The Magic of Variable Speed Drives

By Eric A. Woodroof, Ph.D., CEM, CRM
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Last week I was teaching/introducing the Certified Energy Manager program in Singapore, where the weather is consistently hot and humid, yet they frequently use variable flow HVAC systems. It got me thinking about applications of variable speed drives (VSDs) in data centers and other areas where the cooling load is more constant than a traditional building. In this article, I will explain the "magic" of VSDs regarding traditional energy savings in areas where the weather (cooling load) varies, such as in the USA. At the end, I will discuss the economics of VSDs in general as well as in applications where the loads are more constant… the results surprised me.

Background

According to the Energy Information Agency, motors in fans, pumps and compressors use more electricity than any other device within buildings. The majority of these motors are AC induction motors and this technology has not changed significantly in many years. The "rule of thumb" efficiencies are usually above 90%. Motors, which are simply a collection of wires and magnets ("pole pairs"), are "fixed speed" devices. The RPM ("speed") is determined by the equation below, and most of the variables are fairly constant:

$$\text{SPEED} = \frac{60\,\frac{\text{cycles}}{\text{sec}} \times 60\,\frac{\text{sec}}{\text{min}}}{\text{number of pole pairs}}$$

Note that in the USA, the Electrical System Frequency is 60 Hz (cycles per second)

Thus, after a motor is constructed, the only practical way to adjust the speed is to adjust the electrical frequency, which we can do with modern electronics ("drives"). A variable frequency drive (VFD) is essentially a small computer that modifies the electrical system frequency to manipulate the RPM ("speed") of a motor, which impacts the flow of air in an HVAC system. VSD is a common term for a VFD.

There are other ways to achieve variable flows of air (or any fluid) by using a magnetic clutch, as well as outlet dampers or inlet vane controls. Magnetic clutches offer similar performance when compared to a VFD. However, outlet dampers and inlet vane dampers are not as efficient as a VFD, because using an outlet damper (or throttling) is basically analogous to controlling your car by "putting the gas petal to the metal" and at the same time, controlling your speed by using your brake.

The Magic of VSDs:

VSDs are "magic" because they can achieve over 50% energy savings, which is generally more than most energy retrofits! Although initially unbelievable to most people, this is true because the relationship between power and airflow is not linear as indicated by the famous "fan laws" or "affinity laws". For this article, we will only talk about the most relevant, 3rd Fan Law Equation:

$$\frac{HP_{new}}{HP_{old}} = \left(\frac{RPM_{new}}{RPM_{old}}\right)^3$$

Another interesting "law" is the relationship between speed (RPM) and CFM (Cubic Feet per Minute). CFM (flow) and RPM are generally linear, such that RPM can be substituted with CFM in the equation above.

For example, consider a 100 HP HVAC fan motor that was controlled by a VSD. During a day when the temperature is mild, you could reduce the flow to 50% and still keep occupants comfortable. The equation below shows you what the new HP would be (power required). *In this case-* $CFM_{new} = 0.5 * CFM_{old}$

Therefore, $RPM_{new} = 0.5 * RPM_{old}$
If we insert this into the 3rd Fan Law Equation:
$HP_{new} = HP_{old} (RPM_{new}/RPM_{old})^3$
$HP_{new} = HP_{old} (0.5 * RPM_{old}/RPM_{old})^3$
$HP_{new} = 100\ HP\ (0.5)^3$
$HP_{new} = 100\ HP\ (0.125)$
$HP_{new} = 12.5\ HP$

Although this is an incredible 87.5% reduction in power required (savings), we have to remember that the above calculation is based on the Fan Law Curve and (like thermodynamics) we won't achieve 100% efficiency (or be right on the curve). However, as many experiments have shown, we can get very close to these savings. To be conservative, you may assume that you would achieve 90% of the estimated savings.

Perhaps even more important is to remember that we only achieve the above savings when the system is operating at 50% flow, which is not “year-round”, so we need to measure/estimate how much time we are operating at common load profiles (40%, 50%, 60%, 70%, 80%, etc.). Once we have the profiles, we can use the fan law equation to calculate the savings for each profile and then sum the savings to determine the annual savings. This can be easily done on a spreadsheet. Software also exists that can help you do this, but I like to “check my numbers” whenever I use software that might be biased toward overstating the savings.

Economic Evaluation:

Most of the engineers I have worked with have found VSD applications to have paybacks of less than 3 years (sometimes less than one year if a system is part-loaded frequently). This is why Variable Air Volume HVAC units are pretty much the standard design for most buildings today.

As I asked at the beginning of the article: would VSDs be useful in places that have relatively constant HVAC loads year round (such as data centers or buildings near the equator)? My logical mind would say…probably not. However, according to a study done by Lawrence Berkeley National Laboratory[1], they achieved 24% reduction within a data center and a payback of 2 years. So it appears worthwhile to investigate as an option even when in a data center. *One other factor to consider is maintenance, which will be higher with a VAV system.*

It may also be wise to consider Variable Refrigerant Volume HVAC systems, which offer superior performance at part-load and save energy because they do not bring in outside air (which must be conditioned). These are very popular in Asia, as well as many data centers (that don’t have human occupants on a regular basis). In addition, the VRF systems can take heat from a computer room and move it to another area that might need that heat in the winter season. This also has many applications such as in hospitals, where a lot of equipment heat (MRI, CT and other machines) could be “re-used” in other areas. I am sure the VRF trend will continue to spread into the US and become more familiar in the coming years.

1 Greenberg, S. (2013) “Variable-Speed Fan Retrofits for Computer-Room Air Conditioners”, Prepared for the U.S. Department of Energy Federal Energy Management Program Technology, Case Study Bulletin By Lawrence Berkeley National Laboratory.