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What Speeds can A/C Induction Motors Run at?

This paper explains what the speed limitations are for A/C induction motors that do not use a variable frequency drive (VFD) or fixed frequency converter.

High quality fans and some motion profiles that are powered by AC power use A/C induction motors (versus AC capacitor motors used in home and large building air conditioning). While very high quality in nature it is important for those specifying fans to understand the speed limitations of an A/C induction motor.

AC Induction motors are brushless and therefore have low maintenance. They are made with a laminated stator stack and “barred” rotor assembly (usually copper) and work on the principle of transformer action. As the flux generated by the electro-magnet (coil) passes through the rotor assembly it creates a magnetic field in the rotor and pulls the rotor around as the field transitions. The frequency of field transition is directly proportional to the power frequency input to the motor. The higher the frequency input the faster the motor rotates. Also the fewer numbers of poles the faster the motor will rotate.

Voltage and number of phases of the power provided do not directly affect the speed of the A/C induction motor. Three-phase current input enhances torque output by factoring the SQRT of 1.73. Three phase power is easier to start and reduces the size of the motor for the same speed and torque as compared to single phase but does not affect speed.

Higher voltages do lower the required current for the same speed and torque output. For example a design run from 440 VAC will use approximately half the current as one run from 220VAC for the same speed – torque curve. However this needs to be balanced against the risk of arcing. Higher voltages have higher potential energy and thus a higher risk of arcing across conductors and causing damage.

Variations on the bus voltage input to a given design will induce variations of speed for that specific motor design at a specific load. If the voltage changes to the motor, the speed at load will change because the motor torque drops off. The speed reduces to compensate for the lower torque caused by lower current in the motor windings. So while voltage control should not be used to control AC induction motors it is important to account for the variation in the input voltage and the resulting motor speed-torque performance at the voltage low end. For example if the specification of the input power is 220VAC +/- 5VAC then the fan / motor design should provide enough air or torque at 215 VAC. DAE Systems takes this into account along with other factors when specifying the performance range of existing products. All DAE fan or motor curves define the performance tolerance.

The equation for speed for an A/C induction motor is therefore dependent only on frequency and number of poles and is: **$S = (120 \times f)/P$** where f is the frequency of the input power and P is the number of poles per phase of the motor design and S is the RPM speed.

There must be at least two poles per phase for the motor to operate (one north and one south). Therefore the maximum speed of an A/C motor design that can be achieved for a given power frequency is:
$S_{max} = 60 \times f$

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Typically we see 50 Hz power in Europe and 60 Hz in the U.S. We also see 400 Hz in Aerospace and defense applications. This means that maximum speeds for A/C motors are already known and are:

S_{max} @50Hz = 60 x 50 = 3000 RPM
S_{max} @60Hz = 60 x 60 = 3600 RPM
S_{max} @400Hz = 60 x 400Hz = 24,000 RPM

However there is a phenomenon called "slip" which means that motors can never quite reach this theoretical maximum speed. Slip is the difference in the frequency of the power and the induced magnetic field. One gets behind the other as the motor rotates due to the load. The rotor assembly lags the stator. Load can increase the slip. Normally slip does not exceed 5% and can be much less.

We can look at a couple of Dynamic-Air fan models to see typical impacts of slip.

For example model M111F-9A1 is a 400 Hz model with 6 poles. Therefore the theoretical speed is:

S = 120 x 400Hz / 6 = 8,000 RPM

However a review of the spec sheet shows it rotates at 7,750 or a 250 RPM loss (3.125%).

Similarly model M1292A-1A has a 2 pole motor using 60 Hz. Therefore the theoretical speed is:

S = 120 x 60 Hz/2 = 3600 RPM

However a review of the spec sheet shows it rotates at 3400 or a 200 RPM drop (5.5%).

It is important to choose a fan that will provide enough air at around 5% less than the theoretical top speed for the given power frequency and number of poles as the two above examples demonstrate. Using Tables A – C at the end of this paper makes this easy.

Sometimes it is desirable to vary the fan speed for the application in question. By varying the speed you vary the air volume and pressure output of the fan. A few reasons to do this are:

- Maximum air is preferred during demanding operations but a lower power saving mode is preferred during other conditions.
- The process or equipment where the fan will be installed is pressure or volume sensitive in some modes or air requirements are mode dependent.
- To facilitate logistics simplicity wherein one product can be used in multiple locations and dialed in to the desired performance.

There are two ways to have multiple speeds with AC induction fans. From the speed equation we know that we can either vary the number of poles or the input frequency.

Varying the number of poles is preferred when reliability and/or cost are important. Introducing a VFD (variable frequency drive) adds cost for that item (especially when it must be Mil or Airborne qualified) and lowers the reliability of the air system particularly in extreme temperature environments. VFD's are composed of active and passive electronic components. Active components have a limited life affected by temperature and on/off

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transients. Since A/C induction fans do not have brushes or active components their life is normally only limited by the bearing life and bearings can be easily replaced in a maintenance or repair program at failure. However the limitation of pole speed control is that only 2 or 3 specific speeds may be chosen (see table B and C below) where as VFD's can select an infinite number of speeds between the high and low operating points.

When pole control is used this is done by incorporating multiple windings in the motor. In this case one winding would tie to all of the poles (low speed) while the other winding would tie to only some of the poles (high speed). The number of partial poles used must be equally spaced. For example you cannot use 4 poles of a 6 pole motor as the 4 poles will not be equally spaced because 6 is not divisible by 4. Likewise in an 8 pole motor you could use either 4 or 2 poles as 8 is divisible by both, but not 6. When you use multiple windings you are limited by the number of total poles in the motor, their spacing, and the space the extra winding(s) take up. The stator lamination size and number of slots determines the maximum number of poles a given size motor can have and still produce adequate torque.

The model C050R is an example of a 2 speed A/C induction motor fan. It has 400 Hz single phase power input and 4 poles with one winding using all 4 poles and the other using only 2 poles. Therefore the two theoretical speeds are:

S1 = 120x400/2 = 24000 and S2 = 120x400/4 = 12000

A review of the catalog shows that the actual speeds are:

S1 = 23,400 and S2 = 11,800 which equates to a slip loss of 2.5% and 1.6% respectively.

The tables on the next may to be used for a rough sizing of the fan or motion system required. A conservative guess of 5% speed loss or more is assumed in these tables. These tables should be used for A/C induction motored fans and motion systems only and in conjunction with the fan and motor laws. In other words: when revising the speed of a known A/C fan or motor to achieve a specific CFM and static pressure target or speed / torque curve you must choose a speed that matches one of the below. You cannot choose an alternative speed unless you plan to use a VFD or a frequency converter. You will find that your baseline fan or motor is already very close to one of these speeds if you match the frequency to the number of poles with the difference being the actual slip loss versus the 5% assumed.

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Table A – A/C Induction Motor Speed Estimates

Number of Poles	60 Hz Speed	400 Hz Speed
2	3400	22,800
4	1700	11,400
6	1100	7,600
8	850*	5,700
10	675*	4,550
12	Do not use – too slow	4,000

Table B – A/C Induction Dual Speed Estimates

Number of Total Poles	60 Hz Speed	400 Hz Speed
2	Dual Speed Not Possible	Dual Speed Not Possible
4	3400 &1700	22,800 & 11,400
6	3400 & 1100	22,800 & 7,600
8	1700 & 850 or 3400 & 850*	11,400 & 5,700 or 22,800 & 5,700
10	3400 & 675*	22,800 & 4,550
12	Do not use – too slow	22,800 & 4,000 or 7,600 and 4,000

Table C – A/C Induction Three Speed Estimates

Number of Total Poles	60 Hz Speed	400 Hz Speed
8	3400 & 1700 & 850	22,800 & 11,400 & 5,700
12	Do not use – too slow	22,800 & 7,600 & 4,000

*** Note: Be very cautious about driving an AC Induction motor below 1100 rpm without using a VFD for control. AC motors when driven off line / too slow will tend to "hunt" causing unstable performance. The particular minimum speed of a fan may also be affected by the actual aerodynamic stability region. Every Aerodynamic design has a minimum stall speed.**

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