A closer look at VSD voltage output waveforms
... and their failure effects on motors

By R Melaia, LH Marthinusen

While most motor or Variable Speed Drive (VSD) specialists (or even advanced users) are familiar with VSD input current (and output current) waveforms – not many appreciate the specifics of the voltage waveform that is applied to the motor or to intermediate components between the VSD output terminals and the motor.

Current waveforms are important because they determine the effect of the VSD current on the supply, and the VSD output current is the primary factor that affects thermal aspects of the driven motor. While the latter current harmonics are crucial because they determine the increased operating temperature of the motor - the high frequency components of the VSD voltage waveform stress most sections of the motor insulation to extents that can cause infant failures in serious cases, and even medium- to long-term failures in the case of over-voltage VSD effects (as opposed to purely high-frequency effects).

Naturally – understanding and hence mitigating these high frequency effects can lead to greatly improved motor long-term reliability – or even reduce infant failures – of VSD driven motors. Reliability of the latter has undoubtedly improved drastically over the last decade – but there is still a lack of appreciation for why this is the case, and there are still failures related to misapplication – especially in the case of VSD retrofits to existing motors. Experience is important here and unfortunately too much of this has been bad experience!

The author is reminded of a relevant quote from an unlikely source: The motion picture: ‘The Mechanic’. The author would love to have referenced a more erudite source but the content hopefully excuses the source: ‘Good judgment comes from experience but a lot of that comes from bad judgment’. This should ring true for many readers – not just engineers!

Back to business: The phase-to-phase voltage waveform at the terminals of a VSD-driven motor is presented in Figure 1. The motor is a 500 V unit of low power (approximately 22 kW), driving a fan – with a series reactor at the VSD output terminals (between the VSD and the motor) and fairly long cables (about 100 m) between the drive and the motor. Note the mention of the series reactor, to reduce voltage rise-time (dv/dt) at the motor terminals. Several traces of phase-to-earth voltages before and after the series reactor are included, in order to show the effect of such reactors.

Figure 1: Phase-to-phase voltage at the motor terminals, calculated directly from measured phase-to-earth voltages of two phases. Note that the ringing overshoot is clearly visible and that the peak phase-to-phase voltages are 1 330 V in the positive half-cycle and 1 350 V in the negative half-cycle.

Figure 2: Phase-to-earth voltage at VSD after dv/dt filter, with a long time scale in order to determine peak voltages. Maximum measured peak-to-peak phase to earth voltage is 1 302 V.
Although not immediately obvious from Figures 3 and 4 - inductive-capacitive ringing overshoot phenomena are responsible for the difference in peak-to-peak phase to earth voltages before and after the series reactor. Note that these two figures are for the same installation, with the peak-to-peak voltages being 1 581 V and 1 024 V measured after and before the series reactor – an increase of over 50%.

A closer look at the waveform - over a shorter time-scale (see Figure 8) – reveals that the increase is clearly caused by inductive-capacitive ringing overshoot. The under-damped oscillatory tail of the overshoot voltage waveform is clearly visible, with well-defined relative peak magnitude and resonant frequency.

Inspection of the circuit diagram of Figure 6 – especially the lowest circuit representing the complete phase equivalent circuit of the motor (for high frequencies) – will show that a series reactor (inductor) used as a dv/dt filter will simply add inductance to the equivalent circuit. Accordingly – the voltage rise-time (and fall-time) will increase as shown throughout in this article’s figures – but the Quality factor (Q factor) or Amplification factor of the circuit will increase because it is proportional to overall circuit inductance (Q factor is equal to L/R). Especially if the cable resistance is low – a series inductance can increase the Q factor significantly – as is illustrated in this example (1 581 V and 1 024 V – a ratio of 155%). Care has to be taken to avoid the situation where the voltage rate of change is reduced to acceptable levels but the under-damped oscillatory over-voltage does not exceed the safe levels of the motor!

The case study considered here reflects a rise-time (indicated by the phase-to-earth voltage measurements) of approximately 0,2 microseconds at the VSD terminals (before the dv/dt filter) and 5,0 microseconds at the motor terminals (after the dv/dt filter). Five microseconds is a long time for IGBT VSDs and it falls well within most motor manufacturers’ guidelines for motor terminal voltage rise-time. The voltage measurements before the VSD dv/dt filter indicate that the inherent VSD rise-time is very short and that the filter is therefore functioning as intended, but it is causing a significant increase in peak motor terminal voltage due to the equivalent high-frequency resonant circuit’s increase in Amplification factor (L/R) – a direct result of the added series inductance comprising the dv/dt filter. The latter confirms why some VSD filter suppliers (including VSD OEMs) offer what are termed as ‘damped dv/dt filters’, where the series inductor is shunted with a non-inductive resistor in order to reduce the increase in oscillatory overshoot voltage magnitudes.

How are VSD output voltages accurately measured?

There are many commercially available active differential voltage probes available, which allow isolated measurement of differential voltages of the magnitude considered here (up to approx 1 500 V RMS). However, these probes are generally not fast enough to accurately measure waveforms with rise-times of the order of 50 nanoseconds. For this reason – the measurements presented in this article were performed by measuring phase-to-earth voltages and then calculating the phase-to-phase parameters directly from several phase-to-earth measurements.

Because of the high-frequency equivalent circuit and stray capacitances (see Figure 5) – for many (most in fact) VSD-related insulation failure mechanisms – phase-to-earth voltages are far more important. Accordingly, more of these are presented in this article (than phase-to-phase waveforms), with the objective of understanding the failure mechanisms.

Figure 5: Stray capacitance C (and inductance L) in a coil model.
The measurements were performed using a 200 MHz bandwidth, 100:1 scale oscilloscope probe capable of 4 kV peak voltage, connected to a 100 mega sample-per-second digital-to-analogue converter. Due to site conditions, it was not possible to take two simultaneous phase-to-earth measurements, even though the digital-to-analogue converter is able to accommodate this. Phase-to-earth measurements were performed because high-speed differential voltage readings are difficult to perform accurately and safely. It is however possible to perform the measurements with an additional probe and one extra simultaneous phase-to-earth voltage reading on another phase. With two phase-to-earth measurements, one is able to calculate the phase-to-phase voltage for the two phases measured. If the three phases are balanced, one can also extrapolate the third phase-to-earth voltage and hence the other two phase-to-phase voltages. However - especially under transient conditions (which are the most important conditions for these measurements) - one cannot assume balanced conditions for a VSD driven motor. The latter is another reason why phase-to-earth measurements are so much more relevant when considering the insulation failure mechanisms of VSD-driven motors.

The traces that are presented are self-explanatory, with the exception of the vertical scale: the indicated value should be multiplied by 100 to obtain the actual motor or VSD voltage, for example, 10 volts of the graph is equivalent to 1 000 volts at the motor or VSD. The horizontal axis represents time and the scale varies in each case, but it is indicated on the graph. Comments are made for each relevant trace. The measurements are presented in the order of the voltage at the VSD, before and after the series reactor (dv/dt filter), and then finally the motor terminal voltage (about 100 metres or more from the VSD and the series reactor).

**Avoiding the failure mechanism**

If motors appear to - or are known to – have failed due to inter-turn insulation failure, then rate of change of voltage (dv/dt) is the most important parameter to be considered. The correct and most simple method of increasing (slowing down) voltage rise-time (or dv/dt) is to include a series reactor (inductor) in each lead between the VSD and the motor – as has been done in the installation considered here. It is shown however that although the rise-times are significantly increased – oscillatory ringing over-shoot becomes more of a problem.

The design of a reliable installation therefore requires careful consideration of all these aspects. There is now widespread evidence [1] that excessive transient terminal voltage can lead to partial discharge damage to the stator winding of a (low voltage) VSD driven motor, so peak terminal voltage should be considered with equal importance as voltage rise-time – especially for motors using special ‘inverter-grade’ wire (because it uses increased and improved inter-turn insulation).

Figure 6 illustrates how the stray capacitance and inductance of individual turns (see Figure 5) and coils combines to form a resonant RLC circuit – causing the under-damped oscillatory waveform presented in Figure 8 and less obviously in Figure 4 due to the longer time-base.

**What are the primary failure mechanisms?**

There are two primary insulation failure mechanisms:

- Inter-turn insulation failure, due to excessive inter-turn voltage which is primarily caused by very short rise-times or very high rates of change of voltage (dv/dt).
- Phase-to-phase or phase-to-earth insulation failure, due to excessive terminal voltages which are caused by high-frequency resonance and characteristic impedance mismatches (reflected waves) – also related to the very fast-fronted voltage waveform typical of most modern IGBT-based VSDs. (A VSD-driven motor can theoretically fail because of overheating due to excessive current harmonics but this is rare today and therefore excluded from this article).

**General VSD-driven motor issues – modern trends and guides**

The author is asked so many times what risks are involved in VSD operation of either new low voltage motors or existing motors that are retrofitted with VSDs – hence this article and others. This article is specifically about voltage waveforms effects – more specifically about insulation failures. There are also bearing current and shaft voltage effects, common-mode voltages, electromagnetic interference issues, and over-heating phenomena – among others.

For an excellent single document covering the fundamental treatment of these issues – [2] is highly recommended. [3] – By the same institution is an equally excellent but more broad treatment of the complete system. WEG provides a complete document [4] on their website (www.weg.net), covering detail on all technical aspects related to VSD-driven motors, including those discussed in this article. For this case study - it is important to mention the evidence [1] that exists, which indicates that high motor peak terminal voltage can cause partial discharge damage to low voltage motor windings. The partial discharge damages the strand/wire (interturn) insulation, eventually leading to interturn failure. The process is gradual, explaining why failure only occurs after a significant period of operation.
Both motor terminal peak voltage and voltage rise-time have been treated in detail, but it is in fact the combination of the two which theoretically determines the level of stress to which the interturn insulation is subjected [4]. The traces presented in the report show that the motor terminals are subjected to less than 200 volts per microsecond (phase-to-earth), even for the worst recorded measurement. This value is very low according to most VSD driven motor specifications or guidelines, yet several of these motors’ stators failed within the first six months of operation – all with very similar symptoms. These failures proved that voltage rise-time is not the only parameter of concern, and that motor terminal over-voltage can occur while attempting to treat voltage rise-time – ultimately resulting in failure of the stator insulation due to Partial Discharge (PD) [1].

In terms of potential VSD-driven motor failures - the author suggests that the following aspects be investigated:

- The Corona Inception Voltage of the machines should be known or determined [4], because evidence exists that motor terminal voltages exceeding this value will lead to gradual insulation damage.
- The type of strand/wire enamel covering should be specifically suited to VSD operation and failure stresses. Organic materials are more quickly degraded by partial discharge than inorganic materials, and almost all motor manufacturers now offer specific inverter-grade wire. It is however possible that failures could occur due to more standard insulation punch-through, and be misinterpreted as partial discharge issues. These typically occur within hours to weeks of commissioning, and are caused by defects (punch holes) in the conductor insulation (usually enamel).
- The manufacturing process should be investigated or audited: Aspects such as winding overhang support are even important. It is worth noting that interturn insulation on high voltage motors is more often damaged during manufacture than at any other time. Even the method of coil insertion has been shown [1, 4] to affect the Corona Inception Voltage or the likelihood of premature failure for VSD driven motors.
- The method and frequency of interturn testing on the motors should be investigated, specifically the frequency of testing (since for low voltage machines, these tests are only done intermittently and not on every motor).
- Most importantly – the overall drive system should be considered – not just the motor or VSD as isolated components.

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Recommendations

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- Most importantly – the overall drive system should be considered – not just the motor or VSD as isolated components.

About the author

Rob Melaia graduated from the University of the Witwatersrand in 1993. His first engineering position was at ABB ac Machines in Alrode, South Africa. After almost ten years at ABB, he moved to a small specialist condition monitoring company, Westward Electric. He rejoined ABB a year later as strategic development engineering manager. To feed his interest in failure analysis, diagnostics and maintenance management, Rob joined LH Marthinusen in 2007 where he has remained as technical director of rotating machines. Rob won the first Electricity+Control ‘Best Writing’ competition in 2011. Enquiries: Email: Robm@lhm.co.za.