Research Article

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Influence of the earth connections of the PWM drive on the voltage constraints endured by the motor insulation

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Abstract: The high electrical stresses in the Electrical Insulation Systems of machines fed by pulse width modulation (PWM) inverters remain a limitation of the lifetime. The stress is caused by repetitive over voltages caused by the short switching times of the PWM inverter power electronic circuit. This paper provides measurements made on an industrial drive connected to the grid with standard cables that include a ground connection wire, following the current standards. The phase-to-phase, phase-to-neutral, and neutral-to-ground voltages are measured focusing on short and repetitive voltage spikes. The causes of these voltage spikes are analyzed using a high frequency equivalent circuit of the whole drive, including the earthing system. The simulations are made with the well-known SPICE circuit simulator. This study focuses on the common-mode currents flowing in the earthing connections and its influence on voltage spikes. A solution that can reduce significantly the phase-to-neutral voltage spikes is proposed.

Keywords: PWM drives, fast-fronted voltage pulses, drive earthing, common-mode voltages

1 Introduction

The advances in power semiconductor technologies have brought numerous opportunities to develop motor drives

with high efficiencies, high power densities, and smart control capabilities. Shorter switching times in converters of higher powers constitute a major electromagnetic risk that must be controlled; electromagnetic compatibility (EMC) filters must be added for controlling the propagation of common-mode and differential-mode parasitic currents [1–3]. Most of these studies use equivalent circuits analyzed in the frequency domain. This approach offers a comprehensive knowledge of the broadband behavior of the whole drive and easy comparisons between several solutions and standard requirements. It also gives the possibility to concentrate the investigations on a frequency range that corresponds to specific phenomena such as resonances. Measurements are often made in the time-domain with a specific voltage and current probes before a Fourier transform of the recorded data; a specific care is required for interpreting the recorded data with the probe characteristics [4].

The PWM inverters also create additional voltage stresses on the motor electrical insulation systems (EISs). The earlier aging of inverter fed motor is now well known [5]. The standard IEC 6003 4-18-41, widely based on a time-domain approach, defines the qualification and the test procedures for the machine windings [6]. It is now well known that the fast-fronted voltage pulses imposed by the inverter create a higher voltage stresses between the winding turns near the phase inputs. The theoretical study [7] based on partial differential equations representing the propagation of energy in windings details these phenomena. This theoretical analysis, made in time-domain, yields results that are confirmed by measurements made on a random-wound motor specially equipped for measuring the turn voltage distribution. Other papers based on larger machines confirm these results [8,9].

The phenomenon of accelerated aging of winding EISs is linked to the existence of partial discharges (PDs) inside the very small air-voids remaining between turns in random windings. Several experimental studies have been performed on twisted pairs made of two enameled

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wires; they show that each PD is very short and local ionization in a microscopic zone of air that creates a local abrasion of the wire insulating layer [10]. Each PD also creates local space charges on the insulating surface, which change the local electric field that prevents the formation of another PD at the same microscopic place when the voltage polarity remains unchanged [11]. The ionization phenomena also depend on the air pressure; therefore, it is a major issue in the machines that are used in aircrafts [12]. The winding aging acceleration is a global issue that depends on the cumulative effect of these local abrasions; it depends on a combination of three major factors: the value of the peak turn-to-turn voltage stress compared to partial discharge inception voltage (PDIV), the frequency voltage spikes over the PDIV, and the number of pulse polarity changes [13]. A paper proposes a model that can estimate the remaining lifetime of a motor under electrical stresses that create PD [14].

The characterization of the voltage PWM waves using inverter command strategies has been developed for mitigating the voltage stress in windings [15,16]. The connection cable between the inverter and the motor has also a major role [17–19]. These fast phenomena have been studied with wave propagation theory or equivalent circuits [20–24], considering the voltage fast fronted pulses of the inverter. The coil design can be improved for getting a better voltage distribution between turns [25–28].

This literature review shows that PWM inverters have a major influence on the drive EMC and the motor life expectancy. However, the influence of the grounding system of the 3-phase grid that feeds the whole drive has also an influence on the voltage stress endured by motor windings. This paper considers a standard converter associated with an induction motor with a Y-coupling and the ground connections required by standards. Measurements made on such a drive show large voltage spikes between the Neutral point (N) and the motor frame connected to the Ground wire (G) that may influence the motor winding life expectancy. After presenting the experimental results, this paper proposes an analysis of the grid earthing system on the voltage spikes endured by the motor windings. The interpretation is made with equivalent circuits built considering several simplifications based on the observation of experimental curves. Parameters are determined by specific measurements made on another machine of the same reference insulated from the grounded frame of the testing bench. The equivalent circuits are used with a SPICE simulator in time-domain, following the usual

approach of the scientific community working on the insulation of inverter fed machines and by the corresponding standards. The results are presented in a time window adapted to the motor general behavior. The case on several grid grounding systems is compared. A specific solution is proposed for the most unfavorable cases.

2 Experimental approach with an industrial drive

Figure 1 shows a standard AC machine PWM drive. A 4-wire cable (3 phases + ground wire) connects the converter to the motor; the cable length is 2 m. The standard 400 V/50 Hz AC grid feeds the converter. The specific ground wire is connected to the metallic frames of all the devices for protecting people when an insulation failure occurs. The experimental standard 4-pole 4 kW induction motor has a Y coupling with a non-connected neutral point (N). Measurements were made on an industrial drive situated in a room a more or less 120 m from the grid distribution transformer.

Voltages were measured in the motor connection box between two phases (Ph), a phase and the neutral point (N) and finally between the neutral point and the grounded motor frame (G). Measurements were performed simultaneously by a 4-channel fast oscilloscope and three broadband voltage differential probes. The synchronization was made using the 4th channel connected to the motor with a current probe. The PWM switching frequency is 6 kHz. The industrial converter is made of a rectifier and filtering capacitance that imposes the DC internal bus voltage E_B that feeds the PWM inverter. Figure 2 shows the phase-to-phase voltage. This voltage is made of many voltage pulses with three levels $+E_B$, 0 and $-E_B$. In this figure, the DC bus value is $E_B = 580$ V, which corresponds to a grid slightly over 400 V. The Ph-to-Ph voltages of the other phases are similar but shifted by 6.6 ms. Measurements were made when the motor was at its full speed (1,500 rpm). With

Figure 1: Motor drive circuit with standard ground connections.

Figure 2: PhA-to-PhB voltage on a whole motor period.

this industrial drive, a wide pulse exists in the middle of the positive and negative half period; for lower motor speeds, the wide pulses disappear; the PWM pattern becomes more classical.

Figure 3 shows the Ph-to-N voltage on a whole motor period (20 ms). This figure also shows the theoretical 4 levels $\frac{2}{3}E_B$, $\frac{1}{3}E_B$, $-\frac{1}{3}E_B$, $-\frac{2}{3}E_B$ (386, 193, -193, -386 V) and superimposed large voltage spikes.

For getting a better understanding of these fast phenomena, the voltage between the neutral point and the motor frame was measured. Figure 4 shows this voltage for a large time-window of 20 ms.

Figures 3 and 4 show that many voltage spikes appear on the Ph-to-N voltage. The general shape is complex because the spikes result of the fast-fronted pulses applied to the three phases with a strong coupling inside the machine: the Ph-to-N pulse magnitudes are not identical because several transient states are

Figure 3: Ph1-to-N voltage on a whole motor period.

Figure 4: N-to-G voltage on a large time scale.

superimposed and form a more complex voltage. For estimating the voltage stress corresponding to these spikes, the analysis must be made on a whole period for considering the combination of PWM pulses edges.

Let us remind that, for a standard motor winding, the slot insulation is made with quite thick polymer sheets (i.e. 250 μm). Conversely, the turn-to-turn insulation is made by the thin polymer layer of the enameled wire (30–40 μm depending on the grade and the wire diameter) [29]. For a standard random winding, the probability to have adjacencies between the first turn of a coil and the last one cannot be neglected. For the 3-phase 36 slots experimental machine, made with a 4-pole single layer winding, each phase is made of six 34-turn coils connected in series. For such a random coil, the probability to have the first turn adjacent to the last one inside a slot can be estimated to 25% [30]. Consequently, the thin layers of the enameled wire must withstand the Ph-to-N voltage spikes of a Y-connected motor. The Ph-to-Ph voltage stress exists only in few points, in the end-winding connections, between coils. Additional polymer sheets, similar to the slot insulation ones, are placed between coils in the machine end-windings for solving this insulation problem.

For interpreting the measurements made on a full period, a zoom on a short time window is presented in Figure 5. This short time window is chosen between 2.1 and 2.3 ms, where the global shape is simpler because the voltage between phases A and B remains constant. This figure also shows that the Ph-to-N spike shape has similitudes with the N-to-G one. The natural period of the phenomena can be estimated to $T_n = 18 \mu\text{s}$, which corresponds to a natural frequency of 56 kHz. Figure 5 also shows the relation between the PN-to-N transient voltage and the N-to-G one.

Figure 5: Zoom on the voltages applied to the main parts of the EIS.

3 Analysis with a specific equivalent circuit

3.1 Equivalent circuit structure and hypothesis

The voltage stress analysis is made with an equivalent circuit that considers all the connections of the whole drive. The standard 50/60 Hz grid has its own earthing system, which imposes a ground wire connected to all the metallic frames accessible by users to the Earth's conductive surface [31–33]. For widespread cases, the

neutral point of the grid transformer is connected to a specific earth terminal and the grid ground wires to other earth terminals. Differential circuit breakers provide the protection of users when insulation faults occur.

Figure 6 shows the general circuit of the whole drive assuming an unsaturated induction machine. The voltage pulses are created by the IGBTs legs that make intermittent connections of the motor phases to the + or the – of the DC bus depending on the PWM pattern. The DC bus capacitance provides constant voltage. Each phase-to-phase voltage pulses has a constant magnitude because of the high value of the DC bus capacitance. The gate command of the two IGBTs of an inverter leg is made with a deadtime between the OFF and the ON command for avoiding any short-circuit of the DC bus during simultaneous commands. Despite this deadtime, the free-wheel diode offers a path to the phase current. This deadtime must be considered for studying the EMC of the inverter and the accuracy of the actual pulse width when compared with the command one. Considering the diodes, the three outputs of the inverter are always connected to the + or – pole of the DC bus. Consequently, the deadtimes do not significantly change the shape of the voltage pulse imposed on the input of the cable used to connect the motor.

The phase-to-phase voltages can take only three values $+E_B$, $-E_B$, or 0, depending on the IGBT states as it can be seen on the experimental curves in Figure 2. The neutral point of the machine (N) is not connected anywhere; the voltage between this point and the motor

Figure 6: Whole drive connected to the AC grid with its earthing system. The ground wire offers a path to the common-mode current resulting from the insulated gate bipolar transistor (IGBT) switchings and the complex coupling in the motor. The common-mode current flows through to the grid earth terminals and the phase wires of the grid cable.

Figure 7: DC bus feeding circuit of the industrial converter connected to the AC grid with a 4-wire standard cable.

frame connected to the ground (V_{NG}) depends on the electrical environment of the whole drive:

- the common-mode capacitance existing between the winding copper wire and the motor frame;
- the capacitances between the IGBT chips and the inverter heatsink, which is also connected to the ground wire;
- the HF equivalent circuit of the machine windings;
- the HF equivalent circuit of the connections, including the grounding system;
- the fast-fronted imposed by the IGBT legs to the phase-to-phase voltage (differential mode).

A global equivalent circuit is considered for studying the voltage stresses in the motor windings at the time scale of the oscillations observed on the Ph-to-N and N-to-G voltages. The whole drive acts as a perturbation source connected to the 4-conductor grid cable. The common-mode currents mainly due to the capacitances exist between the motor windings and its frame connected to the ground wire of the cables. The common-mode current loop is schematized in Figure 6 in green. This current comes from the voltage pulses imposed between phases A, B, and C by the inverter and the complex couplings between differential and common modes. Therefore, the ground connection circuit of the grid must be considered because it is a major part of the common-mode current loop.

Figure 7 shows the details of the inverter DC bus feeding system. The grid transformer is represented by 3 voltage sources $e_1(t)$, $e_2(t)$, and $e_3(t)$, which form a perfect 3-phase balanced sine system ($e_1(t) + e_2(t) + e_3(t) = 0$ at any time) and the grid transformer leakage inductance λ . The neutral point of the grid transformer is

connected to an earth terminal G_T . The point G_G represents the general grounding system of the grid, which is very often another ground terminal. The common-mode current flows through the earth between the two earth terminals and in two-phase wires of the grid cable because two diodes of the PD3 rectifier are at the ON state at any time.

The high value of the filtering capacitance C_F creates a short-circuit for the high frequency (HF) differential mode currents coming from the inverter; the voltage E_B can be supposed constant. The equivalent circuit shown in Figure 8 is obtained by splitting the DC source E_B in two equal parts for creating a middle point O . The inverter parasitic common-mode capacitance C_I represents the capacitances between the IGBT chips

Figure 8: Equivalent circuit of the DC bus connected to the grid.

Figure 9: Equivalent circuit of the PWM voltage source of the inverter fed by the industrial grid.

and the heatsink. The equivalent impedance Z_{OGI} , between the middle point O and the inverter frame G_I , depends on the equivalent circuit of the feeding cable and the earth resistance R_G defined between the two earth terminals G_G and G_T . The IGBT leg common-mode capacitance of an IGBT leg is measured with the impedance analyzer connected between the heatsink and the three screws of the module connected together. The result is 85 pF per IGBT module; therefore, $C_I = 255$ pF.

The three inverter legs can be modeled by the 3 voltage sources v_{AO} , v_{BO} , and v_{CO} presented in Figure 9. Each source imposes the voltage pulse defined by the PWM pattern presented in Figure 10 drawn for a ratio of 96 between the PWM switching frequency and the motor

Figure 10: Elaboration of the PWM command of the inverter.

one (switching frequency of 4.8 kHz). When the command signal of the leg X ($X = A, B$, or C) is “1,” the upper IGBT is ON; the lower one is OFF; $v_{XO} = +E_B/2$. When the command is “0” $v_{XO} = -E_B/2$. At a large timescale, the three voltage sources v_{AO} , v_{BO} , and v_{CO} are made of many pulses defined by the PWM pattern. They are used as excitation sources for the equivalent circuit that simulates with SPICE, using the “Piece-Wise Linear” function. Each pulse is defined by four points (low value, high value, rise time, and fall time). A Matlab script has been developed for writing automatically the spice netlist.

Figure 11 shows the equivalent circuit of the motor, which is supposed to operate in linear conditions; R_p , L_s , R_s , and C_s represent the HF behavior of the phase windings; they are associated with the phase resistance and inductance R and L . The parameters are determined with the experimental data. The phase resistance R is measured in DC ($R = 0.35 \Omega$). The other parameters are estimated from the impedance spectrum of the phase windings presented in Figure 12. The impedance spectrum is measured with a HP4294 impedance analyzer connected to another machine, which has the same reference than the motor of the testing bench. The second motor is placed on an insulated plate because the impedance analyzer cannot operate in differential mode and the motor frame cannot be connected to ground. The impedance analyzer is used with short wires when the motor coupling connections are removed. Figure 13 can be helpful for interpreting this impedance spectrum. The 3-phase machine is made of six 34-turn

Figure 11: Equivalent circuit of the motor winding.

Figure 12: Impedance spectrums of the motor phases of an identical motor insulated from ground and impedance computed with the RLC equivalent circuit.

coils per phase placed in the 36 stator slots. Each coil is made with a class 2 enameled wire and placed in two stator slots previously protected by polymer sheets (in white). This protection is mainly aimed at protecting the enameled wire from the remaining burrs of the magnetic core during the automatic winding process; it also reinforces the slot insulation. The thickness of this layer (250 μm) is large when compared with the insulation layer of the class 2 enameled wire of this diameter (40 μm). This picture shows that the turn-to-turn capacitance between adjacent turns in the slots and in the end-windings has a larger influence on the HF behavior of a coil than the copper-iron capacitance of the wires in contact with the slot insulation thicker layer.

The parameters R_p , L_s , R_s , C_s , and L are computed from the specific points highlighted in the experimental impedance spectrum. The phase inductance L is calculated from the low-frequency point; R_p is obtained from

Figure 13: Picture of a random winding of the experimental machine at the end of stator slots.

the parallel resonance point, this resistance includes the damping effect due to iron losses at the parallel resonance frequency. L_s , R_s , and C_s are obtained from the main series resonance point by identification. Results are $R_p = 2.9 \text{ k}\Omega$, $L_s = 2.8 \text{ }\mu\text{H}$, $R_s = 12 \text{ }\Omega$, $C_s = 720 \text{ pF}$, and $L = 3.2 \text{ mH}$. Calculation details are presented in [27]. This figure also shows an inductive behavior up to 100 kHz. Let us keep in mind that these parameters are obtained by identification; they do not represent directly the physical elements on the six coils of a phase but only the global behavior of a phase in a frequency range limited to the main series resonance.

The mutual inductance between two phases $M = -1.5 \text{ mH}$ is measured at 50 Hz using a standard method. Let us remind that a perfect coupling between two identical stator coils of inductance L shifted by an electrical angle α is $L \cos(\alpha)$, which is $-0.5 L$ for a perfect 3-phase motor with coils shifted by $\alpha = \frac{2\pi}{3}$ and $\frac{4\pi}{3}$. The mutual inductances are implemented in the spice netlist using the coupling factor between the two inductances defined by (1).

$$k_{XY} = \frac{M_{XY}}{\sqrt{L_X L_Y}} \quad (1)$$

The electromotive force of each phase $e_X(t)$ ($X = A, B$ or C) are sine functions of time at the fundamental frequency (50 Hz); they correspond to the voltages induced by the rotating field supposed to have a sine spatial distribution along the machine airgap. The magnitudes and phase lag depend on the motor operating point they are computed with the complex equation (2) where $\underline{V}_X$ is the fundamental voltage imposed by the inverter and $\underline{I}_X$ is the corresponding phase current. $\mathcal{L} = L - M$ is the three-phase inductance of the machine. The magnitude and the phase lag of the current is imposed by the motor operating point. The tests were made at no load ($I = 7 \text{ A}_{\text{RMS}} \cos \varphi_0 = 0.2$). This relation supposes a classical PWM command without any zero-sequence component at 50 Hz. Equation (3) is implemented in the SPICE netlist for phase A; the expressions are similar for phases B and C but with an additional phase lag of $-2\pi/3$ and $-4\pi/3$.

$$\underline{E}_X = \underline{V}_X - (R + j\omega\mathcal{L}) \underline{I}_X \quad (2)$$

$$e_A(t) = |E_A| \sqrt{2} \sin(2\pi f t - \arg(E_A)) \quad (3)$$

The winding common-mode capacitance of each phase $C_{\text{CM}} = 22 \text{ nF}$ is measured connecting the impedance analyzer between a phase and the frame of the second motor, posed on an insulated plate when the coupling connections are removed.

Figure 15: Transient state of the motor currents.

Figure 16: Ph-to-N and N-to-G voltages simulated in a short time window where $v_{A0} = C^{te} = +\frac{E_B}{2}$.

Figure 17: Ideal Ph-to-N voltage obtained without any common-mode capacitances with the same grounding connections.

voltage is a perfect 5-level PWM waveform without any spike. Therefore, the slot capacitances existing between the motor frame have a major importance for estimating the voltage stress endures by the motor coils and their turn-to-turn insulation.

Table 1 presents a synthesis of simulations made for several combinations of the grid cable lengths and the ground resistance. These values must be compared with the ideal case (Figure 17), where the maximum Ph-to-N voltage is 386 V. The first case corresponds to the case of an industrial grid with a ground wire connected to the transformer neutral point. This case is described in the IEC 60364 standard, which is used for ensuring user safety without any differential breaker when a direct contact occurs between a phase and a grounded frame. This grid architecture corresponds to the worst case because the damping factor of the oscillations excited by the PWM pulse fronts is very low. The most favorable case is obtained when the ground resistance has the highest possible value defined by the IEC 60364 standard. A better solution is possible for the insulated neutral point grid configuration, but this case is very rare.

A possible solution consists of adding a wire in the cable between the motor neutral point N and the DC bus middle point O. This middle point is easy to materialize by splitting the DC bus filtering capacitance C_F into two equal parts connected in series. Additional resistances are required for stabilizing the DC value of the middle point potential because a slow drift that depends on capacitance leakage currents may occur. Figure 18 shows the corresponding simulation results. This figure also shows a strong reduction of the voltage pulses magnitude applied to the motor winding.

With such a reduction, the peak voltage stress endured by a motor phase is much under the value of the PDIV measured on a twisted pair, which is more or less $800 V_{RMS}$ ($1,130 V_{Peak}$) for a standard class 2 enameled wire [10]. Even in the most unfavorable case, where the first turn of the first coil is adjacent to the last one, the motor can be a guarantee as PD free, considering the addition of the shorter spikes due to the differential mode fast transient widely studied in many publications [17–19].

This solution is very effective from the insulation point of view, but it has a drawback considering the zero-sequence current that may flow in the additional wire of the connection cable. This problem can be overcome using a specific PWM pattern that can control the zero-sequence voltage of the inverter [34]. Standard PWM industrial drive is designed for a 3-wire connection of the motor, without any neutral wire, which

Table 1: Maximum voltage spike of the Ph-to-N voltage

Grid cable length (m)	$R_G = 0.1 \, \Omega$ (V)	$R_G = 1 \, \Omega$ (V)	$R_G = 5 \, \Omega$ (V)	$R_G = 20 \, \Omega$ (V)	$R_G = 100 \, \Omega$ (V)
50	745	740	720	630	570
150	920	725	610	550	525
500	980	770	590	520	470

Figure 18: Ph-to-N simulated voltage for an additional O–N connection.

corresponds to a quasi-infinite zero-sequence impedance. The proposed additional wire between the motor Neutral and the DC bus middle point requires a specific design of the PWM pattern that can control the zero-sequence current flowing in a low impedance. However, solutions exist and are described in the scientific literature [35,36]. They are more complex and require a higher switching frequency.

5 Conclusion

The safety of people using electric drives requires the connection of every motor frame to the grid grounding system and differential breakers in the distribution grid. However, the slot capacitances existing between the motor winding and the stator frame create a parasitic coupling and additional voltage spikes. Experimental measurements with a fast oscilloscope associated with broadband differential probes show the large additional spikes on the Ph-to-N voltage linked to the N-to-G ones. The temporal shape of these spikes shows that they are caused by transient oscillations excited by the fast-fronted voltage pulses of the PWM inverter. The natural frequency of these transient states is much lower than

the well-known ones due to the propagation effects of the fast-fronted voltages in the connection cable and in the motor windings. The two phenomena are superimposed in the machine winding. Large magnitude short voltage spikes may cause PDs and earlier aging of the motor turn-to-turn insulation.

This paper shows the large influence of the grid grounding configuration and the distance between the drive and the grid transformer. The resistance of the earth terminals also has a large importance. Therefore, the life expectancy of the AC motor of a drive changes a lot according to its location in the AC grid. The worst cases correspond to long grid cables associated with very efficient earth terminals. For such cases, the simpler solution is to use a specific motor made with a grade 3 enameled wire rather than a standard machine.

This paper also proposes a solution that consists of connecting the middle point of the converter DC bus with the machine neutral point. This solution is compatible with the general safety rules, but it requires another design of the PWM inverter that can control the zero-sequence current that flows in the additional wire.

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