the refrigerant system, the motor efficiency can be viewed as a source of EER improvement. The amount of motor efficiency improvement obtainable is in turn dependent on the motor material characteristics and the motor size or volume which is usually described as D^2L. Most of the single phase air conditioning applications today use permanent split capacitor motors. This paper shows the relative efficiency improvement obtainable in PSC motors as one makes trade-offs in motor stack height, capacitor size, and steel grade.

The results show that if a 5 to 7 point efficiency improvement is required, starting from an existing 80.0% to 82.0% efficiency level, major design changes in the motor are required. A substantial increase in total motor content in terms of size, conductor volume, and capacitor size is required.

INTRODUCTION

With the advent of this era of the "Energy Crisis" nearly every technical journal in print has some article dealing with conservation of energy. Legislation covering energy use has been introduced from municipal to federal levels. No longer can society be permitted to knowingly use more energy than necessary when more efficient methods are technically and economically feasible.

To place the problem in perspective, the following studies show the trends in energy use in the United States. In 1968 the total national energy consumption was divided as follows:

Table I

Uses of Energy in the United States[1]

Residential	19.2%
Commercial	14.4%
Industrial	41.2%
Transportation	25.2%
Total	100.0% or 60.6 quadrillion BTU's of energy

If the scope is limited to electrical energy and particularly to that involving room and central residential air conditioning use, one can see the importance of improvement in that area. In New York State, for example, the room and central air conditioning electrical energy consumption comprises 2,465,000,000 KWH or nearly 8% of all electrical energy[2]. On a national basis the air conditioning average annual growth is 15.6%[1].

To further illustrate the concern of air conditioning electrical energy consumption is the change of the peak demand from winter to summer. On July 28, 1970 the summer peak demand on Consolidated Edison in New York was 7,041,000 KWH. This is 27% higher than the winter peak demand of 5,526,000 KWH which occurred on January 22, 1970[2].

One final example of a mandate that may affect the lifestyle of the consumer and cause concern to appliance and equipment manufacturers is a ruling in Los Angeles[3]. Effective on January 1, 1974, all customers of the Los Angeles Department of Water and Power are limited to 90% of their 1973 monthly KWH consumption. If the consumption is in excess of this amount, even if only by 1 KWH, a penalty of 50% of the period's electric bill will be assigned. Succeeding violations can result in a cut-off in power ranging from 2 to 30 days.

Based on these legislative trends it is readily apparent that improvements in the coefficient of performance or the energy efficiency ratio must be sought. Of great importance is the method by which this improvement be obtained. In a refrigeration system the likely candidates for improvement are the motor, compressor, condenser, and evaporator. The air conditioner manufacturer usually has control and knowledge of the compressor, condenser, and evaporator systems so that he can effectively make predictable performance changes. However, in the area of motor design and performance, he usually feels less knowledgeable with respect to predicting the motor performance improvements that can be obtained as one makes trade-offs in such design attributes as motor stack height, capacitor size, and steel grade.

For this latter reason a study was undertaken to provide motor performance trend information to help the air conditioner manufacturer make intelligent decisions in achieving a given level of system performance at the lowest possible system cost.

SCOPE OF THE STUDY

The room and central home air conditioners range from about 4,000 BTU to 60,000 BTU cooling capacity. The ratings selected for the study are shown in Table II.

Table II

HP and BTU Ratings of Motors in Efficiency Study

Approx. BTU Rating	HP Rating	Motor Size Frame	OD
14,000	1	30	5.48"
30,000	2-1/2	40	6.29"
60,000	5	40	6.29"

The study was limited to three primary variables which influence motor performance and which could be easily related to a size or cost characteristic by the compressor manufacturers. These three independent variables were:

Stack Height (Inches)
Run Capacitor Size (Mfd)
Steel Grade

A fourth variable, rotor resistance, was added to the study as a means of holding the desired ratio of locked rotor torque (LRT) to maximum running torque (MRT) while at the same time achieving optimum distribution of motor losses.

CONSTRAINTS ON MOTOR DESIGN

The following constraints were added to the study.

Factors Held Constant

1. MRT (Torque at 3000 RPM)
2. LRT (Torque at Standstill)
3. Stator Slot Fullness

Factors Held Below a Maximum Level

1. Main Winding Losses (I^2R) at MRT
2. Main Winding Temperature Rate of Rise at Standstill

Other Considerations

1. Constant Stator Slot Size
2. Copper Stator Conductors
3. Cast Aluminum Rotor Conductors
4. Single Phase Power
5. PSC Motor
6. Constant Load Torque

The reasons for the constraints will be discussed in categorical order. It was assumed that the compressor mechanical design was fixed and therefore required a given level of LRT and MRT to start it and keep it running at the extreme conditions of line voltage and compressor loads. Also, the stator slot fullness was held constant because the space allowed in the compressor casting for stator end turns was fixed.

The motor winding temperature was mathematically limited by holding a maximum level of I^2R losses in the main winding at 3000 rpm. At standstill the main winding current density was held below a given level to prevent the temperature rate of rise from exceeding a given specification.

The other considerations listed merely point out that the motors considered were designed to be of the general type that are presently built and used in air conditioning applications. No unusual or exotic materials were contemplated.

To reiterate, the study was made on the assumption that the compressor and refrigerant system did not change. Any changes in the system that would change the compressor load would also change the motor load. This would establish new motor constraints that could result in a different optimum motor design.

OPTIMIZATION APPROACH

Before the optimization approach is described, efficiency will be defined:

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}} \quad (1)$$

If the input and output are expressed in watts, the torque measured in oz-ft, and the speed in rpm, then the output at a given load torque, T, can be expressed as follows:

$$\text{Output} = \frac{T \times S}{112.7} \quad (2)$$

Since the load torque is constant and the speed is relatively constant, then the output is essentially constant. The losses comprise the following factors:

Rotor I^2R Loss
Steel Loss
Main Winding I^2R Loss
Start Winding I^2R Loss

Miscellaneous Losses (Friction & Windage, Capacitor Loss)

If one is trying to maximize the efficiency at the rated load torque, the goal will be to minimize the sum of the losses while meeting the design specifications and constraints.

The following steps were taken in the optimization approach:

1. Select several levels of stack height and capacitor sizes.

2. At each level of stack height and capacitor size (mfd) determine the main and start winding conductor sizes and turns distributions together

with the rotor resistance required to obtain minimum total losses and maximum efficiency at the rated load.

3. With each optimum design calculate the effect of a change in steel grade.

RESULTS

In order that one understands the performance changes predicted for each rating selected, the major design and performance characteristics will be described together with the range of independent variables. All of the performance data shown in this report are computed values based on the mathematical model used to represent a single-phase motor. The 2½ hp rating will be considered first.

Table III

Characteristics of Present 2½ HP,
230 Volt Motor Design
For 30,000 BTU Compressor

Frame: 40	MRT: 160 oz-ft
OD: 6.29"	LRT: 18 oz-ft
Stack: 2.625"	Rated Load: 86.0 oz-ft
Run Cap.: 35 mfd 370 volt	Rated Ld. Eff.: 82.2%

Table IV

Range of Independent Variables
For 2½ HP Motor Design Study

1. Stack Height: 2.625", 3,000", 3.625"
2. Run Capacitor: 35 to 135 mfd
3. Steel Grade: (two levels)

Present Steel	Low Loss Steel
Unit Loss = 1.0	Unit Loss = 0.5
Unit Cost = 1.0	Unit Cost = 2.0

The rated load efficiency plotted as a function of capacitor size is shown in Figure 1. The characteristic of the efficiency reaching a peak value and then dropping off is caused by the constraints of constant slot fullness, the limit on heavy load losses, and main winding current density at standstill. When the motor stack height is increased, fewer turns are required for the same MRT. The main wire size can then increase and the limit on main winding losses is less restrictive. One should keep in mind the fact that a capacitor motor is a "quasi" two phase motor. In a standard polyphase motor each phase shares the load equally. In a capacitor motor this load sharing is unequal and varies as a function of the load on the motor.

As the capacitor size is increased the impedance of the start winding changes and causes the start winding current to increase and the main winding current to decrease. Each level of capacitor requires a new turns ratio and conductor distribution to result in the minimum total losses for that design. This same optimization is required

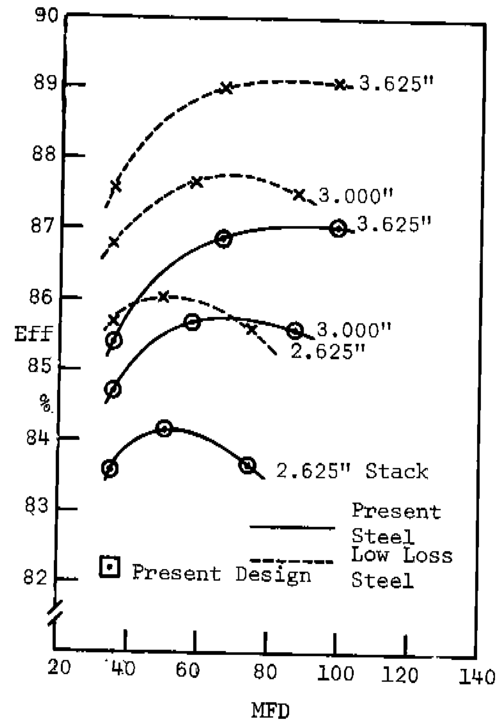

Fig. 1 Efficiency Curves For 2½ HP Motor

at each level of stack height because the different magnetic flux density in the steel requires a new distribution of motor losses for maximum efficiency.

Longer stack heights will result in higher motor efficiency but at a diminishing rate. The system designer must now determine whether to invest more money in compressor and motor or in condenser and evaporator surfaces or some combination. Both pure economics and efficient material utilization must be considered. The low loss steel results in about a 2 point efficiency increase, but not necessarily uniform for different stacks.

A second characteristic worth considering is the capacitor voltage curve. This is shown in Fig. 2. The capacitor voltage curve has an inverse characteristic because the optimum motor efficiency is obtained with a lower start winding impedance as the capacitor size is increased. Although the voltage may be considerably lower than presently encountered, the physical capacitor size may still be larger because the capacitor dielectric thickness has a lower limit for practical reasons. Note that the present design has a capacitor voltage lower than the optimum curve. The higher efficiency of the more optimum designs is largely the result of the higher capacitor voltage and a better distribution of main and start conductor sizes.

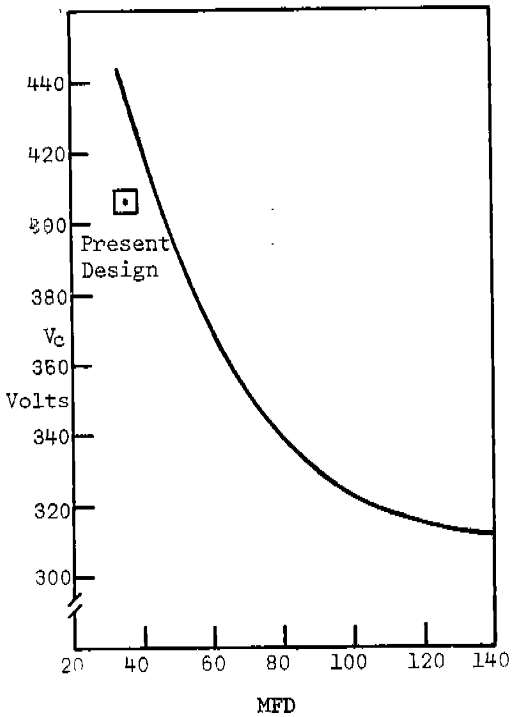

Fig. 2 Capacitor Voltage At Light Load Over-Voltage For 2½ HP Motor

The results of the 1 hp study will be considered next.

Table V

Characteristics Of Present 1 HP, 115 Volt Motor Design For 14,000 BTU Compressor

Frame: 30	MRT: 65.5 oz-ft
OD: 5.48"	LRT: 7.8 oz-ft
Stack: 2.25"	Rated Load: 34 oz-ft
Run Cap.: 35 mfd, 330 volt	Rated Load Eff.: 81.5%

Table VI

Range Of Independent Variables For 1 HP Motor Design Study

1. Stack Height: 3.50" (one level only)
2. Run Capacitor: 35 to 210 mfd
3. Steel Grade: Same levels as in 2½ hp study

The efficiency-capacitor characteristic plotted in Fig. 3 shows a marked improvement in efficiency as the capacitor size is increased from 35 to about 100 mfd. The efficiency then reaches a plateau of about 86.5%. Increasing the capacitor size beyond 90 or 100 mfd for this design would probably be a poor economic choice. The money might better be spent on refrigerant surfaces.

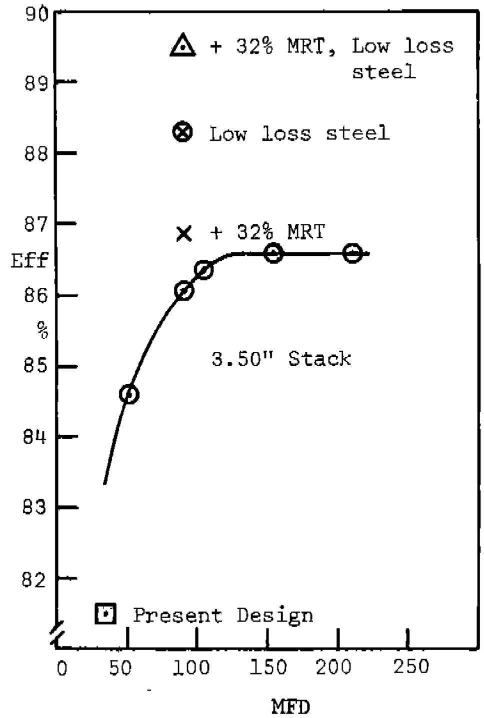

Fig. 3 Efficiency Curve For 1 HP Motor

The capacitor voltage curve shown in Fig. 4 has the same inverse relationship as the 2½ hp motor.

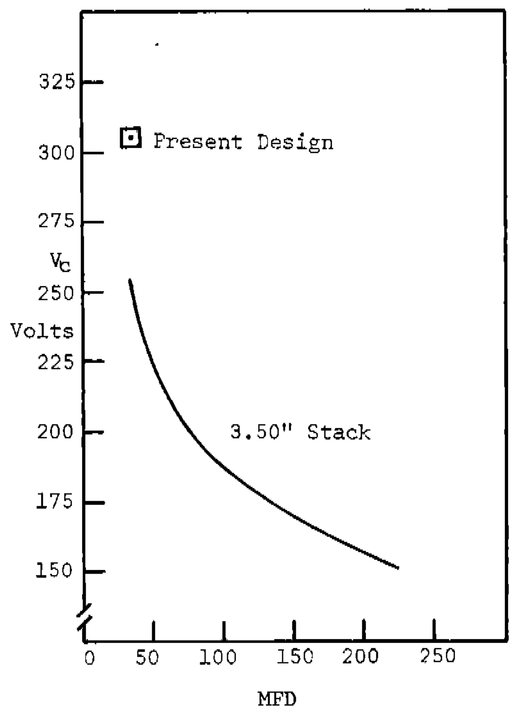

Fig. 4 Capacitor Voltage At Light Load Over-Voltage For 1 HP Motor

Because the 1 hp motor in this study is a 115 rating, the capacitor voltage is essentially half that of the 230 volt design. Many 115 volt PSC motors presently use "shifted" start windings to obtain more optimum performance with relatively low values of capacitance. As the capacitor size begins to approach the much larger value required for balanced two-phase operation, a non-shifted or "quadrature" start winding becomes more optimum. As a result, the non-shifted start winding design will have a capacitor voltage approximately 20% lower than its shifted start winding counterpart.

An additional area investigated in the 1 hp design was the effect of higher MRT. A curve of efficiency vs. torque showed that the efficiency did not peak at the rated load of 34 oz-ft, but rather at a lighter load of about 28 oz-ft. This raised the question as to whether higher efficiency could be obtained at the rated load if the MRT were changed. Because the 3.5" stack resulted in a relatively low motor magnetic flux density, the efficiency increased as MRT increased. The peak efficiency at the rated load occurred with an MRT of 86.5 oz-ft, or an increase of 32%. With a high flux density motor, just the opposite may be true.

Table VII shows the change in performance when the MRT was increased from 65.4 oz-ft to 86.5 oz-ft for a capacitor size of 90 mfd which appeared to be a reasonable economic optimum.

Table VII Comparison Of Motor Performance Improvement With MRT Levels Of 65.4 Oz-Ft And 86.5 Oz-Ft

	Mfd	90.	90.
	MRT	65.4	86.5
Rated Load Performance	Watts In	1213.	1214.
	Watts Out	1044.	1055.
	Watts Loss		
	Main	30.9	23.6
	Start	21.2	20.5
	Rotor	49.0	35.4
	Iron	54.1	65.5
	Friction & Windage	11.4	11.6
	Capacitor	2.3	2.5
	Total Loss	168.9	159.2
	Line Current	10.64	10.56
	Efficiency	86.1%	86.9%
	Power Factor	99.2% (leading)	100.0
	Capacitor Volts at 3500 RPM, 253 Volts	193.	198.
	Locked Rotor Current	47.4	66.5

Since the stack height remained fixed at 3.5 inches and the slot fullness was held constant, the total motor content of the two designs represented in Table VII is essentially constant.

Why then did the performance improve with higher MRT? The answer lies in the fact that a redistribution of losses within the motor resulted in a better utilization of the motor conductor and steel! One factor that should not be overlooked, however, is the 40% increase in locked rotor current. This may require a larger and more expensive line contactor which again points out the necessity of total system cost optimization.

As seen in Fig. 3, the lower loss steel resulted in an efficiency improvement of slightly over 2 points. One should keep in mind the fact that low loss steel which usually incorporates silicon or some other alloying element to raise its resistivity has its best loss and permeability characteristics at low flux densities. At very high flux densities the silicon steel may result in poorer performance than common iron. This indicates that the performance improvement with silicon steel is not linear as stack height is increased. The data showed that low stack heights had less improvement and long stack heights had more improvement when the low loss steel was used.

Finally, the 5 hp design will be considered to illustrate the performance levels and improvement that can be obtained with changes in motor capacitance and stack in that rating. Table VIII shows the basic characteristics of the present design used as a starting point.

Table VIII

Characteristics Of Present 5 HP, 230 Volt Motor Design For 60,000 BTU Compressor

Frame:	40	MRT:	384 oz-ft
OD:	6.29"	LRT:	32 oz-ft
Stack:	5.00"	Rated Load:	211 oz-ft
Run Cap.:	55 mfd, 440 volt	Rated Load Eff.:	84.8%

Table IX

Range of Independent Variables For 5 HP Motor Design Study

1. Stack Height: 5.00" and 6.50"
2. Run Capacitor: 55 to 225 Mfd
3. Steel Grade: (Present Steel only)

The curve of efficiency vs. mfd plotted in Fig. 5 shows that efficiency levels of 89 to 90% are obtainable with a stack height of 6.5" and a capacitor size of 160 to 180 mfd for a motor of this hp rating.

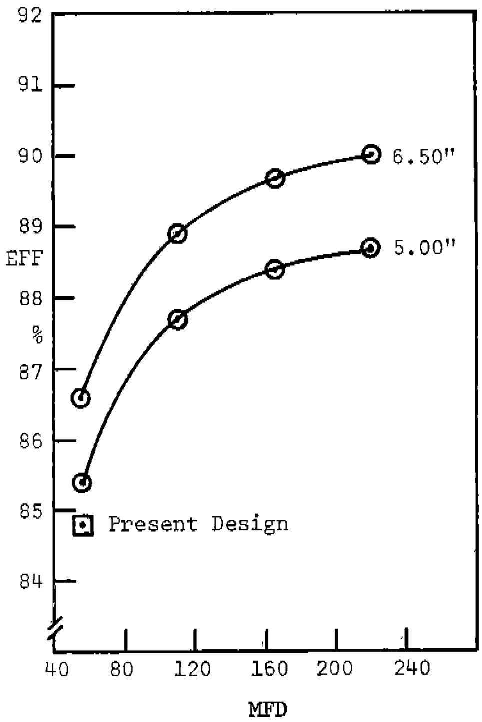

Fig. 5 Efficiency Curves For 5 HP Motor

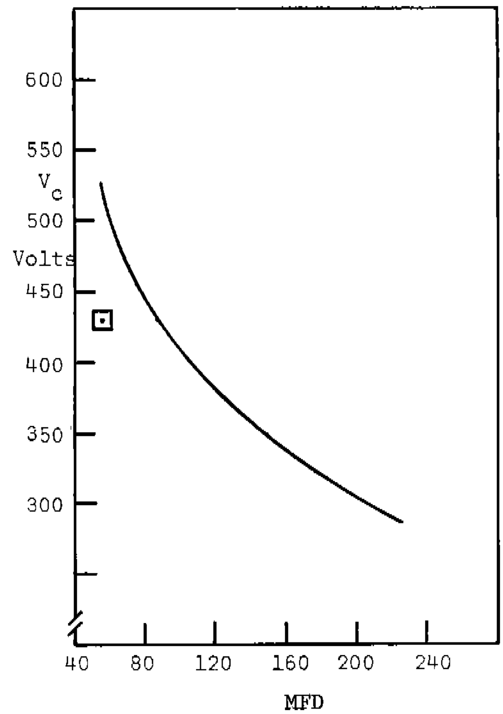

Fig. 6 Capacitor Voltage At Light Load, Over-Voltage For 5 HP Motor

As in the case of the 1 hp rating, the particular constraints in the 5 hp design study did not result in the efficiency peaks shown in Fig. 1. Different compressor configurations could result in different motor design constraints. This illustrates the importance of well defined motor design specifications based on complete calorimeter tests at all of the extreme load conditions necessary to assure reliable motor operation.

Fig. 6 again illustrates the inverse capacitor voltage characteristic. If the 180 mfd design were selected, a 330 volt capacitor could satisfy this application because the light load capacitor voltage would be in the range of 360 to 365 volts.

SUMMARY

In reviewing the analytical results for each of the motor ratings studied, one sees a similar pattern if more efficient single phase permanent split capacitor motors are desired. First, the motors must be designed to operate more like polyphase motors to effect lower losses. This can be achieved through the use of larger run capacitors. Second, longer stack heights will result in lower steel flux densities and lower steel losses. Third, lower loss steel will further reduce the motor losses. Whether this steel option exists as a viable and economically important factor is yet to be determined.

The reduction in motor losses should have a compounding effect on the system coefficient of performance because this represents fewer watts to be dissipated through the refrigerant surfaces.

One final factor not covered in this report but which showed up in tests verifying the computed results is the start capacitor for two-value capacitor motors. The high efficiency motors utilizing large run capacitors required larger electrolytic start capacitors than the predecessor designs in order to achieve the same starting torque. This in turn resulted in higher start capacitor current which could affect the relay contact designs. Further study may be required in this particular area.

OBSERVATIONS AND CONCLUSIONS

1. Increasing the motor material content about 50 per cent will reduce the losses about 20 to 30 per cent.

2. High efficiency motors will require larger capacitors with lower voltage ratings than normally used in air conditioning applications.

Line Voltage	Capacitor Voltage Rating
115 volts	175 to 200 volts
230 volts	330 to 370 volts

3. Achieving maximum efficiency at a specific load may require an adjustment in maximum running torque (higher or lower) and a corresponding change in locked rotor current.

4. Compressors that now use two-value capacitor motors (capacitor start and run) may require larger start capacitors to achieve the desired starting torque. Larger relay contacts may be required to handle the higher start capacitor current.

NOMENCLATURE

EER = Energy efficiency ratio

D^2L = (Motor diameter)^2 x (Motor length)

PSC = Permanent split capacitor

KWH = Kilowatt hours

OD = Outside diameter of motor

MRT = Maximum running torque at 3000 rpm for a 2-pole, 60 cycle motor

LRT = Locked rotor torque

T = Torque in oz-ft

S = Speed in rpm

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