Variable Frequency Drives and Motor Insulation Stress
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Introduction

Variable frequency drives (VFDs) are commonly used to control the speed of standard AC induction motors. VFDs have become popular in a wide range of systems because they improve the control of the system, increase its overall efficiency, and extend its operating life by reducing mechanical and thermal stresses.

Unfortunately, VFDs can sometimes contribute to the degradation of the coils that produce the magnetic field in the motor's stator. This paper will investigate the causes of such degradations and offer some general suggestions to help avoid such problems.

What damage does the motor have?

The vast majority of motor failures are not related to a VFD. Motors failed for decades before VFDs were even invented. This section gives some ideas on how to determine if a motor failure was caused by a VFD damaging the motor's stator windings.

When investigating a problem that occurred with a motor that was controlled by a VFD, it is important to know what went wrong with the motor before looking for a solution. Too often, the report from the field is that the "motor burned out". This shouldn't be taken too literally. Most people use this to describe any motor that simply stopped working. Some additional investigation is needed to understand what really happened to the motor.

- ***"The motor stopped running."***
  This may be what is meant by the statement that the motor "burned out". Unfortunately, it's not very descriptive. Some additional questions may be needed. These could include:
  - If the motor was being controlled by a VFD, what alarm did the VFD display?
  - If the motor was being run in bypass, is the motor overload tripped?
  - Are the system's safety interlocks closed?
  - Is the voltage at the motor's conduit box correct?
  - Does the motor's shaft turn freely?
  - Can the motor run if it is disconnected from the load?

- ***"The motor got really hot and it now smells kind of burned."***
  This is the one case where you could literally say that the motor "burned out". Something caused the motor to draw so much current that its cooling system couldn't keep up. This isn't likely to happen in variable torque applications when a motor is being controlled by the ACH550. Although some people think that the motor will over-heat at low speeds due to reduced air flow from the motor's cooling fan, this isn't

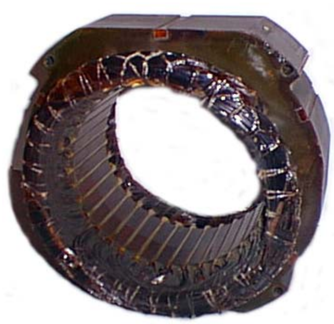

Figure 1: A motor stator with over-heated insulation.

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the case for variable torque loads. While the cooling air flow across the motor does drop off proportionally to the motor's speed, the motor's current drops off much faster, since the torque required by the motor is roughly proportional to the *square* of the motor's speed. To put numbers to this, when the motor is running at 50% speed, its cooling fan is producing 50% of full cooling air flow, but the motor's current (and its heating effect) is around 25% of that at full speed. The motor in a variable torque application should run cooler as the motor's speed is decreased.

So, what could make the motor's stator windings overheat this much? Some possible causes include:

- Blocked cooling to the motor.
- Running at full speed in bypass mode or from a constant speed motor starter and encountering an overload. While the motor overload *should* take care of this, sometimes things go wrong.
- Improper wiring of the motor. Running a 208 V AC motor from 460 V AC will generate a lot of heat quickly.
- In a similar way, entering incorrect motor data into some VFDs can also cause a motor to run hot.
- For a constant torque application, such as a screw compressor, reciprocating compressor, or some industrial application (like a conveyor or hoist), running the motor for extended times at low speed can cause thermal problems. The problem here is that the motor must provide full torque even at low speeds. So, at half speed the motor's fan is providing half cooling while the current through the motor is producing full heating. Not all VFDs effectively protect against this.

- ***"The motor just stopped running and the VFD indicated that it has an output short circuit or earth fault."***

The motor won't smell "burned" and a quick inspection of the motor's stator windings may not reveal any major damage.

A variety of situations could cause this. Some possible causes are:

- Loose wire strands in the motor's conduit box.
- Nicked insulation in the motor cables. This can occur if the conduit wasn't de-burred sufficiently before the motor cables were pulled through it.
- Moisture in the motor or in the conduit between the VFD and the motor.
- Insulation break-down in the motor's windings. An insulation tester, such as a "Megger", can apply a high voltage to the motor's stator windings to confirm if insulation break-down is a problem. This could be caused by the interaction between the VFD and the motor's stator windings. That is the topic of this paper.

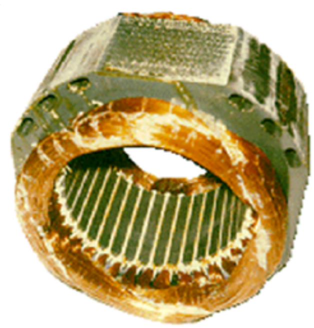

Figure 2: A motor stator with pinhole insulation damage.

What causes VFD-induced motor insulation break-down?

VFD-induced motor insulation break-down is the result of an interaction between the voltage pulses that the VFD applies to the motor and the stator coils of the motor. The motor's coils have an electrical property called *inductive reactance*. This causes these coils to react to a change in the current through the coils by producing a voltage that opposes this change in current flow. This is sometimes called a "back-voltage".

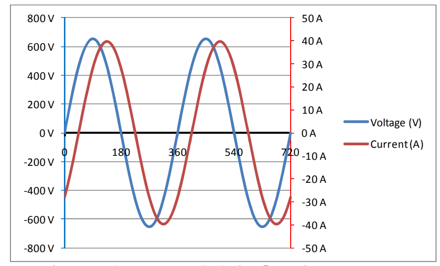

Figure 3: In an AC induction motor, current lags behind voltage.

- If the change in current flow is gradual, such as when a sine-wave AC line voltage is applied to the motor, the motor's reaction is also gradual. The *inductive reactance* of the motor simply delays the change of current through the motor, making it lag behind the applied voltage.

- When a fast-rising voltage pulse is applied to the stator coils of an AC induction motor, the back voltage generated by the motor's coils can cause the voltage pulse to overshoot the voltage that was applied by the VFD. This overshoot interacts with the inductance of motor, the inductance of the motor cables, and the capacitance of the motor cables and the motor to cause the voltage to oscillate. The peak voltage caused by this oscillation is the major point of concern. If this voltage gets to be too high, it can break through the motor's insulation and cause the motor's windings to short.

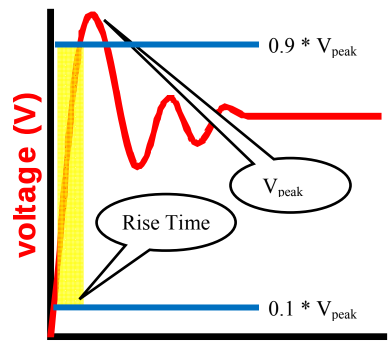

Figure 4: When a voltage pulse reaches a motor, it overshoots and oscillates.

A number of measurements are commonly used describe the shape of the PWM pulse at the motor.

- The **peak voltage** (V_{peak}) determines the amount of stress that is imposed on the motor's stator insulation.

- Another is the **rise time** of the pulse. While the exact definition of this varies throughout the world, in North America this is generally considered to be the amount of time for the pulse to rise from 10% to 90% of the peak voltage of the pulse. This is measured in microseconds (µs). The shorter the rise time, the greater the stress that the pulse will apply to the motor's insulation. A pulse with a rise time of 0.1 µs or shorter is generally considered to be a very fast-rising pulse.

- The other is ***dV/dt***, the rate of rise of the pulse's voltage. This is calculated by considering the yellow rectangle above and dividing the change in voltage (*dV*) by the change in time (*dt*).

  For a given motor voltage, the insulation stress increases as the rise time becomes shorter or the *dV/dt* value becomes larger.

It isn't possible to talk about only VFD's *dV/dt* or peak voltage values. The shape of the pulse that the motor receives depends on the interaction between the VFD, the motor power cables, and the motor.

How high of a peak voltage should a motor be able to withstand?

First, let's review normal AC voltage. When an AC voltage is called 460 V AC, this is the *effective* (or *rms*) voltage of the AC wave. This is the DC voltage that would provide the same amount of power to a resistor as the AC voltage. The AC voltage reaches a *peak* voltage that is $\sqrt{2}$ times the *rms* voltage. In this case, that would be 650 V. This peak voltage is very close to the DC bus voltage that a VFD uses for making the PWM pulses that it supplies to the motor.

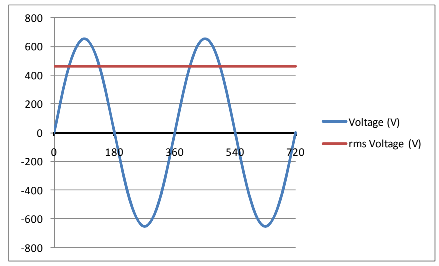

Figure 5: The relationship between instantaneous and *rms* AC voltage.

(In case you were wondering, *rms* stands for "root mean square", which describes the calculation that is used to determine this voltage.)

General Purpose Motors

When the National Electrical Manufacturers Association (NEMA) wanted a standard for how high of a voltage the insulation in a motor should be able to withstand, they knew that it would need to be above the 650 V that the AC power line already provides. The value that was selected for *general purpose motors* with a base voltage rating of up to 600 V was **1000 V**. This is published in NEMA Standard MG 1, Part 30. It is about 150% of the voltage that would be experienced from a normal AC power line. That seems to be safe enough.

Definite-Purpose Inverter-Fed Polyphase Motors

The voltage pulse that a PWM VFD applies to a motor overshoots the DC bus voltage that generated the pulse. When the use of PWM VFDs became more popular, NEMA needed a new standard to ensure that motors had sufficient stator insulation to ensure reliable operation when used with VFDs.

The peak voltage of the pulse can reach is *as much as* two times the DC bus voltage of the VFD. Therefore the 1993 version of NEMA MG 1, Part 31 stated that a *definite-purpose motor* for use with a VFD should have stator windings that can withstand **1600 V**. In 2006, NEMA MG 1, Part 31 provided the following calculation:

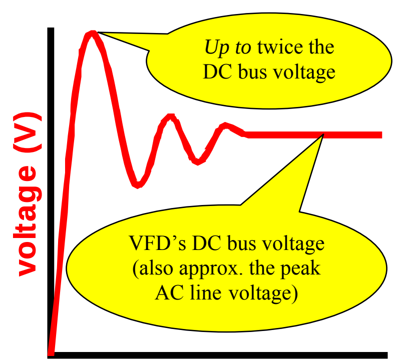

Figure 6: Voltage levels in a PWM pulse.

$$\underset{\text{Safety Factor}}{1.1} * \underset{\text{Max. Voltage Overshoot}}{2} * \underbrace{\sqrt{2} * V_{rated}}_{\text{DC Bus Voltage}}$$

For a 480 V AC power line, this is **<u>1490 V</u>**. There isn't much of a difference between the two versions of this standard.

<u>Note</u>

The motor's peak voltage rating doesn't correlate to the Insulation Class of the motor. The motor insulation class rating describes the *temperature rating* of the insulation and *not* its ability to withstand voltage peaks.

For example, a motor with Class B insulation is rated for a winding temperature of 130°C, while a motor with Class F insulation is designed for a maximum winding temperature of 180°C. The higher insulation class can be useful when operating the motor in a location with a high ambinet temperature, when the motor may experience overloads or a poor supply voltage, or when it must drive a constant torque load at low speed for a long amount of time. While a motor with Class F insulation *might* be able to withstand higher peak voltages, its isn't necessarily designed to.

To get a motor that can handle peak voltages up to 1600 V, it is important to specify a motor that meets the peak voltage requirements of NEMA MG 1, Part 31.

<u>What determines the amount of voltage overshoot?</u>

There are a number of factors that impact the amount of voltage overshoot. This is of interest because, if the peak voltage at the motor can be kept below the 1000 V value, it may be possible to use a *gerneral purpose* motor, rather than a *definite-purpose* motor, with the VFD.

- **<u>The rise time of the VFD's PWM pulses</u>** has a major impact on the peak voltage at the motor.

  When a VFD is designed for industrial applications, fast response is often a prime concern. Some industrial VFDs use high PWM pulse switching frequencies to get precise control of the motor. To achieve this, the inverter section of the VFD must be designed to produce PWM pulses that quickly transition between fully OFF and fully ON. These pulses may have a very short rise time, often less than 0.1 µs.

  While the short rise time allows these industrial VFDs to operate at a high switching frequency, there is a price to pay. The very fast transition causes a very high rate of change of the voltage that is applied to the motor (a high *dV/dt* value). Since the motor's stator coils produce a voltage that opposes this fast-rising voltage pulse, a high voltage overshoot can result. In this example, the peak voltage at the motor is about 1250 V. A general purpose motor isn't appropriate here. A motor that conforms to the peak voltage standard of NEMA MG 1, Part 31 should be used.

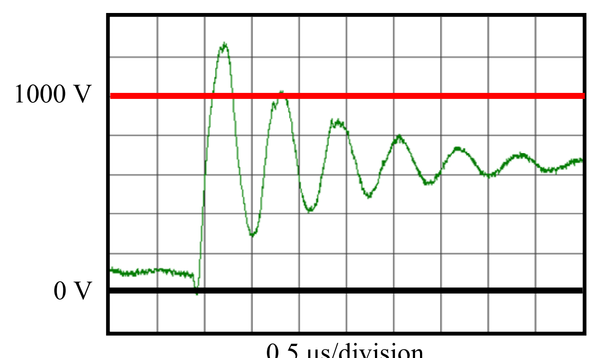

Figure 7: A PWM Pulse with a high *dV/dt* value can cause a large voltage overshoot.

  Not all VFDs are designed for use at high switching frequencies. In commercial buildings, a high switching frequency can generate excessive levels of electrical noise (Radio Frequency Interference and Electro-Magnetic Interference – RFI and EMI). Such interference is reduced by using a lower

PWM switching frequency. When a VFD is designed to operate at a lower switching frequency, it can produce PWM pulses with a longer rise time and so a lower value of *dV/dt*. This results in a lower peak voltage at the motor.

Figure 8 shows the advantage of using a PWM pulse with a lower *dV/dt* value. Both Figure 7 and Figure 8 were made using the same motor, the same motor cable length, and the same load on the motor. The difference is only the VFD that was used. For Figure 7, a VFD that produces very fast-rising pulses caused the motor to experience a peak voltage well in excess of the ratings of a general-purpose motor. For Figure 8, the PWM pulse has a longer rise time. The peak voltage of about 820 V is well within the ratings of a general-purpose motor. There would be no need to replace this motor with a definite-purpose motor that is specially made for use with VFDs.

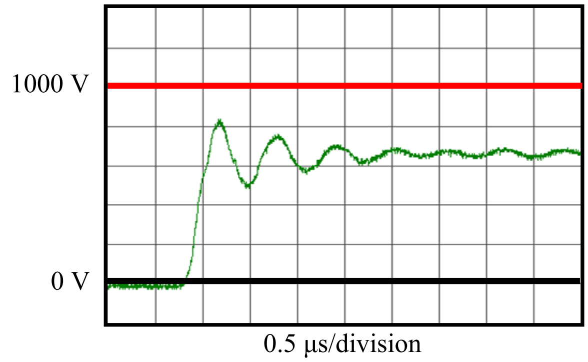

Figure 8: A PWM pulse with a lower *dV/dt* value creates a lower voltage overshoot.

- **<u>The length of the power cables between the VFD and the motor</u>** also has a major impact on the peak voltage at the motor. It is always best to keep this cable length as short as practical.

Much of the energy that causes the voltage overshoot and oscillation of the PWM pulses is from energy that is stored in electromagnetic fields in the motor cable. The longer the motor cable, the greater the stored energy. Here is a pair of examples.

In the first case, the motor cable was 10 feet long. Because of the small amount of cable, not much energy was stored in it with each PWM pulse. As a result, the peak voltage of the PWM pulse was about 800 V, well within the limits of NEMA MG 1, Part 30.

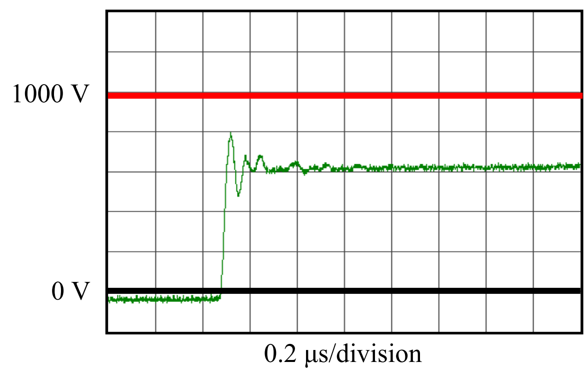

Figure 9: A short motor cable length causes a low peak voltage.

For the second test, the only change was that the motor cable length was now 210 feet. This caused a peak voltage at the motor cables that was about 1220 V.

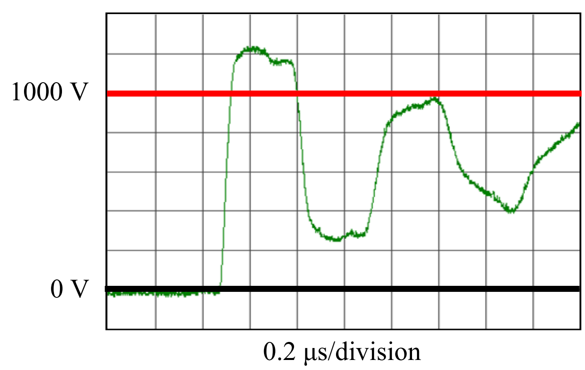

Figure 10: A motor cable length over 200 feet causes a large voltage overshoot.

While it is clear that keeping the motor cable length as short as is practical is a good idea, don't read too much into these examples. It is a *combination* of the *dV/dt* (or rise time) of the PWM pulse and the motor cable length that determines the peak voltage at the motor. For example, I made a measurement of the peak voltage at a motor's terminals for a motor cable length of only 16 feet. Because the VFD that I was testing produced pulses with a very short rise time, the peak voltage at the motor's terminals was over 1500 V.

It is useful to note that the ACH550 produces pulses that have a relatively long rise time. As a result, it causes less motor insulation stress than most competitive VFDs.

Other factors that have an impact on motor insulation stress.

The rise time of the PWM pulses produced by the VFD, the motor cable length, and the design of the motor's insulation system are the main factors that determine the amount of stress that using a VFD will have on the motor. However, there are some other factors that are worth mentioning.

- **Power Line Voltage**

  While this has a major impact on the stress on the motor's insulation, I won't really spend much time on it. While you can choose the peak voltage rating of the motor's insulation, the design of the VFD, and (to some extent) the length of the motor cables, you seldom are able to choose the voltage that is applied to the VFD; you generally use what is available. Even so, it is still important to understand the role that the AC line voltage plays in the stress on the motor's insulation.

208 / 240 V AC

208 / 240 V motors generally have the same insulation system as 480 V motors. Most of the time, the motor can be converted between these voltages by simply re-wiring it. Therefore, a general purpose 208 or 240 V motor should have an insulation system that can withstand 1000 V peak voltages.

Now, consider a VFD that is connected to a 240 V power line. The DC bus voltage of this VFD is 340 V. Even if the motor receives PWM voltage pulses that are twice the DC bus voltage, the motor will only experience a peak of 680 V. This is well within the rating of the motor's insulation, so there is no need for concern.

Unfortunately, I sometimes see specifications that call for a filter to limit the peak motor voltage for a 208 V AC applications. There is no reason to do this.

480 V AC

When a VFD is connected to a 480 V power line, its DC bus voltage will be around 680 V. In a worst case scenario, the peak voltage at the motor's terminals could be as high as 1360 V. This could damage a general purpose motor's insulation. However, as shown above, you don't necessarily need to confront the worst case scenario. If the motor cable lengths are kept short and if the VFD used generates PWM pulses with a relatively long rise time, the peak voltage at the motor can be kept to less than 1000 V.

600 V AC

In Canada (and in a small number of locations in the United States) the power line voltage may be between 575 V and 600 V AC. This represents a voltage that is 25% higher than a 480 V AC power line. In these cases, additional care must be taken to avoid motor insulation problems. This doesn't necessarily mean that the motor must conform to the peak voltage standard of NEMA MG 1, Part 31. However, careful consideration may be needed to avoid problems.

- **<u>Load on the Motor</u>**

  While the load on the motor has a relatively minor impact on the peak voltage at the motor terminals, there is a slight tendency for the peak voltage at the motor terminals to drop as more current is drawn through the motor. The amount of reduction is seldom significant.

- **<u>PWM Switching Frequency</u>**

  The rate of production of PWM pulses (the Switching Frequency) seldom has any impact on the peak voltage at the motor's terminals. In most cases, each pulse continues to act independently.

  As far as motor insulation stress is concerned, the main reason for reducing the switching frequency is to reduce the number of voltage pulses that are received by the motor each second. This will reduce how quickly the impact of these pulses builds up in the motor.

  Here's what is happening. Each voltage pulse generates a large electromagnetic field around the motor's windings, particularly at the ends of the winding, where the bend in the windings tends to concentrate the field. This can cause a corona effect, which may generate some ozone at that point. Ozone is chemically reactive and can attack the organic varnish that is used in some general purpose motors. If this process eventually forms a pin hole in the varnish, the motor will short out and the VFD will immediately stop. Reducing the switching frequency of the VFD can significantly slow the process of generating the ozone.

  When a very high switching frequency is used with a very long motor cable, the PWM pulses can interact and build on each other. Here, the peak voltage at the motor can be more than twice the DC bus voltage. However, such cases aren't common in HVAC applications.

- **<u>The size of the motor</u>**

  From experience it appears that 15 HP and smaller 480 V motors experience more stator insulation problems than larger motors. There are a few factors that may be at work here.

  First, the smaller motors have less space for insulating the stator windings and the wire bends at the ends of each section of coil must be sharper. These combine to make the motor more susceptible to insulation damage.

  In addition, smaller motors have a higher impedance (resistance to AC current flow) than large motors. This can create an impedance mismatch between the motor and the lower impedance of the motor cables and the VFD's inverter section. This mismatch can increase the oscillation of the voltage pulses at the motor.

Common questions about PWM VFDs and motor stator insulation.

How can problems with motor insulation damage be avoided?

There are a number of answers to this question. The most appropriate answer can depend on the requirements of the application. Here are a few thoughts.

1. **Use a VFD that generates pulses with a relatively long pulse rise time.**

   It is the fast increase in the voltage that reacts with the inductance of the motor's coils to cause the voltage overshoot. The ACH550 was designed to reduce the stress in the motor's insulation by generating pulses with rise time that is longer than most other competitive VFDs.

2. **Keep the motor cable length as short as practical.**

   As the motor cable length gets longer, the electrical energy that is stored in the motor cables becomes greater. This additional energy increases the voltage overshoot of the pulses.

3. **Use a motor that conforms to NEMA MG 1, Part 31's peak voltage specification.**

   Normally, the peak voltage produced by the PWM VFD won't be a problem for such a motor.

Do I need to buy a new motor when I convert a constant speed application to variable speed?

1. It isn't always necessary to replace the motor. If the VFD produces pulses with a moderately long rise time and if the motor cable length can be kept short, the peak voltages at the motor can be kept to less than 1000 V, the standard for general purpose motors. For 480 V power lines, if an ACH550 is used, keeping the motor cable lengths less than 100 feet is generally sufficient.

2. If the motor needs to be mounted a significant distance away from the motor, a filter at the output of the VFD can reduce the motor's insulation stress to a reasonable level. Two types of filters are commonly used.

   - One is a set of output reactors (coils). Because coils oppose fast changes in the current passing through them, they will increase the rise time of the pulses at the motor.

     Unfortunately, such reactors occasionally cause problems, particularly for relatively long motor cable lengths. The reactors act like additional wire between the VFD and the motor. The energy stored in the reactors can, in some cases, increase the peak voltage at the motor.

   - A *dV/dt* filter reduces concerns about the possible voltage overshoot at the motor. The three capacitors on the motor side of the reactors absorb energy from any high voltage pulses. The resulting PWM waveform is generally suitable for use with general purpose motors, as defined by NEMA MG 1, Part 30.

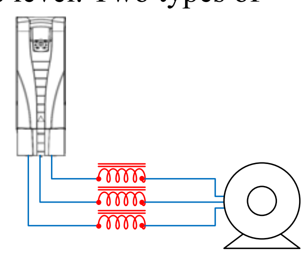

Figure 11: A set of output reactors between the VFD and the motor.

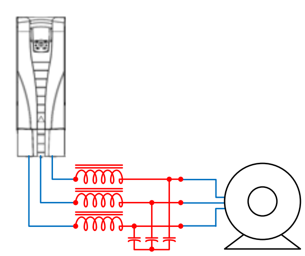

Figure 12: A *dV/dt* filter reduces the rate of rise of the PWM pulse and controls voltage overshoot.

3. While the methods above can allow existing general purpose motors that are in good shape to be used during a retrofit of constant speed motor starters, it can be difficult to know if the motors are in good shape. Unfortunately, no tests can definitively project the "life" remaining in an old motor.

   If the application is critical, it may simply make sense to replace the existing motors with new motors that meet the NEMA MG 1, Part 31 standard.

   However, for less critical applications, many end users have decided to keep their existing motors when an energy retrofit was performed. Most have been happy with their decision.

<u>What do dV/dt filters have to do with power line harmonics?</u>

The simple answer is "nothing". Power line harmonics deal with how the VFD draws power from the AC power line while *dV/dt* filters deal with how energy is supplied to the motor. I am always a bit surprised when I read a specification that instructs us to add output *dV/dt* filters if an analysis of the power line harmonics shows that the system doesn't pass the requirements of IEEE 519. This just doesn't make sense.

<u>The ACH550 User's Manual gives some very long maximum motor cable lengths, some as long as 980 feet. What is the correct maximum motor cable length?</u>

This paper has looked at <u>*motor*</u> insulation stress. The table in the "Motor Connection Specifications" table in the *User's Guide* looks at the limitations <u>*of the VFD*</u> and not the motor. It assumes that the motor has sufficient insulation to handle any peak voltages that may occur.

- The limitations on motor cable length from the VFD's point of view arise because of the PWM pulses that the VFD produces. These pulses have high frequency components that couple electrical energy between the motor leads and from the motor cable to ground via the surrounding conduit. Under normal circumstances, the amount of energy that is "lost" in this way is insignificant. However, when the motor cable is extremely long, a significant amount of energy may be lost through the cable. Among other problems, this may:

  - reduce the energy available to drive the motor at full load.

  - cause the VFD to produce nuisance Earth Fault, Overload, or Short Circuit trips.

  Generally, the motor cable length limitations given in the "Motor Connections Specifications" table are far longer than are seen in HVAC applications. If it is necessary to use a longer motor cable length than the maximum shown in this table, it may be necessary to connect a sine wave filter to the output of the VFD. Such a filter essentially eliminates the PWM voltage pulses on the output of the VFD and smoothes them into a voltage waveform that is nearly sinusoidal. This reduces the coupling of energy from the motor cables to each other or to ground.

  If you have a need for an extremely long motor cable length, contact the HVAC Application Engineers at the factory for advice. *PowerHelp* is an excellent tool to use when you have such questions.

- Shortly after the table mentioned above, the *User's Manual* provides two more tables listing other maximum motor cable lengths. These deal with ensuring that the installation of the VFD will meet various standards for conducted and/or radiated electrical noise. Some of the standards are quite stringent, so some of the motor cable lengths are quite short. These standards are based on European requirements. While they are not commonly applied in North America, it is useful to know about these tables when electrical noise is a major concern.

  I should point out that simply complying with these maximum motor cable lengths is no guarantee of an installation with no electrical noise problems. In this same section of the manual are instructions for wiring the system. It is equally important to follow these instructions carefully when electrical noise is a concern.

- So far, I've avoided directly answering the question about the maximum length of the motor cable. The problem is that there is no definite cut-off where every motor length shorter than it is fine and every motor cable length longer that it is a problem. There are also variables, such as the AC line voltage, the type of motor being used, and so on. To attempt to simplify this, here is a compilation of rules of thumb for motor cable lengths. While a rule of thumb is never perfectly accurate, it at least can provide some degree of guidance.

Rules of Thumb for Maximum Motor Cable Lengths

<table>
<tr><th rowspan="2">Power Line Voltage</th><th colspan="4">Motor Cable Length[1]</th></tr>
<tr><th>up to
75 ft</th><th>up to
100 ft</th><th>up to the max. length in the
"Motor Connection Spec."</th><th>longer</th></tr>
<tr><td>208 – 240 V AC</td><td colspan="3">General Purpose Motor
(NEMA MG 1, Part 30)</td><td>(3)</td></tr>
<tr><td>480 V AC</td><td colspan="2">General Purpose Motor
(NEMA MG 1, Part 30)</td><td>Inverter Duty Motor
(NEMA MG 1, Part 31)[2]</td><td>(3)</td></tr>
<tr><td>575 – 600 V AC</td><td>General Purpose Motor
(NEMA MG 1, Part 30)</td><td colspan="2">Inverter Duty Motor
(NEMA MG 1, Part 31)[2]</td><td>(3)</td></tr>
</table>

1. These maximum motor cable lengths are rules of thumb based on the motor's stator insulation and the VFD's maximum motor cable length capability. RFI/EMC concerns are not taken into account. All lengths are based on the ACH550 VFD. Competitive VFDs may need a significantly shorter motor cable length.
2. Follow the maximum cable length recommendations of the motor manufacturer, if they are more restrictive.
3. For motor cable lengths longer than the VFD's recommendation, a sine wave filter and/or other considerations may be required. Contact ABB.