Some Approaches to Reduce Total Harmonic Distortion & Common Mode Voltage of Inverter Fed Induction Motor

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Abstract

A novel passive filter is proposed in this paper, with an objective of eliminating the common-mode and differential-mode voltage generated . For determining the parameters of filter, the filter transfer function is utilized to achieve a desirable filtering performance. The detailed design procedure of the filter parameters is given. The validity and effectiveness of proposed filter are supported by the simulation and experimental results carried out on 220V/3Hp induction motor system.

Index Terms – passive filter, common-mode voltage, differential-mode voltage.

I.   INTRODUCTION

Switching frequencies of 1 to 20 kHz and rising time of 0.1µsec.are possible with modern insulated gate bipolar transistors (IGBTs) rated at 600V or 1,200V . This makes it possible for being widely used in medium voltage system and a great contribution to improve the controllability of voltage , current , and torque . It also helps in reduction of acoustic noise . However, this improvement is accompanied by some side-effects. In 480/575V applications, the dv/dt value of inverter output differential mode and common mode voltage can reach as high as 7000V/sec. If a long cable is used to connect the inverter and motor, the dv/dt value at motor terminals can reach 11000V/sec. This high dv/dt value occurs at each switch transient of power device, and with the increase in switching frequency, the rate of application of stress on motor is increased and has been attributed to many problems, including the well-known bearing current, winding failures[1],[2] etc. Furthermore, the percentage of high common mode voltage at motor terminals has been shown to contribute to high frequency leakage current to ground as well as induce shaft voltage due to electrostatic coupling between the stator and rotor[3],[4]. While high magnitudes of leakage current to ground have been shown to interfere with ground fault protection systems in industrial facilities and contribute to wide-band electromagnetic interference (EMI) issues. The induced shaft voltages have been shown to cause bearing currents which result in pitting, fluting, and subsequent failure[5]. Recently, filters are employed at the output of voltage source PWM inverters for the purpose of eliminating the side-effects mentioned above. Generally, the filters are classified into two categories: passive and active. So far, various types of passive filter configuration, based on inductors, capacitors and resistors or diodes, have been proposed in [6]-[11]. For example, Sul, *et al*., have proposed a normal-mode filter referred as a "clamping filter" in [9]. Although this filter is effective in suppressing the high differential-mode voltage gradient at motor terminals when a cable feeder between an inverter and motor is very long, it has little capability of mitigating common-mode voltage. Other solutions based on combination of passive components and active devices such as complimentary transistors have been described in [11],[12] and [13]. Ogasawarea, *et al* have proposed a circuit consisting mainly of complimentary transistors and a common-mode transformer for achieving active cancellation of common-mode voltage [11]. This method effectively eliminates the line-to-line common-mode voltage and shaft voltage, but it makes no contribution for reducing differential-mode overvoltage occurs at motor terminals when a long cable is used to connected PWM inverter and motor. At the same time, the active circuits of [11],[12] and [13] have limitations because complimentary transistors rated at 600V or higher are presently not available in the market.

In response to these concerns, this paper proposes a new inverter output terminal passive filter focusing on reducing common-mode and differential-mode voltage gradient simultaneously and detailed design procedure of parameters is given. The proposed filter consists of three inductors, three capacitors, one resistor and a common-mode transformer.

Compared with conventional passive filters, the proposed filter can suppress the dv/dt value of common-mode and differential-mode voltage symmetrically by connecting one terminal of common-mode transformer to the midpoint of dc-link. The validity and effectiveness of proposed filter are supported by the simulation and experimental results carried out on 220V/3Hp induction motor system.

II.   Experimental System Architecture

The filter consists of three differential-mode inductors, capacitors, resistor and a four-

winding common-mode transformer. A set of three inductors, three capacitors and resistor forms a differential-mode filter to eliminate the differential-mode voltage from three phase line-to-line voltage. Although this installation makes the line-to-line voltages sinusoidal, it makes no effect on each line-to-neutral voltage. Meanwhile, the capacitors C, resistor R and common-mode transformer $L1$ and $L2$ forms the common-mode voltage filter for the purpose of mitigating common-mode voltage generated. It can be shown that the network of capacitors C has two functions, one is to form a differential-mode voltage filter together with inductors L, another is to act as a common-mode voltage detector and also provides drive current for the common-mode transformer. The common-mode transformer has all the four-phase windings wound with the same polarity on a common magnetic core structure. This construction provides a high common-mode impedance and almost zero differential-mode impedance thus enable to design the differential-mode filter and common-mode transformer separately. The midpoint could be achieved by connecting two capacitors in series between dc-link so that the dv/dt value of common-mode and differential-mode voltage could be reduced symmetrically.

III. DESIGN OF THE PASSIVE FILTER
A. Design of the Differential-Mode Filter
Because of the special structure of common-mode transformer, the inverter output differential-mode voltage drops across the inductor $L1$ should almost be zero. This means the resistor R is connected to midpoint of dc-link for the design of differential-mode filter. The single-phase equivalent circuit of differential-mode filter has the transfer function follows

$$H(s) = \frac{V_0(s)}{V_i(s)} = \frac{3RCs+1}{LCs^2+3RCs+1} = \frac{2\zeta_1\omega_{1n}s+\omega_{1n}^2}{s^2+2\zeta_1\omega_{1n}s+\omega_{1n}^2} \quad (1)$$

where ζ_1 and ω_{1n} are the damping ratio and resonance angular frequency respectively and determined by

$$\begin{cases} \zeta_1 = \frac{3R}{2}\sqrt{\frac{C}{L}} \\ \omega_{1n} = \frac{1}{\sqrt{LC}} \end{cases} \quad (2)$$

It can be seen that formula (1) has low-pass characteristic.Therefore, by selecting circuit parameters to make $\zeta_1>1$, the filter can lower the dv/dt value of differential-mode voltage effectively. According to the definition of cut-off angular frequency , it is determined by

$$|H(j\omega_c)| = 1/\sqrt{2} \quad (3)$$

Thus, by selecting $\zeta_1>>1$,the value of the cut-off angular frequency ω_{1c} is given by

$$\omega_{1c} \approx \omega_{1n}\sqrt{2(1+2\zeta_{1}^2)} \quad (4)$$

To satisfy filtering requirements , the lowest cut-off angular frequency ($\zeta_1=1$) is determined by

$$\omega_{1c} = 2.45\omega_{1n} = 2.45/\sqrt{LC} \quad (5)$$

For the differential-mode filter , the value of C is usually selected in the rang of 20-60uF in order to achieve a higher output voltage.
According to formula (4), the cut-off frequency should far less than the switching frequency of inverter ($\omega1c << 2\pi fs$) for the purpose of eliminating the high-frequency harmonic component exists in inverter output voltage. Generally, the value of $\omega1c$ is selected as 0.2~0.4 times as that of switching angular frequency. Hence, for a given ζ_1 , the value of inductor L is given by

$$L = (0.2 \sim 0.4)\frac{2(1+2\zeta_1^2)}{(2\pi f_s)^2 C} \quad (6)$$

B. Design of the Common-Mode Filter
When selecting the midpoint of dc-link as reference potential, the magnitude of common-mode voltage changes in the range of $Vdc/2$, $Vdc/6$, $-Vdc/6$, $-Vdc/2$ with the same frequency as carrier and a high dv/dt value occurs at each switch instant. This high-frequency common-mode voltage would induce shaft voltage through stray capacitor distributed between stator and rotor and produce high-frequency common-mode leakage current to ground.
Under zero initial conditions, the characteristic equation of common-mode transformer can be described as

$$\begin{bmatrix} V_1(s) \\ V_2(s) \end{bmatrix} = \begin{bmatrix} 3L_1s & 3Ms \\ 3Ms & (L_2+2M)s \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \end{bmatrix} \quad (7)$$

where M is the mutual inductor of common-mode transformer. $V1$ and $V2$ represents the voltage drop across the inductor $L1$ and $L2$ respectively. Considering the connection mode of R, L and C, The transfer function is expressed by

$$H_{ov}(s) = \frac{Vcd(s)}{Vcm(s)} = \frac{3(L_1-M)Cs^2+3RCs+1}{(3L_1+L)Cs^2+3RCs+1} \quad (8)$$

Formula (8) should has low-pass characteristic to eliminating the high-frequency components existed in common-mode voltage. The mutual inductor is defined as $M = kLL$,where k is the coupling coefficient of common-mode transformer. Therefore the following relation should exist

$$L_1 - M = L_1 - k\sqrt{L_1L_2} = 0 \quad (9)$$

This demand is satisfied by choosing $L1=L2$ and $k=1$

therefore resulting in $M=L1=L2$ which means the common-mode transformer should has a better coupling performance. Thus formula (8) is simplified as follows

$$H_{ov}(s) = \frac{3RCs+1}{(3L_1+L)Cs^2+3RCs+1}$$

$$= \frac{3RCs+1}{(3L_1+L)C[s^2+2\zeta_2\omega_{2n}s+\omega_{2n}^2]} \quad (10)$$

where $\zeta2$ and $\omega2n$ are the damping ratio and resonance angular frequency of common-mode equivalent circuit respectively and determined by (11). Depending on formula (10), the large the value of $L1$, the better the performance of low-pass characteristic. Because the main harmonic components of common-voltage exist in integer multiple of switching
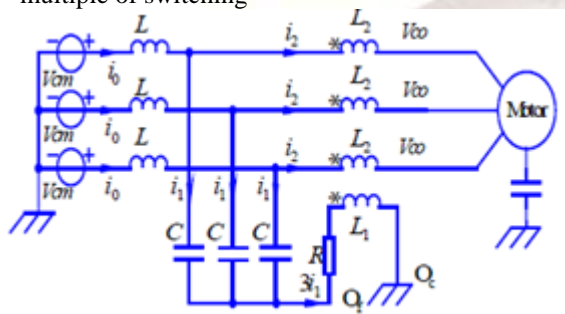
Fig 1 Common Mode Equivalent circuit
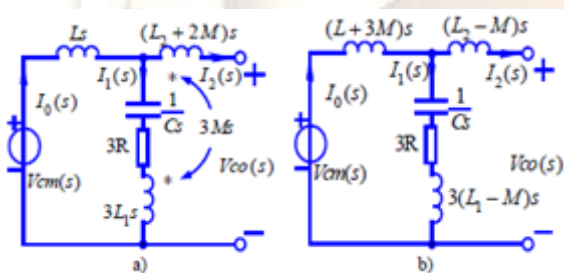
Fig 2   Equivalent circuit of single-phase common mode filter,
a) with mutual inductor coupling,
b) without mutual inductor coupling

$$\begin{cases} \omega_{2n} = \dfrac{1}{\sqrt{(3L_1+L)C}} \\[3mm] \zeta_2 = \dfrac{3R}{2}\sqrt{\dfrac{C}{(3L_1+L)}} \end{cases} \quad (11)$$

frequency, hence the value of the resonance frequency of common-mode filter should far less than that of switching frequency. Thus the following relation exist

$$\omega_{2n} = 2\pi f_{2n} = \frac{1}{\sqrt{(3L_1+L)C}} < \frac{1}{\sqrt{LC}} \ll 2\pi f_s \quad (12)$$

According to formula (12), theoretically, the resonance of higher-order harmonics could barely happen which means that the value of inductor $L1$ can be selected freely. The value of inductor L is

determined by (6) and the value of $L1$ is selected by (13) to satisfy both the formula (12) and the requests for reducing the loss, weight and cost of common-mode transformer. For a given damping ratio $\zeta2$, the value of resistor R is determined by (14).

$$L_1 \approx (2\sim3)L \quad (13)$$

$$R = \frac{2\zeta_{52}}{3}\sqrt{\frac{3L_1+L}{C}} \quad (14)$$

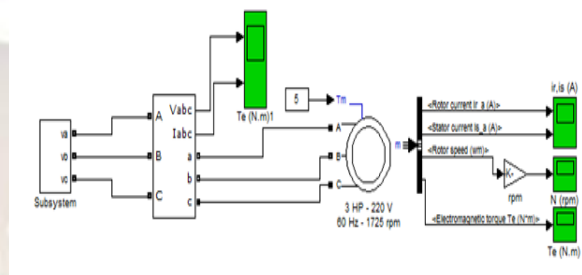## IV.   Simulation and Experimental Results
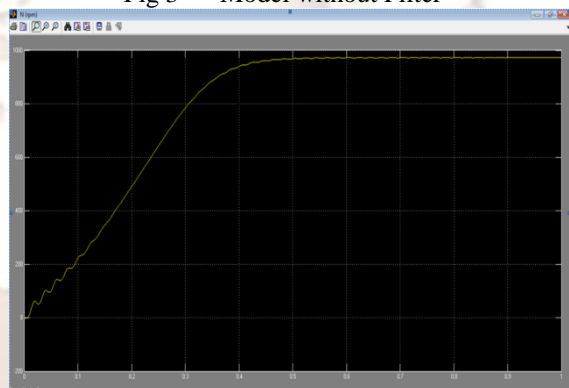

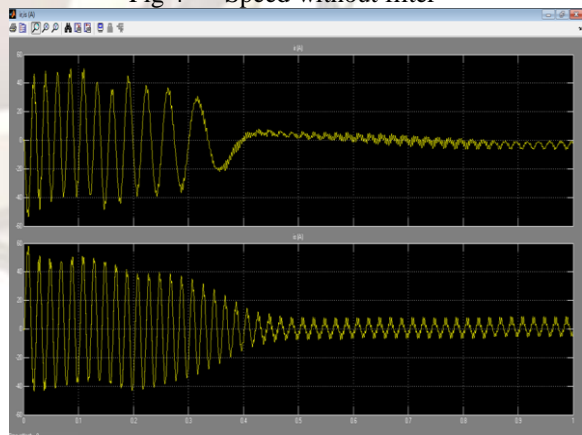Fig 3   Model without Filter

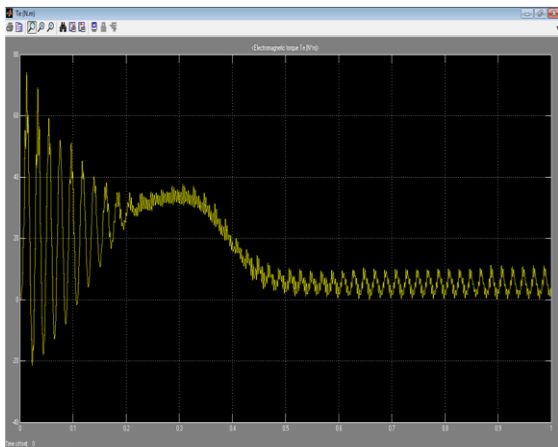Fig 4   Speed without filter

Fig 5   Rotor and Stator Current without filter
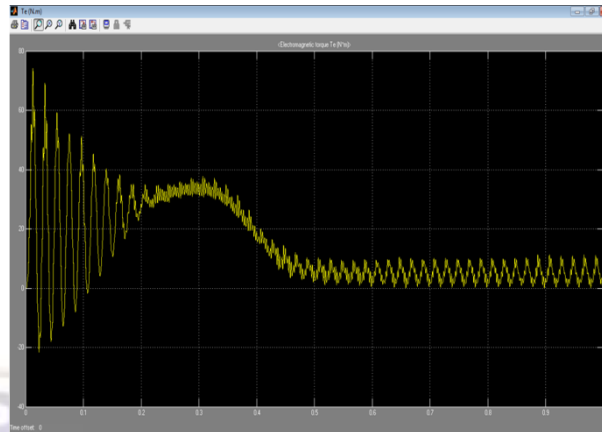
Fig 6   Torque without Filter

Fig 7   Model with Filter

Fig 8   Speed with filter

Fig 9   Rotor and Stator current with filter
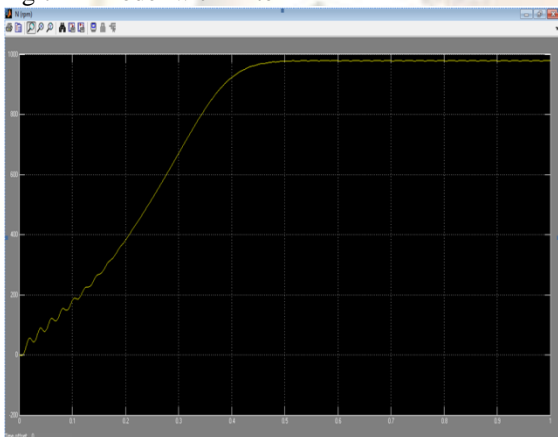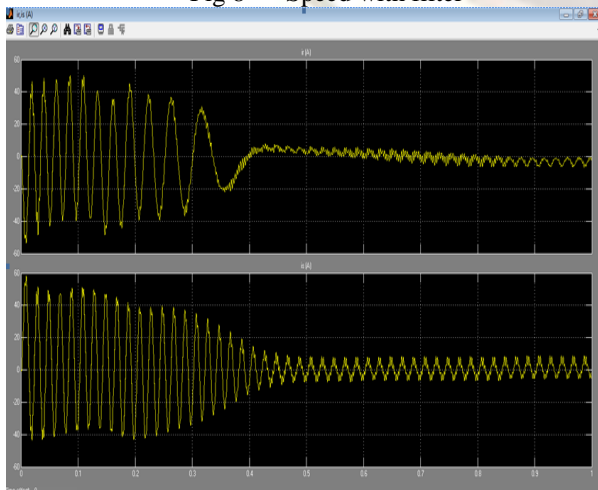

Fig 10   T orque with filter

V.   CONCLUSIONS

This paper has described the design and implementation of a passive filter . The purpose of the proposed filter is to eliminate both high-frequency common-mode and differential-mode voltage from the ac output voltage simultaneously. The validity and effectiveness of proposed filter have been verified by simulation and experimental results carried out on 220V/3Hpmotor system. Furthermore, it can also be concluded that by eliminating common-mode and differential-mode voltage, the side-effects induced by them such as shaft voltage, bearing current, leakage current and overvoltage at motor terminals when a long cable was used to connect the inverter and motor could also be reduced effectively.

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