Output filter design for conducted EMI reduction of PWM Inverter-fed Induction Motor System

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Abstract-- In this paper, filtering techniques to reduce the adverse effects of motor leads on high-frequency PWM inverter fed AC motor drives will be examined. The filter was designed to keep the motor terminal from the cable surge impedance to reduce overvoltage reflections, ringing, and the *dv/dt, di/dt.* Therefore, filtering techniques are investigated to reduce the motor terminal overvoltage, ringing, and EMI noise in inverter fed ac motor drive systems. The output filter is used to limit the rate of the inverter output voltage and reduce EMI(common mode noise) to the motor. The performance of the output filter is evaluated through simulations (PSIM) and experiment on PWM inverter-fed ac motor drive(3phase, 3hp(2.2kw), input voltage 220/380V, induction motor). An experimental PWM drive system reduction of conducted EMI was implemented on an available TMS320C31 microprocessor control board.

Finally, experimental results showed that the inverter output filter reduces more CM noise than the LPF(low pass filter) and reduce overvoltage and ringing at the motor terminal.

I. INTRODUCTION

In recent years, development of high-speed power semi-conductor devices has brought high-frequency switching operation to power electronic equipment and has improved the performance of pulse-width modulated(PWM) inverters for driving induction motors. Switching frequency of 2 to 20kHz and rise time of 0.1μs are possible with IGBT technology. However, EMI noise has been pointed out as a serious problem. the fast *dv/dt* that happen at these high speed switching and breed leakage current through stray capacitor that exist between a stator winding and the motor frame, such a conducted noise ingredient bring to EMI problem and electric motor bearing damage is given and in serious case electric motor becomes insulation destruction. Specially, the CM noise problem is appearing greatly with susceptible equipment present, high system input voltage, large quantity of system drives, and long length of motor leads[1],[2],[3].

The higher output switching *dv/dt* increases peak CM ground current. Higher carrier frequency, increases the sum of transient CM noise to ground, and motor cable lengths less than 20ft(6.5m) exhibit low cable line to ground capacitance and low CM noise risk from capacitive *dv/dt* ground current. But, if cable length becomes long, capacitance of cable increase and CM ground connection charging current increases. At long cable lengths, the high frequency oscillation of the reflected wave voltage transients(about 2 times Vdc) also appear on motor terminal, to creates CM noise through the stator winding and cable capacitance[4],[5]. Fig. 1 shows configuration to PWM inverter system and noise measuring equipments (spectrum analyzer, LISN).

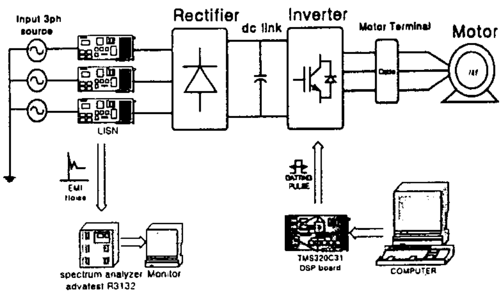


Fig. 1: PWM inverter system configuration

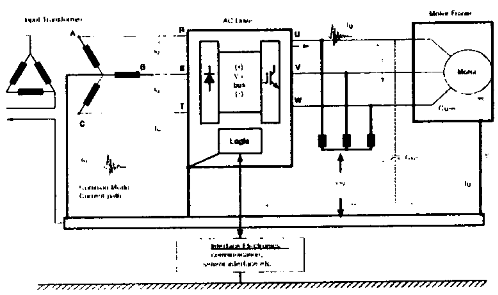


Fig. 2: Parasitic line-to-ground noise paths in PWM inverter system

This paper proposes an inverter output filter configuration to reduce conducted noise at the motor terminal. The EMI filter techniques have been evaluated through experiment for a 220V, 3hp, PWM inverter fed AC motor drive system. Fig. 2 is a detailed representation of the CM noise path in PWM inverter system. The CM noise is passed through ground connection.

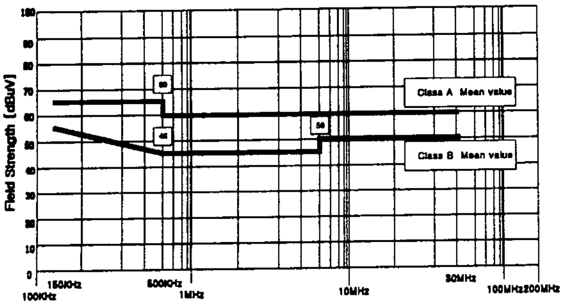


Fig. 3: Limits of CISPR Pub.22/ EN55081-1

Fig. 3 shows the limits of CISPR Pub.22/ EN 55081-1. In the use of switched-mode power supplies or adjustable speed drives, several types of emission may be generated on the power line. Another issue concerns EMI. PWM inverter fed AC motor drive systems generate both conducted and radiated EMI noise. The high speed IGBT switching devices create a magnetic field and radiate wide band EMI. Further, the high *dv/dt* can couple through the capacitance between the motor winding and frame, causing high frequency currents to flow in the return ground conductors which can cause tripping of ground current relays installed for protection.[6]. The proposed output filter analysis and design approaches are compared and verified in simulation and experimentally for cable length on 220V PWM(IGBT) ac motor drive system.

Conducted EMI noise consists of two modes :

1. Common mode interference is EMI noise present on the line and neutral referenced to earth ground. Most noise problems are caused by common mode interference.
2. Differential mode interference is EMI noise present on the phase line referenced to the neutral.

II. COMMON MODE VOLTAGE ANALYSIS

In this section, common mode voltage analysis is described. The analysis is done for conditions when long motor terminals are present between the inverter and the motor, with output filter present in inverter system[1][2].

A. Analysis with long motor cable

Fig. 4 is schematic diagram of PWM inverter system that has a long electric motor terminal. The common mode voltage V_{cm} at electric motor terminal can be defined as the following.

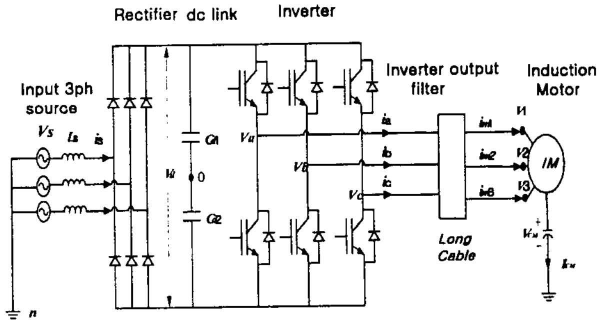


Fig. 4: Inverter system configuration.

$$V_1 - V_{cm} = R_l i_{m1} + L_l \frac{d i_{m1}}{dt} \quad (1)$$
$$V_2 - V_{cm} = R_l i_{m2} + L_l \frac{d i_{m2}}{dt} \quad (2)$$
$$V_3 - V_{cm} = R_l i_{m3} + L_l \frac{d i_{m3}}{dt} \quad (3)$$

Also, the common mode voltage can be expressed as,

$$V_{cm} = V_1 - (R_l i_{m1} + L_l \frac{d i_{m1}}{dt}) \quad (4)$$
$$V_{cm} = V_2 - (R_l i_{m2} + L_l \frac{d i_{m2}}{dt}) \quad (5)$$
$$V_{cm} = V_3 - (R_l i_{m3} + L_l \frac{d i_{m3}}{dt}) \quad (6)$$

where, V_1, V_2, V_3 are voltages of induction motor terminal voltage, R_l and L_l are per phase equivalent resistance and inductance of the induction motor respectively. Adding eqns.(4) to (6) yields,

$$3V_{cm} = V_1 + V_2 + V_3 - \{(R_l(i_a + i_b + i_c) + L_l \frac{d}{dt}(i_{m1} + i_{m2} + i_{m3})\} \quad (7)$$

Assuming $i_{m1} + i_{m2} + i_{m3} \cong 0$ since $i_{cm} \cong 0$ in KCL, it Can be defined by eqn.(8).

$$V_{cm} = \frac{V_1 + V_2 + V_3}{3} \quad (8)$$

And motor terminal voltage can appear by following eqns.

$$V_1 = V_{1,0} + V_{0,n} \quad (9)$$
$$V_2 = V_{2,0} + V_{0,n} \quad (10)$$
$$V_3 = V_{3,0} + V_{0,n} \quad (11)$$

Here, $V_{1,0}$, $V_{2,0}$ and $V_{3,0}$ are the voltages between electric motor terminal and dc_link midpoint '0' and, $V_{0,n}$ is the voltage between '0' and the neutral (earth ground) 'n'. If substitute equation.(9), (10), (11) to equation.(8), Finally, we can get following equation.(12).

Tab. I **Inverter states and common mode voltage**

UPPER IGBT SWITCHING PATTERN	$V_{1,0}$	$V_{2,0}$	$V_{3,0}$	V_{cm}
V0 [0, 0, 0]	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$
V1 [0, 0, 1]	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{6}$
V2 [0, 1, 1]	$-\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{6}$
V3 [0, 1, 0]	$-\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{6}$
V4 [1, 1, 0]	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$\frac{V_{DC}}{6}$
V5 [1, 0, 0]	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{6}$
V6 [1, 0, 1]	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{6}$
V7 [1, 1, 1]	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$

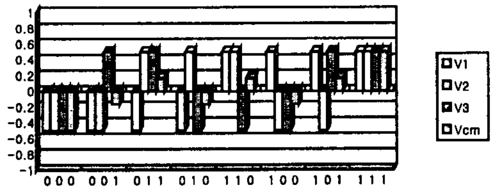


Fig. 5: Each inverter switching pattern and V_{cm} Magnitude

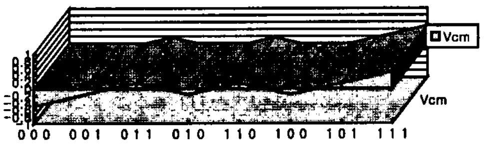


Fig. 6: V_{cm} Magnitude at happened inverter switching

In a three phase electric machine, the common mode voltage V_{cm} is defined as the voltage between the star center and the ground is given by:

$$V_{cm} = \frac{(V_{1,0}+V_{0,n})+(V_{2,0}+V_{0,n})+(V_{3,0}+V_{0,n})}{3} = \frac{(V_{1,0}+V_{2,0}+V_{3,0})}{3} + V_{0,n} \quad (12)$$

By supplying the motor through a PWM inverter the common mode voltage is always different from zero, and its value depends on the state configuration as summarized in Table I. Three switches are conducting at any given instant and constitute eight switching state with Table I according to switching method. Fig.6 is V_{cm} magnitude by inverter switching pattern and Fig.7 shows only V_{cm} magnitude happened at inverter switching. In a three phase inverter, three switches are conducting at any given instant and constitute eight switching state. The case of that two upper rectifier switches become ON and one lower rectifier switch becomes ON or one upper rectifier switch becomes ON and two lower rectifier switches become ON, that is $V_{a,0}+V_{b,0}+V_{c,0} \cong \pm V_{dc}/2$. However, with long motor terminals, the motor terminal voltage is nearly twice than at the output due to transmission line effect[1]. In this case, the summation is $V_{a,0}+V_{b,0}+V_{c,0} \cong \pm V_{dc}$. Substituting this equation in (12) yield. $V_{cm,inst} \cong \pm V_{dc}/3+(V_{0,n})_{inst}$. Therefore the V_{cm} can be expressed as,

$$V_{cm,inst} = \pm V_{DC} + (V_{0,N})_{inst} \quad [\text{in non\_effective vector switching}]$$
$$\pm \frac{V_{DC}}{3} + (V_{0,N})_{inst} \quad [\text{in effective vector switching}] \quad (13)$$

Here, the instantaneous common mode voltage at motor terminals can be 2.5 times than the operated under PWM drive system with long motor terminal between inverter and the motor[1],[2],[9].

B. Analysis with output

Fig. 7 is schematic diagram of PWM inverter system that has a long electric motor terminal.

The purpose of the output filter is reduction of the inverter output line-to-line voltage *dv/dt* and voltage reflection phenomena, which contributes to reduction of motor stress[10],[11]. Specially, the common mode noise has a negative influence on the behavior of high switching frequency motor drives, leading to such problems as the following:

- Damage to motor bearing;
- Increased electromagnetic pollution;
- Unwanted ground-fault shutdowns.

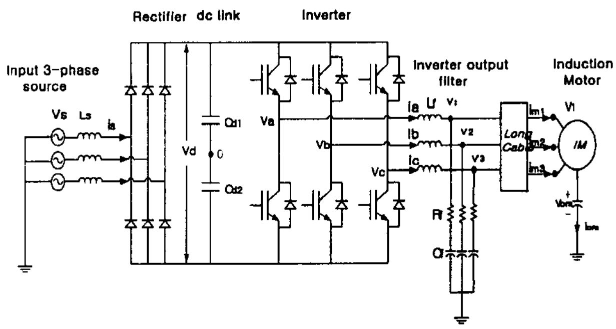


Fig. 7: The Inverter system with output filter

The limiting common mode noise in modern electric drives is, thus, of main concern[3],[4]. The output filter components could be designed to sufficiently attenuate the inverter output voltage *dv/dt.* Therefore, the filter input voltages V_1, V_2, V_3 are nearly the same as V'_1, V'_2, V'_3, at motor terminals. So, the CM voltage can be expressed as following.

$$V_{cm} = \frac{V_1'+V_2'+V_3'}{3} \cong \frac{V_1+V_2+V_3}{3} \quad (14)$$

also,

$$V_a = V_1 + L_f \frac{di_a}{dt} \quad (15)$$

$$V_b = V_2 + L_f \frac{di_b}{dt} \quad (16)$$

$$V_c = V_3 + L_f \frac{di_c}{dt} \quad (17)$$

Adding the above eqns, are calculated according to the following expression,

$$V_1 + V_2 + V_3 - V_1 + V_2 + V_3 = \{L_f \frac{d}{dt}(i_a + i_b + i_c)\} \quad (18)$$

assuming $i_a + i_b + i_c \equiv 0$ since $i_{cm} \equiv 0$, it can be defined by eqn.(19)

$$V_{cm} = \frac{V_a + V_b + V_c}{3} \quad (19)$$

V_1, V_2, and V_3, are calculated according to eqns.(9) to (11), is as following.

$$V_1 = V_{1,0} + V_{o,n} \quad (20)$$

$$V_2 = V_{2,0} + V_{o,n} \quad (21)$$

$$V_3 = V_{3,0} + V_{o,n} \quad (22)$$

If arrange substituting eqns.(20), (21), (22) into eqn. (19), that is defined as

$$V_{cm} = \frac{(V_{a,0} + V_{b,0} + V_{c,0})}{3} + V_{0,n} \quad (23)$$

Assuming that, the output filter is sufficiently attenuate the inverter output voltage dv/dt.
Therefore, the V_{cm} can be expressed as,

$$V_{cm,max} = \pm\frac{1}{2}V_{DC} + (V_{0,N})_{max} \quad [\text{in non\_effective vector switching}]$$

$$\pm\frac{1}{6}V_{DC} + (V_{0,N})_{max} \quad [\text{in effective vector switching}] \quad (24)$$

Thus, in case of the common mode voltage with the output filter is the same as when long motor leads were absent

III. FILTER DESIGN

A. The output filter design

The output filter placed at the output terminals of an inverter can be specially designed to slow down the inverter output pulse rise time. Therefore significantly reducing the overvoltage and ring at the motor terminals[2]. The designed output filter in inverter system is as follows. The load and source reflection coefficients L_L and L_s, respectively, can be expressed as

$$L_L = \frac{R_L - Z_0}{R_L + Z_0} \quad (25)$$

where R_L is the load resistance and Z_0 is the characteristic impedance given by

$$Z_0 = \sqrt{\frac{L_C}{C_C}} \quad (26)$$

where L_C and C_C are cable parameters. And the time(t_t in μs) for the inverter output pulse to travel from the inverter terminals to the motor terminals can be expressed as

$$t_t = \frac{l_c}{v} \quad (27)$$

where v is the pulse velocity and is given by[2]

$$V = \frac{1}{\sqrt{L_C + C_C}} \quad (28)$$

l_C : cable length;
L_C : cable inductance per unit length;
C_C : capacitance per unit length;
t_t : time for pulse to travel the length of the cable once.

Therefore, the critical rise time can then be calculated by substituting the maximum desired voltage overshoot as shown bellows.

$$SET \quad \frac{3 * l_C * \Gamma_L}{v * t_r} \leq 0.2 \quad (29)$$

$$\therefore \quad t_r \cong \frac{3 * l_C * \Gamma_L}{v * 0.2} \quad (30)$$

Γ_L : reflection coefficient at the load
(typically 0.9 for motor less than 20 hp)

Than, Calculate t_r (switching rise time) value in condition that electric motor cable length is 10m and gets into overvoltage 20% low by cable (14AWG) for electric power. We can calculate f_c (cutoff frequency) by eqn.(31)[8],[9].

$$f_c = \frac{1}{2t_r} \quad (31)$$

$$\therefore \quad t_r \cong \frac{3 * l_C * \Gamma_L}{v * 0.2} \cong \frac{3 \times 10(m) \times 0.9}{160 \times 0.2} \approx 0.844(\mu s) \quad (30)$$

Inverter system applies to 10m (30ft) motor terminal cable. Filter cutoff frequency can be calculated by eqn.(31),

$$f_c = 592.6[KHz] \quad (31)$$

and the attenuation is 3dB at the cutoff frequency $w_c = 2\pi f_c$,
The output filter transfer function H which defines,

$$H = \frac{V_o}{V_i} = \frac{1 + jwR_f C_f}{1 - w^2 L_f C_f + jwR_f C_f} \quad (32)$$

where the effective attenuation in decibels is

$$A = 20\log\left|\frac{1}{H}\right|$$
$$= 20\log\left|\left(\frac{1+jwR_fC_f}{1-w^2L_fC_f+jwR_fC_f}\right)^{-1}\right|$$
$$= 20\log\left|\frac{1-w^2L_fC_f+jwR_fC_f}{1+jwR_fC_f}\right| \quad (32)$$

the filter resistor R_f is designed for the filter component values to result in an overdamped circuit [2].

Therefore,

$$R_f \geq 2\sqrt{\frac{L_f}{C_f}}$$
$$\cong 190\ (\Omega) \quad (33)$$

Thus, for 3dB attenuation at a specified cutoff frequency, and (32)-(33) can be solved for appropriate values of L_f, C_f.

Therefore, for 10m(30ft) of cable, the output filter component final value is

f_c = 592.6 [KHz]
R_f = 190 [Ω]
C_f = 6600 [pF]
L_f = 51.03 [μH]

B. Conventional LPF design

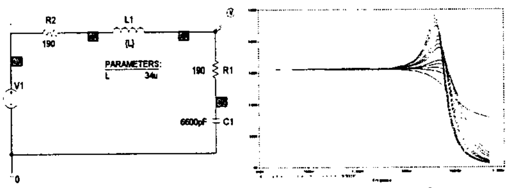
The conventional LPF can be used to isolation circuit from noise source (power supply noise, invert switching noise, etc). and to keep EMI noise from entering the circuit. The LPF resonance frequency is as following[7][11].

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (34)$$

Therefore, the LPF parameter design values in this paper is as following.

f_c = 17.897 [KHz]
C_f = 6600 [pF]
L_f = 12 [mH]

Also, designed by R_f =190[Ω] to set a maximum power transfer ratio. Figure 8(a), (b) are simulation schematic and cutoff frequency about LPF.



(a) LPF schematic (b) simulation results

Fig. 8: The simulation schematic of the LPF

Care must be exercised to see that this resonant frequency is well below the pass band of the circuit connection filter, as shown in Fig.8.(b).

IV. SIMULATION AND EXPERIMENT RESULT

A. SIMULATION

Fig.9 shows the PSIM circuit for a output filter simulation on sinusoidal PWM inverter fed induction motor system. Simulation results were conducted on a 220V, 3hp, ADS test stand. Fig. 10(a), (b) show the CM current output waveform of the motor and neutral-to-ground voltage.

Fig. 10(a), (b) show an accurately the effect of the output filter on PWM inverter fed ac motor drive systems. The simulation shows the leakage current (the top side) and neutral-to-ground voltage (the bottom side).

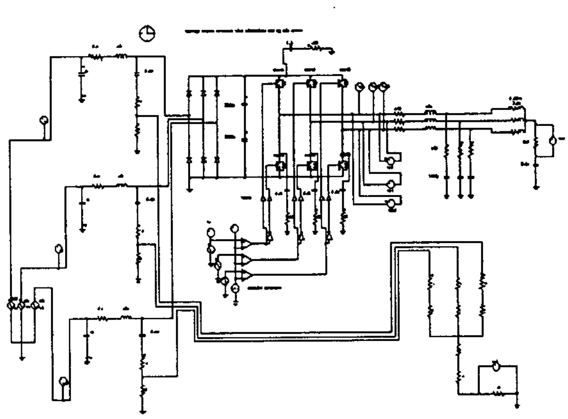
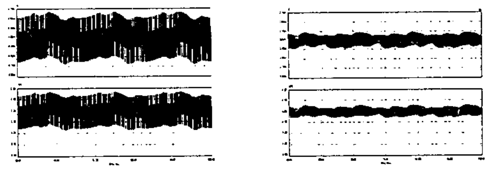


Fig. 9: The simulation schematic of the PWM inverter system



(a) without filter (b) with output filter

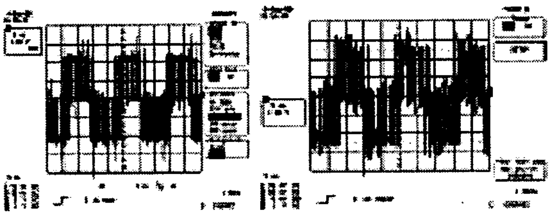
Fig. 10: Output filter simulation results.
(upper) leakage current (0.25mA/10ms)
(lower) neutral-to-ground voltage (0.1v/10ms)

(a) top: leakage current(0.25mA/ 10ms), bottom: neutral -to-ground voltage(0.1V/ 10ms) without filter. (b) top: leakage current, bottom: neutral-to-ground voltage with output filter.

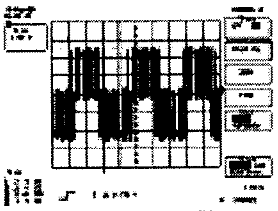
Comparing Fig.10(a) to (b), it is clear that reduced leakage current and neutral-to-ground voltage was reduced when the output filter was installed.

B. EXPERIMENT RESULT

Fig.11 shows the experimental results on sinusoidal PWM inverter fed induction motor in fig.1. Experimental results were conducted on a 220v, 3hp, induction motor. It shows the measured line to line voltage at the terminal. A 10m(30ft) cable between the inverter and the motor was employed. In this paper, system composition for an experiment intercepts other entire EMI noise that flows in from outside, and the system is grounded at the neutral point of the transformer's secondary. Notice that, in the case of without filter of Fig.11(a) and with LPF of Fig.11(b), peak voltage at motor terminals is nearly double the line to line voltage.



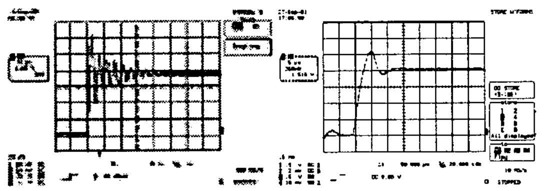
(a) without filter (b) with LPF



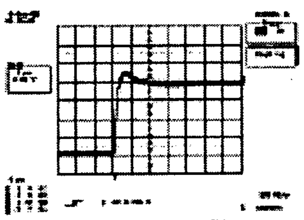
(C) with output filter

Fig. 11: The experimental results line-to-line voltage at the motor terminal(scale: 150V/div, 5ms/div).

Besides, the case with the output filter[Fig.11(c)], the reduction in overvoltage at the terminal line to line voltage.



(a) without filter (b) with LPF



(C) with output filter

Fig. 12: The experimental results motor terminal voltage

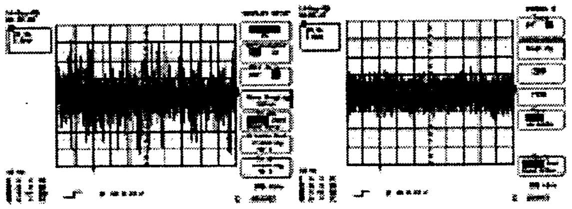
(a) without filter (scale: 80V/div, 5 μs/div)

(b) with LPF (scale: 80V/div, 2 μs/div).

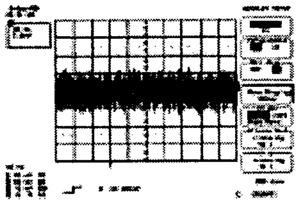
(c) with output filter (scale: 80V/div, 2 μs/div)..

Fig.12 shows the motor terminal voltage without and with LPF, with output filter for 10m(30ft) of cable from a 220V PWM inverter fed ac motor drive systems. It should be noted that the voltage ringing at the terminal of the motor with the output filter of Fig.12(c) installed is reduction more than other cases of Fig.12(a) ,(b). We can see that ringing was removed by output filter in the experiment waveform.

Therefore, the filters were designed to determinate the long cable surge impedance to reduce overvoltage reflection, ringing, and the *dv/dt* at motor terminals [1],[2],[4],[6].



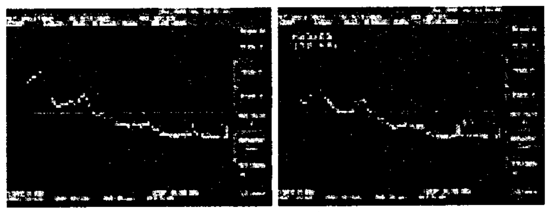
(a) without filter (b) with LPF



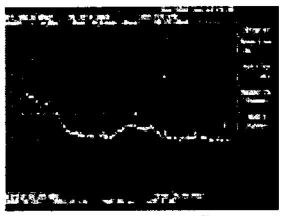
(C) with output filter

Fig. 13: The experimental results the leakage current to ground (scale: 100mA/div, 10ms/div).

Fig.13 shows the measured leakage current to ground at the motor. Specially, comparing Fig.13.(a), Fig.13.(b), and



(a) without filter (b) with LPF



(C) with output filter

Fig. 14: Spectrum results of conducted EMI (scale: frequency range:3kHz~30MHz).

Fig.13.(c), the case of LPF and output filter, obtained reduction of leakage current significantly. And experimental result shows inverter output filter reduces more EMI(CM noise)

than LPF(low pass filter). Fig.14 shows the conducted EMI measured form 3hp, 4-pole, rectifier/inverter driving induction motor. Particularly, fig.14(c) shows a significant reduction of conducted EMI compared with fig. 14(a), (b).

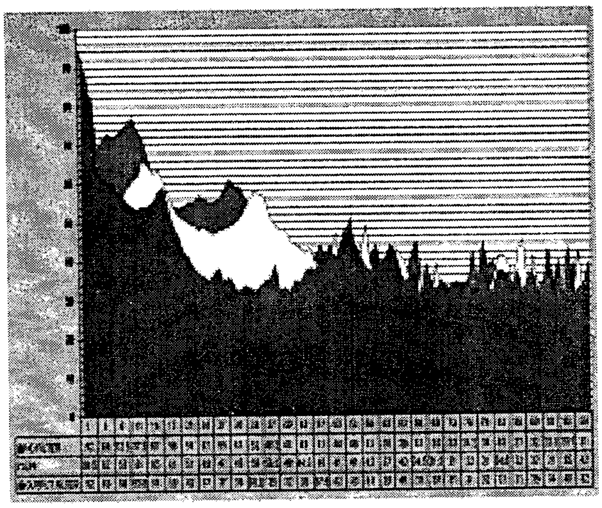


Fig. 15: Spectrum results of conducted EMI (scale: frequency range:3kHz~30MHz).

Fig.15 shows the spectrum results of no filter, conventional LPF and output filter at inverter drive system. Case with output filter at inverter drive system, conducted EMI noise magnitude is the lowest.

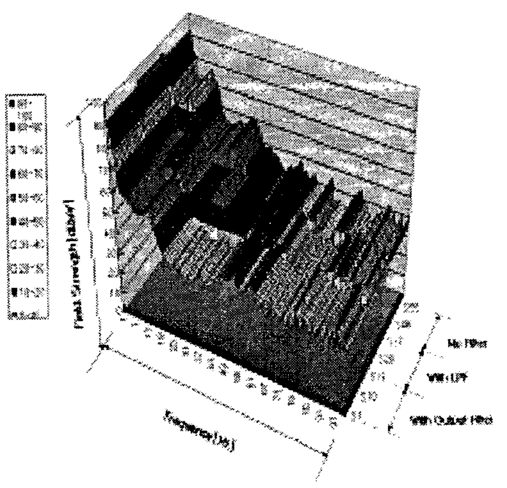


Fig. 16: Spectrum results of conducted EMI

Fig.16 shows 3 dimensional representation of the spectrum results in conducted EMI. We show that inverter system with output filter is CM noise reduction more than LPF and without filter.

V. CONCLUSION

In this paper, filtering techniques to reduce the effects of motor terminal on PWM inverter fed AC motor drives have been examined.

The proposed output filter design techniques have been compared with the conventional LPF in order to analyze their effects on the noise conducted to the mains.

Experimental results have been shown to verify that the effectiveness of the output filter to reduce the overvoltage at the motor terminals and to damp the ringing, lower *dv/dt* of the PWM switching pulse.

The performance of the proposed filter have been evaluated through experiment for 3Φ, 220V, 3hp, PWM inverter fed AC motor drive system.

An experimental PWM drive system to reduce the conducted EMI, is with implemented on an available TMS320C31 microprocessor control board.

Finally, The output filter was then compared with the LPF designed to reduce EMI noise in motor drive system. And we could confirm that the output filter was more better than LPF in noise attenuation effects.

REFERENCE

[1] A.Rendusara, "An improved inverter output filter configuration deduces common and differential modes dv/dt at the terminals in PWM drive systems", IEEE Transaction On Power Electronics, VOL. 13 NO.6, November, 1998.

[2] Annette von Jouanne, IEEE Transaction On Industry Applications, VOL. 33, NO,5, September/October, 1997.

[3] ION Boldea and S.A.Nasar, Electric Drives, pp.353 ~ 374.

[4] Gary L,Skibinski, Russel J, Kerkman, and Dave Schlegel, EMI Emissions of modern PWM ac Drives, IEEE Industry Applications Magazine, November/December, 1999.

[5] G, Skibinski, "Installation issue for IGBT ac drives," Allenbardley, Rockwell sutomation, Duke Power Semina,may 8,1996.

[6] Annette von Jouanne, Haoran Zhazg, Alan Wallace, " An evalution of mitigation techniques for bearing current , emi and over-voltages in asd applications", IEEE Trans. 1997. University of Catania, ITALY.

[7] TAMU, "filter t o reduce differential mode and common dv/dt at the motor terminals in PWM drive systems", U.S patent disclosure, 1996.

[8] Mario cassiato, Alfio consoli, Antonio Testa, "Continuous PWM to square wave inverter control with low common mode emissions" Department of Electronic and Systems Engineering.

[9] A, von Jouanne, P. Enjeti, et. al." Application Issues for PWM Adjustable Speed AC Motor Drives", IEEE industry application magazines,pp.10-18,sept/oct 1996.

[10] Dudi A.Rendusara, P. Enjeti. "New inverter output filter configuration reduces common mode and differental mode dv/dt at the motor terminals in PWM drive systems", IEEE PESC Conf. Rec.pp., 1996.

[11] Richard Lee Ozenbaugh, "EMI Filter Design"pp.2 ~115, pp.127 ~186, pp.229 ~238.