Inverter-Rated Motors: What They Are and How to Identify Them

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ABSTRACT

An increasing number of industry specifications, especially those for specific projects written by engineering companies, call for inverter-rated motors. Despite this being a common request, Australian standards do not provide an official definition for the term inverter-rated electric motor. By and large, users are left to decide on their own, the motor requirements suited for use with inverters. On the other hand, suppliers are free to interpret the term inverter-rated in whichever breadth and depth they wish. This paper reviews the significant effects an inverter has on an induction motor; it summarises the international guidelines for inverter-driven motor applications, mainly those contained in the latest International Electrotechnical Commission (IEC) technical specifications. The requirements of other standards such as NEMA MG1 parts 30 and 31 are not covered herein as they are not commonly referenced in Australia. This paper also includes a study investigating current leading inverter brands, and discusses how the results influence these standard guidelines. It proposes additional technical considerations for a given electric motor to be used safely and reliably with modern IGBT-based inverters.

INTRODUCTION

Inverters, also known as Variable Speed Drives (VSDs), Variable Frequency Drives (VFDs), Variable Voltage Variable Frequency Drives (VVVF), Frequency Converters or simply Drives, were first used commercially in the late 1960s. The evolution of semiconductor-based transistors, from BJTs to IGBTs, has propelled their development and demand. Anecdotal industry data suggest that today, in developed countries, 4 in every 10 low voltage motors are used with inverters. This ratio is said to increase as technology evolves and becomes more economical.

Invariably when an engineering company writes up a technical specification, a set of additional requirements exists for motors to be used with inverters. Generally these focus on motor insulation, bearing protection against stray currents, and less commonly on load aspects. The preface to any specification is an unequivocal list of standards to which a bidder must comply in full. Nonetheless, the absence of normative requirements for inverter duty motors and the possible inadequacy of existing recommendations defers any impositions to additional clauses in the purchaser's technical specifications. The end users' plant reliability, mean time between failure (MTBF), up-time and operational cost could be heavily impacted by how these clauses encompass characteristics of motors to be procured for use with inverters. A robust set of requirements will capitalise on available technology, bringing peace of mind to users. In order to explore these potential requirements, a review of the major drawbacks of modern IGBT inverters is required.

SUPPLY VOLTAGE v. INVERTER WAVEFORM

There are two main types of inverters: current source (CSI) and voltage source (VSI). As the majority of low voltage inverters are of the VSI type, this paper will focus on this topology. Figure 1 shows a typical VSI: line power is rectified by a diode bridge (1), which is then filtered by capacitors (2). This DC voltage is finally converted back into a variable amplitude, variable frequency AC voltage via a three-phase IGBT bridge (3).

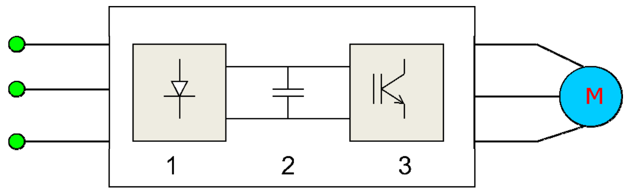


Figure 1: A typical VSI topology

The Pulse Width Modulation (PWM) technique used generates a series of variable width voltage pulses in an attempt to emulate a sinusoidal supply (Figure 2).

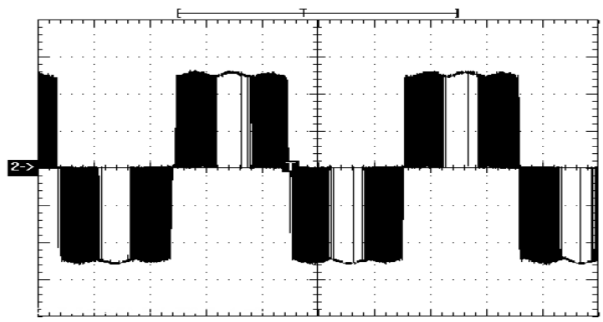


Figure 2: PWM Voltage waveform

One cycle of the PWM voltage waveform is in fact made up of thousands of pulses. The number of such pulses depend on the inverter carrier or switching frequency, (typically set from 2 to 8kHz). In some applications where audible noise is an issue the switching frequency is set to higher values and can reach up to 20kHz. The fundamental voltage is controlled by pulse duty cycles. The motor voltage is comprised of this fundamental voltage and high order harmonics. When amplified in a time-scale, each pulse at VSI output terminals has particular characteristics such as rise time and voltage peak depicted in Figure 3.

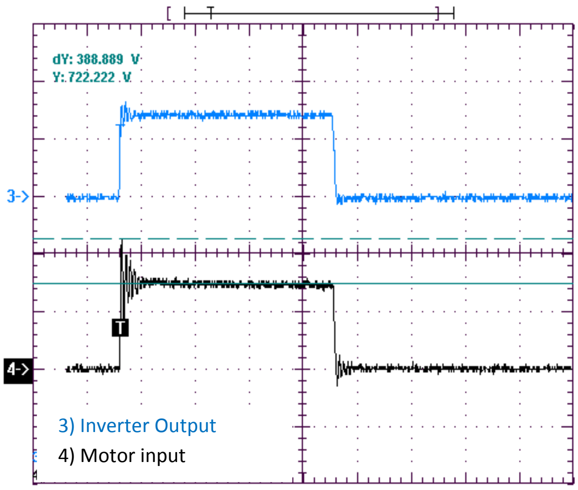


Figure 3a: Time scale 10 µs/div

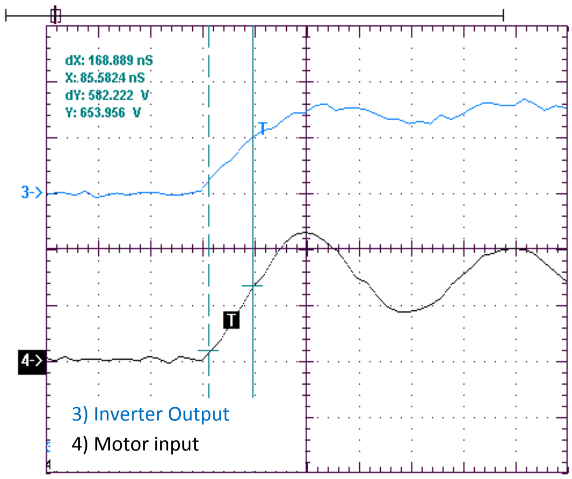


Figure 3b: Time scale 200 ns/div

Figure 3: Typical PWM pulse at VSI output terminals shown in two different time scales (line voltage = 575V, motor 22 kW 575 VAC, 20 meters shielded cable)

The pulses at motor terminals are distorted/amplified due to impedance mismatches between converter and motor terminals. The cable acts as a transmission line with the motor high frequency impedance as the load. The typical pulse waveform is presented in Figure 4.

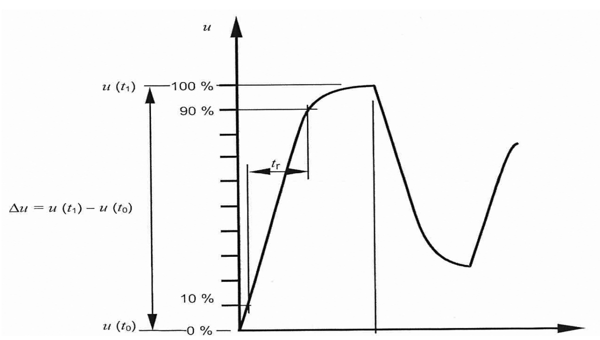


Figure 4: Enlarged typical PWM pulse at motor terminals as per IEC TS 60034-25 (2007: p. 28)

The rate of rise of voltage or dV/dt is one important parameter. It is defined as the time with which the voltage pulse takes to go from 10 to 90% of its amplitude, and is measured in Volts per microsecond. Typical values across brands of PWM inverters vary depending on several parameters such as IGBT characteristics, gate-driving conditions and dc link inductance. Values can achieve 10,000Volts/µsec or even higher with modern IGBTs. High dV/dt values at VSI output are related to non desirable effects such as insulation stress, bearing currents, electromagnetic emissions, and others. It is important to design VSI components to restrict dV/dt to a limited range. For comparison purposes a 415V mains supply generate dV/dts on the order of 0.01 V/µs.

On the other hand, voltage surges at motor terminals can rise to 4 times the inverter DC link voltage, that is up to 5.4 times the level of mains supply. The actual voltage amplification process which takes place between inverter output and motor terminals (the voltage peak at motor terminals is higher than inverter output) is due to a number of mechanisms and dependent on inverter IGBT rise time, switching methodology, cable topology and length. An example of motor terminal voltage on 380Vrms supply, with an IGBT inverter and 54m cable run is depicted in Figure 5. Note that $V_{pk\text{-}pk}$ = 2,008V.

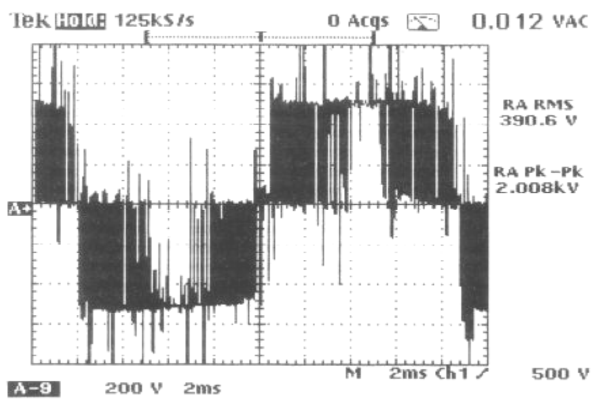


Figure 5: IGBT Inverter voltage waveform with 54m cable run

Some steps can be taken at either VSI design or at application level to reduce voltage spikes. Adequate pulse modulation strategies can reduce voltage spikes to 2 x DC link voltage, but it cannot reduce dV/dt values.

These changes in the power supply to the motor have serious implications for motor insulation and bearings, as well as possible impact on cables, couplings and driven equipment. Indeed, IEC technical specification TS 60034-25 (2004, p. 9) classifies motors in either of two types: **general purpose** standard cage induction motors primarily designed for fixed speed but which can also be used with inverters, and **cage induction motors specifically designed** for inverter operation. There are fundamental construction differences between these two types of designs, especially in what concerns insulation systems. The former is generally built with grade 2 enamelled wire, standard size slot insulation and impregnation methods. The latter incorporates an enhanced insulation system comprising of spike-resistant wire, as well as a possibly reinforced slot insulation and impregnation. There may also be differences in bearing types (standard to insulated type), and less commonly fan and rotor constructions.

By and large industry produces general purpose motors, with a limited number of manufacturers offering a truly inverter-rated motor line. This perhaps stems from the higher costs and patent limitations of inverter-rated insulations.

THE EFFECT ON MOTOR INSULATION

The combination of high voltage peaks and dV/dts stress the main insulation, that is coil to ground and phase to phase; as well as inter-turn insulation. The end result might be a significant reduction in motor life, for its insulation system might fail prematurely. Figures 6a and 6b show examples of inverter-induced motor failures.

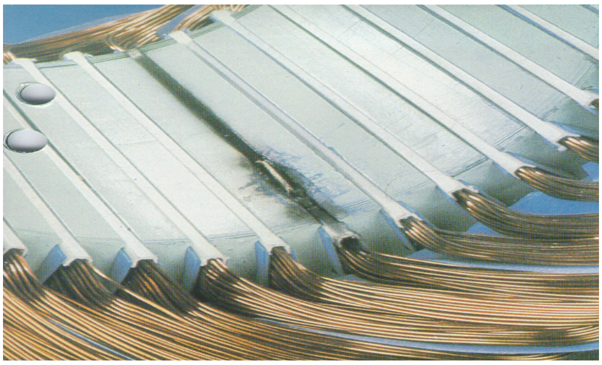


Figure 6a: Inverter-induced failure

Figure 6b: Inverter-induced failure

The failure mechanism of low voltage motor insulation is a consequence of one or more of the following:

Rise Time - The rise time (t_r) has a direct influence on the insulation life, for the faster the pulse wavefront rises, the greater the dV/dt ratio over the first coil and the higher the voltage level between turns, causing the insulation system to age more quickly. Therefore the motor insulation system should have superior dielectric characteristics in order to withstand the elevated voltage gradients inherent to the PWM supply (Pires, W. D. L, 2009).

Switching Frequency - Its influence on motor insulation and motor bearings is not addressed in the standards. There is no simple correlation between insulation life and switching frequency but studies has shown that the higher the switching frequency, the faster the degradation of the motor insulation. Research on this topic has suggested that (Yin, W; Bultemeier, K; Barta, D; and Floryan, D, 2005: pp. 257-261):

- If $f_s \leq 5$ **kHz** the probability of insulation failure is directly proportional to the switching frequency
- If $f_s > 5$ **kHz** the probability of insulation failure is quadratically proportional to the switching frequency.

Higher switching frequencies can also accelerate bearing damages. On the other hand, as the switching frequency increases, the motor current ripple, temperature rise and audible noise decreases (Pires, W. D. L, 2009).

Cable Length - The cable length is a predominant factor influencing the occurrence of voltage peaks at the inverter fed motor terminals. The cable can be considered as a transmission line with impedances distributed in sections of inductances/capacitances series/parallel connected. At each pulse, the converter delivers energy to the cable, charging those reactive elements. The signal arriving at the motor through the cable is partially reflected, because the motor high frequency impedance is greater than the cable impedance. This voltage reflections results in an overvoltage at the motor terminals. Therefore, long cable runs increase the amplitude of voltage overshoots at the motor terminals. Voltage measurements at inverter and at motor (V_{rated} = 400 V) terminals with different cable lengths are presented in Figure 7. The overshoots also depend on the type of cable used, therefore the waveforms shown are illustrative only (Pires, W. D. L, 2009).

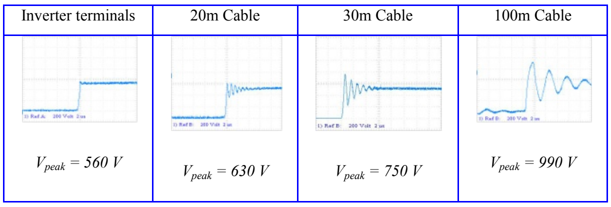


Figure 7: Overshoots for different cable lengths

Special care must be taken in multimotor applications, as shown in Figure 8. When there is more than one motor connected to a single VSI, additional overshoots can occur due to reflections from each motor. Effective motor cable length must be considered as the sum of all individual motor cables (Pires, W. D. L, 2009).

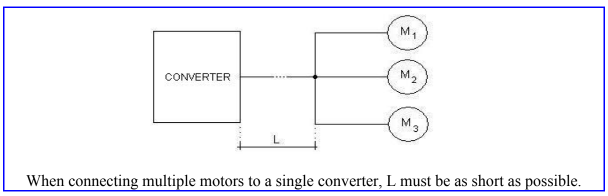


Figure 8: Overshoots in multi-motor configuration

PWM pulses time frame – pulse pattern combined with motor cable characteristics can lead to excessive peak voltages at motor terminals. IEC 60034-25 quotes those overvoltages in excess of 2 times DC bus VSI voltage if double pulse transitions occur or the time between two successive PWM pulses is not matched with the time constant of the motor cable.

Double transition occurs when one phase transition from minus to plus DC bus voltage occurs at the same instant that another phase switches from plus to minus. This can be controlled by PWM modulation strategy.

In order to match the time between two successive PWM pulses with time constant of the motor cable the user must rely on VSI manufacturer application information to select motor cable length and types to limit voltage peaks.

Partial Discharges (PD) - Depending on the quality/homogeneity of the impregnation the impregnating material may contain voids (cavities), in which the failure mechanism of the inter-turn insulation develops. The deterioration of the motor insulating system due to voltage overshoots occurs by means of PD, a complex phenomenon resulting from Corona (Kaufhold, M.; Börner, G.; Eberhardt, 1996). Between adjacent charged conductors there is a relative voltage, which gives rise to an electric field. If the established electric field is high enough (but below the breakdown voltage of the insulating material), the dielectric strength of the air is disrupted. That is, if there is sufficient energy, oxygen (O_2) is ionized into ozone (O_3). Ozone is highly aggressive and attacks the organic components of the insulation system. For this to happen though the voltage on the conductors must exceed a threshold value, the so called "Corona Inception Voltage". That is, the local breakdown strength in air (within the void). The CIV depends on the windings design, insulation type, temperature, superficial characteristics and moisture (Pires, W. D. L, 2009). The ensuing insulating damage is depicted in Figure 9.

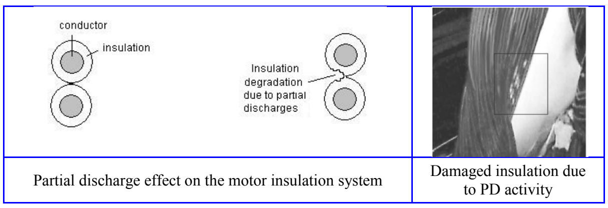


Figure 9: PD damage on random wound insulation

HOW QUICKLY CAN A MOTOR REALLY FAIL

Premature failures of inverter–rated motors depend on the adverse combination of properties of the inverter used, the length of cable, motor characteristics and PD level in the air gaps of the motor insulation system.

These types of failures, when they occur, tend to be slow onsetting over the course of a few years. In severe cases, e.g. in high ambient temperatures such as Kilns (90^0 to 110^0C), a winding failure may occur within a few months. Short-term failures have also been observed in applications with long-cable runs or with high dV/dt drive topologies.

To avoid premature failures motor manufacturers should design their inverter-rated motors to withstand specific limits of voltage spikes, dV/dt and rise time at a certain repetition rate.

PULSE VOLTAGE AND RISE TIME LIMITS

IEC 60034-17 (2006: pp. 29-31) contends that motors rated up to 500V built with random wound enamelled wires will typically endure the pulse voltages of Figure 10 without significant reduction of lifetime. For motors rated over 500V a.c., an enhanced insulation system and/or filters at the converter output may be required.

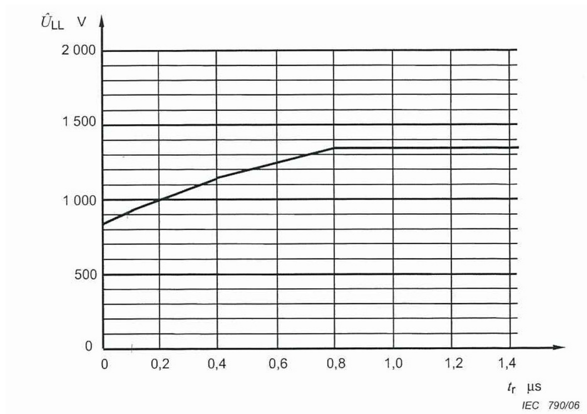


Figure 10: Impulse motor voltage limits as function of rise time for General-Purpose Motors as per IEC 60034-17

From Figure 10 and considering 0.1 µs as the rise time, the maximum permitted pulse voltage at motor terminals is 900 V. Common values for the peak voltage is 2 times DC link voltage so, for 400V line 2 x 1.35 x 400 = 1080V which exceeds 900V.

IEC 60034-25 (2007: p. 30) brings another set of limits for inverter-rated induction motors, herein depicted in Figure 11. IEC 60034-25 recommends two thresholds: one for motors up to 415V (curve A), and one for motors up to 690V (curve B).

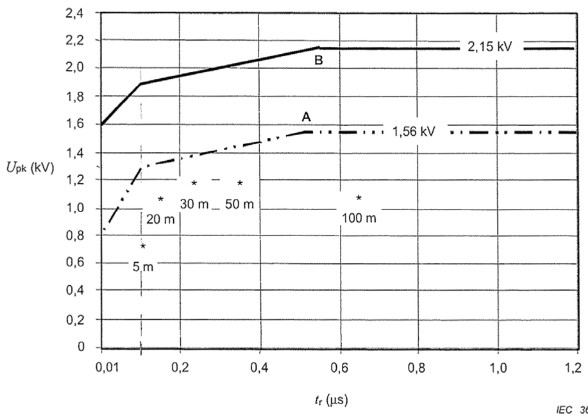


Figure 11: Impulse motor voltage limits as function of rise time for Inverter-Rated Motors as per IEC 60034-25

Figure 11 also contains typical impulse levels for different cable lengths (dots). No detailed reference is however made to the type of cable, which is known to influence impulses and rise time. Nothing is defined about the repetition rate of these rapid voltage impulses. This is however also an important factor in the stress levels imposed on motor insulation.

Although IEC warns that different assumptions used to derive Figures 10 and 11 render them not directly comparable, one can still use the aforementioned thresholds to evaluate these recommendations on the face of typical inverter-generated values.

As IGBT rise times evolve in a similar fashion to the computer chip industry, typical inverter dV/dt level data must be up-dated periodically. This cross-sectional study of some leading brands revealed that low voltage inverters have a dV/dt ranging from some thousand to many thousands of Volts per microsecond. Certainly the limits set forth by the relevant IEC recommendations are exceeded in many instances. On the other hand, the majority of motors is still produced with grade 2 random wound wire, a technology dating back to the 70s prior to the popularisation of inverters. A preliminary conclusion may be that most inverter-operated motors are subject to electrical stress levels beyond their capacity.

TYPICAL INVERTER dV/dt

In a series of tests conducted using leading Australian inverter brands, in this study by the authors, it was found that:

a) dV/dt varies greatly between brands (Figure 12)
b) Some inverters may output higher dV/dts for increases in switching frequency up to 12kHz (Figure 13). Others have a nearly constant dV/dt, whatever the switching frequency.
c) The addition of shield to a cable significantly increases dV/dt (Figure 13)
d) The increase in switching frequency significantly increases the repetition rate of voltage impulses impressed onto motor insulation

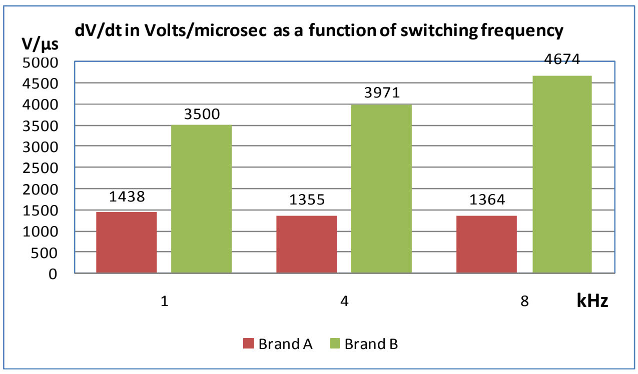


Figure 12: dV/dt across brands for identical cable topology and switching frequency ($4mm^2$ 3core + earth unshielded)

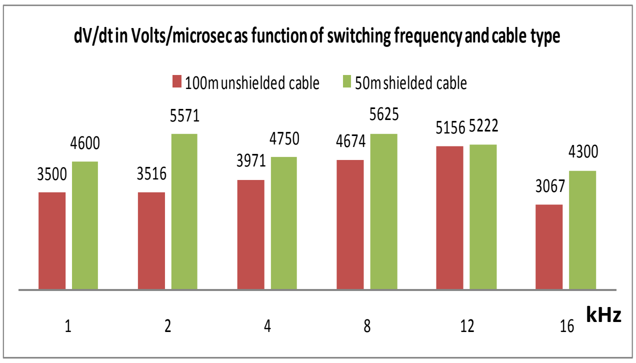
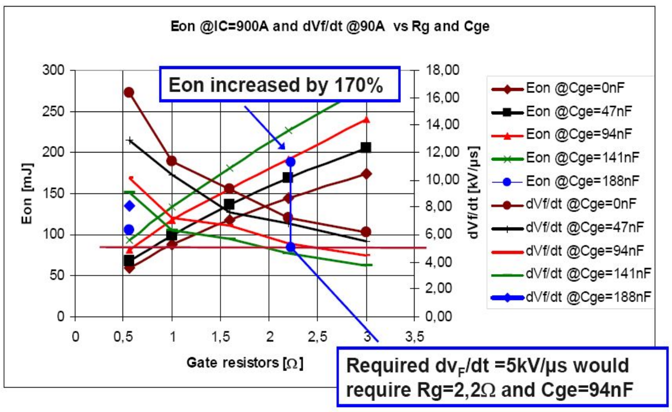


Figure 13: dV/dt variation with switching frequency and cable type ($4mm^2$ 3core + earth shielded & unshielded)

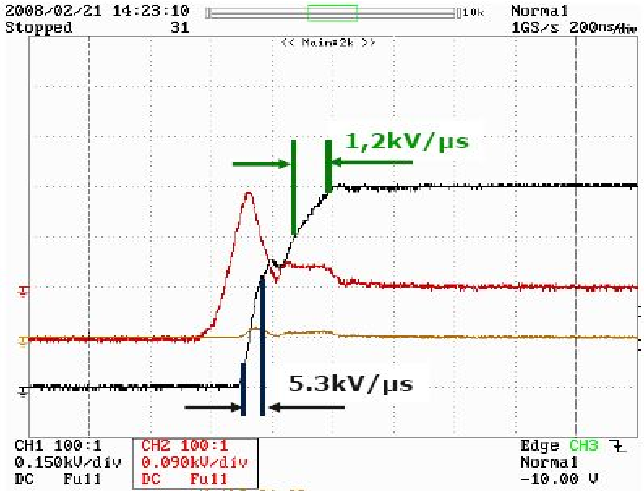
INVERTER RISE TIME AND dV/dt LIMITATION BY DESIGN

Referring to the inverter output terminals, the dV/dt depends on the IGBTs switching speed characteristics, gatedriver circuits and DC link inductance, which combined with motor cable length influences V_{peak}. Naturally the final stress values impressed onto the motor depend highly on the cable length, its topology, the high frequency impedances in the inverter-motor electrical circuit and the time frame of the IGBT pulses.

More recently some VSI designers have paid more attention to components topology and selection in order to control the dV/dt at VSI output terminals to a limited range. One example is showed in Figure 14(a) for the IGBT FF900R12IP4 PrimePACK module from Infineon. This figure shows the typical dV/dt dependence of gate resistor (Rg) and gate-emitter capacitor (Cge) as well the energy losses at turn-on (Eon). The energy losses at turn-off are almost independent of Rg and Cge. The dV/dt values shown in Figure 14(b) are as defined by the manufacturer as the highest value at switching, this differs in methodology from Figure 4. A proper combination of Rg and Cge can be used to adjust dV/dt switching values. In order to reduce the dV/dt an increase in Eon, and consequently in switching losses is expected.



(a) dV/dt and Eon as function of Rg and Cge



(b) Example with Rg=2.2 Ω and Cge= 94 nF

Figure 14 – Practical dV/dt and on energy losses for FF900R12IP4 module
Courtesy: Infineon Technologies AG

PRESERVING MOTOR LIFE

From a systems engineer viewpoint a solution is needed to render the inverter-driven motor a similar life span obtained in a mains supply installation. There are basically two approaches:

a) Improve motor insulation endurance
b) Decrease the magnitude, frequency and speed of voltage stresses

Motor insulation endurance is impacted by choice of:

- wire insulation (enamel type and thickness)
- phase and ground insulation
- impregnation system and material
- operating temperature
- cleanliness and dryness

Special enamelled wire, commonly termed spike-resistant, is the most significant of all technological improvements. Resin-based impregnation methods which increase the percentage of retained solids improve the insulation's overall partial discharge inception voltage (PDIV). Keeping temperature low, the insulation clean and dry will also maintain a high PDIV level. Although various techniques exist, a common theme is that a special insulation system is required to produce a true inverter-rate electric motor.

Medium voltage motors are a somewhat a more vexed issue. The depth and breadth of a design changes depend on the inverter type and topology. Usually the groundwall insulation thickness has to be increased significantly (by 50%). Thicker insulation hinders heat transfer, which ultimately pushes stack sizes up with a possible increase in motor frame. Consequently motor cost and characteristics may change according to inverter make.

In order to decrease the magnitude and rise time of voltage stresses, the following techniques apply:

- Keep cable to an optimal and short length
- Install an AC output reactor
- Use dV/dt or sinusoidal filters
- Regulate the minimum IGBT inter-pulse time
- Use higher step inverters

In practice choice of optimum cable length and type is somewhat heavily hindered by pre-determined process requirements or civil constraints, leaving a low degree of freedom to electrical design engineers. On the other hand, reactors are readily available and can be retrofitted with relative ease. A 2% impedance is somewhat sufficient in most cases to bring dV/dt and V_{peak} to acceptable levels. Care must be taken with the voltage drop across such reactors, its temperature and the subsequent impact in motor torque loss and heat.

Output dV/dt or sinusoidal filters are a good solution, with beneficial impact also on EMC. These filters must be selected considering their switching frequency limits. Care should be taken however when using sinusoidal filters, since they may impact on system stability in vector control modes. They also decrease the system's dynamic response, important in applications which require rapid torque changes or constant torque at low speeds.

Choice of higher step (3 or more) inverters increase VSI cost significantly, also adversely affecting inverter efficiency due to the higher number of power semiconductors and consequently higher losses. Use of higher step inverters is hence generally limited to medium voltage motors.

When WEG low voltage induction motors are used with inverters, limits to protect their insulation system from inverter-induced stresses are summarized in Table 1.

Table 1: WEG Motors dV/dt and V_{peak} levels

Motor rated voltage	Voltage Spikes At Motor terminals	*dV/dt* At Inverter terminals	*Rise Time** *Inverter terminal*	MTBP* Minimum time between pulses
$V_{rated} \leq 460V$	≤ 1600V	≤ 5200 V/µs		
$460V < V_{rated} \leq 575V$	≤ 1800V	≤ 6500 V/µs	≥ 0,1 µs	≥ 6 µs
$575V < V_{rated} \leq 690V$	≤ 2200V	≤ 7800 V/µs		

* Informed by the converter manufacturer

The maximum recommended switching frequency is 5kHz.

Selection of inverters with an inter-pulse time greater than 6µs is said to prevent double transition, that is the simultaneous and inverse change of voltage amplitude in two phases, bringing the maximum voltage surge at motor terminals down from 4 to 2 p.u. or V_{dc}.

BEARING CURRENTS

Electrically-induced bearing failures have been researched as early as 1907. It has been found that air gap eccentricity and rotor shorted turns could generate irregularities in the magnetic circuit which results in an electromotive force between motor shaft ends. This shaft voltage can also derive from electrostatic build-up, stator or rotor magnetic asymmetries, and common mode voltages originated from PWM inverters (Langhorst, P. and Hancock,C.). Common mode voltages are inherent to the topology and control algorithm of the inverter (IEC 60034-17, 2006: p. 35).

Inverter-related high-frequency bearing currents may stem from circulating, capacitive discharge or shaft earthing currents. These in turn originate from inverter-generated common mode voltages, which in the closed electrical circuit formed by the rotor, shaft and bearings, give rise to a current flowing to earth through existing motor stray capacitances (see Figures 15 and 16).

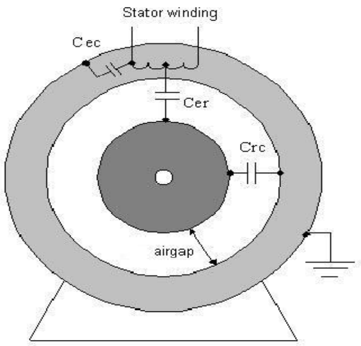


Figure 15: Motor Circuit Model for Bearing Current Analysis

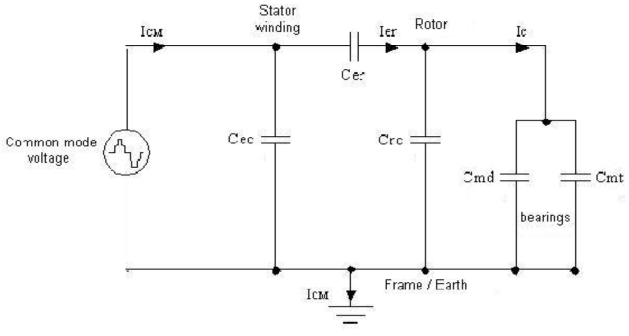


Figure 16: Motor stray capacitances

- Cer : Capacitor formed by the stator winding and the rotor lamination (Dielectric = airgap + slot insulation + wire insulation)
- Crc : Capacitor formed by the rotor and the stator cores (Dielectric = airgap)
- Cec : Capacitor formed by the stator winding and the frame (Dielectric = slot insulation + wire insulation)
- Cmd e Cmt : Capacitances of the DE (drive end) and the NDE (non-drive end) bearings, formed by the inner and the outer bearing raceways, with the metallic rolling elements in the inside. (Dielectric = gaps between the raceways and the rolling elements + bearing grease)
- ICM : Total common mode current
- Ier : Capacitive discharge current flowing from the stator to the rotor
- Ic : Capacitive discharge current flowing through the bearings

When motor parasitic capacitances are charged by the common mode voltage, they eventually discharge through the bearing. This is called capacitive discharge current. Knowing that capacitance is directly proportional to the area of the capacitor's conductive plates (A) and inversely proportional to the distance (d) between them, $C = \varepsilon A/d$, it can be understood that larger motors (larger stack area A and small air gaps d), exhibit higher parasitic capacitances. As the energy stored in a capacitor is $0.5CV^2$, by increasing C the discharge energy increases.

Finally, when the motor shaft potential is lower than the motor frame, a pulse-shaped, shaft-earthing current will flow through the bearings. The latter situation occurs when motor shaft is earthed closer to the inverter potential, for instance through a conductive coupling or gearbox, and the motor frame is not adequately earthed.

The end result might be a premature bearing failure herein depicted in Figure 17. The time to failure may vary from a few hours to a few months. In a severe case, the authors have seen a new bearing fail within 72 hours.

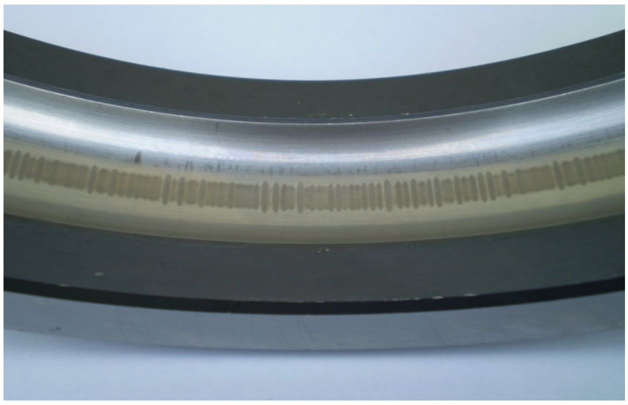


Figure 17: Bearing fluting caused by inverter-generated currents

Recommendations to prevent bearing failure may encompass (IEC TS 60034-25):

a) Use of one insulated bearing
b) Insulate both bearings
c) Insulate both bearings and coupling
d) Insulate one bearing and use a shaft grounding brush on opposite shaft end

e) Use a shaft grounding brush
f) Use two shaft grounding brushes, one on each end of the motor shaft
g) Use conductive grease
h) Design rotor as a Faraday cage
i) Use common mode voltage filter at inverter output

From these, options (b), (c), (d), (f) and (i) are effective against all three possible current types, circulating, capacitive discharge and shaft earthing. The remainder options are either impractical (h) or ineffective against one or more types of high-frequency currents.

Users must follow recommendations from motor manufacturer with regards to appropriate measures to prevent bearing life reduction in inverter applications.

SPEED LIMITS AND MECHANICAL ASPECTS

The maximum safe operating speed of a direct-coupled inverter-rated motor depends on a multitude of electrical, mechanical and thermal constraints.

Electrical limitation is related to motor torque capability above base speed. It must be ensured that the breakdown torque at any point within the defined speed range shall not be less than 150% of the torque at that frequency when rated voltage is applied.

Mechanically, bearing speed limitation, fan and rotor peripheral speeds, as well as general mechanical construction limit operation above rated frequency. Maximum speed limits can be found in item 9.6 of IEC60034-1 (2004: p. 113) herein reproduced as Table 2. Operation at higher speeds may be permitted when indicated by the manufacturer. A special motor design may be required.

Table 2: Speed limits for continuous operation of single-speed squirrel-cage motors to frame 315 and 1000V

Frame number	2 pole	4 pole	6 pole
≤ 100	5 200	3 600	2 400
112	5 200	3 600	2 400
132	4 500	2 700	2 400
160	4 500	2 700	2 400
180	4 500	2 700	2 400
200	4 500	2 300	1 800
225	3 600	2 300	1 800
250	3 600	2 300	1 800
280	3 600	2 300	1 800
315	3 600	2 300	1 800
NOTE The above values may have to be reduced to meet the requirements of IEC 60079.			

Thermal limitations exist for operation below the rated speed. Totally enclosed fan cooled motors, with integral shaft-driven fans, need minimum air flow to maintain their temperature within permissible limits. Traditionally, motor derating or fan forced cooling have been used to allow for operation below 40Hz (for 50Hz motors).

MOTOR LOSSES & EFFICIENCY

The square-shaped PWM voltage waveform of a VSI inverter contains multiple harmonics of the fundamental frequency which increase copper and iron losses in any given motor. High-frequency harmonics increase joule losses (stator and rotor) due to skin effect. These also increase eddy current losses in the laminations. The end result is a decrease in motor nominal efficiency. Indeed, IEC TS 60034-25 (2007: p. 18) indicates that inverter-induced losses may amount to about 1 to 2% of the motor’s rated output. IEC (2007: pp. 18-21) also lists a series of measures that can be taken to minimise these additional inverter-induced losses. On the motor side it cites traditional measures to combat skin-effect and eddy current related losses, such as thinner and better insulated laminations. On the inverter side it speaks of motor flux and inverter pulse pattern optimisation, increase in switching frequency and use of multi-level converter topology.

It is important to consider the overall power drive system (PDS) efficiency, i.e. the efficiency of VSI, cable and motor, beyond motor efficiency. For instance, the use of higher switching frequencies increase inverter switching losses and can lead to the reduction of PDS’ overall system efficiency.

From the above, differentiated design measures for inverter use need to be incorporated into the motor from its original construction. Pulse-pattern is locked into inverter design, as is multi-level inverter topology which is hardware based and usually used for medium voltage inverters only. Motor flux optimisation is generally available in the form of programming choice for parabolic torque loads. The same is applicable to switching frequency, which can be changed in situ by a simple parameter change. Users are then left with limited choice to counter-balance inverter-generated additional motor losses.

Use of higher switching frequency to decrease additional inverter-induced losses is illustrated in IEC TS 60034-25 (2007: p. 20) here represented by Figure 18.

Some specifications require motor efficiency, usually tested at 50%, 75% and 100% load, to be measured with the inverter. This creates an impasse, for not only choice of inverter make and model affect motor losses, but there is not yet a recognised method for testing motor efficiency on a inverter supply. Indeed, IEC TS 60034-25 (2007: p. 21) state that “the recommended methods to determine the motor efficiency are given in IEC 60034-2, but there is not yet a standard procedure for motors fed by converters.”

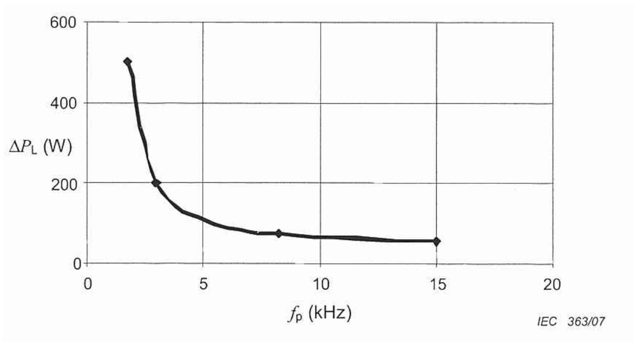


Figure 18: Motor additional losses ΔP_L as a function of switching frequency.

However, working groups from IEC and CSA (Canadian Standard Association) are developing standard methods for testing and evaluating the efficiency of inverters, inverter driven motors and the efficiency of the complete motor control system. The future defined methodology will possibly take into account line conditions, inverter parameters, motor constraints and motor power range. It may also make possible the comparison between manufacturers.

TORQUE DERATING FACTOR

IEC 60034-17 (2006: p. 23) clarifies that "when the motor is supplied from a converter at the motor rated frequency, the available torque is usually less than the rated torque on a sinusoidal voltage supply due to increased temperature rise (harmonic losses). An additional reason for the reduction may be the voltage drop of the converter. Maintaining of the rated torque may reduce insulation service-life." A typical torque derating (reduction) curve is depicted in Figure 19.

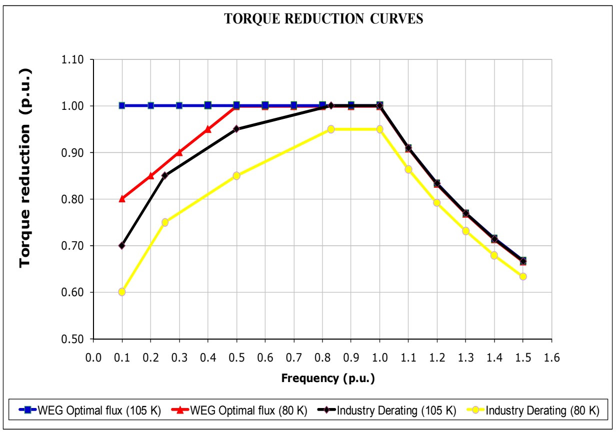


Figure 19: Torque derating curve for general inverter operation (yellow and black) and for WEG motors and drives with optimal flux™ (red and blue)

Should one wish to maintain the inverter-driven motor temperature rise identical to that of mains supply (yellow curve), even at rated speed a torque reduction of 5% is required to compensate for the additional heat generated by inverter output harmonics. If no derating is applied the motor will operate above its sinusoidal supply temperature rise (black curve). If, for instance, the motor's temperature rise is 80^{0}C, the equivalent temperature rise with inverter at rated speed and no derating might reach 100^{0}C or higher. As the speed is reduced a larger derating factor is necessary to compensate also for the decreased cooling, unless the motor is of the forced ventilated type (TEFV). Above rated speed, a derating is required to account for reduction in motor flux (Φ = [(kV)/f], where K is a constant, V is the motor voltage, and f the frequency) due to operation at constant voltage and increased frequency.

Optimal FLUX, the newest technology which optimises motor electromagnetic flux at any operating point (Mello, H.,G.G., Pires, W. L.), minimises inverter-induced losses, dispensing with the requirement for torque reduction or forced cooling even at motor rated torque at speeds as low as 5Hz (blue curve). Should the inverter-driven motor temperature rise be maintained similar to that of mains operation, then a small derating is required (red curve), but optimal flux still results in a smaller torque reduction factor, and therefore a smaller size motor for any given application, continuing to save energy for the life of the installation.

THE IMPLICATIONS FOR HAZARDOUS AREAS

Standards such as AS /NZS 60079.20 quantify the ignition energy of the gases comprising groups I and II. These energy levels, herein reproduced in Table 3, can be quite low.

Table 3: Ignition Energy for Groups I and II Gases

GROUP	Ignition Energy	Minimum Igniting Current
I	525 µJ	85mA
IIA	320µJ	70mA
IIB	160µJ	40mA
IIC	40µJ	21mA

The phenomenon leading to a premature winding failure in an inverter-driven electric motor is of a partial discharge (PD) nature. Whereas PD is an acceptable inherent characteristic of medium and high voltage motors, above 4KV, there is generally not much consideration given to PD activity in low voltage electric motors. The literature has documented explosions with high voltage Ex-n motors attributed to partial discharges as the ignition source (Jones, N., 1994: p. 20). The question whether the PD energy in an inverter-driven motor may exceed the ignition energy of the surrounding flammable gas, remains.

In addition, premature bearing failures in inverter-driven motors may occur due to capacitive discharges. Experimental data show shaft voltages may reach upwards from 90V. Knowing the energy stored in a capacitor equals $0.5CV^2$, would that energy exceed the maximum ignition energy of the hazardous atmosphere? Should the practice of using two insulated bearings, one on each end of the motor, be prohibited for if may constantly keep the motor shaft voltage above earth potential?

Based on Equipment Protection Levels (EPL) introduced by AS/NZS 60079:26, would for instance an Ex-e inverter-driven motor be classed as EPL Gb or Gc? In order to meet Gb level it should not be "a source of ignition in normal operation or when subject to faults that may be expected, though not necessarily on a regular basis (2007: p. 12)." Does the fact that partial discharges are expected to occur in inverter-rated motors make it a source of ignition?

These are pointed questions yet to be answered by the appropriate experimental research. In the mean time, the authors caution users to rethink the use of Zone 1 motors, e.g. Ex-e, with inverters. Whereas the testing regime to certify an Ex motor for use with inverter hones in the temperature effects of harmonics and speed variation, they do not make reference to discharge energy. It appears that certification alone may fall short of addressing all safety concerns of using hazardous area motors with inverters.

MOTOR DESIGN REQUIREMENTS

From the preceding sessions it is inferred that inverters create additional challenges to motor design. IEC TS 60034-25 (2007: p. 16) summarises the considerations for motor designers, herein reproduced in Table 4.

Table 4: Motor Design Considerations

Required Aspect of Application	Design Consideration
Long-term operation at low speed	Thermal oversizing or forced cooling. For long-term operation of sleeve bearings below 10% of base speed, the bearing performance should be confirmed by the manufacturer.
Large ratio of speeds	Cooling independent of speed (separate fan, or other cooling medium, for example, water)
Speed feedback device	Precautions for mechanical interface. Speed sensor may need to be electrically insulated.
High speed (field weakening)	Mechanical aspects. High breakdown torque (i.e. small leakage reactance). U/f characteristic is constant until $f > f_0$
Improved motor efficiency with converter supply	Rotor cage designs (rotor bars with low current displacement are preferred). May adversely affect starting capability.
Line bypassing or line start capability	Rotor cage design must be appropriate. Consequently the design may not be optimized to reduce losses and improve efficiency – balanced compromise necessary.
High breakaway torque	If possible, increase flux by 10% to 40% (depending on motor size) at near-zero frequencies.
Voltage drop in the converter because of modulation or filter or cabling	Adaptation of the rated motor voltage to compensate for the voltage drop.
Multi-motor operation at approximately synchronized common speed	Similar slip/torque characteristics of the motors.

Of course motor suppliers can simply disregard some or all additional stress factors imposed by inverters, permitting the use of their general purpose motor. Risk of premature failure is somewhat mitigated by a multitude of factors such as choice of inverter, cable length and topology, user's reliability and technical requirements, and the generalised absence of root cause failure analysis in industry.

This last point merits further explanation. When a motor fails it may be sent off to a repair shop for further inspection. Motor repairers generally disassemble and carry out a visual inspection, perhaps accompanied by some basic tests such as insulation resistance. A verbal or written report may be generated. The report usually captures the type of failure, the extent of repairs needed, cost and turnaround time. An example would be: winding failure caused by a short between turns, motor must be rewound. If the failure occurs within the warranty period, the supplier may be actioned, but otherwise there is a generalised lack of concern for the root cause of failure. Often the motor is simply repaired and put back into service. What if this inter-turn short was caused by inadequate insulation? What if the premature failure was a result of using a general purpose motor with an inverter? In the authors' experience these questions are often left unanswered. The lack of root cause failure data shadows any statistical study on the frequency and ratio of inverter-induced failures.

Whereas the recommendations in Table 3 fall short of addressing the stress factors impacting the electrical aspects of winding and bearing design, these are covered in the body of IEC TS 60034-17, 60034-25 and 60034-18-41 Technical Standards. Based on measured dV/dt levels presented in previous sessions, the authors believe that additional requirements, over and above IEC recommendations, may be necessary in certain applications. These relate to voltage impulse and rise time withstand levels, as well as mechanical design for high speed operation.

MOTOR INSULATION TESTING REQUIREMENTS

IEC TS 60034-18-41 (2006: p. 11) divides PDS into "those which are **not** expected to experience partial discharge activity in their service lives (Type I) and those which **are** expected to withstand partial discharge activity throughout their service lives (Type II)." This document specifies the appropriate tests motor manufacturers must undertake to class their insulation system as Type I. Type 2 systems are addressed by IEC TS 60034-18-42 document.

IEC 60034-18-41 clarifies that (2006: p. 9) "before undertaking any testing, the manufacturer must decide upon the level of severity that the system will be required to withstand. The severity is based on how large the voltage overshoot and how short the impulse rise time will be at the machine terminals." It also states (2006: p. 35) that "machines with a rated voltage ≤ 700V r.m.s. may have either Type I or Type II winding insulation. Above 700V r.m.s. the winding insulation is usually Type II."

Stress categories for Type I insulation systems, to which the motor manufacturer shall declare conformance, are defined. These are reproduced in Table 5 below (IEC TS 60034-18-41, 2006: p. 37).

Table 5: Stress Categories for Type I Insulation Systems

Stress Category	Overshoot factor U_p/U_{dc}	Impulse rise time T_r in μs
A- Benign	≤ 1.1	≥ 1
B – Moderate	≤ 1.5	≥ 0.3
C – Severe	≤ 2.0	≥ 0.1
D – Extreme	≤ 2.5	≥ 0.05

As this is a relatively new document with very specific test requirements, manufacturers at large may not yet be equipped to carry out these tests. Indeed, the authors have not yet seen motor documentation or nameplate stating such a classification level.

WHO IS RESPONSIBLE?

IEC TS 60034-25 (2004: p. 29) attributes responsibility to the system supplier, for he or she "is responsible for specifying the voltage stress level at the motor terminals, taking into account possible voltage reflection depending on the topology and operating mode of the converter, cable type and length, earthing, etc. Relevant parameters for insulation stress are: transient peak voltage values, peak rise time, repetition rate, etc. The motor manufacturer should check the voltage stress withstand capability according to the system supplier's specification." This is reinforced by IEC TS 60034-18-41 (2006: p. 35) "the converter drive integrator must specify to the motor designer the voltage that will appear at the motor terminals. It should be included in the purchase specification."

If equipment is being procured from various sources, e.g. different motor and inverter suppliers, who is then the system supplier? Even when motor and inverter are procured from a single-source, is the motor supplier made aware of important design parameters such as cable length and topology which affect voltage peak and dV/dt?

What about changes to design speed ranges, which may be further implemented by the end user? And what happens to the retrofitting of inverters to motors originally procured for direct-on-line (DOL) operation?

It appears that the owner-occupier of the plant is ultimately left with the responsibility of ensuring inverter-driven motors are operated within the motor manufacturer's recommendation. On that point, it may be more practical to specify minimum dV/dt, Vpeak and repetition rate levels then measure these parameters for each installation. From field measurements on current leading brands of inverters, the authors recommend a minimum of 1,400V and 4,000V/μs at 4kHz for motors under 460V. With respect to the inverter, the authors concur with IEC TS 60034-18-41 (2006: p. 27) recommendations that voltage impulses at motor terminals can be minimised by selection of inverter which limits double transition and allow a minimum time between pulses of 6μs.

MOTOR & INVERTER CHOICE

Choice of ideal inverter and motor combination is usually simplified by procurement of a single-source supply. Although this tends to put the responsibility in one set of hands, it fails to capture any other measurable benefit.

A combined design approach, that is, designing motors to suit the demands of the average inverter and the inverter to minimise stresses onto the motor, brings important technical and commercial advantages. A step further is to integrate the two intricately at machine level, thus effectively providing a truly matched inverter-motor combination. This has been achieved with the patented Optimal Flux technology developed by WEG R & D engineers.

Optimal FLUX incorporates another layer of control over the top of the vector algorithm, optimising motor electromagnetic flux at any operating point (Mello, H.,G.G., Pires, W. L.). The end result is an improvement in motor efficiency by minimisation of inverter-induced losses. In practical terms, users gain benefits from lower energy consumption and heat generation, e.g. higher system efficiency and longer motor life.

Optimal FLUX is proof that integration of motor and drive can achieve levels beyond the adjustments recommended by IEC TS 60034-25, and certainly far beyond the commercial simplification of liability for package performance.

CONCLUSIONS

The requirements of the current IEC Technical Specifications 60034-17, 60034-25 and 60034-18-41 summarised in this paper are not normative, but rather technical guidelines. Australia Standards Limited has neither published standards, nor technical guidelines, to address specific requirements for motors suited for use with inverters.

If motor manufacturers consider the full breadth and depth of inverter-generated stress factors, they will produce motors which can withstand, in the long-term, these electrical and mechanical stresses. This means choice of enhanced winding wire type (spike-resistant), impregnation material (resin v. varnish), impregnation method (immersion v. VPI v. resin flow), bearing protection against shaft currents, thermal consideration for low speed applications, as well as mechanical aspects for operation above rated speed (bearing, grease, rotor, fan and endshield). Even if and when all these variables are addressed in motor design, there are usually no distinguishable external features that can visually separate inverter-rated from general purpose motors, nor do the former bear any special marking. The identification of inverter-rated motors is hence linked to manufacturers' technical specifications.

The results of this study of leading inverter brands have shown that dV/dts and rise time vary greatly between brands, and may exceed the recommendations of IEC. The increase of switching frequency was found to increase the repetition rate of voltage impulses and, in some brands, significantly increases the dV/dt at motor terminals. Shielded cables seem to have had an adverse effect as far as high dV/dts and Vpeaks are concerned.

In hazardous areas some questions remain to be answered by future research. Further tests are also required to arrive at specific, quantitative conclusions about the influence of cable length and type. In medium voltage, drive topologies and technology vary greatly. Possible effects on the driven motor require investigation.

As to what inverter-rated motors are, by and large, this depends on the purchaser's specifications and own definitions, at least until such time as there are relevant and up-to-date normative standards published.

Inverter rise time and dV/dt may be limited by inverter design, especially gatedriver Rg and Cge. There are modern motor insulation systems (enamel and impregnation type) better suited to cope with high impulses and dV/dt. Optimal FLUX eliminates the need for torque reduction and forced cooling motors below rated speed.

As motor life depends on the level of dV/dt, V_{peak} and their repetition rate, users are cautioned to deploy PDS design measures that limit these to the levels permitted by the motor manufacturer.

Choice of compatible motor and inverter type deliver significant technical benefits such as enhanced life, improved reliability, and higher operational efficiency. Responsibility for specifying the correct requirements lies with the system supplier, albeit the plant user or occupier is ultimately who bears the costs.

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