The Reflective Wave Phenomena

Note to Specifiers

This application note contains Cutler-Hammer's recommendations for the application of filters for the purpose of suppressing motor terminal dV/dt and minimizing motor terminal voltage peaks. Using this document as a guideline, review the application and determine if a potential dV/dt problem exists. If necessary, specify a dV/dt limiting option or provide a motor rated for the dV/dt and peak voltage under worst case conditions.

General

The IGBT transistor is the inverter-switching device of choice in today's Adjustable Frequency Drive (AFD). The IGBT requires less power to operate than the older bipolar transistor, resulting in less heat dissipation and therefore smaller AFD packaging. Another benefit from the IGBT device is its faster "turn-on" time. An IGBT will typically switch in less than a microsecond. This allows for the use of higher switching (carrier) frequencies. An AFD with IGBT technology may now have the capability of switching to 20 kHz and beyond. The higher carrier frequencies create less audible motor noise, which may be an issue in HVAC and other applications.

The high rate of change in voltage with respect to time (dV/dt) of IGBT transistors causes a large voltage to be developed on the first turns of the motor winding, stressing the insulation. As the motor cable length (distance between the AFD and motor) increases, dV/dt at the motor becomes less of a concern, since the electrical characteristics of the cable filter the steep vertical edge.

Unfortunately, dV/dt also influences another phenomenon associated with long transmission lines which tends to cause a "ringing" effect, resulting in voltage peaks at the motor. Voltage peaks will begin at a small value and continue to increase in magnitude as cable length increases. Higher dV/dt levels cause the larger voltage peaks to develop at even shorter cable lengths. It is possible that voltage peaks might become as large as double the internal DC "Bus" voltage, corresponding to nearly 1500 volts peak for a 480 VAC rated AFD. Voltage peaks at this level are capable of damaging a standard motor.

It is extremely difficult to determine at what motor cable lengths voltage peaks will begin to rise or at which length peak voltages might become objectionable. One of the major contributors to the phenomenon is the motor capacitance, which will vary significantly from motor to motor. Smaller HP motors (particularly on multiple motor applications) experience higher voltage peaks than larger HP motors. The cable characteristics and cabling methods (conduit, cable tray, buried, gauge, etc.) will also have an effect. A conservative approach is recommended, using appropriate filters where applicable, and possibly verifying peak voltage levels at the motor during startup.

It is important to note that the extended lead length voltage peak effect is normally not an issue on 208/240 VAC AFD's and motors, since these motors typically use the same 600VAC rated insulation as 460 VAC motors. Additionally, 380VAC motors are typically European manufactured and have 1000VAC insulation. Therefore, the theoretical worst case voltage doubling effect is still within the capability of the insulation.

Motor Cable Distances, Carrier Frequency, Output filters, and Corona

Acknowledgments

This section is largely based upon the Marathon Electric Manufacturing Company's March 1997 publication "NEMA's Inverter Motor Standard: the Problems... the Solution", by David Hyppio, Project Engineer, and Jerry Muelbauer, Senior Application Engineer.

General

NEMA MG 1-31-40.4.2 requires that a definite purpose inverter fed motor with a base voltage of ≤600V be able to withstand 1600V spikes with rise times as short as 0.1 uSec. This might seem a stringent design requirement, but it does not address the specific application conditions in which the motor must meet the requirement. As a result, motor suppliers cannot (or should not) claim compliance with Nema MG-1 without thoroughly reviewing various criteria that impact insulation life.

At 12 kHz carrier frequency, a 575V IGBT AFD can produce 1600V spikes (on a long motor cable) at the rate of 1 billion per day. If the AFD is running on a 10% high input line voltage, we can expect 1 billion 1790V spikes per day! Additionally, recent US research verifies that almost all types of 460V AFD's will produce some percentage of output pulses that exceed 1690V (2.6 x DC Bus) with a motor cable length of over 600 ft! These phenomena are likely to reduce insulation life on a standard motor.

Nema MG-1 does not specify acceptable duration of insulation life while a motor is operated on an AFD. Although IEEE Standard 1-2.3.9 and IEEE 57 provide for a normal insulation life of 20,000 hours, many users will desire or expect an insulation life of 50,000 hours! Fortunately, this is not outside the realm of possibility, provided that we allow for the factors that impact *Partial Discharge,* or *Corona.*

Partial Discharge and Corona

Partial Discharge (PD) and Corona are terms often used interchangeably in reference to motor insulation breakdown.

The PD level is the voltage at which a localized portion of the motor insulation (usually the air) begins to break down. The process begins when electrostatic fields surrounding opposite polarized conductors strip electrons from surrounding air molecules, providing the air molecules with an electrical charge (ionization). The ionized air particles then accelerate towards and bombard the insulated surface of the motor winding. Additionally, ozone, a byproduct of ionization, combines with nitrogen in the air to form nitrous oxides, which chemically attack the insulation, leading to embrittlement and fracture. As these processes expose bare wire, arcing can occur from phase to phase or phase to ground.

Unfortunately, the PD level for the motor insulation is not determined by the insulation alone. Temperature, altitude, and winding contamination all affect the PD level.

As temperature or altitude increase, the dielectric strength of the air surrounding the insulation decreases, reducing the PD level. For a given PD level, as winding temperature increases from 25° C to 130° C for class F insulation, the insulation life is reduced to 17% of the life at 25° C. And, if the PD in a given motor is 1000V at sea level, it may be only 700V at 5000 feet of altitude.

Any contamination on the surface of the motor windings (grease, oil, carbon, detergents, metal dust, salts, etc.) will create conductive paths along the surface of the windings and subsequently reduce the PD level. In lab tests, graphite contamination reduced the PD from 1300V to 500V.

Corona Pulse Power

Corona Pulse Power (in watts) refers to the destructive energy of the AFD's output waveform on the motor insulation. It is proportional to the square of the difference between the PD voltage and the PWM pulse height (assuming that pulse height exceeds the PD voltage, otherwise there is no destructive power). There is considerably more corona pulse power in a PWM waveform than in a sine wave of equivalent magnitude, since a sine wave only exceeds the PD level at the peaks. The PWM voltage potentially exceeds the PD level throughout the waveform. As input voltage to an AFD rises, the DC bus voltage rises, and the PWM pulse height rises. Since pulse power is proportional to the square of the difference between pulse height and PD level, any increase in line voltage could result in a considerable increase in the destructive power of the PWM waveform.

Switching Corona Power

Switching corona power (in watts) is proportional to the corona pulse power and the carrier frequency of the AFD. It takes into account the voltage overshoots that occur on top of each pulse of the basic PWM waveform. Higher carrier frequencies increase the number of pulses, and therefore the number of overshoots. As AFD to motor cable length increases, the voltage peak amplitude increases. The amount of energy stored in the cable also increases, with resultant increases in the corona switching power. It is the corona switching power, and not the PWM peak voltage, that more directly determines insulation life.

Motor Surge Impedance

Smaller horsepower motors, since they have higher surge impedance, tend to reflect more of the applied PWM pulses than larger motors. As a result, smaller motors experience higher voltage peaks than a larger motor at the same cable distance.

General Recommendations for Long Motor Life on AFD's ①

1. ***Minimize AFD to motor cable distance***.
2. Minimize output carrier frequency. 3.0Khz is optimal.
3. Limit applied line voltage to 506VAC on 480V model AFD's, and 633VAC on 575V model AFD's.
4. Maintain motor ambient temperature at less than 40°C, and altitude to less than 3300 feet.
5. Operate motor at less than rated insulation class limit. Operating in service factor or outside of rated speed range will shorten insulation life.
6. Use totally enclosed construction (TEFC/TENV/TEAO/TEBC/TEHX, etc.) when contaminants or moisture are expected.
7. Use ODP (Open Drip Proof) only in area which are clean and dry.

8. Use space/trickle heaters to prevent condensation, if required. Take steps to ensure that grease is not introduced into the motor housing during maintenance.
9. **<u>For Standard Duty (Non-Inverter Duty) Motors</u>**, as a general guideline, limit carrier frequency and cable length as follows ②:

TABLE 1

Carrier Frequency	Max Cable Length in feet for 230V motors	Max Cable Length in feet for 460V motors	Max cable length in feet for 575 V motors
3	600	125	40
6	600	100	25
9	600	85	20
12	600	75	15

10. To extend the allowable cable distances listed, refer to AF91 and SV9000 Guidelines.

Note ①
50K Hour recommendations #1, #2 and #3 do not apply to 208/230/380V motors applied to 208/230/380V AFD's. If a 208/230/380V motor is fed from a 460V or 575V AFD, follow 460V or 575V requirements as appropriate. Single motor / Single AFD applications are assumed.

Note ②
For AF91, maximum recommended cable length is 33ft without an output filter. Refer to AF91 and SV9000 Guidelines for cable lengths exceeding the specified distance in Table1.

Inverter Duty Motors

Motors that are "Inverter Duty" are not necessarily designed for the higher dV/dt levels or for the peak voltages that could be encountered with long cable lengths. "Inverter Duty" originally meant that the motor insulation had been upgraded for the higher internal temperatures encountered due to harmonics and reduced cooling at lower speeds. The meaning of the term has since evolved to incorporate more stringent design requirements.

Inverter duty motors referenced in this document (in accordance with NEMA MG 1-1993, Rev 1, Part 31, *Definite Purpose Inverter-Fed Motors*) should have the capability of handling unfiltered voltage peaks of up to 1600 V, and rise times of 0.1 μsec. Cutler-Hammer MT series 31/33/37/39 motor all utilize MAXGUARD™ insulation for superior performance and exceed the requirements of NEMA MG1 part 31. Consult the motor vendor to verify the motor capabilities, since the meaning of "inverter duty" can vary between vendors.

Multiple Motor Applications

There are many applications where more than one motor is run from an AFD simultaneously. However, having multiple motors connected through multiple cable lengths will aggravate the reflected voltage phenomenon and complicate the application of preventive measures against reflected voltage. For example, a 15HP motor at a given cable length on a 15HP AFD will not reflect as much voltage as (5) 3HP motors at the same cable length.

The connected multiple motors should all be of the same winding configuration, i.e. delta wound motors should not be connected in parallel with Wye wound motors. This can cause circulating currents between the motors.

Using 208/240V AFD's and motors may be the best solution in some cases, particularly if the cumulative cable lengths exceed 600 feet. This ensures that even a worst case 2.6 times DC bus voltage will yield less than 1000v reflected voltages.

If 480V or 575V motors are to be used, the following steps will minimize reflected voltages or increase insulation life (use as many as practicable):

1. Follow general requirements for 50K Hours of insulation life.
2. Run separate conductors from the AFD to each individual motor. Next best method is a common header, with taps for each motor along the header length. Avoid "daisy chains" from motor to motor. Minimize cable length as much as practicable.
3. Use MT- 31 / 33 / 37 / 39 Motors, which utilize MAXGUARD™ insulation for superior performance, or an equivalent suitable Part 31 inverter-duty motor.
4. Follow AF91 or SV9000 Guidelines to extend allowable cable distances.

Consult Cutler-Hammer for other special AFD and output filter considerations on multiple motor applications.

AF91 Guidelines

The AF91 is a third generation IGBT inverter with a carrier frequency adjustable up to 16 kHz. This allows the selection of carrier frequencies that are above the acoustically significant audible noise range.

The AF91 output line dV/dt filter is approved for use in extending the acceptable motor lead length for single, standard NEMA Design B motors from 33 feet to 500 feet. The approximate value of inductance is 3%, chosen to minimize the voltage drop from the AFD to motor while limiting the motor terminal voltage peaks.

For multiple motor applications and for cable runs in excess of 500 feet, contact Cutler-Hammer.

SV9000 Guidelines

The SV9000 is an IGBT inverter with a carrier frequency adjustable up to 16 kHz. This allows the selection of carrier frequencies that are above the audible noise range.

There are several different methods for extending the allowable motor cable distances (up to 600ft) in order to avoid the formation of damaging levels of voltage peaks at the motor. The various methods are summarized, along with advantages and disadvantages, in the following paragraphs.

Filter Options for the SV9000

1. Line Reactors, located at the AFD.
2. SV9000 MotoR$_x$™ Filter (Hybrid R-L-C with clamping/energy recovery circuit)
3. Reflected Wave Trap (RWT)
4. Output Sinewave Filter (R-L-C Filter)

Output Line Reactors at AFD (Inductors)

Output line reactors (generally 2 – 4%) do reduce dV/dt. Line reactors with 0.5 to 1.0% may generate higher peak voltages at the motor than without a filter, since the motor capacitance may resonate with the filter and cable inductance. Performance should be verified during commissioning.

Advantages

- ♦ Less initial cost than other methods
- ♦ May be used with wide range of carrier frequencies

Disadvantages

- More voltage drop between AFD and motor than SV9000 MotoRx™ filter and RWT
- Available only as open core and coil or NEMA 1 for external mounting

SV9000 MotoRx™ Filter Operation

This filter is comprised of a 0.5% impedance line reactor, followed by capacative filtering and an energy recovery/clamping circuit. The 0.5% LC filter is used to reduce the dV/dt of the AFD output waveform. A three-phase diode bridge clamps the resultant output voltage to the AFD's internal DC Bus (nominally 660 VDC) through a pair of resistors. The energy in the voltage peaks is primarily recovered for reuse by the AFD with some resistor losses.

Advantages

- Two filter versions available for specific application
- Recovers energy and returns it to the DC Bus
- Internally mounted in oversized enclosures
- Reduces dV/dt *and* peak voltage
- Much lower voltage drop than Line Reactor

Disadvantages

- Not available as a field installable option

Reflected Wave Trap (RWT)

The RWT is installed at the motor terminals and limits reflected wave spikes to less than 900 Volts. The device employs a hybrid zener technology that clamps only the overvoltage peaks and dissipates the peak energy as resistive heat. The RWT allows drive/motor cable length up to 600 feet (480V, 25 degree C, 2 kHz carrier frequency. These filters can be mounted up to 26 feet from the motor terminals. They are available for Class I, Division 2 hazardous locations. They can also be used in conjunction with an AFD mounted line reactor to modify the pulse slope (dV/dt). The RWT can be applied on retrofit and new drive installations.

Advantages

- Available in enclosures suitable for mounting in typical motor environment (NEMA 1 and NEMA 4X Class I, Div 2 hazardous locations)
- One size fits all Hp and voltage applications (up to 600 V)
- Better voltage peak suppression than other methods
- Cost effective solution for applications above 15Hp
- No additional voltage drop between the AFD and motor
- Lower operating temperature and longer cable lead lengths compared to other RC motor terminating designs

Disadvantages

- Not suitable for deep well applications

- ♦ Clamps voltage spikes but does not modify pulse dV/dt

Output Sinewave Filter

This is an R-L-C filter similar schematically to a common dV/dt filter, although the component values have been selected to produce a sinusoidal output waveform. The line reactor is typically 5%. These filters are mounted at the AFD output.

Advantages

- ♦ Since output is essentially sinusoidal, dV/dt issues are eliminated
- ♦ Ultimate solution for 575VAC applications

Disadvantages

- ♦ More wattage losses than other filters (particularly at higher HP)
- ♦ More voltage drop from AFD to motor than other methods
- ♦ Requires separate NEMA1 enclosure

Summary

IGBT based AFD’s when applied with long motor lead lengths will greatly reduce the life expectancy of a standard NEMA B motor. As this document has described, three design considerations exist:

1. Minimize motor lead distance if possible. If motor lead length exceeds those listed in Table 1 employ mitigating devices such as;
2. Apply an output filter and/or RWT; and/or
3. Apply a NEMA1 part31 motor (consult motor manufacturer for lead distance limitations)

Appendix

Available Filter Options for the SV9000

Depending on your specific application requirements, use the following table to extend the acceptable motor lead length for single, standard 460/575V NEMA Design B motors. For multiple motor applications and for cable runs in excess of 600 feet, contact Cutler-Hammer.

Enclosure	Horse Power ④	Filter Type
Compact NEMA 1	1 – 30	External NEMA1 3% Line Reactor or Motor mounted RWT③
Standard Chassis	3 – 300	
Standard NEMA 1	3 – 300	
Standard NEMA 12	3 – 300	
Oversized NEMA 1	1 – 30	Line Reactor
Oversized NEMA 1	40 – 300	Line Reactor or MotoRx™
Oversized NEMA 12	3 – 300	Line Reactor or MotoRx™

NOTE ③

The RWT has specific application guidelines, which must be followed. Refer to the Reflected Wave Trap Installation and Operation Manual (TS RWT1198)

NOTE ④

208/230/380 VAC applications do not require filtering. For 460/575VAC applications above 300Hp, use the RWT.