Optimum Pole Configuration of A-C Induction Motors Used On Adjustable Frequency Power Supplies

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OPTIMUM POLE CONFIGURATION OF AC INDUCTION MOTORS USED ON ADJUSTABLE FREQUENCY POWER SUPPLIES

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ABSTRACT

For a "fixed frequency" (line powered) AC induction motor, a simple relationship exists between the number of magnetic poles and the synchronous speed. Specific choices of pole number and the common line frequencies of 50 and 60 Hz result in discrete available speeds for these motors.

When matching AC induction motors to variable speed applications using adjustable frequency power supplies, there is a temptation to assume that 50 or 60 Hz will be the "base frequency," and therefore the "base speeds" achievable are those provided by varying the number of motor poles. That assumption not only limits the choices of base speeds, but also results in suboptimal performance from the motor. This paper will explain the physics of why the optimal choice of the number of motor poles is more a function of the motor torque (size), rather than the motor speed, when considering adjustable frequency applications. In fact, the exclusive use of a four pole configuration results in optimal performance for a significant range of ratings. The parameters which can be optimized via the correct choice of pole configuration include - torque density, speed range, efficiency, power factor, overload capability, and acoustic noise.

I. INTRODUCTION

Sometimes a user who is familiar with fixed speed AC induction motors may specify a variable speed AC requirement with a preconception of the number of motor poles. This is appropriate in the case of an application where the motor will be run “across-the-line,” and is expected to run at the same speed and load as provided on inverter operation. If, on the other hand, “bypass” operation is not required, a more optimal choice of motor designs might be available.

For example, an application requiring 3000 or 3600 RPM operation would demand a 2 pole motor design if bypass (at 50 or 60 Hz) must be provided. However, when bypass is not required, it is often the case that a smaller motor can be provided in a four pole design (utilizing 100 or 120 Hz base frequency) compared to a two pole configuration.

Another aspect of applying adjustable frequency power supplies to AC induction motors is that it allows an essentially infinite number of possible “base speeds,” including base speeds in excess of 3600 RPM.

II. FIXED FREQUENCY AC - POLE NUMBERS

In the world of fixed frequency, “line power” applications, AC induction motors operating on 50 or 60 Hz power are restricted to a set of synchronous speeds as defined by the number of motor poles (Table I). These speeds simply are the result of the “physics” of AC induction motors as described in Equation (1). The motor designer does not have any “choice” as to the number of poles to use for a specific motor speed.

$$N = 120 \times \frac{f}{P} \qquad (1)$$

where N = speed in RPM

f = applied frequency in Hz

P = number of magnetic poles

TABLE I
AC MOTOR SYNCHRONOUS (NO LOAD) SPEEDS AT 50 AND 60 Hz INPUT FREQUENCIES

	Frequency (Hz)	
	50	60
Poles	Synchronous RPM	
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600
14	429	514

Fixed frequency motor designs are optimized in regard to operation at predictable frequencies and speeds as well as for operation such as “line starting.” There is not any reason to necessarily conclude from this relationship that the optimal choice for a motor to run 3000-3600 RPM is 2 poles, nor that 10 poles makes the best 600 or 720 RPM motor. While there are some aspects of motor performance (such as core losses) which tend to favor an inverse relationship between speed and the number of magnetic poles, there are other motor performance issues which are often more compelling.

The graph in Figure 1 illustrates typical motor power factors seen in a range of industrial AC motors built in 2, 4, 6, and 8 pole configurations. The superiority of the designs with fewer poles in this aspect of performance will be seen to result in further advantages in other areas of performance.

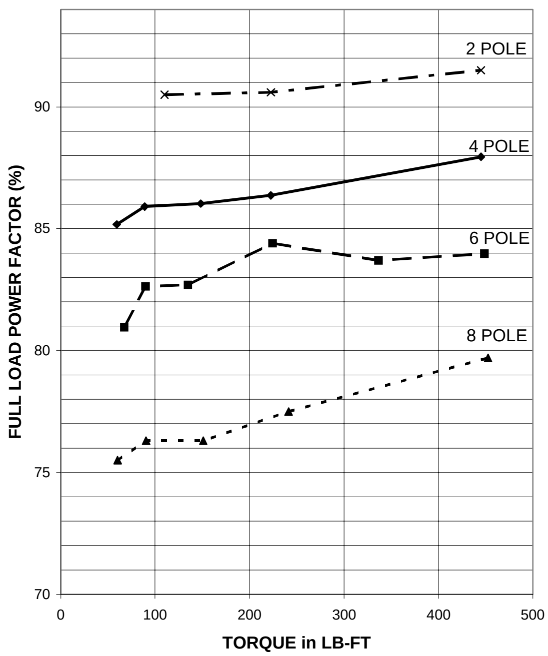


Figure 1 - Typical Full Load Power Factors of 2, 4, 6, 8 Pole Fixed Speed AC Induction Motors

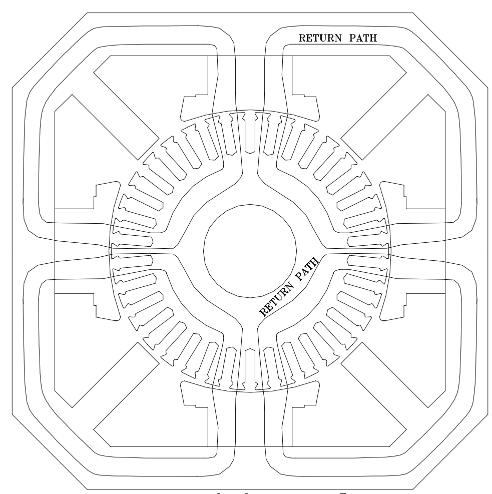
III. DC MOTORS - NUMBER OF POLES

In the design of industrial DC motors, there exists the opportunity for the motor designer to select the number of magnetic poles to use in a given frame size. This is different than the situation for fixed frequency AC induction motors (discussed previously) due to the difference between Equation (2) and Equation (1). In Equation (1), the variables are speed, frequency, and poles. This does not allow any freedom to select the number of poles for a given speed, since frequency is not something the (fixed frequency) motor designer can influence. Equation (2) however, includes as a variable the number of conductors (z) which is certainly within the control of the motor engineer.

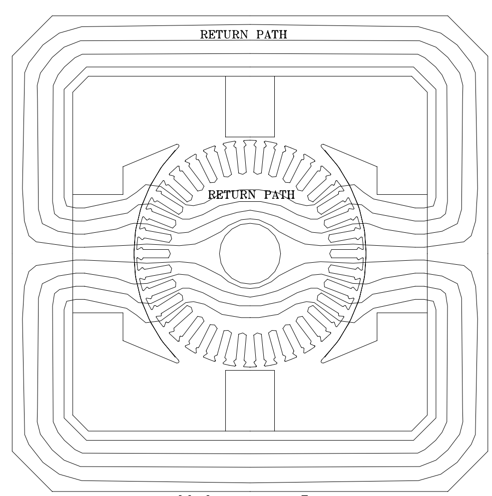
$$RPM = \frac{E_g \times a \times k}{\Phi \times z \times P} \qquad (2)$$

where -
E_g : motor counter emf
a : number of parallel circuits
Φ : flux (per pole)
z : number of armature conductors
P : number of magnetic poles
k : constant related to units

This means that the motor engineer can choose to design a given rating and speed using various possible combinations of “poles” and “conductors.” When a product line of DC motors is being developed, the opportunity exists to select a “number of poles” which provides optimal performance and cost for each frame size. Some of the DC motor performance aspects impacted by the choice of the number of poles are speed regulation, torque linearity, commutation, inertia, torque density, etc. Many of these performance issues then impact the motor cost, as the motor might have to be designed with more material to make up for any performance deficiency which might otherwise be caused by the selection of a certain number of poles.



(a) 4 pole



(b) 2 pole

Figure 2 DC Motor Cross Section Comparison of 2, 4 pole Designs

It is fairly easy to visualize one impact which the choice of the number poles has on DC motor design. Comparing Figures 2a and 2b, it can be seen that for a given total flux in a motor, the "return" flux paths have to carry more flux when a smaller number of poles is selected. The return paths have to carry one half of the "flux per pole," so as the number of poles goes down, the flux per pole increases. In order to not saturate these magnetic paths, the thickness of the return path has to be larger for a lower number of poles. This thicker return path cross section subtracts from the available space for windings and for torque production.

Offsetting the "return flux path" preference for higher numbers of poles is the increased amount of space consumed by insulation materials on the field and commutating poles. The additional wind and connect times for higher numbers of poles can also add cost to a dc motor. Another effect of a higher number of poles is a reduction in armature circuit inductance. This can negatively impact rating capability on rectified power sources, as the inductance helps reduce the "ripple" current.

Also working in favor of higher numbers of poles is the reduced "end turn" length which occurs. This shorter end turn results in less resistance in the windings, providing less I^2R loss. This effect occurs both for armature as well as for field and commutating windings.

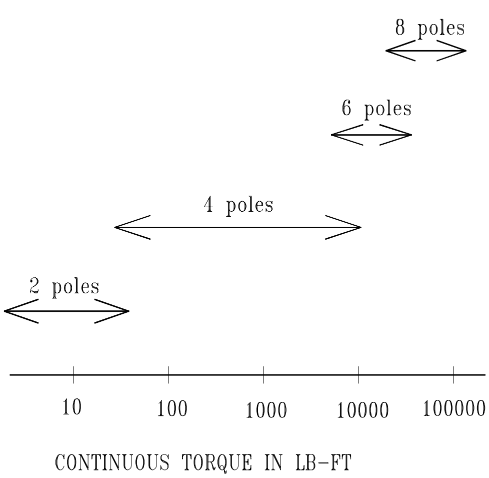


Figure 3 Optimal Pole Numbers for Industrial DC Motors

The end result is that the optimal number of magnetic poles is a function of the motor size (or torque rating). While any optimization result is highly dependent on what aspects of performance (torque density, cost, speed range, inertia, commutation, efficiency, etc.) are most important, the trend always remains that as DC motor size increases, a higher number of poles is optimal. It will be seen later that this same trend occurs in variable speed AC induction motors as well. Figure 3 documents the optimal range of various numbers of poles for industrial DC motors.

IV. ADJUSTABLE FREQUENCY AC MOTORS - NUMBER OF POLES

In comparing the relative merits of AC motor designs with various numbers of magnetic poles, it is tempting to use existing "fixed frequency" (60 Hz) designs of each pole configuration as the basis for comparison. These fixed frequency designs, however, are optimized around operation at a single frequency and single speed. This type of optimization results in a selection of fan diameters, air gap lengths, etc which are appropriate for that specific frequency and speed. Comparing these designs to each other creates distorted results, due to operating the motors away from their specific design point.

As a more appropriate comparison of the benefits of designing variable speed motors with different numbers of poles, we can begin with "adjustable frequency" designs which are <u>not</u> optimized around a different frequency and/or speed for each pole configuration. Irrespective of the number of magnetic poles, these designs should be optimized for operation across a <u>range</u> of speeds, and at the frequencies required to achieve those speeds. A comparison of some of the characteristics of such a set of designs follows.

A. Return Flux Paths

Similar to the discussion of numbers of poles in DC motors, a straightforward aspect of changing the number of poles in an AC motor is the impact on "return flux paths." Again, the return paths have to carry one half of the "flux-per-pole," resulting in an inverse relationship between the number of poles and return path "thickness." Figure 4 shows the significant change in electromagnetic proportions between 2 and 4 pole configurations. The need for a thicker return path takes away from the available space for windings and other "torque-producing" material.

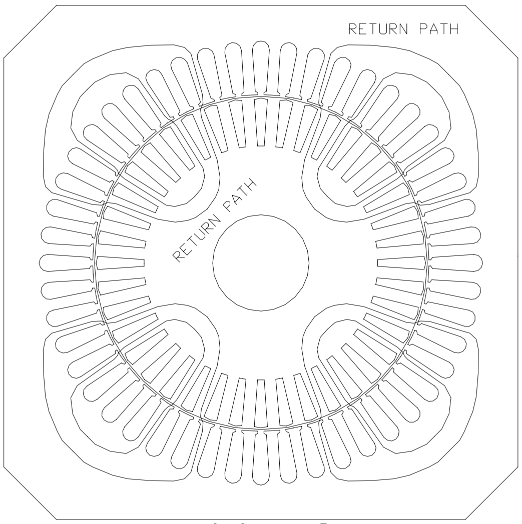
This results in a motor configuration which allows a larger rotor and shaft diameter to be used for designs with a higher number of poles. This tends to improve the "torque density" or rating per frame size which can be achieved with a higher number of poles. As will be seen later, a degradation of motor power factor which occurs with an increased number of poles is a key effect which works against the desirability of a higher number of poles. (Figure 1)

B. AC Induction Motor Losses

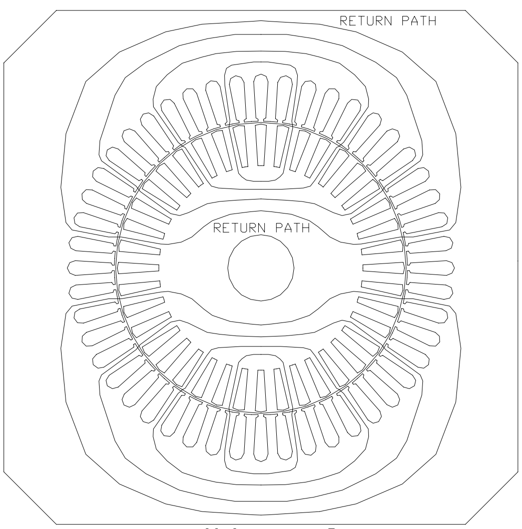
One aspect of motor design which is a significant issue in any consideration of "optimization" is the motor losses. The

losses of a three phase AC induction motor can be classified as:
- primary (stator) I^2R
- secondary (rotor) I^2R
- core (iron) losses
- friction and windage
- stray load losses

We can examine each of these losses to see how they might be impacted by the selection of the number of poles.



(a)4 pole



(b) 2 pole

Figure 4 AC Induction Motor Cross Section Comparison, 2 and 4 pole Designs

C. Stator I^2R Losses

The primary I^2R loss is the result of the full load current and the stator winding resistance. The shorter end turns of a higher number of poles will tend to reduce this loss by reducing the winding resistance. The amount by which the resistance is reduced is a function of the motor core length, and so cannot be broadly quantified. For "short core length" designs, this effect has more significance. Figure 5 shows the trend toward a lower percentage of the stator winding resistance due to the end turns for higher numbers of poles. The transition from 2 to 4 poles results in a larger percentage change (reduction) in the end turn length than do further increases in the number of poles. Also, the reduced "return flux path" cross section discussed above for higher numbers of poles provides more area for windings - further reducing stator winding resistance with increasing pole numbers.

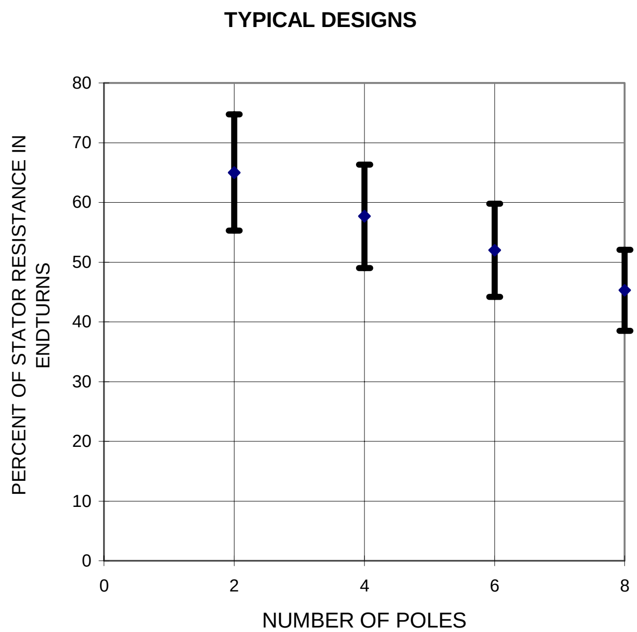


Figure 5 Variation in Endturn Contribution to Stator Winding Resistance as a Function of Number of Poles

The power factor of AC induction motors tends to fall off significantly as the number of poles is increased. This reduction in power factor results in an increased level of full load current, which then increases the primary I^2R loss for motors with a higher number of poles. The reductions in power factor with increasing numbers of poles are most significant for "integral HP" motors of less than about 0.15 HP/RPM. Figure 1 shows typical power factors for a range of ratings built in 2, 4, 6, 8 pole designs.

These effects combine to result in a wide range of motor sizes for which stator I^2R losses are minimized by using a four pole design. This advantage of a four pole configuration is maintained for designs up to about 800 to 1800 lb-ft of continuous torque, depending on ventilation schemes and other specific design aspects.

D. Rotor I^2R Losses

The secondary (rotor) I^2R losses behave in a similar fashion to the stator I^2R losses as the number of poles is varied. The losses in the rotor end rings are diminished for higher numbers of poles (due to having a shorter path length). Similarly, as the required return flux path area diminishes with increasing numbers of poles, there is more “room” for rotor conductors, reducing the rotor resistance. However, there is no equivalent effect to the stator’s reduced power factor, so the rotor I^2R loss has a generalized reduction with increasing pole numbers.

E. Core (Iron) Losses

Induction motor core (iron) losses have two basic components, those due to “hysteresis” effects, and those due to “eddy currents.” Both of these components have dependencies on the level of magnetic induction and the frequency of the changing induction. If we assume that irrespective of the number of magnetic poles chosen, we would like to operate with the lamination steel at a certain percentage of its “saturation” point, then we can examine the effects of changing the number of poles.

The hysteresis component (at a given level of induction) will vary nearly linearly with frequency. This would appear to favor designs with a lower number of poles, as they could operate at a given speed with a lower stator frequency. However, the core losses are characterized in terms of the loss “per pound” of lamination steel operating at that level of induction. Since the lowest number of poles requires the greatest cross section of lamination steel for the return flux paths, this counteracts the improvement expected from reducing the operating frequency.

The eddy current component of core loss actually varies as nearly the square of the stator frequency. However, the same issue of increased pounds of lamination steel in motors designed with a lower number of poles tends to offset this effect. The net result is that there is not a great dependence of core loss on the number of poles, or that the motor designer can make small changes in the design to compensate for such effects.

F. Friction and Windage and Stray Load Losses

The friction and windage losses are not significantly affected by the choice of poles numbers. Operation of existing, self-cooled, 60 Hz designs of various pole numbers at a common speed would contradict this, however, that would be due to operation of fans designed for one speed at a much higher speed - with the resulting increase in windage loss.

The stray load losses are not sufficiently impacted by the choice of pole number (compared to other design choices which affect stray load loss) to strongly influence the optimal choice of poles.

V. MOTOR “PERFORMANCE” ISSUES

There are a number of aspects of AC induction motor performance which are influenced by the choice of the number of poles. These include efficiency, power factor, slip, magnetizing current, and peak torque. Each of these can impact the suitability of a motor design for the demands of variable speed (adjustable frequency) applications.

If the motor efficiency is degraded due to a suboptimal choice of poles, then the increased losses may reduce the torque density, or the rating per frame size which can be achieved. Having to build a given rating in a larger frame size in order to dissipate these losses will typically result in a higher cost motor.

The product of motor efficiency and power factor (Eq. 3) will determine the inverter output kVA required to operate a given motor rating. As discussed previously, increasing the number of poles tends to reduce the motor power factor, particularly for ratings below 750 - 1000 lb-ft of torque. If the product of efficiency and power factor gets too low, the inverter kVA will not be sufficient to supply rated input to the motor, and it (the inverter) would have to be oversized.

$$\text{Motor kVA}_{in} = \frac{HP \times .746}{\text{effic} \times pf} \qquad (3)$$

For “field-oriented,” or “vector control” inverters, two key motor parameters which need to be set in the inverter are the slip and the magnetizing current. The tendency is for a system to be “more forgiving” to misadjustments of these parameters when the motor slip and magnetizing current are not too low. Higher magnetizing current tends to favor a higher number of poles, but higher slip tends to favor a lower number of poles. This results in a mutually exclusive situation, where adjusting the number of poles is not going to unconditionally help or hinder performance with field-oriented inverters.

Finally, the peak torque which can be provided by an AC induction motor determines how wide of a constant power speed range that a particular motor can achieve (in addition to determining overload capability). As the number of poles is varied (as long as the basic flux level is held constant), the peak torque does not vary in a generalized way. In fact, there are several effects which influence the peak torque in different directions - such as the deeper slots which may be used in higher pole designs resulting in higher slot leakage reactance and lower peak torque. Also the relationship of reactances to resistances changes as the number of poles is varied, which has a bit more complicated relationship to the peak torque.

VI. SUMMARY AND CONCLUSIONS

The results of any "optimization" are highly dependent upon the definitions of what it is to be optimized. In our case of variable speed (adjustable frequency) AC induction motors, there may be opportunities to optimize in regard to:
- maximized torque density
- maximized efficiency
- maximized reliability
- maximized speed range
- maximized overload

- minimized cost
- minimized inertia
- minimized temperature rise
- minimized noise, etc.

The results of attempting to provide a broadly applicable, industrial, variable speed AC induction motor design across a range of ratings and frame sizes leads to the wide use of a four pole design across a wide range of ratings. As the motor sizes increase to handle loads exceeding about 1000-1500 lb-ft of continuous torque, there is some desirability to increasing the number of poles further to at least a six pole design.

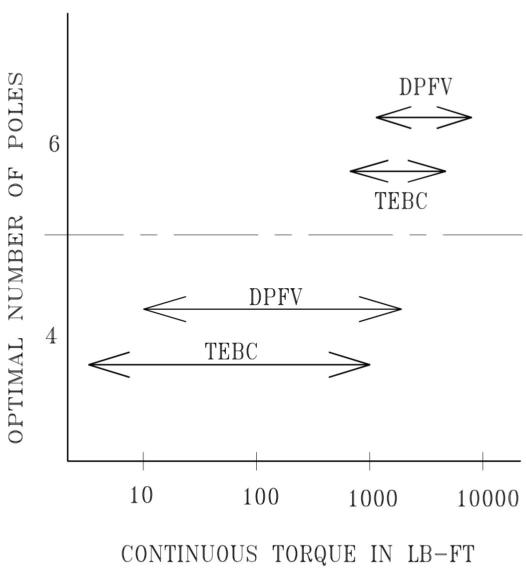


Figure 6 Optimal Numbers of Poles for Variable Frequency AC Induction Motors across a Range of Ratings

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