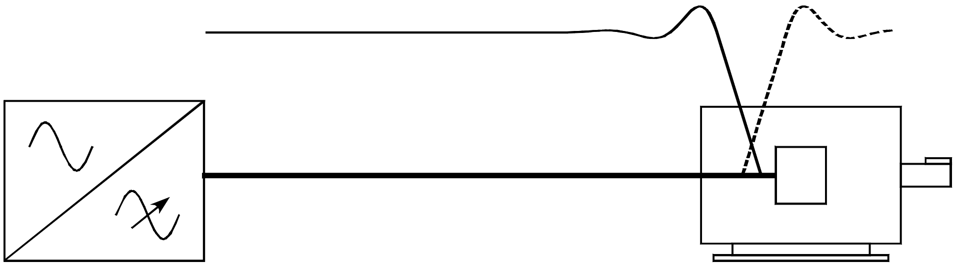
Technical Guide No. 102

Effects of AC Drives on Motor Insulation

- Knocking Down the Standing Wave



“A guide to understanding installation concerns and analyzing the use of motors with AC Drives below 600VAC”

Technical Guide:

The discussion, illustrations, charts and examples given in this article are intended solely to illustrate the theory and application of drive technology. Because of the many variables and requirements of applications, ABB Industrial Systems, Inc. cannot assume responsibility or liability for actual use based on the content of this article.

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1.0 Introduction

Standard AC Motors Used With Adjustable Speed Drives

Standard induction motors that have been designed to operate from fixed frequency sinusoidal power, are being used with adjustable frequency drives (AFDs) in an increasing number. It is estimated that there are more than two million (2,000,000) standard motors successfully operating in the U.S. in adjustable frequency drive applications. Application of AC induction motors to Pulse Width Modulated (PWM) drives continues at a rate of approximately 250,000, per year. Insulation damage caused from a PWM drive, on the other hand, has been minimal. This guide is intended to provide insights to both the consulting community and users, into the effects on motor insulation by AC drives using newer generation output switching devices.

The output voltage waveform of today's PWM adjustable frequency drive is not a sine wave, but a series of square wave pulses that produces a reasonable approximation of sine wave current. Although there is an extensive history of successful use of standard motors on this type of waveform, the possible effects on the motor should be carefully considered.

The inherent rise times of later generation Isolated Gate Bipolar Transistors (IGBTs) used in AFDs create an effect called voltage overshoot. If the turn-on time of the output device is slow, the capacitance of the motor has an opportunity to charge and discharge with the IGBT. However, if the output device's turn-on time is fast, the capacitance of the motor is not able to keep up with the charge and discharge. Instead, the voltage applied across the lead increases. Therefore, more energy is stored, resulting in more overshoot voltage. Motor insulation not designed to protect against this voltage overshoot may fail prematurely. This concern applies primarily to motors and drives operated on 380Volt (V), 480V and 600V power systems. With 208V and 240V power systems, stresses due to voltage overshoot occur, but are not sufficient to normally cause concern.

This technical guide addresses the extra voltage stress on the motor's insulation system, related to the square wave pulses comprising the PWM AFD's voltage waveform, and gives recommendations regarding ABB drives.

Using This Guide

This guide has been designed to provide an understanding of the characteristics of adjustable frequency PWM drives as related to insulation voltage stress in the motors that are used with them. The background discussion leads to recommendations regarding selecting, specifying and applying motors and drives to maximize drive system reliability.

Readers wanting to gain an understanding of AC drives and the reasons for insulation voltage stress concerns should start at Section 2.0 (page 3).

For recommendations regarding selecting, specifying and applying motors and drives, please go straight to Section 5.0 (page 18).

2.0 PWM Adjustable Frequency Drives

ABB Adjustable Frequency Drives (AFDs) are Pulse Width Modulated (PWM) drives, as are most AFDs available today. Figure 1 illustrates the basic principles of an ABB PWM drive. The rectifier converts input line power, which has a nominally fixed voltage and frequency, to fixed voltage DC power. The fixed voltage DC power is then filtered to reduce the ripple voltage resulting from the rectification of the AC line. The inverter then changes the fixed voltage DC power to AC output power, with adjustable voltage and frequency.

The output waveform consists of a series of rectangular pulses with a fixed height and adjustable width. The overall pattern of positive vs. negative pulses is adjusted to control the output frequency. The width of the individual pulses is modulated so that the effective voltage of the fundamental frequency is regulated in proportion to the fundamental frequency.

One (1) cycle of the output waveform at a given output voltage can be made from many narrow pulses or fewer wider pulses. To generate a waveform containing more pulses, the transistors or other switching devices in the inverter must switch more often. The rate at which the switches operate is called the switching frequency or carrier frequency.

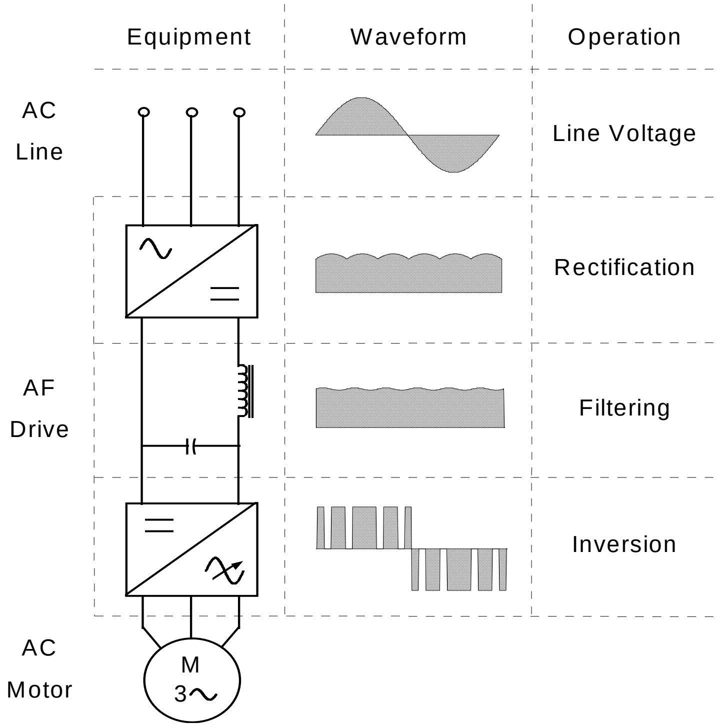

Figure 1 Principles of Operation for ABB Adjustable Frequency Drives

3.0 Motor Insulation Systems

Motor Stator Construction

The stator of an AC motor consists of a stack of steel laminations that have coils of magnet wire set into slots. Figure 2 is a representation of a stack of stator laminations showing the slots that receive the coils of wire. A number of coils are distributed among the slots to provide a group of coils that define each pole of the motor. For each pole, there are coils designated for connection to each phase of power.

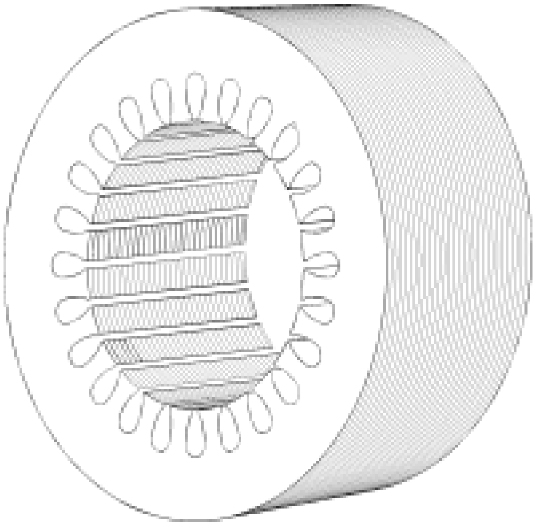

Figure 2 Motor Stator Lamination Stack

The various electrical conductors that form the motor stator windings must be electrically insulated from each other and from the metal parts of the motor structure. Insulation is required wherever there is a difference of electrical potential between two (2) conductors. Turn-to-turn insulation prevents one (1) turn of a coil from short circuiting to an adjacent turn. Coil-to-coil insulation prevents various series or parallel connected coils from shorting to one another. Phase-to-phase insulation separates the coils of one (1) phase from those of an adjacent phase. Winding-to-ground insulation prevents any part of the stator windings from shorting to the stator laminations.

A Typical Motor Insulation System

Motor insulation systems vary considerably among the various motor manufacturers, but the following paragraphs provide a general description of the various components that comprise a typical insulation system.

Magnet wire is insulated with a thin coating of a varnish that is specifically designed as an electrical insulation material. The magnet wire insulating varnish provides the turn-to-turn insulation and a portion of the other elements of the motor insulation. In most motors, a large part of the winding-to-ground insulation is provided by a paper insulation lining in the stator slots. Paper insulation is also used to separate the windings of different phases. These components of the insulation system are called *Slot Papers* and *Phase Papers*. A rigid piece of insulation called a *Top Stick Slot Wedge* may be inserted in the opening of the slot to hold the windings securely in position. A diagram of a stator slot, showing the slot paper, a phase paper and the top stick are shown in Figure 3, below.

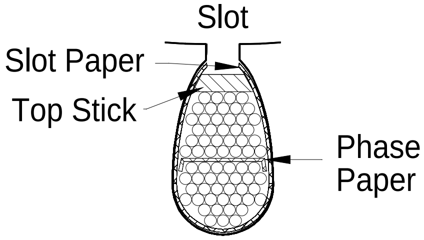

Figure 3 Stator Slot Insulation -- Slot Paper, Phase Paper and Top Stick

At each end of the stack of laminations, portions of the coils of wire, called the end-turns, pass from one slot to another. The end-turns are often separated from one another by paper insulation. Once the coils are wound into the stator laminations, the stator is dipped into a tank of insulating material, and baked, to coat the windings with another layer of insulation. This additional coating compensates for nicks and irregularities in the original coating, created during the manufacturing process and adds insulation to the magnet wire. After the additional coating cures, the stator may be dipped a second time for added protection from contaminants and moisture. This second, and subsequent dips and bakes, are typically an option offered by motor manufacturers.

Design Variations

The types and amounts of insulating materials used can vary considerably from one (1) manufacturer to another. Some manufacturers may omit some or all of the paper insulating components and depend upon the varnish coated wire to serve in their places. This is, however, more typical of fractional horsepower (HP) motors, due to the cost of the added insulation in relation to the overall cost of the motor. Manufacturers often offer various motor product lines that provide a variety of application benefits at various price levels. One such example is the “inverter duty rated motor”. Some of these product lines include differences in the designs of their insulation systems. From time to time, new insulating materials are introduced with improved electrical, mechanical, thermal or chemical properties. An example of new magnet wire insulation technology is Phelps-Dodge’s Inverter Spike Resistant (ISR)® wire. This wire was originally purported to provide adequate protection against voltage overshoot caused by the fast rise times of IGBTs without the need for additional motor phase papers or sheets. Field reports, however, have shown that this wire alone provides only a minimal extension to motor longevity.

Insulation Stresses

Several different physical phenomena can cause electrical insulation to deteriorate or fail. These include thermal, contamination, mechanical, vibration, voltage, carrier frequency and the method of winding the turns of insulation.

Thermal

The service life of an insulation system is generally determined by thermal stress. All insulation systems deteriorate over a period of time due to the effects of thermal stress. If the insulation always remains at its rated temperature, it should not fail during its rated service lifetime. If the insulation continually exceeds rated temperature, its lifetime will be shortened in proportion to the level and duration of the excess temperature. The insulation may last longer than the rated lifetime if its temperature remains below the rated level for significant periods of time. Figure 4 shows the relationship of insulation life versus temperature normalized at 25°C (100% life). Increasing the temperature to 130°C decreases insulation life to 83% from nominal. Increasing the temperature further to 155°C (Class F insulation limit) or 180°C (Class H insulation limit) will further reduce insulation life.

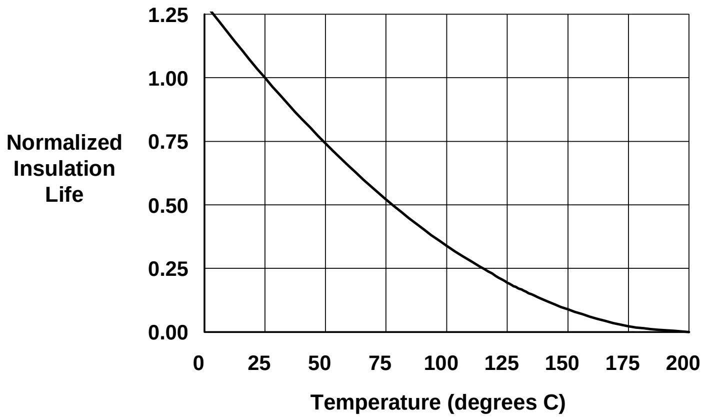

Figure 4   Insulation Life versus Temperature

Environmental

Contamination of the motor windings reduces dielectric strength dramatically, especially when fast rise time, high frequency voltages from IGBT inverters, are involved. A drip-proof motor that has successfully operated in a moist, sloppy pump pit may fail in short order when transferred from line power to inverter power. This is because contaminants such as oil, salt, acid, alkalies, grease, dirt, detergents, disinfectants, carbon black, chlorines or metal dust create conductive paths along the surface of the varnished windings, especially when combined with moisture from the surrounding environment. This facilitates high frequency surface tracking, which can effectively produce short circuits between otherwise insulated portions of the windings.

Mechanical

When a motor is line-started at full voltage, the powerful magnetic fields produced push and pull the stator coils back and forth, and large inrush currents generate rapid heating of the stator conductors, causing them to expand. The surrounding iron stator core heats up less, has a lower thermal expansion rate, and doesn't move at the same rate as the copper coils it supports. As a result, the copper coils strain against the varnish that adheres them to the core, causing fractures where the coils exit the core. Each successive across-the-line motor start repeats the cycle of flexing and expanding, worsens these breaks, and increases the chance that a conductor will abrade it's remaining insulation and short to ground. Once the insulation has cracks, moisture and contaminants will find their way in, further reducing insulation integrity. Similar expansion rate differences are present in the motor's rotor circuit, where the iron core expands slower than the copper conductors (used in large motors) it holds, and faster than aluminum conductors (used in smaller motors). Generally, however, the stator windings fail before the rotor does.

During inverter starts, however, motor voltage and frequency are slowly increased rather than applied at full value. Motor coils are not subjected to the excessive heating and flexing that occurs during line starts, thus extending motor life. Only when the inverter is bypassed, does the motor experience the starting stresses described above.

Vibration

One mechanical stress phenomenon that is more likely to appear on inverter applications than line-started ones is resonance (when a mechanical system oscillates at it's natural frequency). A common example of resonance is the vibrations noted on the side view mirror on an old car. As the car accelerates from standstill to freeway speeds, engine and frame vibrations are transmitted to the mirror's mounting base. At some point during acceleration, these vibration frequencies change and the mirror stabilizes again. Motor, pump and machinery designers all take resonance into account when designing their product. They will add mass, change support struts, or increase mounting base lengths to ensure that the item's natural frequency is well above 60Hz. When the machine is assembled onto a base, coupled to a motor, and bolted to a concrete pad, the natural frequency decreases, but, by design, remains higher than the running speed when excited to 60Hz. However, as the machine speed is changed with an inverter, the likelihood of stumbling onto the system's resonant frequency increases dramatically. Once resonance is reached, severe vibrations can occur in the motor, stressing stator coils, brinelling bearings, and even fatiguing bolts and castings to the breaking point. As the coils continue to move, they'll ultimately chafe through all layers of insulation, and a failure will result. Since this new resonant point is determined not by the parts of the machine, but instead by the assembly of parts, it must be corrected at the system level. This is best done during start-up. Although additional supports can be welded onto bases and belt ratios altered, the most cost effective method to avoid these resonance frequencies is to program an offset to the critical frequency. During acceleration and deceleration the inverter will pass through the critical resonance frequency but the critical frequency offset will prevent the inverter from operating at the programmed frequency band, thus avoiding the mechanical resonance.

Voltage or Dielectric

The *Dielectric* properties of a material are the characteristics of the material that make the material an electrical insulator rather than a conductor. When there is a voltage difference across the thickness of an insulating material, the voltage causes a *Dielectric Stress* that opposes the material's ability to prevent current from flowing through the material. The *Dielectric Strength* of a material is a measure of the material's capability to withstand dielectric stress. An insulation system's rated operating voltage is determined by the dielectric strength of the insulating materials. If the insulation is subjected to excess voltage, it can fail suddenly and catastrophically. Gradual deterioration can be caused by voltage levels that exceed the insulation rating but do not cause catastrophic failure. The other forms of stress - thermal, environmental, mechanical and vibration - lead to a reduction in the insulation's ability to withstand dielectric stress. The insulation ultimately fails when it can no longer withstand the applied voltage and the flow of short circuit current causes catastrophic failure.

Carrier Frequency

As the inverter's carrier frequency is increased, the output current waveform supplied to the motor becomes more sinusoidal. This improved output current waveform decreases motor heating thus improving motor insulation life.

At this higher carrier frequency, however, more individual voltage pulses are output and for a given cable length, rise time and motor surge impedance, the potential for voltage overshoot increases. The power generated during this overshoot will be dissipated in the motor's windings, and insulation life will be decreased.

Figure 5, below, shows insulation life of a generic motor, when both cable length and inverter carrier frequency (f_c) are varied. Note that with a 150 ft. cable length, insulation life drops from 100,000 hours to 25,000 hours, when carrier frequency is increased from 3 to 12 Khz. The longest life occurs with short cable lengths and low carrier frequencies.

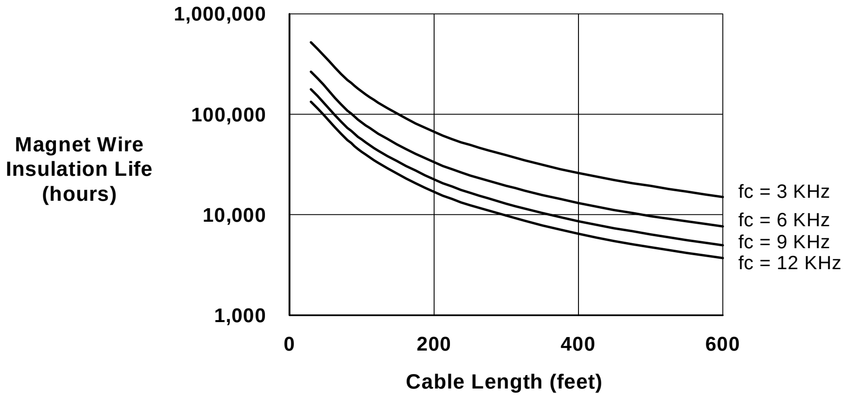

Figure 5 Insulation Life versus Cable Length and Carrier Frequency (f_c)

Significance Of Winding Configuration and Method

Figure 6 is a representation of one (1) coil of a motor winding consisting of several turns. The coil voltage is distributed among the turns so that the turn to turn voltage is less than the full coil voltage.

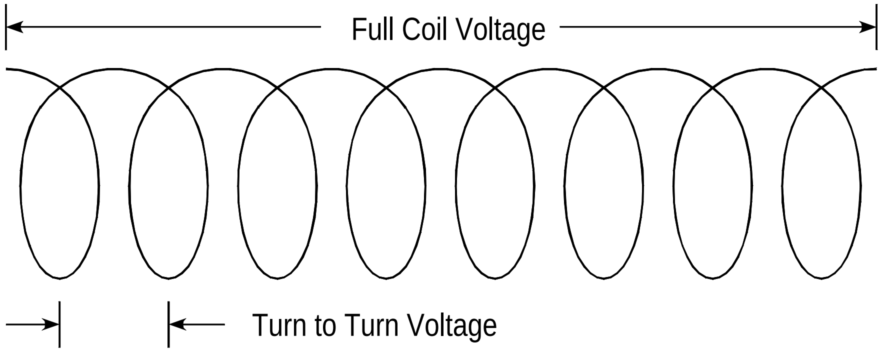

Figure 6 Turn to Turn Voltage

If the coil is wound concentrically, each turn of the coil is wound next to the previous turn and the coil is built up in successive layers. This ensures that each turn of the coil is in contact only with immediately preceding and successive turns, and the first turns in the coil are separated from the last turns. This means that the voltage between two (2) conductors that are next to each other is always less than the full voltage that is applied to the coil.

If the coils are wound randomly, the positions of the individual turns are not controlled. With random winding, it is possible that the first turn of the coil may be in contact with the last turn. If the first turn of the coil is in contact with the last turn, two (2) layers of magnet wire insulation must withstand full coil voltage. Figure 7 shows the comparison between concentric and random winding. Most motors rated for operation at 600V or less have random windings.

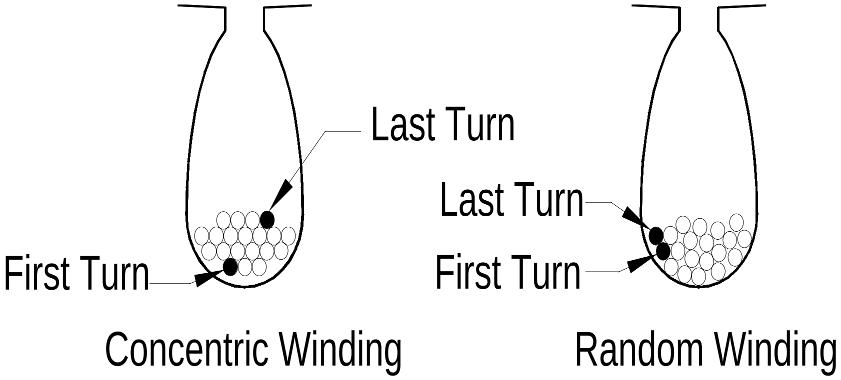

Figure 7 Concentric Winding vs. Random Winding

4.0 Motors Used With PWM Drives

The output voltage and current waveforms produced by PWM drives are a source of particular concern for the stresses placed on motor insulation systems. PWM waveforms contribute to increased thermal, vibration and dielectric stresses. As long as PWM drives have been in use, these stresses have generally been recognized as factors in selecting and applying motors for PWM duty. Recent advances in drive technology, however, have increased the impact of certain elements of dielectric stress.

Output Pulse Shape

Figure 8 shows three (3) examples of an enlarged view of a single pulse of a typical PWM output waveform. At the beginning of the pulse, the voltage rises rapidly from zero (0), overshoots to a peak and then settles back to the normal pulse height, which is the same as the rectified DC voltage. Note that there may be little or no overshoot or the voltage may oscillate or “ring” before settling back to the normal pulse height. The rise time, the dv/dt and the total peak voltage, including the overshoot, are very important in our consideration of motor insulation voltage stress.

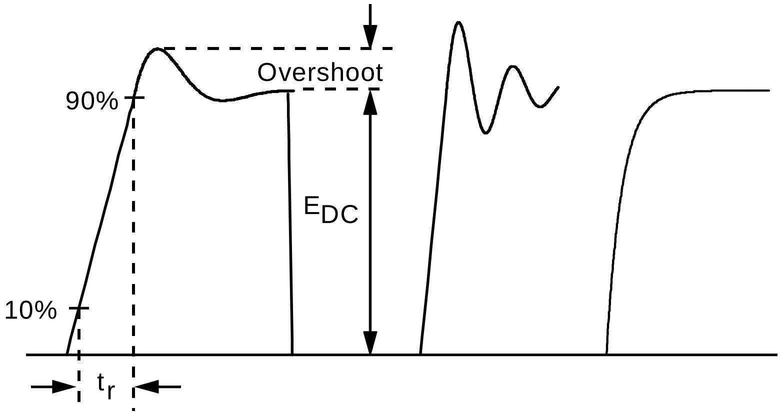

Figure 8   Typical PWM Output Pulse Shapes

Rise Time and dv/dt and Peak Voltage

Rise Time, shown as t_r in Figure 8, is usually defined as the time required for the voltage to rise from 10% to 90% of the peak voltage. The *dv/dt* is the slope of the voltage rise in volts per microsecond (μ). The dv/dt can be approximated as 80% of the peak voltage divided by the rise time.

Eq. 1:

$$dv/dt = \frac{Peak\ Voltage\ \times .8}{t_r}$$

In calculating dv/dt from a stated rise time, it is essential to know what definition has been used to determine the stated rise time. Various discussions of this topic may use different definitions of rise time and dv/dt. Sometimes rise time has been defined as the time required for the voltage to rise from zero (0) to the peak voltage and dv/dt is defined as peak voltage divided by rise time. The rise time has also be defined as the time required for the voltage to rise from 10% to 90% of the DC bus voltage. This paper uses the definition for pulse rise time given in the IEEE Standard Dictionary of Electrical and Electronics Terms. (See page 16 of this paper for a discussion of rise time and dv/dt related to NEMA Standard MG 1.)

The rise time is primarily determined by the switching characteristics of the inverter switching devices (darlington transistors, IGBTs or GTOs) and associated components. Other factors that can influence the rise time and the height of the overshoot, include the load current and the design and construction of the inverter circuitry. Some significant aspects of the inverter circuitry are the snubber circuit design and the internal resistance, inductance and capacitance of all components, wiring and mechanical elements of the circuitry. The characteristics of the motor cable can also influence the output pulse shape.

Considering various drive brands and models, the rise time is typically 0.1µ for drives using third generation IGBTs. First generation IGBTs had rise times of 0.25µ. Drives using ordinary bipolar transistors typically have rise times in the 0.5µ to 1.5µ range. Drives which use GTOs typically have rise times in the 15µ to 20µ range. Drives still using Silicon Controlled Rectifiers (SCRs) have rise times in the order of 40µ to 100µ.

Pulse Shape At The Motor Terminals

Reflected Voltage Pulses

When ripples travel across a pond and strike a barrier, they reflect back from the barrier and combine with the incoming ripples. In a similar way, a voltage wave travelling down a transmission line is reflected back from the transition between the line impedance and the load impedance at the end of the line. If the load impedance is equal to the characteristic impedance of the line, there is no reflected wave. If there is a large difference in impedance, the amplitude of the reflected wave will approach the amplitude of the original or incident wave. A positive reflection occurs if the load impedance is greater than the line impedance.

The conductors that connect a motor to a PWM controller act as a transmission line. Since the characteristic impedance of a motor cable is typically less than the characteristic impedance of a motor, classical transmission line theory predicts that a voltage reflection will occur at the end of a motor cable. The characteristic impedance is significantly less for larger motors than it is for smaller motors while there is a smaller range of values for typical cable impedances. This means that the magnitude of the reflected voltage is significantly less for larger motors as compared to smaller motors.

Although the output pulse travels from the PWM controller to the motor at about half the speed of light, it is possible that the time required for a pulse to reach the motor may be more than half the rise time of the pulse. This is the case when the length of the motor cable is greater than or equal to the critical length. The critical length can be estimated as one half (1/2) of the speed that the pulse travels from the drive to the motor multiplied by the rise time.

$$L_{critical}(feet) = \frac{V_{cable} \times t_r(\mu s)}{2}$$

> *V_{cable} (sometimes referred to as propagation factor) is the speed that the pulse travels from the drive to the motor in feet per μ. The value of V_{cable} depends on the type of cable, the type of conduit or cable tray and other details of the cable installation. V_{cable} is often estimated as 500 feet per μ.*

Typical values of critical cable length can be 25 to 200 feet for IGBT-type drives, 150 to 400 feet for drives using ordinary bipolar transistors and 750 to 2500 feet for GTO-type drives. These estimates are based on V_{cable} = 500 ft./μs and the previously mentioned rise times that are typical for various drive brands and models.

If the time required for a pulse to travel from the controller to the motor is more than half the rise time of the pulse, the reflected pulse will combine with the incident pulse to increase the amplitude of the pulse at the motor. If the motor impedance is much greater than the cable impedance, the amplitude of the reflected pulse can equal the amplitude of the incident pulse resulting in a peak voltage at the motor that is twice the peak voltage at the controller. The peak voltage at the motor can be increased to more than twice the peak voltage at the controller by ringing as discussed below.

For cable lengths longer than the critical length, transmission line theory would predict that points of maximum voltage would occur at cable lengths that are multiples of the critical length. At intermediate lengths, “null” points should be found where the voltage is less than the maximum. However, the cable and waveform are not sufficiently uniform to allow the cable length to be “tuned” to position the motor at a “null” point where high voltage peaks would not occur. In addition, the combined effect of reflected voltage pulses and ringing results in a continual increase in voltage as described below.

Ringing

The inductance and capacitance of the cable, the motor and the output circuit of the drive may constitute a resonant circuit that can cause the edges of the voltage pulses to assume an underdamped ringing waveform. Combined with the voltage reflection phenomena, this ringing can result in voltage peaks that are significantly more than twice the bus voltage of the drive. For a 460VAC input line typical bus voltage is 650VDC. With a 10% high line this voltage could increase to 715VDC. Ringing can create voltage peaks of more than twice this voltage or in excess of 1430V.

Figure 9 shows the effect of ringing and voltage reflections on the output pulse shape at the motor.

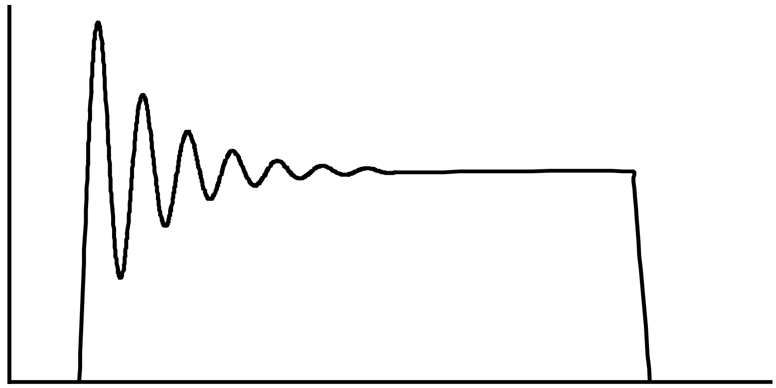

Figure 9 Reflected Voltage at the Motor Terminals With Ringing

Combined Effects

Using simulation and empirical methods to determine the combined effects of voltage reflections and ringing, various investigators have determined that the total magnitude of the voltage peaks at the motor terminals is related to cable length and motor surge impedance as shown in Figure 10. The surge impedance is generally inversely proportional to motor horsepower (HP). Higher HP have lower values of surge impedance. However surge impedance is also related to other factors such as number of poles and frame size.

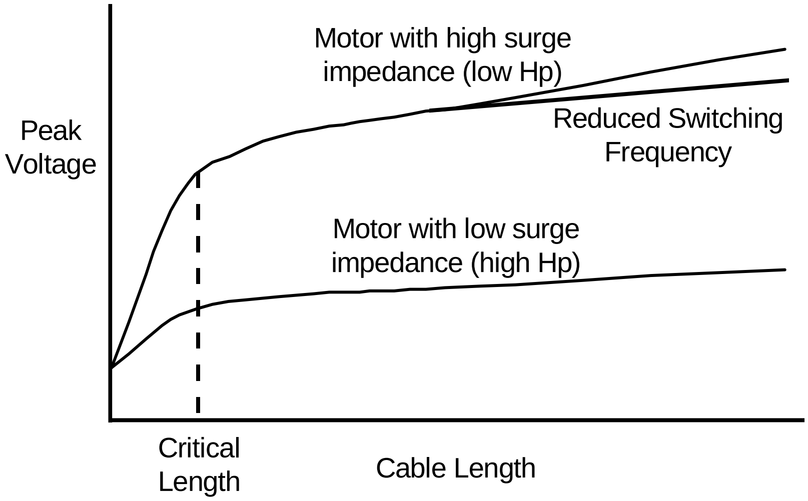

Figure 10 Peak Voltage At Motor vs. Cable Length

Note that peak voltage increases rapidly as the cable length is increased until the critical cable length is reached. For cable lengths longer than the critical length, the peak voltage continues to increase at a reduced rate. At longer cable lengths, the rate of voltage increase vs. cable length is also influenced by the switching frequency.

The voltage curves for larger motors fall below the curves for smaller motors. This is due to the differences in the characteristic impedances of the motors as discussed in the section entitled *Reflected Voltage Pulses* on page 12.

Since the DC bus voltage is unregulated, the peak voltage curves move up and down in direct proportion to AC line voltage variations. The peak voltage for cable length zero (0) is the same as the DC bus voltage of the controller. Therefore, the peak voltage curves are also influenced by the DC bus filter design.

Effects On Motor Insulation

High peak voltages of short duration create stresses that can cause motor insulation to deteriorate and fail. The rise time or the dv/dt is of concern because short rise time or high values of dv/dt cause the voltage peaks to be unevenly distributed across the motor windings. With high dv/dt, up to 85% of the voltage can appear between the first and second turns of the winding.

Partial Discharge

Each voltage peak can cause a small breakdown called a partial discharge (PD) in any air-filled voids in the insulation material. Repeated PD breakdowns gradually destroy the insulation. Reducing the inverter switching frequency slows the rate of deterioration but does not eliminate it, because deterioration is more a function of rise time versus repetition. Deterioration is eliminated only by assuring that the amplitude of the voltage peaks is less than the PD inception voltage of the motor insulation. Insulation deterioration and failure can also be caused by dielectric stress of the wire insulating coating.

Corona Discharge

Corona discharge occurs when the air is ionized by the electric field between the windings. Current will not flow through the ionized air as long as the insulating materials remain intact, but the ionized air can cause the insulating materials to deteriorate. The voltage at which corona discharge occurs is reduced by increasing temperature and humidity and by contaminants in the air or on the surface of the windings. This should be kept in mind when considering the use of open drip-proof motors in applications where the motor may be subjected to high peak voltages and the environment may not always be cool, clean and dry.

Determining Motor Insulation System Requirements

The special requirements of insulation systems of motors for PWM duty can best be quantified by specifying the maximum peak voltage and dv/dt at the motor terminals. Unfortunately, the maximum peak voltage and dv/dt can not be precisely determined from the characteristics of the PWM controller. Even with a known length of cable between the controller and motor, there may be significant differences in cable characteristics from one installation to another. The type and size of wire, the type and size of conduit and the motor characteristics all influence the result.

Various interested parties are attempting to define realistic motor insulation requirements that will ensure reliable operation in most installation circumstances without excessively increasing the cost of the motor.

NEMA Standards

Introduction

Motors manufactured in the USA conform to the standards of the National Electrical Manufacturers Association, NEMA. Section IV of NEMA Standard MG 1-1993 is entitled “Performance Standards Applying To All Machines.” Part 30 of Section IV defines terms and discusses application considerations for general purpose motors that are designed for constant speed use but applied with adjustable frequency drives. Part 31 of Section IV defines performance standards for “Definite-purpose Inverter-fed Motors” that are specifically designed for use with adjustable frequency drives. Each of these parts of MG 1 includes information related to the insulation stress issues discussed in this technical guide.

General Purpose Motors Used With PWM Drives

Part 30 of NEMA MG 1 states that motors rated for operation at 600V or less should not be subjected to voltage peaks that are higher than 1000V with a rise time that is less than 2µ.

Unless suitable protection circuitry is provided, motors connected to 480V or 600V IGBT-type drives by more than 25 feet of cable will likely be subjected to peak voltages higher than 1000V at rise times less than 2µ.

It should not be assumed that operation within the limits of NEMA MG 1 Part 30 is sufficient to assure problem-free operation in every case. While most good quality motors will provide reliable service if operated within these limits, it is best to check with the motor manufacturer.

Definite-purpose Inverter-fed Motors

Part 31of NEMA MG 1 states that motors rated for operation at 600V or less should be capable of withstanding voltage peaks up to 1600V with a rise time that is not less than 0.1µ. Motors meeting this specification are suitable for use with 480V, IGBT-type drives in typical installations. In 600V installations and in some 480V installations, measures may need to be taken to limit the peak voltage and dv/dt to the specified levels.

Rise Time and dv/dt

The 1993 NEMA standards do not define rise time or specify dv/dt. However, the most common interpretation of the NEMA standard seems to be that rise time is the time required for the voltage to rise from 10% to 90% of the peak voltage. Using this interpretation, the dv/dt is 12,800V per µ for a 1600V peak with a 0.1µ rise time.

Motor Compliance With The NEMA Standard

As of this guide’s publication date, not all motor manufacturers offer motors that completely comply with MG 1 part 31. Some manufacturers are apparently waiting for further development of the standard before introducing conforming products. Future revisions of the NEMA standard can be expected to clarify the relationship between rise time and dv/dt. Other aspects of the standard may also be revised as drive manufacturers, motor manufacturers, the manufacturers of magnet wire and others make progress in developing their respective products and learn more about the effect of IGBT drives on motors.

This guide will be revised whenever a substantial change is observed in the status of the NEMA standard and motor compliance

5.0 Recommendations

Overview

Only a very small percentage of AFD installations have experienced motor failures related to the effects of PWM waveforms. In most circumstances, AFD installations employing **good quality** general purpose motors can be expected to provide many years of reliable service. The following recommendations describe a conservative approach to applying motors to help identify circumstances requiring special attention and minimize the possibility of voltage stress problems.

Installation Considerations

A motor insulation system that is subjected to thermal and environmental stress may be at the limit of its capability to withstand dielectric stress regardless of the waveform of the applied voltage. Before addressing the stresses due to the PWM waveform, proper attention must be paid to limiting stresses due to other factors.

The motor must be properly selected to remain within suitable operating temperature limits. This means selecting a motor that is suitable for the ambient temperature, load requirements and speed range.

Make sure that the motor is suitably protected from atmospheric contamination. Unless the nature of the installation assures that the environment will always be quite clean, it is probably best to select a totally enclosed motor. *It is best to consult the motor manufacturer regarding all aspects of motor selection.*

Note that long motor cables can contribute to performance problems other than the motor insulation voltage stress concerns that are discussed in this paper. Additional concerns include excessive voltage drop between the controller and motor, problems caused by high frequency ground leakage current and problems caused by line-to-line capacitance between the conductors of the motor cable. Refer to the appropriate PWM drive installation and start-up manual for additional information.

Using An Existing Motor

Application Considerations

General purpose motors have a wide range of capabilities for withstanding fast-rising pulses of high peak voltage. Because of the insulation system design variation that are described in Section 3 of this paper, peak voltage withstand capabilities range from less than 1000V to more than 1600V. In using an existing motor, it is important to remember that the remaining useful life of the insulation can not be accurately determined. Even though standard motors are commonly used successfully with PWM drives, drive duty places higher levels of dielectric stress on the motor insulation than are normally present under sine wave duty. If the motor insulation is nearing the end of its useful life, connecting the motor to a PWM drive may lead to more rapid insulation failure.

It is always prudent to seek the advice of the motor manufacturer. Only the manufacturer of a particular motor can determine the peak voltage withstand capability of that motor. If the motor manufacturer says that a particular motor model is not suitable for PWM duty or use with IGBT drives, a new motor should be installed. If the motor manufacturer says that similar motors have been successfully used with IGBT drives, it is still important to consider the age and condition of the motor. If the motor has been rewound, the insulation may be new, but the insulation system may not conform to the original design specifications. Motors that have been rewound may not retain their original level of suitability for PWM duty.

It is particularly important to be cautious when applying small motors, motors of the 180 frame size and smaller. Motors of the 180 frame size and smaller would generally be 7-1/2 HP and smaller at 3600 RPM, 5 HP and smaller at 1800 RPM and 2 HP and smaller at 1200 RPM. Small motors are more susceptible to voltage stress problems because they tend to be more often manufactured with lower cost, less robust insulation systems. In small motors, the wire insulation is more vulnerable to mechanical stress and nicks during manufacturing or rewinding because the wire is smaller and the end turn bending radius is tighter. Smaller wire also tends to lay more randomly in the slots increasing the chance that turns near the beginning of a winding may be in contact with turns near the end of a winding.

With smaller motors, higher values of reflected voltage are also more likely to occur. Because small motors have relatively high characteristic impedances, there is a large impedance mismatch between a small motor and the cable that connects it to the PWM controller. As explained in Section 4.0 of this guide, it is this impedance mismatch that allows the reflected voltage pulses at the motor.

Since 230V motors are usually designed for either 230V or 460V operation, their insulation systems are usually rated for 460V operation. A 230V/460V motor powered from a 230V PWM controller, therefore, has a large safety margin to accommodate voltage peaks that may occur at the motor terminals.

Recommendations

Whenever an IGBT drive is connected to an existing motor with a motor cable length exceeding 25 feet, the most conservative approach is to use an inverter output reactor as described under the heading *Inverter Output Reactor*s on page 18 of this guide. The use of an output reactor is usually the most convenient and economical means of minimizing the possibility of motor insulation failure due to the voltage stress caused by the interaction between the inverter waveform, the motor cable and the connected motor. Since the quality and condition of the motor insulation is unknown, an output reactor can only minimize the risk of insulation damage, it can not provide a guarantee.

Selecting A New Motor

Recommendations

Whenever a a new motor is selected for use with a PWM drive, use a motor that is recommended by the motor manufacturer as suitable for use with an IGBT-type adjustable frequency drive.

Several motor manufacturers are currently providing motors that meet this requirement and additional motor manufacturers are soon expected to meet this requirement. Some motor manufacturers may recommend only inverter duty motors for use with IGBT controllers while others may designate certain models of general purpose motors as suitable.

Installing Drives With Waveform Filters

Introduction

There are a number of approaches to the problem of filtering the PWM waveform to alleviate the condition described in this paper. The most common approaches are inverter output reactors, inverter output dv/dt filters and motor cable termination filters. Each of these approaches has been successfully implemented in practical applications. All three (3) of these approaches are described in the following paragraphs, but ABB recommends use of an output reactor for motor cable lengths in excess of 25 feet but less than 200 feet. For motor cable lengths in excess of 200 feet, use of an inverter output dv/dt filter is recommended. For more specific recommendations, see Table 10 on page 19 of this document. The dv/dt filters are easily and generally applicable in a wide variety of installation circumstances with a wide range of motor cable lengths. They are easy to install and cost effective considering the price of the filters plus the installation and operating costs.

Inverter Output Reactors

Inverter output reactors are simply inductors that are installed in series with the motor. They are very similar to the input line reactors that are used to limit harmonic distortion. However, it is important to note that input line reactors are not suitable for use on the output unless they are specifically designed to accommodate the harmonic spectrum of the output waveform. Reactors are reasonably inexpensive and readily available from several sources.

Reactors increase the voltage rise time and thus increase the critical cable length, but they reduce the peak voltage at the motor only to the extent that the critical cable length is increased significantly beyond the length of the installed cable. If the cable length in a given installation exceeds the critical cable length as extended by the effect of the reactors, the motor may still be subjected to the same peak voltage as would occur without the reactors. Reactors will reduce the dv/dt at the expense of increasing the width of the voltage pulse. If the width of the voltage pulse is increased without reducing the amplitude, the motor insulation may be subjected to voltage stress exceeding the stress that would occur without the reactors.

Unless the reactors are installed in the inverter enclosure, they will require mounting space and increase installation cost.

Reactors introduce a voltage drop between the PWM controller and the motor. The resulting reduction in the motor operating voltage may reduce the motor’s operating efficiency and power factor thus increasing the motor’s operating temperature. Because of this voltage drop, the motor may not provide rated torque without exceeding rated current and/or rated operating temperature and it may be necessary to derate the motor. The increased inverter output current will also increase the losses in the inverter and further reduce the overall operating efficiency

Recommendations

Inverter output reactors are difficult to properly select without quantifying and considering all of the application factors cited above. For this reason, we recommend contacting ABB Drives Application Engineering at the number listed on the back of this publication for further assistance.

Inverter Output dv/dt Filters

An inverter output dv/dt filter is a device that is mounted at the output of the drive that consists of a tuned resistor-inductor (RL) circuit that forms a damped, low pass filter. A tuned RL filter increases the voltage rise time and reduces dv/dt more efficiently and effectively than just an inductor.

Since a dv/dt filter introduces only about a 1.5% voltage drop between the controller and motor, voltage drop effects are not considered to be a significant disadvantage.

The cost of a dv/dt filter is only a little more than the cost of an output reactor. In some cases, a dv/dt filter can be mounted inside the PWM controller enclosure or it can be mounted in a separate enclosure in close proximity to the drive.

Recommendations For Use With Existing Motors

The most conservative approach is to use dv/dt filters with existing motors in applications where the motor cable is longer than 200 feet. A dv/dt filter will provide protection for the motor by slowing the rate of voltage increase and minimizing the peak voltage that occurs at the motor terminals. Since the original capability and the present condition of the existing insulation are unknown, there is no way to guarantee an indefinite continuation of uncompromised insulation integrity and uninterrupted motor operation. However, the use of a dv/dt filter is a convenient and economical means of minimizing the risk of motor insulation failure due to the voltage stress caused by the interaction between the inverter waveform and the connected motor.

ABB has designed and developed a cost effective dv/dt filter that is commercially available. In addition to ABB’s product offering, a similar product is available from an independent manufacturer of drive accessories. Both of these filters were tested and found to be effective under a wide range of application conditions. For additional information, contact ABB Drives Application Engineering at the number listed on the back of this publication.

Recommendations For Use With New Motors

Some motor manufacturers may recommend that a new motor should not be used with an IGBT-type drive without limiting the peak voltage and dv/dt at the motor terminals. ABB recommends dv/dt filters for motor cable lengths in excess of 200 feet as the most convenient and economical means of providing this protection if recommended by the motor manufacturer.

Cable Termination Filters

Cable termination filters are intended to match the impedance at the motor to the impedance of the cable. If the total impedance at the end of the cable closely matches the cable impedance, there will be no reflection of the voltage pulse. This would be an effective technique if it could be effectively implemented.

The ideal implementation would require the motor and cable characteristics to be accurately determined and a termination filter designed for each individual installation. A practical implementation must be a compromise based on an imprecise determination of ideal component values and physical limitations inherent in applying this technique to a power circuit. Since it is located at the motor, the filter circuit itself must be designed to withstand any voltage peaks that are not suppressed. Note that published information regarding the performance of cable termination filters indicates that they limit the peak voltage at the motor terminals without increasing the rise time.

Cable termination filters have very limited availability. At the time that this paper was published, they were not available from any known independent supplier of drive accessories and they are not available from ABB.

Cable termination filters require mounting space at the motor. This presents a problem in most situations. For example, an environment that requires an explosion proof motor would also require an explosion proof cable termination filter. The cost of mounting and wiring the termination filters will increase the overall installation cost.

Installing Drives Without Waveform Filters

Many IGBT drive installations have a history of reliable operation without use of an output reactor, dv/dt filter or terminating device. The primary reason for the success of these installations is probably that the motors are capable of withstanding fast rising voltage pulses that significantly exceed 1000V. Figure 10 shows that the peak voltage that actually occurs at the motor terminals can vary widely from one application to another. There is a substantial possibility that a given drive installation can operate reliably without use of any of these devices.

In deciding whether or not to use an output reactor or dv/dt filter, the party responsible for the installation must weigh the risk of premature motor insulation failure and the associated cost of motor repair or replacement against the cost of installing one of these devices. The manufacturer of a particular motor should be able to provide information regarding the capability of that motor to operate reliably with an IGBT drive. Figure 10 shows that the risk is greatest with small motors and long cable lengths. With small motors of the 180 frame size and smaller, the risk is compounded by increased susceptibility of the motor, as previously described on page 20 in the paragraphs under *Using An Existing Motor*. The application engineering department of the drive manufacturer can provide more specific information to assist in evaluating individual applications.

Estimating Cable Length Restrictions

Table 1 provides estimates for the maximum motor cable lengths that should be observed to minimize the risk of motor insulation damage due to voltage stress. Cable lengths are listed for various levels of peak voltage withstand capability with and without dv/dt filters.

The listed peak voltage withstand capabilities are peak voltages that motors must withstand at a rise time of 0.1µ and a 3 kHz switching frequency. The motor insulation must withstand these peak voltages continuously for a normal operating lifetime. The 1000V capability level is the minimum that should be considered for use with an adjustable frequency drive application. If a motor with a lower capability level is connected to a PWM drive, only a limited service life can be expected. When new, many good quality standard motors have a peak voltage withstand capability of 1200V to 1300V. ABB can provide inverter duty motors that can withstand 1600V peaks with the waveform characteristics encountered with ABB drives.

Table 1 Maximum Motor Cable Length Recommendations

	480 Volt Motors						**600 V Motors**	
	1000 V Peak Withstand		**1200 V Peak Withstand**		**1600 V Peak Withstand**		**1600 V Peak Withstand**	
	Output Reactor	**dv/dt Filter**	**Output Reactor**	**dv/dt Filter**	**Output Reactor**	**dv/dt Filter**	**Output Reactor**	**dv/dt Filter**
Up to 60 HP	>25 ft.	>200 ft.	>40 ft.	>200 ft.	>375 ft.	>600 ft.		Any Length.
60 - 150 HP	>40 ft.	>200 ft.	>150 ft.	>200 ft.	>375 ft.	>600 ft.		Any Length
Over 150 HP	>40 ft.	>200 ft.	>250 ft.	>300 ft.	>375 ft.	>600 ft.		Any Length

Notes for Table 1:

Cable length estimates are based only on peak voltage considerations. Refer to the drive instruction material for other restrictions that may apply to specific AC drive models.

Cable length estimates are based on operation at the nominal 480V or 600V line voltage. Reduced cable lengths apply to installations that experience sustained operation at high line voltages.

Cable length estimates apply to motors that are not subjected to abnormal thermal and environmental stresses. Refer to the application, installation and operating guidelines provided by the motor manufacturer.

Cable length estimates for installations with dv/dt filters are for filter designs that have been evaluated with ABB drives. Contact ABB for information regarding the availability of these filters.

Data for motors rated to withstand 1600V peaks applies to inverter duty motors furnished by ABB.

6.0 Summary

This technical guide has discussed the characteristics of adjustable frequency PWM drives as related to insulation voltage stress in the motors that are used with them. Following are some important points to remember:

Insulation Voltage Stress Concerns

- Motor insulation can be subjected to unexpected stresses arising from the characteristics of the PWM waveform in combination with other factors in the installation. This concern applies primarily to motors and drives operated on 380V, 480V and 600V power systems.
- The electrical insulation systems in motors vary considerably among different motor models. Stresses that can cause insulation to deteriorate and fail include thermal stress, environmental stress, mechanical stress and dielectric stress. Dielectric stress opposes an insulator's ability to withstand voltage and block the flow of current.
- The PWM waveform is comprised of a series of square wave pulses. At the beginning of each voltage pulse, the output voltage rises very rapidly from zero (0) to the normal pulse height. The output waveform has high frequency characteristics that are associated with this very rapid voltage risetime. Spikes of high peak voltage at the motor terminals result from the combined high frequency characteristics of the PWM waveform, the motor windings and the cable that connects the motor to the drive. High voltage spikes cause dielectric stress that can lead to insulation failure.
- The peak voltage at the motor terminals is related to the risetime and switching frequency of the PWM waveform, the length and characteristic impedance of the motor cable, the surge impedance of the motor and other factors.

Recommendations

- A motor insulation system that is subjected to thermal and environmental stress may be at the limit of its capability to withstand dielectric stress regardless of the waveform of the applied voltage. Before addressing the stresses due to the PWM waveform, proper attention must be paid to limiting stresses due to other factors such as high temperature and atmospheric contaminants.
- It is always prudent to seek the advice of the motor manufacturer. Only the manufacturer of a particular motor can determine the peak voltage withstand capability of that motor. Whenever a a new motor is selected for use with a PWM drive, use a motor that is recommended by the motor manufacturer as suitable for use with an IGBT-type adjustable frequency drive.
- Many IGBT drive installations have a history of reliable operation without dv/dt filters. The primary reason for the success of these installations is probably that the motors are capable of withstanding fast rising voltage pulses that significantly exceed 1000V. In deciding whether or not to use dv/dt filters, the person responsible for the installation must weigh the risk of premature motor

insulation failure and the associated cost of motor repair or replacement against the cost of installing dv/dt filters. The manufacturer of a particular motor should be able to provide information regarding the capability of that motor to operate reliably with an IGBT drive.

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7.0 Glossary

Cable Termination Filters
Filters installed at the motor, designed to match the terminating impedance at the motor to the characteristic impedance of the power cable between the drive and motor.

Concentric Windings
Motor windings that are wound so that each turn of the coil is wound next to the previous turn and the coil is built up in successive layers. This ensures that each turn of the coil is in contact only with immediately preceding and successive turns.

Corona Discharge
Ionization of the air around a conductor due to the electrical field around the conductor.

Critical Cable Length
The length of cable between a drive and motor at which the time required for a voltage pulse to reach the motor is equal to half the rise time of the pulse. When the motor cable length is greater than or equal to the critical length, reflected voltage pulses can cause the peak voltage at the motor to reach twice the nominal voltage.

Definite-purpose Inverter-fed Motors
Motors that are specifically designed for use with adjustable frequency drives, also called "inverter duty motors." Section IV Part 31 of NEMA Standard MG1-1993 defines performance requirements for "Definite-purpose Inverter-fed Motors."

dv/dt
The term dv/dt comes from differential calculus and means the derivative of v (voltage) with respect to t (time) or the instantaneous rate of change in voltage with respect to time. To conform to the mathematical definition, the dv/dt of a voltage pulse should be defined as a function that describes the rate of change in voltage at any time during the duration of the pulse. In most discussions of motor insulation voltage stress, the term dv/dt is applied to the average rate of voltage change as voltage rises from 10% to 90% of the peak voltage or

$$dv/dt = \frac{\text{Peak Voltage} \times .8}{\text{Rise Time}}$$

Dielectric Strength
A measure of an electrical insulating material's capability to withstand dielectric stress.

Dielectric Stress
A stress that opposes an electrical insulating material's ability to prevent current from flowing through the material.

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