July 2013

Output Filters and EMC Screened Cables on Variable Speed Drives

The question of output filters on AC variable speed drives (VSD) comes up all too often. Customers ask "So do you need them or don't you?" and "What about EMC screened motor cables?
Whilst fundamentally this depends on the installation, cable length and the motors used, it is important to understand what effect VSDs can have on AC motors, and what EMC emissions result in motor cables. How do we address these issues and make informed decisions without risking substantial production losses? Interference issues, the ensuing investigation, rectification and possible reinstallation to address EMC problems can easily be avoided.
Unfortunately, there are suppliers making universal claims that compliance to IEC EMC Emission Standards can be met without using output filters or screened motor cables on their particular drives based on one or two isolated successful installations. These claims are "backed" by sketchy explanations that also incorrectly show that their VSDs provide a dV/dt of 500V/µs. All these types of claims do is add confusion and raise questions of credibility.

Electronic Power Solutions Pty Ltd has many years of experience in AC motor Control in the Australian market. The following technical information should assist in dispelling some of this confusion. Our aim is to assist our customers in gaining a much better understanding on this topic to then be able to ask the right questions from suppliers and not to accept information on face value.

VSD Output Voltage

The output voltage of a VSD comprises a series of pulses with a variable width and amplitude to provide the desired frequency and voltage applied to the motor (pulse width modulation or PWM). Each pulse requires a finite time to increase to its full value (rise-time tr), so every time a transistor in the VSD output stage switches, the voltage across the motor terminals increases by a ratio dV/dt that is dependent on

- the motor cable (type, cross-section, length, screened or unscreened, inductance and capacitance),

And

- the high frequency surge impedance of the motor

Because of the impedance mismatch between the cable impedance and the motor impedance, a wave reflection occurs, causing a ringing voltage overshoot at the motor terminals (Fig.1).
Note that the motor surge impedance decreases with the increase of motor size due to a reduced mis-match with the cable impedance.
With parallel cables the cable characteristic impedance is reduced, resulting in a higher reflection coefficient and higher overshoot.

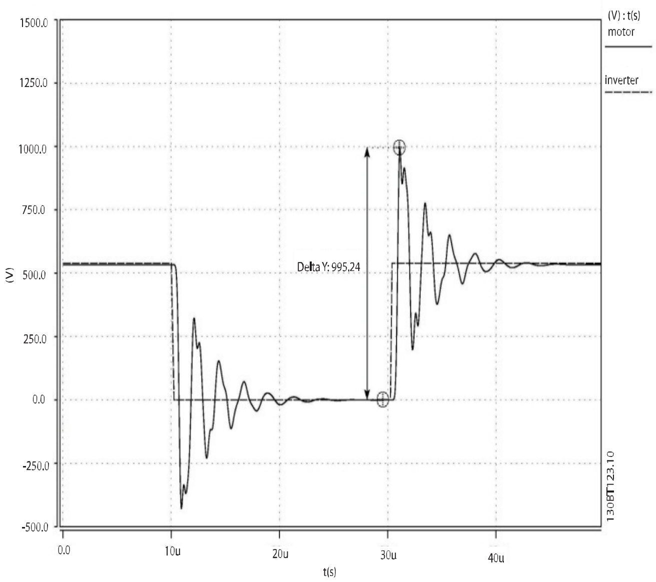


Fig 1 - Example of Converter Output Voltage (dotted line) and Motor Terminal Voltage with 200m of Cable (solid line

Rise Time

IEC standards define Rise time (tr) as the time taken for the voltage to rise between 10% to 90% of the peak voltage (Upeak) measured at the motor terminals

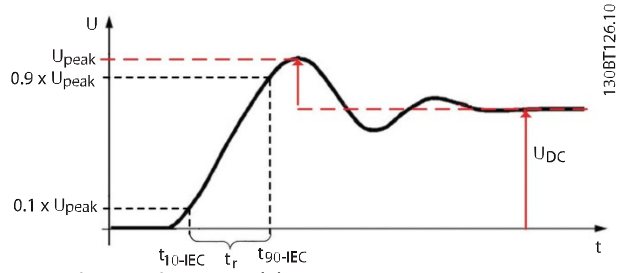


Fig.2 definition of Rise Time (t_r)

For example, for a rise in voltage between 0.1x U_{peak} and 0.9x U_{peak} of 500Volts over a rise time of 250ns (0.25µs) equates to a dV/dt of 2000V/µs. Whilst there is some paranoia over dV/dt levels, if the motor used meets the relevant IEC standards, dV/dt rarely causes an issue (see below). Motor quality and ensuring manufacture to relevant standards should be of more concern.

Peak Voltage Limits

Various standards and technical specifications present limits of the admissible U_{peak} and t_r for different motor types. Some of the most used limit lines are shown in Figure 3.

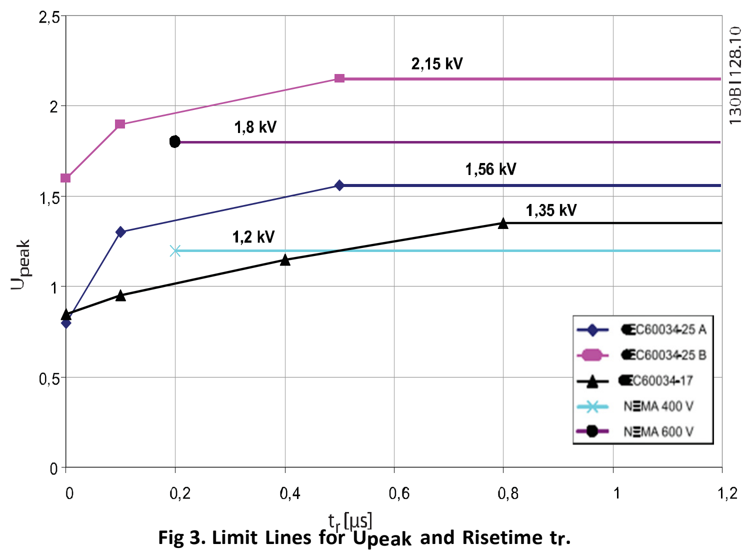


Fig 3. Limit Lines for Upeak and Risetime tr.

- IEC 60034-17 – limit line for general purpose motors when fed by frequency converters, 500V motors.
- IEC 60034-25 – limit line for inverter 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.

Fig.3 can be used to plot Peak voltage and the rise time as measured at your motor terminals and if in your application the coordinates place a point on the graph that is above the Upeak limit that applies for the motor, an output filter should be used for protecting the motor insulation.
It should be noted that the dV/dt could still be relatively high even if the measured result plot is below the relevant motor limit line. Eg. A measured Upeak of 1000V with a rise time of 0.3µs, is below the IEC 60034-17, and complies, even though the dV/dt equates to 3333V/ µs.

To obtain approximate values, use the following rules of thumb:

1. Rise time increases with cable length.
2. UPEAK = DC link voltage x (1+Γ); Γ represents the reflection coefficient and typical values can be found in table below
   (DC link voltage = Mains voltage x 1.35).
3. $dV/dt = \frac{0.8 \times UPEAK}{t_r}$ (For IEC Motors)

Motor Power (kW)	Z_m (Ω)	Γ
<3.7	2000-5000	0.95
90	800	0.82
355	400	0.6

Table 1 Typical Values for Reflection Coefficients (IEC 61800-8).

For Example: for a 75kW motor and a mains voltage of 415V, use a Reflection Coefficient of 0.82 (from the table).

U_{PEAK} = 415x1.35x(1+0.82) = 1020V
With a rise time of 0.4µs, dV/dt = 0.8x 1020V/0.4µs = 2040V/µs

High Frequency Electromagnetic Noise

When no filters are used, the ringing voltage overshoot that occurs at the motor terminals becomes the main source of high-frequency noise Figure 4 shows the correlation between the frequency of the voltage ringing at the motor terminals and the spectrum of the high-frequency conducted interference in the motor cable.

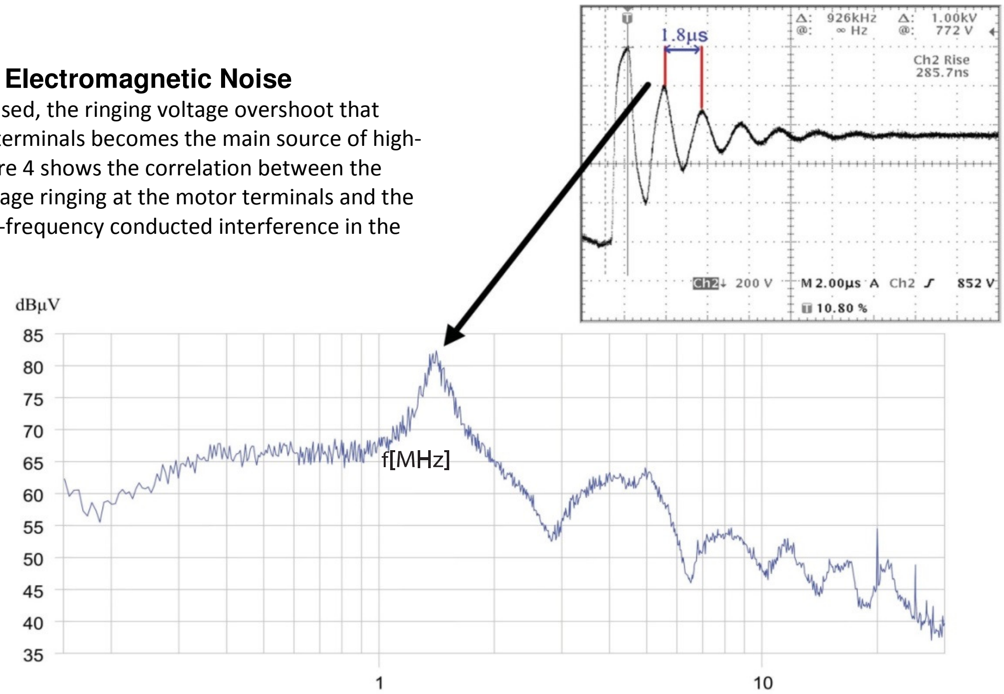


Fig 4. Correlation between the Frequency of the Ringing Voltage Overshoot and the Spectrum of Noise Emissions.

Besides this HF noise, there are other noise components you should be aware of, such as

- The common-mode voltage, which is measured between phases and ground at the switching frequency and its harmonics – high amplitude but low frequency.
- High-frequency noise (above 10MHz) caused by the switching of semiconductors – high frequency but low amplitude.

An output filter achieves the following:

- A dV/dt filter reduces the frequency of the ringing oscillation below 150kHz as shown in figure 5.
- A sinusoidal filter completely eliminated the ringing oscillation and the motor is fed by a sinusoidal phase-to-phase voltage, removing the necessity to use EMC cables.

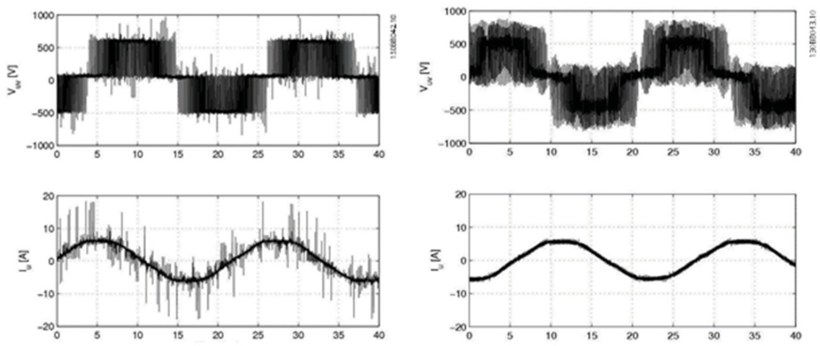
Remember, that the other two noise components are still present, but High-frequency common-mode filters (ferrite cores) will reduce the common mode voltage to predominantly address bearing wear - they can also reduce the high-frequency emissions from the motor cable which can be used, for example, in applications with unshielded motor cables.

Please note however that Common Mode Filters should not be used as the sole mitigation measure. Even when HF-CM cores are used, the correct EMC installation rules must be followed. Common Core filters fit easily inside the VSD and take up very little space.

While the use of unshielded motor cables is possible with filters other than sinusoidal filters, the layout of the installation should still ensure that noise coupling is prevented between the unshielded motor cable and the mains line or other sensitive cables (sensors, communication, etc.) by cable segregation and placement of the motor cable in a separate, continuous and grounded cable tray.

Which Output Filter should you use?

Table 2 shows a performance comparison of dV/dt, Sinusoidal and HF-CM, which provides a guide to determine which filter to use with your application – the following table is based on Danfoss VLT Drives, however the same principals apply to most VSD's



without a dV/dt filter with a dV/dt filter

Fig.5 Comparison of Voltage and Current waveforms – without and with a dV/dt Filter

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Performance criteria	dV/dt filters	Sinusoidal filters	High-frequency common-mode filters (Ferrite Cores)
Motor insulation stress	Up to 150m cable (screened/ unscreened) complies with the requirements of IEC 60034-17[1] (general purpose motors). Above this cable length the risk of "double pulsing" (two time mains network	Provides a sinusoidal phase-to-phase motor terminal voltage. Complies with IEC 60034-17 [1] and NEMA-MG1 requirements for general purpose motors with cables up to 500m (1km for VLT frame size D and above).	Does not reduce motor insulation stress
Motor bearing stress	Slightly reduced, only in high-power motors.	Reduces bearing currents caused by circulating currents. Does not reduce common-mode currents (shaft currents).	Reduces bearing stress by limiting common-mode high-frequency currents
EMC performance	Eliminates motor cable ringing. Does not change the emission class. Does not allow longer motor cables as specified for the frequency converter's built-in RFI filter.	Eliminates motor cable ringing. Does not change the emission class. Does not allow longer motor cables as specified for the frequency converter's built-in RFI filter.	Reduces high-frequency emissions (above 1MHz). Does not change the emission class of the RFI filter. Does not allow longer motor cables as specified for the frequency converter.
Max motor cable length	100m ... 150m With guaranteed EMC performance: 150m screened. Without guaranteed EMC performance: 150m unscreened.	With guaranteed EMC performance: 150m screened and 300m unscreened. Without guaranteed EMC performance: up to 500m (1km for VLT frame size D and above)	150m screened (frame size A, B, C), 300m screened (frame size D, E, F), 300m unscreened
Acoustic motor switching noise	Does not eliminate acoustic switching noise.	Eliminates acoustic switching noise from the motor caused by magneto-striction.	Does not eliminate acoustic switching noise.
Relative physical size	15-50% (depending on power size)	100%	5 - 15%
Voltage drop	0.5%	4-10%	none

Table 2 - Comparison of dV/dt, Sinusoidal and HF Common Mode (Ferrite Core) Filters

The subject of Filters for use with Variable Speed Drives extends well beyond the information provided above. For more detailed information on Filters and their applications, please click here or contact Electronic Power Solutions Pty Ltd for the right advice. Get it right first time…….

Acknowledgement: Danfoss Document MG.90.N5