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Stress Due to Transient Voltage Distribution in the Windings of Random Wound Motors Fed by PWM Converters

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Abstract: The presence of semiconductor switches like IGBTs and MOSFETs in pulse width modulated drives has increased the occurrence of steep fronted voltage surges (<500ns) in motors used as adjustable speed drives. Technical literature published confirms this. Most of the literature is confined to study on form wound windings and only portion of the literature deals with random wound coils. However, the combined effect of pulse duration and rise times, on intercoil and interturn voltage distribution has not received enough attention. Current technology uses IGBT drives upto around 50 kHz and MOSFET drives above 50 kHz. This study explores the combined effect on intercoil and interturn voltage distribution due to pulse duration and steepness with particular reference to random wound machines through modelling and simulation techniques.

Key words: Adjustable speed drives, pulse rise time, pulse duration, intercoil voltage, interturn voltage

INTRODUCTION

Induction motors have been the most preferred drives in the 20th century due to their robustness and easy availability. These motors are available from medium voltages to low voltages. While, medium voltage motors use form wound coils, low voltage motors use either form wound or random wound coils. Interest in inter-coil and inter-turn voltage distribution started when medium voltage motors controlled by vacuum switches started failing due to surges generated by prestrikes and restrikes in the switch. Subsequently this problem was sorted out using better electrode materials.

Emphasis on energy conversion and lower cost resulted in the increased use of Pulse Width Modulated (PWM) drives for low voltage motors. The technology for PWM modules used thyristers in 1980s superseded by GTOs. Bipolar transistors (BJT) increased the efficiency of such devices with increased switching speeds. Since, all above switches had turn-on times of a few microseconds, problem with the devices was thermal consideration due to losses. Voltage controlled IGBTs made their entry in 1990s and provided low loss devices at reasonably at high switching frequencies. Unfortunately, inverters incorporating IGBTs gave rise to steep fronted surges (typically<500ns). Such steep-fronted surges cause a highly non-linear inter-coil and inter-turn voltage distributions. This has been widely studied and published. Coupled with high incidence of such surges (due to high switching frequencies) and manufacturing errors, motor insulation (primarily inter-turn insulation) became more prone for premature failures.

While, it is relatively easier to predict surge distribution and protect form wound coils against surges; the same cannot be said for random wound coils. Only limited work has been reported on random wound machines. In published literature, prominence has been given to surge steepness and connecting cable length as factors that can cause a higher voltage-stress on the line end coil turn insulation.

Steep-fronted surges due to vacuum switches and inverters and their effect on motor insulation have been the subject of interest from 1930s onwards (Boehne, 1930; Gupta *et al*., 1986a; Murano *et al*., 1994a; Rhudy *et al*., 1986; Mclaren and Abdel-Rahmanm, 1988). Different models of machine windings have been considered by Richard and Frank (1997) and Wright *et al*. (1983a). However, it is only in 1990s after the advent of IGBTs, increased numbers of published literature started appearing for low voltage random wound motors (Melfi *et al*., 1997; Sidney and Sung, 1997). Here again there are varied opinions as to mode of winding insulation failure (Bell and Sung, 1997; Lowery and Petro, 1994; Stone *et al*., 1992). But there is no difference of opinion on such failures occurring due to the combined effect of voltage surges and quality problems in manufacturing (Bell and Sung, 1997).

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TRANSIENT VOLTAGE DISTRIBUTION IN RANDOM- WOUND MACHINE

Multiconductor Transmission Line Concept Simulation Using MULTISIM.

Winding model: For a surge impinging on the motor winding, the winding presents itself like transmission line. Most of the motors have very low winding resistance, exhibiting essentially a low loss transmission line. Inter-turn capacitive coupling to earth overrides any mutual inductive couplings. The core might be represented as a magnetic member with a very low susceptance (Oyegoke, 1997). The stator core would provide the return path for the surge current since the active conductors are insulated. Further the stator winding are either connected in delta or in star with insulated neutral. Hence for most part of the winding, the surge would travel without attenuation and also get reflected at coil junction at stator and overhang portions of a coil. The deviation from uniform theoretical transmission line model values due to actual construction can aggravate the situation. Such a deviation is very pronounced in stator windings using random windings (Bell and Sung, 1997). As far as the inter-turn coupling is concerned, for the high speeds of switching of IGBTs (typically <500ns), the inter-turn capacitive coupling can be safely assumed to be much greater than inter-turn mutual inductive coupling.

With this background information, a typical 2.2 kw (3HP), 3-phase mush-wound induction motor was taken up for representing the winding model. The design parameters that were used to model the winding are given:

Machine: 2.2 kW, 400 V, 50 Hz, 3-Φ, 4-pole, squirrel cage, Δ-connected induction motor.

Stator winding details: Single layer mush winding; 24 slots; 416 turns/phase; slots/pole/phase; coil span of 5 slots; 4 coils/phase; 104 conductors per slot; conductor: bare diameter of 0.95 mm, insulated diameter of 1.041 mm and area of 0.709 mm^2; length of mean turn = 0.68 m; phase winding resistance at 75°C = 8.37Ω (ρ= 0.021 μΩ-m mm^{-2} at 20°C).

Based on above data the machine winding with winding per phase was modelled as shown in Fig. 1. The winding consisted of four coils in series. Windings of the next phases have been accordingly connected to show the effect of reflected waves at the remote end of the winding due to Δ and Y connections.

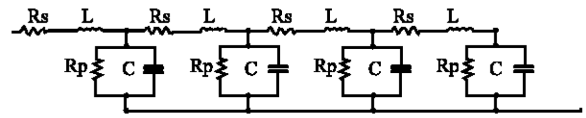

Fig. 1: The machine winding with winding per phase

For the physical parameters of the motor winding, calculations yielded following coil parameters: Coil Resistance: Rs = 2 Ω; Inductance: L = 85 μH; Earth Capacitance: C = 100 pF: Winding Insulation Resistance: Rp = 1 GΩ.

Line-end coil model to study the inter-turn winding has been considered as a multi-conductor transmission line. For the inter-coil voltage distribution, R,L,C values of individual coils have been considered. However, for the study of inter-turn voltages the first three turns of the line end coil have been considered. This is based on the findings that the initial voltage distribution due to fast fronted surges in the line end coil is mostly decided by the first few turns (Oyegoke, 1997). Also, the variance of earth capacitance in the overhang and slot regions have been considered for calculating the interturn voltages.

Inter-coil voltage distribution

Delta connection: For delta connected stator, the R-phase was impulsed. The other two phases were connected in series and connected across the R- phase. The other end was grounded (Fig. 2). Effect of polarity of positive and negative pulses on the interturn voltage distribution was negligible. Hence, the input was applied as a single square pulse and repetitive pulses of positive polarity with 50% duty cycle. The input peak voltage was 50 V and rise times used were 50 and 200 ns (Table 1).

Star connection: For the star connection, the impulsed R-phase winding was connected in series to the parallel combination of other 2 phase windings. Line end winding voltage tapping were as in earlier circuit shown in Fig. 2. The input peak voltage was 50 V and rise times used were 50 and 200 ns (Table 2).

Inter-turn voltage distribution: Based on inter-coil voltage studies, it became apparent that the initial voltage distribution was more relevant to line end coil. The line end coil model used was to represent the first three turns of the coil. The effect of surrounding conductors in the same slot that act as shielding elements for the interaction of the flux generated by other conductors in the same slot has been considered (Tavner and Jackson, 1988). Also since the capacitance values are unaffected by the high frequency components, static capacitance value has been considered.

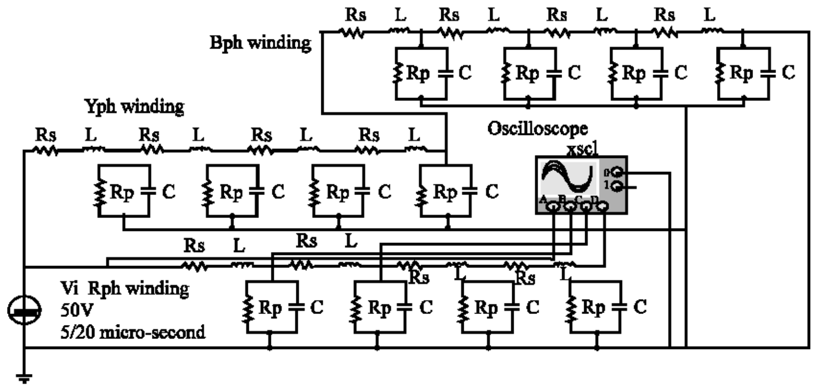

Fig. 2: Inter coil voltage distribution

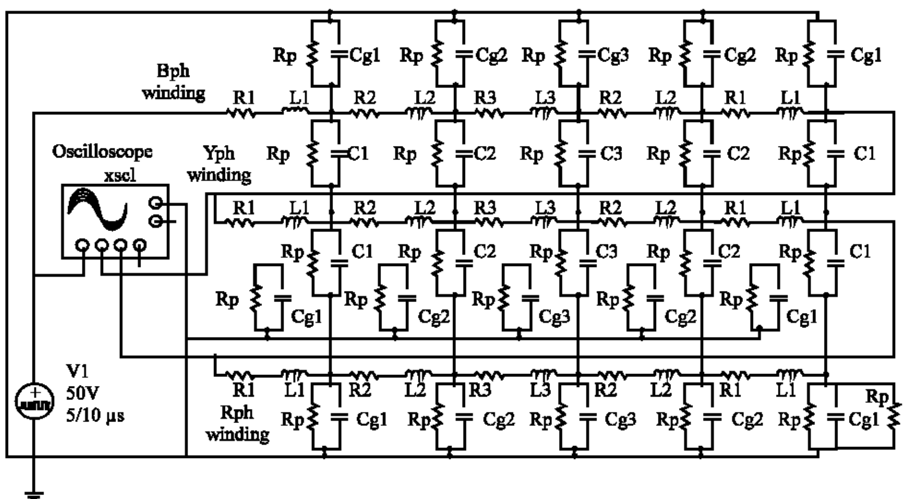

Fig. 3: Inter turn voltage distribution

The inter-turn model assumed that in the slot region, 6 conductors placed on the periphery of the impulsed conductors can totally shield the conductor from all other conductors and from the core. Capacitance of the conductor subtended on the encircling conductors was used for slot region and a dielectric permittivity of 2.5 was chosen. However, due to the loose arrangement of the turns in the overhang where the effect of air overrides the enamel insulation, air permittivity was used. All the unit distance values were converted into real values, using the overhang and slot lengths of the conductors. The coil was divided into cable side of the overhang, slot region and the overhang in the rear of the machines. The line end coil model is shown in Fig. 3.

Values of interturn parameters:

- Overhang parameters at line end side: R1 = 6.4 mΩ; L1 = 0.3 µH; C1 = 30pF; Cg_1 = 20pF.
- Overhang parameters at rear side: R3 = 12.7 mΩ; L3 = 0.6 µH; C3 = 60pF; Cg_3 = 40pF.
- Slot portion parameters: R2 = 3.7 mΩ; L2 = 0.2 µH; C2 = 50pF; Cg_2 = 100pF.
- Insulation resistance Rp = 1G Ω; Earth Capacitance denoted by Cgk, k = 1, 2, 3.

Table 1: Details of signal square pulse

Pulse details	Line-end coil voltage (%)	Max. earth voltage across a coil in the R-phase (%)
200 ns		
2.5/5 µs	50	195
5/10 µs	50	250
10/20 µs	50	180
Single pulse, 10/1000 µs	78	250
50 ns		
2.5/5 µs	95	1200 (Oscillogram 2)
5/10 µs	95	500
5/20 µs	95	290
10/20 µs	95	150
Single pulse, 10/1000 µs	92	250

A great part of the line end coil voltage was dropped in the first few turns of the coil and any increase in the

Table 2: Star connection implication

Pulse details	Line end coil voltage (%)	Max. earth voltage across a coil in R- phase (%)
200 ns		
2.5/5 μs	50	180
5/10 μs	50	200
10/20 μs	50	290
5/1000 μs	50	140
50 ns		
2.5/5 μs	92	150
5/10 μs	92	300
10/20 μs	92	300
5/1000 μs	92	150

Table 3: Inter turn voltage due to reflections

Pulse details		Voltage across impulsed turn	Max. voltage turn no.3
200 ns			
	5/10 μs	83.4% (201ns)	154% at 8 μs
	10/20 μs	83.4% (201ns)	360% at 31 μs
	2.5/5 μs	83.4% (201ns)	154% at 11 μs
	10/1000 μs	83.4% (207ns)	210% at 11.3 μs
50/50 ns			
	2.5/5 μs	93.6% (96ns)	150% at 11 μs
	5/10 μs	93.4 % (95ns)	130% at 7.5 μs
	10/20 μs	93.5% (96ns)	360% at 31 μs
	50/100 μs	93.5% (96.5ns)	210% at 11 μs
	10/1000 μs	93.4% (96 ns)	210% at 11.1 μs
50/200 ns	10/1000 μs	93.6% (96ns)	210% at 11.1 μs

inter-turn voltage due to reflections was devoid of high frequency components of applied voltage. The end turn was terminated using surge impedance of proceeding turn (Table 3).

RESULTS AND DISCUSSION

Inter-coil voltage distribution: Pulse with rise time of 200 ns caused a voltage drop of 50% across line end coil and a rise time of 50 ns caused 95% voltage drop. These results are generally in line with published literature. However, referring to oscillograms much higher voltages of value between 1.5-5.0 p.u. are found to occur towards the neutral end of impulsed phase winding. Such voltages are possible due to the fact that the winding acts as a low loss under damped line [Rph = 8.63 Ω whereas the surge impedance is 114 Ω] and there are multiple reflections inside the winding. Further, the oscillograms indicate that the frequency of application and duration of the pulse also affect the voltage magnitudes. The type of stator winding (either star or delta) also modifies the inter-coil voltage stresses. This is amply clear from the oscillograms shown below.

Immediate inter-coil voltage stress is high, typically 90% of applied voltage for a 50 ns pulse (Oscillogram 1, Fig. 4). But the voltage stress duration is around 50 ns. However, for a 20 kHz frequency, subsequent voltages are much higher (upto 10 p.u.) and the voltage has a rise time

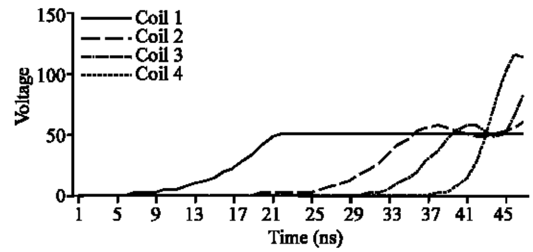

Fig. 4: Oscillogram 1

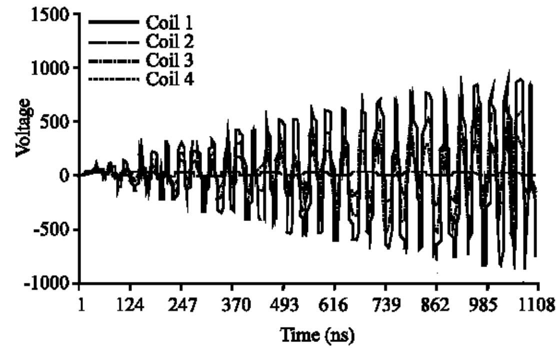

Fig. 5: Oscillogram 2

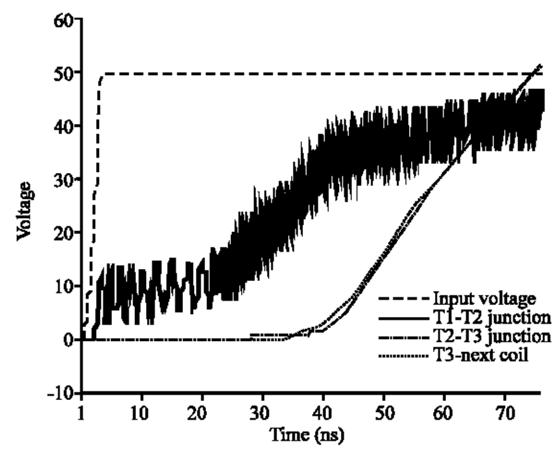

Fig. 6: Oscillogram 3

of around 500 ns (Oscillogram 2, Fig. 5). These stresses repeat according to recurrence of pulses. Also, the stresses are aggravated by the frequency and rise time of the pulses rather than by their duration. (The critical wave length is also a contributor to increased inter-coil stress.) Wave propagation velocity is 88 m/μs and travel time is 3.3 μs for the entire phase winding consisting of 4 coils in series.

Inter-turn voltage study: Maximum inter-turn voltage stresses can reach high magnitudes, several times that of normal working stress. Simulation study gives an inter-turn voltage of 83.4% of applied voltage for a 200 ns

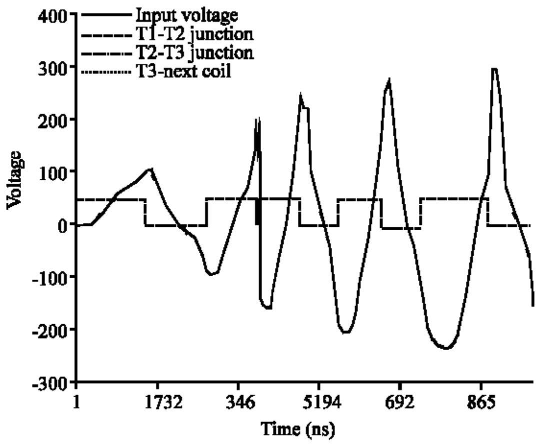

Fig. 7: Oscillogram 4

rise time and 93% for a 50 ns rise time (Oscillogram 3, Fig. 6). This agrees well with published literature, though the stress is on the higher side. This higher stress can be attributed to the specific R, L, C parameters of the motor. Further the turn to ground voltages can reach up to 6 p.u. decided by the rise time and frequency of input (Oscillogram 4, Fig. 7). These stresses can be very damaging particularly in the overhang region when turns of different coils can run alongside each other. A study of oscillograms indicates that pulse duration is a more important factor than rise time for voltage stresses due to reflections.

Decided by a combination of natural frequency of the line end coil and critical wave length, the build up of over voltages along the turns of the line-end coil can reach dangerous values since the coils have very low resistance values.

IGBT and MOSFET switches can generate pulses with very fast rise times. Inter-coil and inter-turn voltages are influenced by these pulses. While published literature elaborate on the effect of pulse rise time, only a few papers talk on the effect of pulse duration. But there are hardly any references that discuss the effect of reflected waves that occur under repetitive pulse environment.

Line-end voltage can reach values of upto 50% of applied pulse for 200 ns rise time and 92% for 50 ns rise time. Based upon the natural frequency of the winding and wave length, reflected voltage waves can reach up to even 5 p.u. along the winding with the rise time of around 500 ns for a delta stator connection near the junction of any 2 phase windings. Such coil to ground voltage can easily get applied across the turn insulation of the coil at the overhang regions or at points where he turns of the next coil cross over. This situation can get aggravated due to the fact that the break-down strength of the insulation gets lower with longer duration and repetitive incidence of the over voltage. Thus, the risk of main insulation failure in the overhang region poses a big threat, if not more, as that of inter-turn failure in the case of random wound stator windings both of mush type and concentric type.

Inter-turn voltage can reach values of 83% for 200 ns rise time and 92% for 50 ns rise time on line-end coil voltage. This would mean around 40% of applied voltage for 200 ns rise time and 80% for 50 ns rise time, would be the inter-turn stress. Since, IGBTs are used below 50 kHz switching frequency range and MOSFETs above 50 kHz range, pulse durations can be from 100 μs to 5 μs with rise-times of less than 500 ns.

CONCLUSION

Voltage across line-end coil can reach up to 50% of incident surge for a 200 ns rise time surge and up to 92% for a surge with 50 ns rise time.

The types of stator winding (either delta or star) modify the overvoltage magnitudes; with delta connection showing a higher coil-to-earth stress.
Inter-turn voltages can reach up to 80% of applied voltage for surges with 50 ns rise time.

Pulse rise times play a major role in the initial voltage distribution and pulse durations determine the final voltage distributions caused by internal winding surge reflections.

Coil to earth voltages can reach dangerous magnitudes towards the winding end due to reflected waves inside the stator. These overvoltages can easily become inter-turn voltages in the overhang region, causing premature insulation failures.

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