Transient Distribution of Voltages in Induction Machine Stator Windings Resulting from Switching of Power Electronics

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Abstract— The fields of application of adjustable speed drives fed by voltage source inverters is constantly increasing. For better exploitation of the system's capabilities all drive components are more and more operated near and even above their rated values. This leads to more strains for the drive. However, at the same time the demands for reliability are also increasing. To reach this requirement different strategies like fault tolerant design, fault detection and condition monitoring can be implemented. However, to implement such strategies a deep understanding of the effects that lead to problems or faults in the drive system is necessary. The fast switching of modern voltage source inverters leads to transient overvoltage stressing the machine's insulation system. A short literature study presenting the characteristic of and the parameters influencing the non-linear voltage distribution in the stator winding of inverter-fed machines will be presented. Furthermore the findings will be compared with experimental results on an induction machine with tapped windings.

Keywords— AC motors, Electrical Insulation, Induction motors, Power system transients, Pulse inverters, Pulse width modulation inverters, Surges, Voltage measurement

I. INTRODUCTION

The need for adjustable speed drives in many different sectors from industrial plants to transportation systems leads to an increased demand for inverter-fed machines. Although generally highly reliable the requirement for continuous faultless operation in many applications like safety-critical devices and traction drives is leading to growing awareness of this topic and the need for fault-tolerant operation, condition monitoring and fault detection methods. According to [1] and [2] stator-related faults account for about 35% of all machine breakdowns. Different causes can lead to a degradation of the winding insulation. Among these is thermal, electrical, environmental and mechanical stress [3]. In case of inverter-fed operation the high rise times of the voltage pulses applied by the voltage source inverter (VSI) in combination with the mismatch of cable and machine impedance lead to reflection of the pulse at the machine terminal and thus to transient overvoltage. This overvoltage additionally stresses the machine's winding insulation. This effect is not discoverable in Markus A. Vogelsberger Drives Development Center, PPC Bombardier Transportation Austria GmbH Vienna, Austria markus.vogelsberger@at.transport.bombardier.com

mains-fed operation. Many investigations have been carried out to understand the effects causing this transient overvoltage and to determine its parameters. However, not all aspects could be covered so far. This paper shall give an overview of the different findings obtained in published investigations and compare these to measurements carried out on an industrial induction machine especially adapted with tapped windings.

II. CHARACTERISTICS OF TRANSIENT OVERVOLTAGE

As mentioned in the introduction the mismatch of cable and machine impedance and the high rates of voltage rise of modern switching devices like IGBT lead to transient overvoltage at the beginning of the applied pulse voltage. This phenomenon can be described with traveling wave theory [4]. In comparison to the cable impedance the machine impedance is by far bigger. Thus, the reflection coefficient is close to +1 and the applied voltage pulse is theoretically fully reflected [4]. For high frequencies the machine acts like an open circuit. The reflection results in an oscillating overvoltage with decaying amplitude. The cable length defines the propagation time of the applied voltage pulse and thus, influences the characteristic of the reflection. The reflection occurs if the propagation time is longer than the rise time of the voltage pulse applied by the inverter [5].

The peak voltage can reach up to twice and for fast switching even four times the DC-link voltage. The oscillation frequency is in the range of tens kHz to tens MHz [6].

III. PARAMETERS INFLUENCING THE TRANSIENT OVERVOLTAGE

Many characteristics of the drive system influence the shape of the occurring overvoltage due to inverter switching. In [4] rise time and amplitude of the applied voltage pulse and cable length are described as important parameters influencing the transient overvoltage. According to [7] the cable's characteristic parameters also determine the shape of the transient overvoltage as the oscillation frequency depends on the propagation time of the voltage pulse in the cable. The

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propagation time increases with increasing cable length and thus, leads to decreasing oscillation frequency [4],[6],[8]. With increasing cable length the overvoltage increases too [6]. Overvoltage also occurs for short cable length if the anti resonance frequency of the cable and the machine are close [8]. Furthermore decreasing rise time leads to an increase of transient overvoltage (peak voltage) [6].

The operating frequency and load condition only negligibly influence the transient overvoltage. However, in case of high switching frequency the stress on the winding insulation is increased due to the more frequent occurrence of transient overvoltage.

According to [6] and [8] the machine itself influences the oscillation frequency too. The machine's anti resonance frequency defined as the turning point between inductive and capacitive behavior in the frequency spectrum is an important parameter determining the machine's high-frequency properties. It depends on the machine rating and decreases with increasing power rating. The stator-to-frame stray capacitance primarily depending on the first turns of the winding determines the anti resonance frequency that is also influenced by temperature [7],[8].

An increase in the oscillation frequency leads to increased damping due to the increased resistance of the conductors caused by skin effect [4],[6]. As the oscillation frequency also decreases with increasing cable length the damping decreases with increasing cable length.

Two influences can lead to transient overvoltage exceeding twice the DC-link voltage. These are described in [9] and denoted double pulsing and polarity reversal.

Two different characteristics of the occurring overvoltage additionally stress the machine's insulation system – the rate of voltage rise (dv/dt) and the amplitude of the overvoltage. The high voltage that occurs due to the fast inverter switching can lead to immediate damage (breakdown of insulation and resulting short circuit). The high rate of voltage rise on the other hand causes damage after longer operation. [6]

IV. VOLTAGE DISTRIBUTION IN INVERTER-FED DRIVES

The voltage distribution in mains-fed operated machine windings is linear. This is not the case for the voltage distribution in inverter-fed drives [10]. The characteristics of the applied voltage pulse (rise time, magnitude, shape), the machine cables (insulation type and size, shielding, installation layout) and the machine itself (stator resistance, stator inductance and the parasitic capacitances) influence the voltage distribution [11]. For mains-fed operation the inductances connected in series determine the voltage distribution within the windings whereas the high rates of voltage rise lead to uneven voltage distribution for inverter-fed operation. Different investigations show that the highest overvoltage occurs in the first turns of the machine's stator winding [8]. Thus, these turns are subject to the highest stress. The voltage drop across the first turn [12] or the first coil [13] increases with increasing rate of voltage rise and thus, with

decreasing rise time. The voltage drop across the first coil can reach up to 70% of the voltage across the whole phase winding according to [13].

The cable length also influences the voltage distribution. For increasing cable length the occurring peak voltage increases. However, according to [14] the voltage drop across the first turns stays the same. Thus, the voltage drop across the last turns has to increase with increasing cable length.

The arrangement of the wires in the stator slots is important to assess the stress for the winding insulation especially for random-wound machines. As the highest turn-to-ground voltage occurs at the first turn and the lowest at the last, the stress for their insulation is very high if they are adjacent [12].

V. EXPERIMENTAL INVESTIGATIONS OF TRANSIENT VOLTAGE DISTRIBUTION

The measurements are carried out on an industrial 5.5kW, 2-pole, squirrel-cage induction machine with tapped stator windings and an unskewed rotor cage. The stator winding consists of two coil groups per phase that are connected in series. The series connection is available at the machine terminal ('1U2'). Each coil group consists of six coils and each coil of five turns. The first ('AU1'), second ('AU2'), fifth ('AUL'), 28th ('AU*V') and 29th ('AU*L') turn of phase winding U is tapped. In phase winding V the first, second, 28th and 29th turn and in phase winding W only the first and second turn is tapped. Furthermore the star point is available at the machine terminal. Thus, it is possible to measure the voltage between different turns, between turns and star point and between turns and the grounded machine housing to investigate the transient voltage distribution. The voltage pulses are applied by an IGBT-voltage source inverter. The inverter is controlled by a combination of a real-time system programmable under MATLAB/Simulink and a National Instruments FPGA for PWM generation and data processing. The sampling is carried out with external 16bit analog-todigital converters (ADC) with a sampling rate of 40MS/s. The ADCs communicate with the FPGA via data buffers (FIFOs). The DC-link voltage is about 440V.

A. Distribution of Turn-to-Ground Voltage

To determine the distribution the voltage is measured between different taps of the winding and the grounded machine housing. The overshot and oscillation frequency are analyzed.

Furthermore the pulse waveform is changed in the different measurements. Fig. 1 shows the turn-to-ground voltage measured at different taps in phase winding U. The applied change of switching state is from lower short circuit (000) to positive active switching state +U (001). A 15m long cable connects the machine and the VSI. The voltage measured at the beginning of the stator winding (at the machine terminal connection) and at the series connection is denoted '1U1' and '1U2', respectively. The other taps are denoted according to the description above. The decaying, oscillating overvoltage

after the switching instant is clearly visible.



Fig. 1. Turn-to-ground voltage for different taps; switching from lower short circuit (000) to active switching state U (001).

At the end of the first coil group the relative overshot is the highest. The dominant oscillation frequencies do not change during propagation of the voltage pulse into the stator winding. However, at the last turns of the stator coil an additional dominant frequency component is visible. Furthermore, rate of voltage rise (dv/dt) decreases with increasing distance from the machine's terminal connection. The relative overshot and dominant oscillation frequencies (calculated by Fourier transformation) for the measurements depicted in Fig. 1are summarized in Table 1

TABLE 1

RELATIVE OVERSHOT AND DOMINANT OSCILLATION FREQUENCIES FOR TURN-TO-GROUND VOLTAGE MEASURED AT DIFFERENT TAPS OF PHASE WINDING U DURING SWITCHING TRANSITION FROM LOWER SHORT CIRCUIT TO POSITIVE ACTIVE SWITCHING STATE U.

Тар	Relative overshot	Oscillation frequency
1U1	14%	78.13kHz
AU1	15%	78.13kHz
AU2	14%	78.13kHz
AUL	16%	78.13kHz
AU*V	101%	78.13kHz/351.6kHz
AU*L	109%	78.13kHz / 332kHz
1U2	115%	78.13kHz / 351.6kHz

The same measurements are carried out for a change of switching state from positive active (+U; 001) to negative active (-U; 110). This is a switching transition that can be exploited for sensorless control purposes as e.g. described in [15]. These switching transitions are less frequent but could be more severe. The resulting turn-to-ground voltages are depicted in Fig. 2. Again the relative overshot of the turn-toground voltage for the turns more distant from the machines terminal connection are the highest. However, the occurring relative overvoltage for the other turns is increased in comparison to the switching transition shown in Fig. 1. Thus, the stress on the turn-to-ground insulation for this switching transition is higher.

The relative and absolute overshot for the measured voltage distribution of the switching transition between two active switching states are summarized in Table 2.



Fig. 2. Turn-to-ground voltage for different taps; switching from positive active (+U, 001) to negative active switching state (-U, 110).

TABLE 2
RELATIVE AND ABSOLUTE OVERSHOT FOR TURN-TO-GROUND VOLTAGE
MEASURED AT DIFFERENT TAPS OF PHASE WINDING U DURING SWITCHING
TRANSITION FROM POSITIVE ACTIVE TO NEGATIVE ACTIVE SWITCHING STATE
IN PHASE U.

Тар	Relative overshot	Absolute overshot
1U1	38%	-312.3V
AU1	38%	-313V
AU2	35%	-295.3V
AUL	48%	-304.7V
AU*V	141%	-205V
AU*L	148%	-200.9V
1U2	179%	-197.9V

The calculated values of the overshot clearly show the increase of the relative overshot in comparison to the results of the switching transition from lower short circuit to active switching state +U depicted in Fig. 1. The highest absolute value of the peak turn-to-ground voltage occurs at the first turns. However, the relative overshot is again clearly higher for the investigation at the later turns.

TABLE 3 RATE OF VOLTAGE RISE FOR TURN-TO-GROUND VOLTAGE MEASURED AT DIFFERENT TAPS OF PHASE WINDING U DURING SWITCHING TRANSITION FROM LOWER SHORT CIRCUIT TO POSITIVE ACTIVE SWITCHING STATE U.

Тар	Rate of voltage rise
1U1	1.29kV/µs
AU1	1.33kV/µs
AU2	1.30kV/µs
AUL	1.15kV/µs
AU*V	0.37kV/µs
AU*L	0.34kV/µs
1U2	0.34kV/µs

Another important conclusion that can be drawn from the results presented in Fig. 1 and Fig. 2 is that the rate of voltage rise clearly decreases with increasing distance of the investigated turn-to-ground voltage from the phase connections. Thus, the stress for the turn-to-ground insulation due to high rate of voltage rise decreases too. The resulting rate of voltage rise for the switching transition from lower short circuit to positive active switching state in phase U is summarized in Table 3 for the investigated turn-to-ground voltages at the different taps.

B. Distribution of Coil Voltage

A further investigation concerning the voltage distribution across the two coil groups of phase winding U has been carried out. In this investigation a comparison of two different cables used to connect the inverter and the machine is done. The two cables used differ in length. One cable is the one used in the investigation presented in Fig. 1 and Fig. 2. Its length is fifteen meters. This cable will be denoted as cable 'C15m' in the following. The second cable is six meters long and will be denoted as 'C6m'. The voltage across the two coil groups consisting of six coils each and 30 turns per coil group for the application of cable 'C16m' is depicted in Fig. 3. The voltage across coil group 1 is measured between phase connection '1U1' and the series connection '1U2'. The voltage across coil group 2, on the other side, is measured between series connection '1U2' and the machine's star point.



Fig. 3. Voltage across the two coil groups for different taps; switching from lower short circuit (000) to active switching state U (001); Cable 'C15m' applied.

Comparing the steady state voltage after the transient oscillation has decayed for the voltage across the two coil groups it can be concluded that the voltage distribution is uniform for application of cable 'C15m'. The occurring peak voltage, however, is significantly higher across coil group 1. The absolute value of the peak voltage across coil group 1 can be identified to 323.2V. For the coil group 2 it is 218V. The steady state value is 147V and 150V (DC-link voltage: 440V), respectively. In this case the voltage across the first coil group is even slightly smaller than across the second group. The same investigations have been carried out if cable 'C6m' is applied. The resulting traces are depicted in Fig. 4.

In case of the shorter cable ('C6m') used the occurring peak voltage is different. It can be identified to 278.2V and 230.4V for coil group 1 and 2, respectively. In comparison to cable 'C15m' the peak voltage for the measurement across coil group 1 is reduced. However, for coil group 2 it is increased. This is in contradiction to the results presented in [14]. In that investigation the voltage drop across the first turns stays the same independent of the cable length. The general assumption that the peak voltage increases for increasing cable length can be confirmed as the voltage across the whole phase winding increases from 362.9V to 420.7V. The steady state values for the measurements with cable 'C6m' applied are identified to 138.6V for the first coil group and 158.4V for the second coil group.



Fig. 4. Voltage across the two coil groups for different taps; switching from lower short circuit (000) to active switching state U (001); Cable 'C6m' applied.

The steady state voltage distribution is non-linear in this case. The steady state voltage drop across the second coil group is higher than across the first. In comparison to the measurements with cable 'C15m' the steady state voltage drop across coil group 1 increases with cable length. The steady state voltage drop across the second coil group, however, decreases with cable length. As the applied voltage pulse has the same magnitude in both scenarios the steady state voltage drop across the whole phase winding U is the same and can be identified to 297V.

C. Dependency of Rate of Voltage Rise on Cable Length



Fig. 5. Voltage across phase winding U for cable 'C6m' (blue) and 'C15m' (green); switching from lower short circuit (000) to active switching state U (001); Cable 'C6m' applied.

Concerning the dependency of the rate of voltage rise on the cable length the voltage across the whole phase winding U is investigated. The investigated switching transition is again from lower short circuit (000) to positive active switching state in phase U. Again the two cables 'C6m' and 'C15m' are investigated. The resulting trace of the voltage across the phase winding is depicted in Fig. 5. The two traces are very similar. This may result from the fact that the difference in cable length is too small. However, as the previous investigation of the coil voltages showed the voltage distribution significantly differs for the two investigated scenarios. The rate of voltage rise slightly decreases for increasing cable length. For the shorter cable the rate of voltage rise can be identified to $1.37 \text{kV/}\mu\text{s}$, for the longer cable ('C15m') to $1.19 \text{kV/}\mu\text{s}$.

D. Propagation of Voltage Pulse on Cable

The investigation of the phase-to-phase voltage can be used to analyze the voltage propagation on the supply cables. Thus, the phase-to-phase voltage at the inverter output and at the machine terminal connections is measured. The analyzed voltage pulse is again from lower short circuit to positive active switching state in phase U. The voltage between phase U and V is analyzed. The resulting measured voltages for cable 'C6m' applied to the drive are depicted in Fig. 6.



Fig. 6. Phase-to-phase voltage measured at the inverter's output and machine's terminal connection of phase U and V for cable 'C6m'; applied voltage switching from lower short circuit ('000') to positive active switching state ('001', \pm U).

A comparison of the resulting traces shows that no significant change between the phase-to-phase voltage at the inverter output and the machine terminal connection can be detected. The delay of the applied voltage pulse is negligible in comparison to the time resolution of 25ns of the acquisition system (sampling rate of 40MS/s). The propagation speed of the applied voltage pulse on the cable is determined to be in the range of approximately half the speed of light in [4] and [5]. For a length of six meters this leads to a propagation time of the voltage pulse on the cable of approximately 40ns. This short time is very difficult to evaluate.

An oscillation superimposed to the applied voltage pulse due to the reflection cannot be detected in the phase-to-phase voltage at the machine terminal. Whether this oscillation occurs also depends on the cable length. Thus, the same investigation has been carried out for the longer cable 'C15m' applied to the machine. The measured phase-to-phase voltage at the inverter output and the machine's terminal connection is depicted in Fig. 7. In case of the phase-to-phase voltage measured at the machine's terminal connection a clear oscillating overvoltage resulting from the reflection of the applied voltage pulse can be detected. Furthermore the delay between the two investigated phase-to-phase voltages can be seen. It results from the propagation delay of the pulse traveling on the cable. Again - assuming a propagation speed of half the speed of light - the delay results to 100ns for a cable length of approximately fifteen meters. This time delay is clearly detectable with the used acquisition system.



Fig. 7. Phase-to-phase voltage measured at the inverter's output and machine's terminal connection of phase U and V for cable 'C15m'; applied voltage switching from lower short circuit ('000') to positive active switching state ('001', \pm U).

Comparing the phase-to-phase voltages at the machine's terminal connection for the two investigated cable configurations leads to a difference in the propagation time of 60ns. This comparison of the phase-to-phase voltages measured at the machine's terminal connection for phase U and V is depicted in Fig. 8.



Fig. 8. Phase-to-phase voltage measured at the machine's terminal connection of phase U and V for cables 'C6m' and 'C15m'; applied voltage switching from lower short circuit ('000') to positive active switching state ('001', +U).

The difference between the rising edges of the two voltage traces arriving at the machine terminal connection can be identified to two sample instances. This results in a difference in the delay of the voltage pulse of 50ns. This is in the range of the estimated difference.

With the presented results the propagation speed of the voltage pulse applied by the inverter on the machine cables of approximately half the speed of light can be confirmed.

However, an exact identification of the propagation time would require additional measurements.

VI. CONCLUSION

The paper summarizes the findings of different investigations concerning the voltage distribution in inverterfed machines. The various influences determining the shape of this overvoltage are described. In comparison to mains-fed operated machines, transient overvoltage occurs in the machine's stator winding due to reflections of the applied voltage pulse at the machine terminal connections. This transient overvoltage leads to additional stress on the machine's insulation system.

Different findings of the presented short literature study have been investigated in experimental studies on an induction machine equipped with tapped windings. The turn-to-ground voltage has been investigated at different taps and for different applied switching transitions by the inverter. The result is that the occurring absolute voltage is the highest for taps at the first turns. The overvoltage in relation to the steady state turn-toground voltage, however, is the highest for taps at the later turns.

Further investigations have been carried out concerning the voltage across the two coil groups (connected in series) of the investigated machine. The cable length was varied in this investigation. The result is that the voltage across the coil groups is distributed more linear for the longer cable.

The rate of voltage rise can lead to deterioration of the machine's insulation. Thus, the dependency of the rate of voltage rise on the cable length has been carried out. The rate of voltage rise is slightly decreasing for increasing cable length.

In a last investigation the propagation of the applied voltage pulse has been investigated. A significant difference between the propagation times of the voltage pulse for the two investigated cable configurations could be detected. Furthermore for the longer cable a transient oscillation in the phase-to-phase voltage could be measured at the machine terminal connections. This effect is not present for the shorter cable.

Generally spoken the qualitative conclusions drawn from the obtained results can be expected for other random-wound squirrel cage induction machines with similar power rating. However, regarding quantitative conclusions an individual identification of each machine within a series seems to be necessary due to the random distribution of the inter-turn capacitances.

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