Application Aspects of Modern PWM AC Motor Drive Systems
Part II: Overvoltages and EMI Problems

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***Abstract* - This paper reports the result of a survey of representative literature on two important aspects related to the use of fast IGBT inverters, namely, overvoltages and conducted EMI. The mechanisms that produce overvoltages are reviewed, with particular emphasis to voltage wave reflection, that, associate with long cable feed lines and inadequate modulation techniques, can lead to overvoltages in excess of 3 pu of DC bus voltage. Conducted EMI generation mechanisms are also discussed, and found to be related to the coupling currents. These are also responsible for the appearance of some form of overvoltage in a machine winding. Techniques to mitigate these problems are also discussed.**

I. INTRODUCTION

As discussed in the first part of this paper, the high dv/dt that IGBT inverter driven AC motors are subjected also imposes stresses to stator winding insulation, creates overvoltages, radiated and conducted electromagnetic interference (EMI).

Overvoltages are particularly serious when the motor is located at a long distance from the inverter, due to voltage wave reflection [1]. This problem now occurs with relatively short cable leads due to the use of fast IGBT inverters. Another mechanism that generates overvoltages is also discussed, and found to be rooted on the coupling currents. The coupling currents also play a major role in explaining the conducted EMI. The understanding of the several phenomena that contribute to overvoltages and EMI problems is essential to the proposition of possible solutions. Some of these will be reviewed here.

II. OVERVOLTAGES

a) Due to coupling currents

It was already discussed that coupling currents are present at every switching instant, causing distortions in the input current, as well as voltage overshoots. The latter are produced by the interaction of winding inductances and resistances with the high frequency current ringing. Due to the distributed nature of parasitic winding capacitances, the coupling current distribution is not uniform along a phase winding, as indicated in Fig. 1. In fact, the first coil, adjacent to motor terminal, will carry the highest current. Assuming that the per unit length impedance of the winding is constant, the first coil will experience the greatest interaction with coupling current, and therefore, will be submitted to the largest voltage overshoots. This is a plausible explanation for the fact observed in practice, that most winding failures occur in the first coil of the winding. Up to 85% of the breakdowns may occur in the first turns [2].

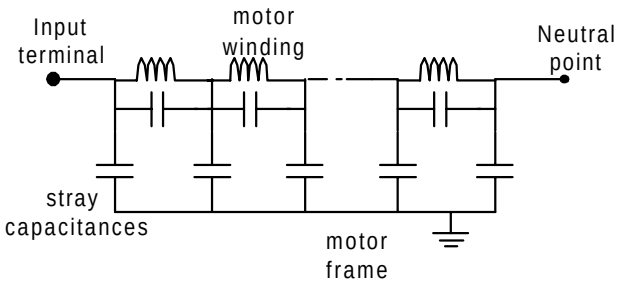

Fig. 1: Distribute circuit representation of capacitive coupling in a stator winding[8].

The problem is more severe with low voltage (<600 V) random wound motors. In this case, during the winding and insertion processes, the first and the last turn of a given coil could become adjacent to each other. In such case the full coil voltage would appear as adjacent turn voltage, i.e., the coil voltage would not be equally distributed among the turns, as would occur with form coil winding, typical of medium to high voltage motors [3].

Fig. 2 shows the coupling current induced overvoltage (in excess of 100 V), occurring in a phase to neutral voltage V_{aN}, for a 15 kHz IGBT inverter. It can be confirmed that the voltage spikes (lower trace) coincide with the coupling current spikes shown in the upper trace, thus supporting the above explanation [4]. Other experimental observations have found that, for high dv/dt rates the voltage across the first coil reaches 75% of the line voltage, and that the overshoot can reach 100% of the DC bus [3], even for short cable length.

b) Due to long cable effects

The motor can be installed at a long distance from the inverter, due to practical constraints. This fact, in association with the high dV/dt rate, produces voltage wave reflections, such that the motor terminal voltage can reach in some cases, twice the voltage in the inverter's terminal.

The voltage reflection is associated with the length of the feed lines as well as with the pulse rise time. Fig. 3 shows the behavior of the motor voltage, for the case where the propagation time (t_p) is less than 1/2 the pulse rise time(t_r), characteristic of short cables. Due to the high impedance of the motor (Z_L) compared to the cable characteristic impedance (Z_c), the motor voltage reflection coefficient Γ_L ($\Gamma_L = (Z_L - Z_c) / (Z_L + Z_c)$) is nearly +1. As a consequence,

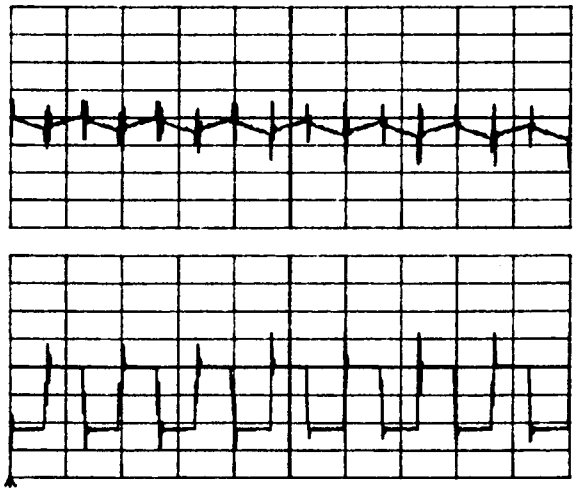

Fig. 2: Experimental phase current and voltage showing coupling current in a stator winding. Upper: Ia, 2A/div, Lower: V_{na}, 100V/div. Time: 50 μs/div [4].

when the incident voltage pulse reaches the motor terminal, a full wave reflection occurs (first reflection), that travels towards the inverter terminal. In contrast to machine impedance, the inverter is nearly an ideal voltage source, therefore, its impedance (Z_s) is close do zero, and consequently, the inverter reflection coefficient Γ_S is nearly - 1 ($\Gamma_S = (Z_S - Z_c) / (Z_S + Z_c)$). A new traveling wave, of negative polarity, now travels towards the motor, and reaches it after $2t_p$ of the first reflection, as indicated. As this negative reaches the motor terminals while the first reflection is still in this process, the result will be a lower than 2pu resultant motor voltage, as indicated.

For longer cable lengths, the second wave reflection would arrive too late to prevent a full voltage reflection, and a 2pu (of bus voltage) overvoltage occurs, as shown in Fig. 4. Therefore, the critical cable length is defined as the one that results in a propagation time equal to 1/2 the pulse rise time.

In practice, cable resistance, and dielectric losses result in a damped oscillation, as the wave is reflected from one end of the cable to another, as shown in Fig. 5.

The effect of cable length on motor terminal voltage is illustrated in Fig. 6, for a 25 hp induction motor. It can be seen that the overvoltage increases as the cable length is increased. Machine horsepower also plays a role in the magnitude of the overvoltage, as indicated in Fig. 7. In fact, as machine size increases its surge impedance decreases, i.e., it approaches the cable's characteristic impedance, causing the reflection coefficient to decrease. As a results, for a fixed (150 ft) cable length, the higher the machine lip, the lower the overvoltage. As a consequence, overvoltage problems are more severe for the cases of small motors fed by long cables.

Table I shows the critical cable length for which the overvoltage reaches 2 pu, as a function of power switch rise time. It is clear that, for fast IGBT (t_r = 0.1 μs), even a modest cable length of 6 m can result in voltage doubling.

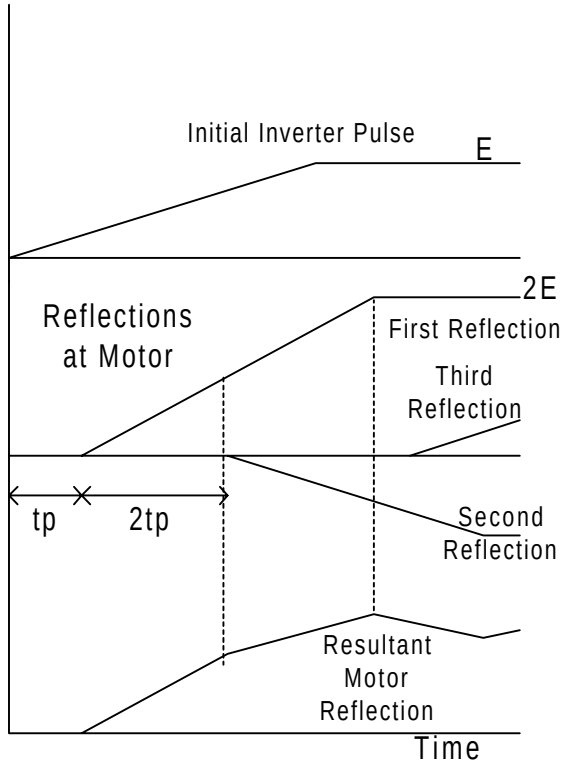

Fig. 3 : Propagation time<1/2 rise time: reduced voltage reflection [9].

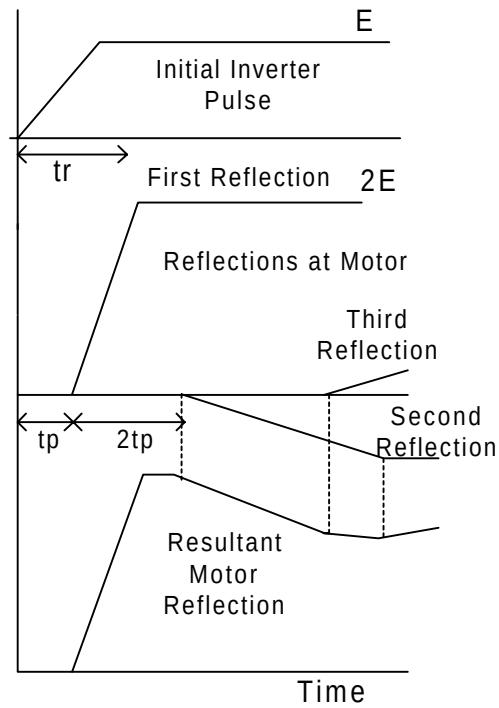

Fig. 4: Propagation time >1/2 rise time: full voltage reflection [9].

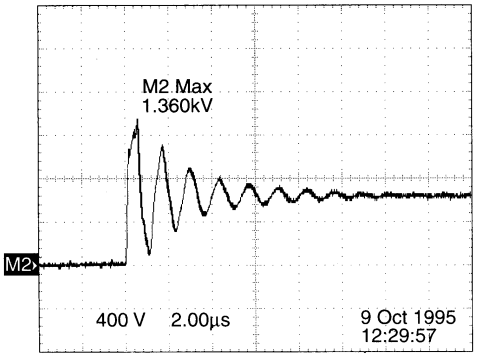

Fig. 5: Voltage pulse at motor terminal. Input 460Vac, cable lengh=42 meters[9].

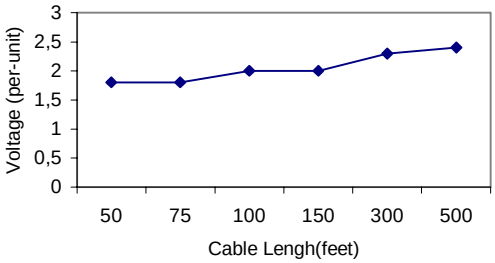

Fig. 6: Maximum overvoltage at motor terminals for various cable lengh [5].

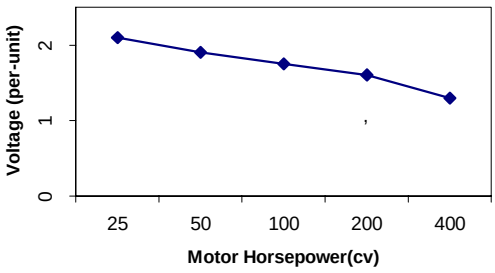

Fig. 7: Maximum overvoltage at motor terminals for various horsepower ratings - 150 foot cable lengh [5].

c) Due to modulation technique, carrier frequency and long cables

While overvoltages reaching values <2-pu, are associated to factors such as cable length, cable-to-motor surge impedance matching,, and also the rise time of the PWM output voltage pulses. There are certain modes in a PWM Modulation cycle that, combined with long cable length, can lead to motor stress greater than theoretical 2pu, explained by transmission lines theory. Overvoltages with magnitudes of 3 to 4-pu of bus voltage are possible.

Fig. 8 shows such a condition, caused by very short pulses, where the last cable transient has not fully decayed before the application of the next pulse, so that a residual trapped cable charge condition exists that may lead to 3-pu overvoltage. It can be seen that, while the inverter output

TABLE I: Minimum Cable length and PWM Rise Time After Which Virtual Voltage Doubling Occurs at the Motor Terminal for Given Cable Parameters

PWM Pulse Rise Time	*Minimum Cable length and PWM Rise Time After Which Virtual Voltage Doubling Occurs at the Motor Terminal (meters)*
0,1 µs	6
0,5 µs	39
1,0 µs	59
2,0 µs	118
3,0 µs	177
4,0 µs	236
5,0 µs	295

line-to-line voltage (upper trace) is limited to the DC bus voltage (of 650V), at the motor terminal (lower trace), it reaches a peak value of 1670V (2.57 pu). Similarly, the authors have identified that even more severe voltage spikes (greater than 3pu) can happen in the case of polarity reversal, i.e.,

when the line-to-line voltage suddenly changes from $+V_{DC}$ to $-V_{DC}$ (or vice-versa). This in practice occurs due to overmodulation, or due to the intersection of the modulating (reference) waves (i.e., $V_a^* = V_b^*$, etc) The carrier switching frequency and modulation technique have a predominant effect on a motor voltage, due to spacing of modulation pulses, while inverter rise time has a lesser effect in this mode [6].

III. Electromagnetic Interference

By identifying coupling currents paths circulating in the motor, it is possible to detect the generation mechanism of conducted electromagnetic interference. Thus, as the coupling currents are composed of two components, namely, common mode and differential mode, the current circulation path characterize the type of interference produced by the drive when the AC supply is part of the path for these currents. Fig. 9 shows the path for the common mode currents, where Cc is the capacitance from

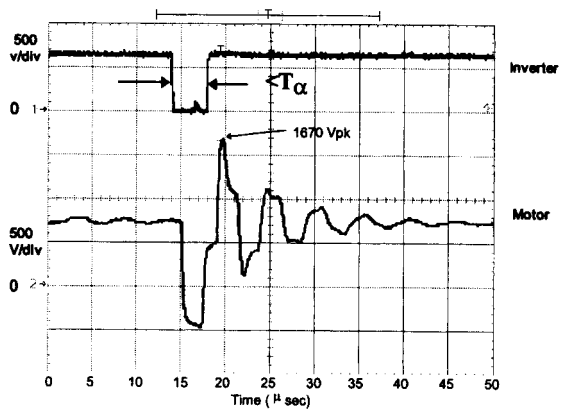

Fig. 8: PWM and the effects of double pulsing [6]

winding to the stator and rotor laminations. As they circulate through the earth ground, they have a greater influence on EMI. Fig. 10 shows the flow of the differential mode coupling current. It is mainly supplied by the DC link capacitor. However, during transients in the load, a portion of the coupling current might be drawn from the AC source via the rectifier [4]. This is indicated by the dashed lines enclosing the source, and will contribute to conducted EMI generation. Notice that the common mode component can not be supplied by the DC link capacitor, therefore, all common mode current will flow through the AC source, and cause interference with other equipment.

IV. Techniques To Mitigate The Effects Of The Overvoltages And The Coupling Currents.

There are many techniques to minimize the effects of the overvoltages and the coupling currents at the motor terminals. The most commonly used are the passive filters as listed bellow[7]

i) Output Line Inductors

This is the simplest and lowest-cost method to minimize the effects of the overvoltages. It can reduced the the dv/dt applied to the inverter end of the cable and the dv/dt at the motor terminal. The use of low-loss ferrite core inductors should be avoided since they can actually make the motor voltage worse due to extended ringing as a result of a low damping factor. Fig. 11 show the resultant motor terminal voltage of the same motor of Fig. 5 when operated from a 460 V AC with 42 meters of cable and a 3%, laminated core output inductor. However, the inductor creates a voltage drop that reduces the deliverable machine torque.

ii) Output Limit Filter

Its design utilizes inductors, capacitors, and diodes. This filters limit dv/dt and the voltage peaks at motor terminal. This type of filter still allows full voltage utilization of the inverter trough modulation adaptation and also allows motor parameter identification and self-tuning functions to operate properly. Fig. 12 shows that the motor terminal overvoltage is dramatically reduced.

iii) Sine-Wave Filter

Its utilizes output inductors, shunt capacitor and, when necessary, damping resistors to form a conventional low-pass filter. This filters shunt the high-frequency harmonics currents. The currents and voltages applied to the motor are nearly sinusoidal. At the motor, no transient voltage occurs, no additional losses are present, and it also helps to reduce the motor noise due the absence of harmonics.

iv) Motor terminal Filter

It generally utilizes the first-order resistor/capacitor filters that are connected in parallel with the motor terminal. The current trough the circuit is reduced so that the resistor mainly dissipates energy during the leading edge of pulses. Fig. 13 shows the motor terminal voltage for this type of filter.

V. Minimizing The Conducted EMI Problem

Once the mechanisms of generation of common mode as well as differential mode coupling currents are identified, it is possible to devise means to minimize their EMI effects.

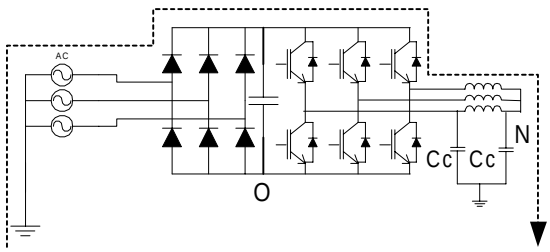

Fig. 9: Flow of common mode coupling current.[4]

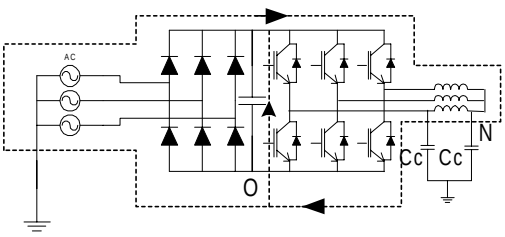

Fig. 10: Flow of differential mode coupling currents, that contribute to conducted EMI [4].

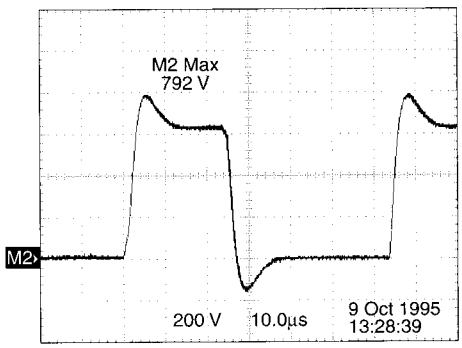

Fig. 11:Voltage pulse at motor terminal, Input voltage 460Vac, cable lengh=42 meters, 3% output inductor [7].

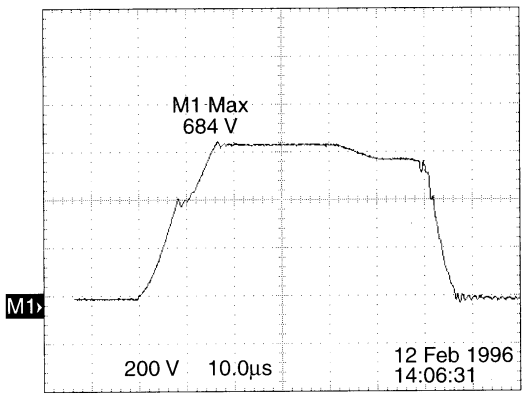

Fig. 12:Voltage pulse at motor terminal, with output limiter filter. Input voltage 460Vac, cable lengh=42 meters [7].

The differential mode component can be effectively suppressed with the introduction of LC filter between the rectifier output and the DC link capacitor as shown in Fig. 14. The presence of the inductor L prevents the high frequency differential current to propagate to the AC line; while the shunt capacitors provide low impedance paths for their flow.

The attenuation of the common mode current effect on the AC source can be achieved with the use of a filter structure as shown in Fig. 15, placed between the AC source and the rectifier input. The presence of the inductor L increases the common mode impedance, while capacitor bank C_{f2} provides a low impedance path for their circulation. The filter, however, has no effect on the coupling currents that circulates in the machine.

A quite different approach to eliminate all the harmful effects of common mode currents has also been proposed in the literature [9]. It consists in common mode voltage cancellation, such that it detects the total common mode voltage (V_{in}), and introduces a negative common mode voltage ($-V_{in}$) in series with the inverter output, ideally resulting in a complete cancellation. Another approach seeks to derive new modulation strategies that minimizes the undesirable common mode voltages[10].

VI. Conclusion

This second part discussed the overvoltage and conducted EMI problems that arise due to the use of fast IGBT switches. It should be emphasized that by knowing the mechanisms that generate these problems, it becomes possible to formulate solutions.

This has been a recent topic for research, and the main lines include the use of filters to reduce the dv/dt, and consequently minimizes all the undesirable effects, as well as to seek new converter topologies that do not generate large dv/dt, and inherently minimizes the common mode voltages.

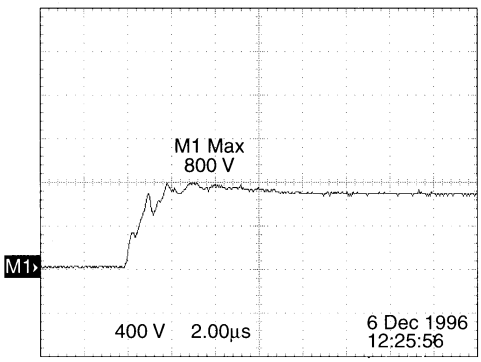

Fig. 13: Voltage at motor terminal, input voltage of $460V_{AC,}$ cable lengh 42 meters, motor filter [7].

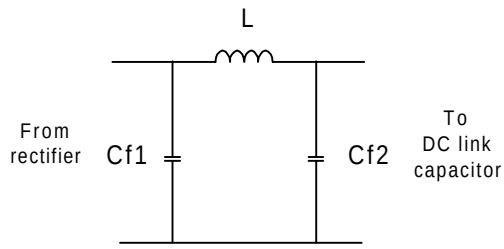

Fig. 14: Differential Mode EMI filter in the DC Link[4]

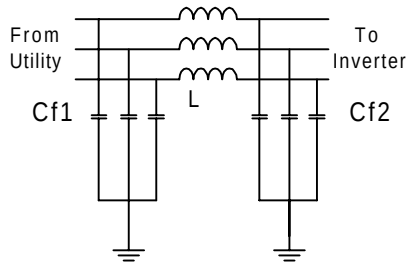

Fig. 15: Common Mode Filter/Choke[4].

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