An Improved Approach for Connecting VSD and Electric Motors

by Heu Vang and Marco Chiari

Executive summary

When electric motors are connected with Variable Speed Drives, some precautions must be taken. Motor cable length can create short time overvoltage at the motor terminal. This phenomenon results in premature ageing of the motor winding insulation, and, if not properly designed, will lead to motor failures. End users and consultants often underestimate this problem and neglect to apply best practices or to specify adequate countermeasures. This white paper provides guidance on how to avoid this potentially problematic situation.

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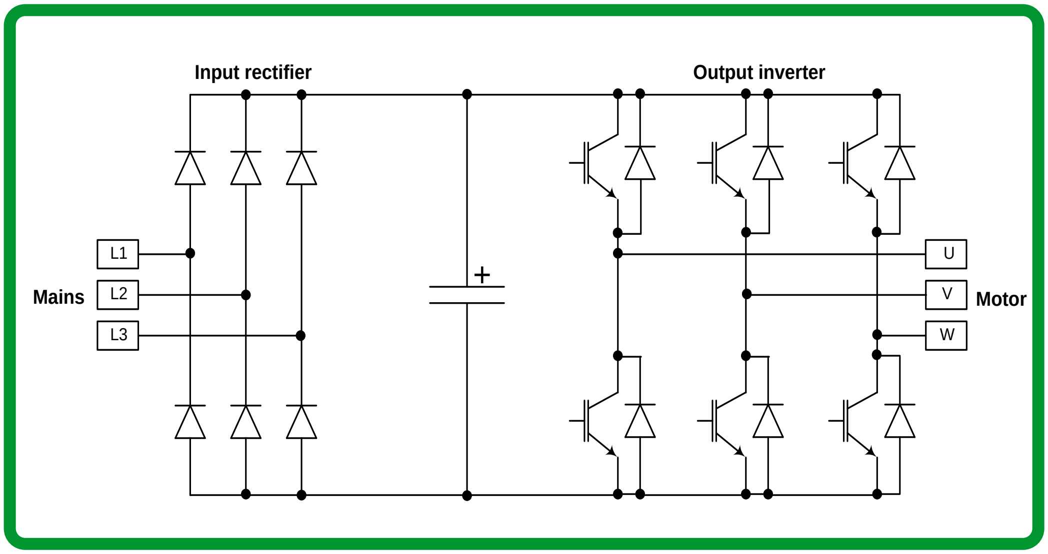
Introduction

In industrial environments, flexible control, energy efficiency, and low cost maintenance are all well documented benefits of variable speed drives (VSDs). However, when long cable lengths are utilized to connect VSDs to motors, motor winding insulation can deteriorate more quickly, and eventually the motor itself may fail. To understand the risks involved around this issue and the solution options available to address the situation, the technical characteristics of the drive and the motor first need to be understood.

Within the VSD, the AC supply voltage is converted into DC by the use of a rectifier. DC power contains voltage ripples which are smoothed using filter capacitors. This section of the VSD is often referred to as the DC link. This DC voltage is then converted back into AC (see **Figure 1**). This conversion is typically achieved through the use of power electronic devices such as IGBT power transistors using a technique called Pulse Width Modulation (PWM). The output voltage is turned on and off at a high frequency, with the duration of on-time, or width of the pulse, controlled to approximate a sinusoidal waveform. Advancements in power component technology have enabled both increases in switching frequency and reductions in losses. IGBTs are commonly used in scenarios characterized by switching frequencies of up to16 kHz and motor output frequencies of up to 1kHz.

Figure 1

A basic schematic of a variable frequency drive linked to a motor



In typical situations, the higher the switching frequency, the lower the output ripple motor current. In order to compensate for the losses, the IGBTs are switching fast (up to 1 µs). This high speed of switching coupled with a long length cable between the drive and the motor, creates a temporary overvoltage at the motor terminal connection. In fact, the overvoltage can exceed twice the DC bus voltage of the drive (see **Figure 2**). This can result in damage to the motor winding.

The overvoltage condition occurs at the motor terminal. Below are examples of how overvoltage and overcurrent conditions can have an impact in the system:

- **Effect on variable speed drive** – The main risk of an overcurrent condition in the speed drive is Short Circuit Fault (SCF). The peak current, due to the switching, can be read by the current sensors of the drive and lead to an unexpected fault. Another consequence of the capacitive peak current is a rise in IGBT temperature in relation with the switching frequency. These higher than normal temperatures reduce the lifetime of the speed drive.

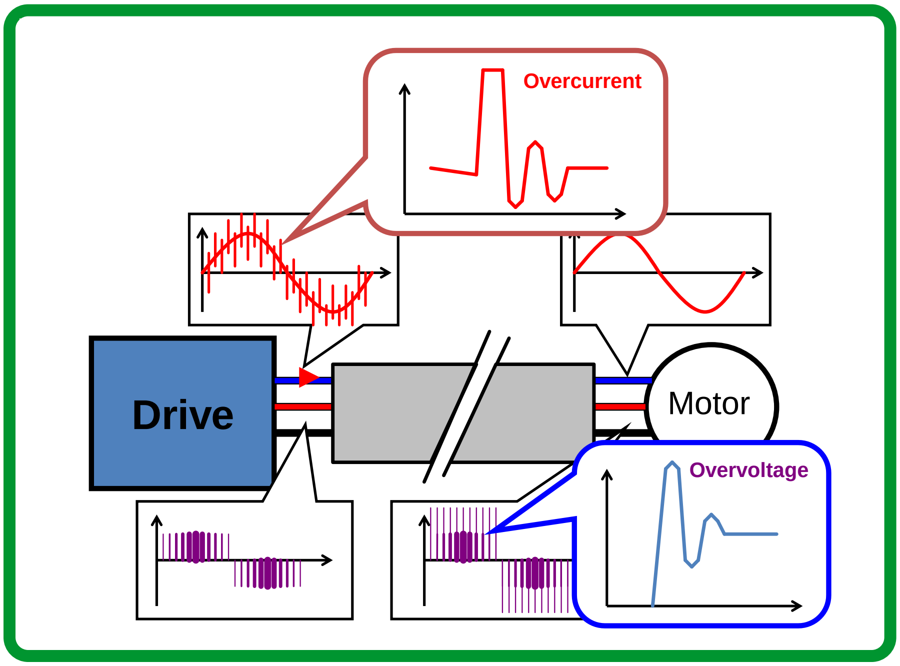


Figure 2
The impact of long motor cable length can manifest itself as both overcurrent and overvoltage situations

- **Effect on the electric cabinet** – The disturbances that result from the long cable and motor interactions create high frequency circulation current into the ground and can disturb appliances that are connected on the same network. A frequent consequence is the triggering of differential protection relays which are located upstream of the drive. The high frequency currents that run through the cable motor also generate radiated emission which can disturb electronic devices around the motor cable.

- **Effect on motor –** The overvoltage condition at the motor terminal can appear between two motor windings and can create partial discharge and premature ageing of winding insulation. This can then lead to complete motor failure. Note that the admissible overvoltage is dependent upon the class of the motor insulation (see **Figure 4**).

End users and consultants often underestimate these types of phenomena and do not specify adequate countermeasures. Even if short term cost savings can be achieved by avoiding the extra cost of supplemental devices and options, in the long run this improper design approach can lead to motor breakdown or unexpected interruption of the applications. In critical applications like a water supply plant or a power station, this level of risk is not acceptable.

Long motor cable length side effects

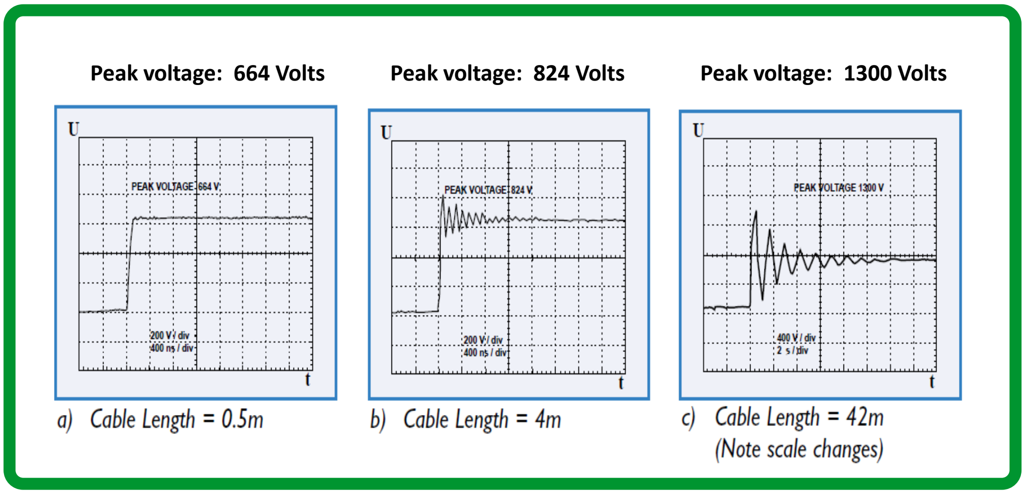
In standard applications, when the motor cable exceeds 10 meters (32 feet) in length, overvoltage occurs. The longer the motor cable is, the higher the overvoltage that occurs (see **Figure 3**)[1]. This negative effect is amplified when using a shielded cable. However, the overvoltage is limited to twice the DC bus voltage.

The voltage rise time at the output of the drive, often referred to as dV/dt, generates higher transient peak current at higher switching frequencies. This is the result of parasitic capacitance (occurs when two conductors, such as the motor and the motor cable, at different potentials are in close physical proximity to one another. They are affected by each

[1] GAMBICA Association for Instrumentation, Control and Automation, *GAMBICA Technical Report N°1, Second Edition* "Variable Speed Drives and Motors, Motor Insulation Voltage Stresses under PWM Inverter Operation".

others' electric field and store opposite electric charges like a capacitor). These transient currents increase the drive, cable, and motor losses.

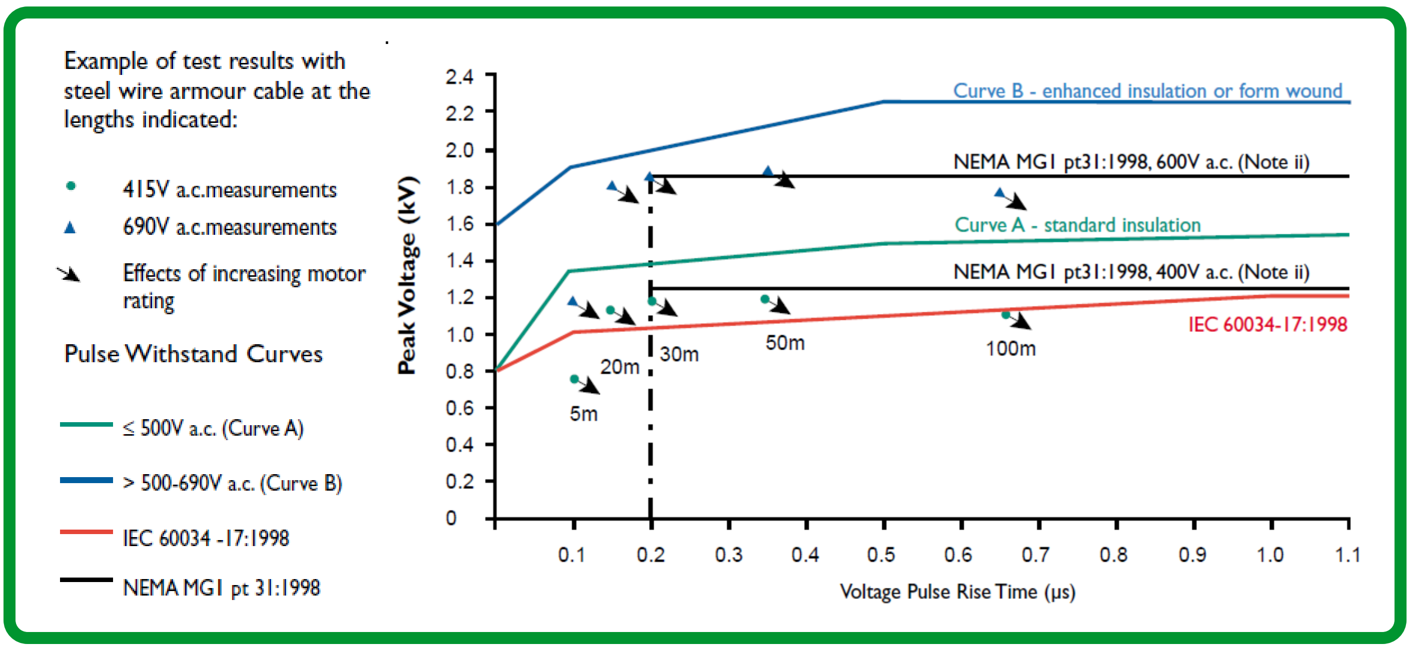
Figure 3
Longer cable lengths between drive and motor produce higher peak voltage at the motor terminal



The most common IEC and NEMA standards, technical specifications, and guidelines for admissible voltages and current for various motor types are highlighted in **Figure 4**[2]**.** The admissible overvoltage is dependent upon the class of the motor insulation. The relevant IEC and NEMA standards include the following:

- IEC 60034-17 – Limit line for general purpose motors when fed by frequency converters, 500V motors.
- IEC 60034-25 – Limit for converter rated motors: curve A is for 500V motors and curve B is for 690V motors.
- NEMA MG1 – Definite purpose inverter-fed motors.

Figure 4
Limit lines for voltages of multiple motor types



2 GAMBICA Association for Instrumentation, Control and Automation, *GAMBICA Technical Report N°1, Second Edition* "Variable Speed Drives and Motors, Motor Insulation Voltage Stresses under PWM Inverter Operation".

For critical applications, a motor IEC60034-25 class B or NEMA 600V shall be specified. To reduce risk of motor fault when used with speed drive motor, IEC60034-25 B or NEMA 400 should be prescribed.

Another side effect of using a VSD is the degradation of motor bearings. This is caused by common mode voltage generated by the inverter of the VSD (noise induced into a cable by the switching) and it generates high frequency current into the bearings of the motor. Depending upon the type of motor, and whether or not the bearing is isolated, three different common mode current loops could occur in the motor:

1. A loop between stators, windings, and the motor shaft. In this case the induction current flows around the bearing twice.
2. A loop between parasitic capacitor windings and motor shaft connected to ground by the load. This case can occur when the frame is not adequately grounded. The pulse capacitive current flows to the drive end bearing.
3. A loop between the parasitic capacitor of the stator, rotor windings, frame, and bearing. In this case, the frame is correctly connected to ground and the bearing current is a percentage of the common mode voltage. The bearing current occurs because of capacitive electrostatic discharge.

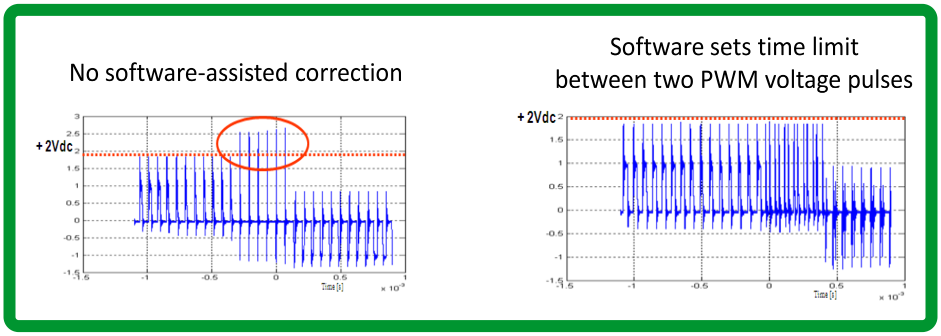
Preventive measures

In order to limit the impact of overvoltage and current peaks, several solutions should be evaluated. The viability of each solution is dependent upon the environment of the application.

Software Protection

Some VSDs are pre-configured with software which makes the solution more dependable. These modern variable speed drives always integrate a motor control that prevents a condition called “double transition”. This occurs when, simultaneously, one motor phase switches from minus to plus DC while another phase switches from positive to negative.

Figure 5
Impact of software on the prevention of a double transition condition



A PWM pulse which is too short with respect to the time constant of the cable can lead to the superimposition of 2 oscillations thus generating an overvoltage greater than 2 times the voltage bus DC condition. The latest generation of VSD technology avoids the superimposition of voltage reflection situation by setting a minimum time between two PWM voltage pulses (see **Figure 5**). Although setting this time limit slightly degrades the speed drive performance (-3% of torque), under normal conditions overall system performance is not impacted.

Output reactor

Output reactors oppose rapid changes in current and are generally installed in motor driven equipment to limit starting current. They may be used to protect variable-frequency drives and motors. In essence, a motor choke associated with the parasitic capacitance of the motor cable reduces the dV/dt and peak voltage. The effect will depend on the cable type and length. However, care is needed as reactors can theoretically extend the duration of overshoot (when an electronic signal exceeds its target) if an improper output reactor is selected.

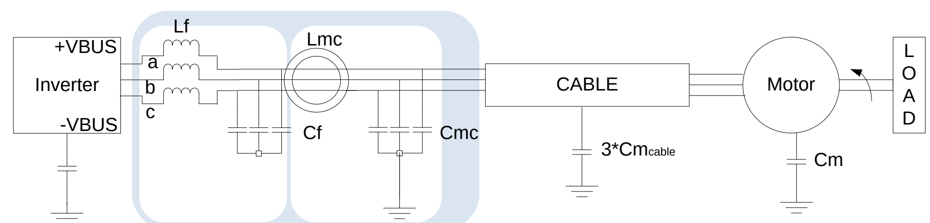
Output dV/dt filter

Output dV/dt filters are the most cost effective solution to guarantee motor protection and reduction of overcurrent impact on speed drives. This filter reduces the dV/dt so the overvoltage effect and the capacitive leakage current between phases and phases to ground are minimized. Such filters offer flexibility because they can be used with most motors and any cable (independent of the type and length) without creating a problem. This method is recommended if the specifications of a particular motor are unknown.

Sinus filter

A special design of low pass filter (an electronic filter that passes low-frequency signals and reduces the amplitude of signals with frequencies higher than the cutoff frequency), called a sinus filter, allows high frequency currents to be shunted away. The result is that the voltage waveform at the motor terminal becomes pure sinusoidal. The differential sinus filter allows the complete suppression of the overvoltage effect, and reduces electro-magnetic compatibility (EMC) disturbance.

Figure 6
Diagram of how a sinus filter works



If the Sinus filter is associated with a common mode filter, this allows for the suppression of bearing currents (see **Figure 6**) and the reduction of the conducted EMC disturbances to the mains. The combination of those two filters presents the most robust solution for avoiding VSD-to-motor connection issues. This solution is also very cost effective if a long motor cable is used as long as a shielded cable is not required.

Application Examples

Some application areas are more directly impacted by the long cable length phenomenon than others. For example, in hoisting applications, motors spend a large part of their operating life in braking mode. The braking energy is transferred through freewheeling diodes back on to the intermediate DC link, thereby generating a 15-20% increase in the DC link voltage (and also, therefore, an increase in the the peak motor voltage).

The effect is similar to increasing the voltage supply by up to 20%. In such cases, a 400V application should be treated as if it was being supplied with 480V. In applications where motors are run in parallel, the appropriate cable length should be calculated based on the sum of all the cables. For example, if three motors in parallel are connected to a single VSD, each with a 20 meter (66 foot) cable, the total length that should be calculated in not 20 meters, but should be 60 meters (197 feet). Precautions must be taken to protect the VSD from any unexpected tripping.

Table 1

Recommended preventive measures will depend on motor characteristics and cable length

Motor cable length (unshielded cable)	Motor conforming to IEC60034-25	Motor NOT-conforming to IEC60034-25
1 m (66 ft) < Lm < 50 m (164 ft)	Filter not required	dV/dt filter
50 m (66 ft) < Lm < 100 m (328 ft)	Filter not required	Sinus filter
100 m (328 ft) < Lm < 300 m (984 ft)	Filter not required	Sinus filter
300 m (328 ft) < Lm < 500 m (984 ft)	dV/dt filter	Sinus filter
500 m (328 ft) < Lm < 1000 m (984 ft)	Sinus filter	Sinus filter

Note: When calculating cable lengths for the purpose of guarding against these overvoltage situations, a shielded cable should count as twice the length of an unshielded cable. For example, if a shielded cable is 100 meters in actual length, it should be considered to be equal to a 200 meter length standard cable in the calculation.

Conclusion

When variable speed drives (VSD) are used with motors, a combination of fast switching transistors and 'long' motor cables can cause peak voltages up to twice the DC link voltage. In extreme cases, this high peak voltage can cause premature ageing of motor winding insulation which leads to overall motor failure. To ensure that motor life time is not compromised, a number of simple steps can be taken:

- Specification of a motor designed for speed drive applications (IEC60034-25 B or NEMA 400 should be prescribed).
- Specification of VSDs that integrate voltage reflection superimposition software suppression
- If possible reduce to a minimum the distance between motor and VSD
- If possible use unshielded cables
- Reduce the VSD switching frequency (a reduction to 2.5KHz is recommended)

Following these simple recommendations, a 300 meter (984 feet) long cable (or shorter) can be utilized without having to purchase any additional options. For cables above 300 meters (984 feet) in length, the use of a dV/dt output filter or sinus filter is recommended depending upon the circumstance. If motor insulation levels are unknown (e.g., retrofit application), or if non-standard motors are deployed, depending on the motor cable length, a dV/dt filter or a sinus filter is recommended.

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