Measurement of Heat in the Stator Windings of an Open Loop Controlled Three Phase Induction Motor Using AC Filters

Y.R. Manjesha [1] Jyothi Balakrishnan[2]

Abstract – A method for the minimization of temperature rise in the stator windings of an induction motor is presented. This is done by reducing the switching noise produced by the pulse width modulated (PWM) inverter that drives the three phase induction motor. The inverter switching noise is reduced by placing an AC filter at the output of the three phase inverter, with the filter neutral point connected to the DC link mid-point of the capacitors. The main use of the AC filter is the significant reduction of the high dv/dt switching noise of the inverter. The common mode (CM) and differential mode (DM) voltages caused by high dv/dt switching noise are also reduced. Considering harmonic content and dv/dt effects on three phase induction motor the temperature rise in the stator windings with and without filter is measured. It is observed that inclusion of the filter substantially reduces the heating of the motor.

Keywords – Harmonics, common mode voltage, differential mode voltage.

I. INTRODUCTION

The voltage/frequency method is used to control the speed of the three phase induction motor. The solid state PWM drive is designed using a microcontroller. The temperature of the stator windings is measured. Solid state PWM drives Fig. 2 used with induction motors have created concerns with regards to the negative impact it has on the insulation system of the motor [11, 12]. This is mainly because the insulation systems are not designed to withstand impulse like voltages produced by the drive. They have been designed to operate solely at power frequency (50/60Hz). Most of the problems that occur due to the use of these drives result from the steep front pulses (high dv/dt) and added harmonic content of the output waveforms, that cause overshoots at the motor terminals [13], increased motor heating [15], and bearing currents [5]. The large overshoots that occur at the terminals result from using long feeders to supply the motor. These overshoots shown in Fig.1, occur because there is a mismatch between the cable impedance and the motor impedance. This mismatch causes the traveling wave produced by the inverter to be reflected back upon itself. The superposition of the reflected wave and the incoming wave can cause spikes of up to two times the nominal voltage that appear at the motor terminals [13].

The increased motor heating is a result of the additional harmonic content found in the PWM waveform compared with that of the sinusoidal 50Hz waveform. These harmonics do not contribute to the output power of the motor and are simply converted to heat, which may speed up the thermal degradation of the insulation.

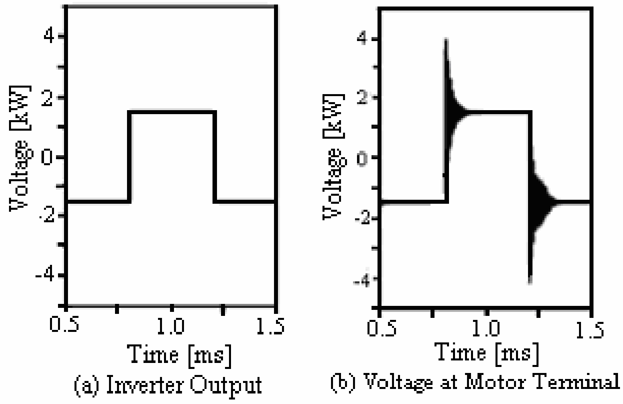

Fig. 1: Inverter output voltage (a) motor terminal voltage (b) motor connected with long feeder.

The PWM inverter uses high speed switching devices such as IGBT's. Due to high speed switching and fast changes in voltages and currents, leads to the following serious problems.

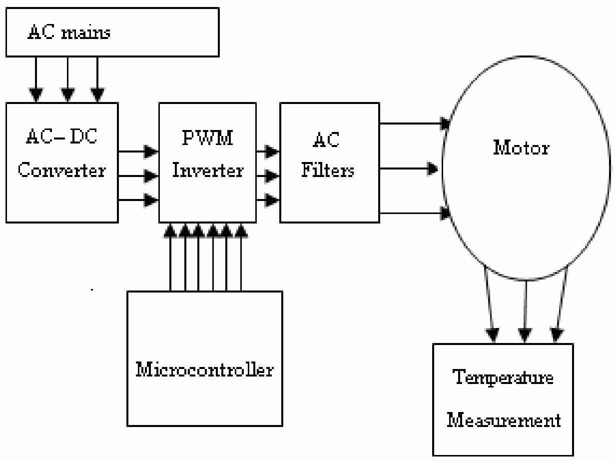

Fig. 2: Three phase induction motor with temperature measurement

1. Ground current flows to earth through stray capacitors inside the motor [1,2].
2. Electromagnetic interference generation [3,6].
3. Generation of shaft voltage and bearing current [7,9].
4. Heating of stator windings
5. Shortening of insulation life of motor [10,13].

Due to the parasitic stray capacitance inside the induction motor and the change in voltage and current caused by

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high speed switching high frequency oscillatory common mode (CM) and differential mode (DM) currents are produced at the instant of every switching shown in Fig. 3. This oscillatory current produces a magnetic field and radiates electromagnetic interference (EMI) noise [4, 14] that introduces a bad effect on induction motor windings.
To reduce the impact of the CM and DM noise due to high dv/dt'sa three phase AC filter is introduced between the inverter and the motor shown in Fig. 5. There are several AC filter topologies that have been used to minimize CM or DM noise which causes temperature rise in stator windings of induction motor. Rendusara [15] proposed the use of R-L-C filter in a star connection with the neutral point of the filter connected to the mid-point of the series DC capacitors in the system Fig. 4. This technique reduces the CM, DM voltages and leakage current. The advantage of this AC filter is that it can be connected at the inverter AC terminals without consideration of the AC cable transmission issues [8].

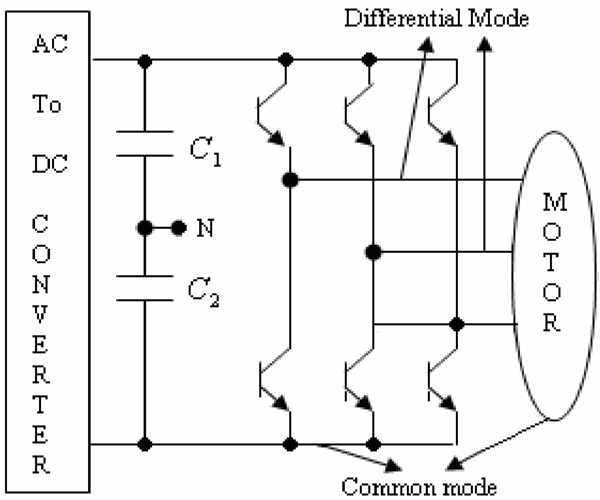

Fig. 3: Inverter drive with common mode and differential mode

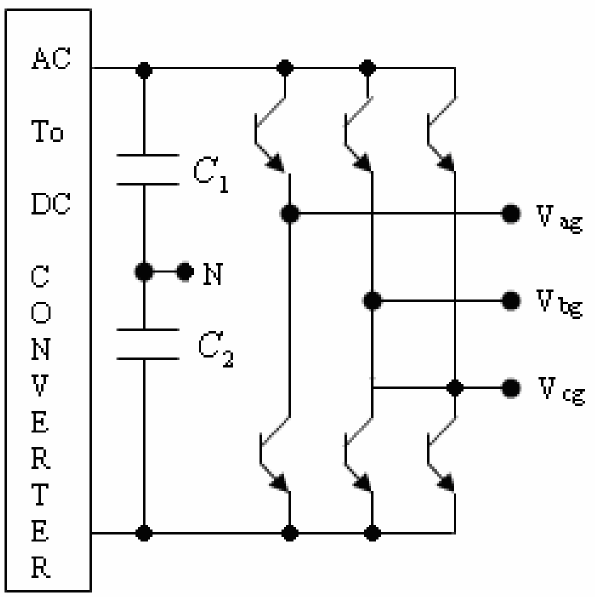

Fig. 4: Motor drive with neutral point

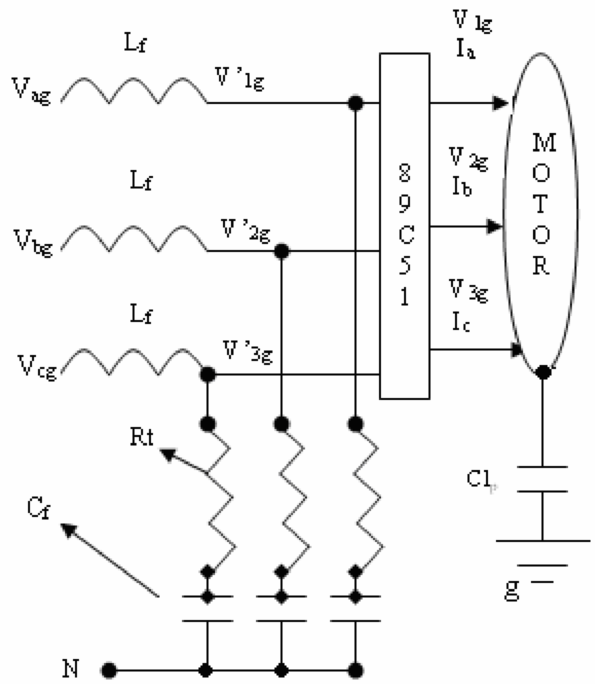

Fig. 5: Filter circuit with neutral point

II. THEORY

The V/F method is used to control the induction motor. The PWM inverter switches at a high frequency of 40 kHz. The three phase induction motor used in the system has a rating of 415V, 50Hz, with a maximum speed of 1300rpm. A variable high torque load is applied to the induction motor which causes the temperature rise in the induction motor. The present system is for a low speed high torque application [17].

III. COMMON MODE VOLTAGE AT MOTOR TERMINALS WITHOUT FILTER

The common mode voltage (V_{cm}) of the induction motor in terms of motor terminal voltages with respect to DC mid-point '0' when no filter is introduced between the inverter and induction motor can be calculated as follows[16].
The common mode voltage (V_{cm}) can be

$$V_{1g} - V_{cm} = R_m I_a + L_m \frac{dI_a}{dt} \quad (1)$$

$$V_{2g} - V_{cm} = R_m I_b + L_m \frac{dI_b}{dt} \quad (2)$$

$$V_{3g} - V_{cm} = R_m I_c + L_m \frac{dI_c}{dt} \quad (3)$$

where V_{1g}, V_{2g} and V_{3g} are the voltages at the motor terminals with respect to ground 'g' and R_m, L_m are the per phase motor winding resistance and inductance respectively.

Adding equations (1), (2) and (3) we obtain

$$V_{1g} + V_{2g} + V_{3g} - 3V_{cm} = R_m + L_m \frac{d}{dt}(I_a + I_b + I_c) \quad (4)$$

Since motor is a balanced system $I_a + I_b + I_c = 0$ therefore the common mode voltage can be expressed as

$$V_{cm} = \frac{V_{1g} + V_{2g} + V_{3g}}{3} \quad (5)$$

The motor terminal voltages with respect to ground 'g' can also be expressed in terms of the DC link middle point '0' of the capacitors as follows.

$$V_{1g} = V_{10} + V_{0g} \quad (6)$$

$$V_{2g} = V_{20} + V_{0g} \quad (7)$$

$$V_{3g} = V_{30} + V_{0g} \quad (8)$$

Therefore

$$V_{cm} = \frac{V_{10} + V_{20} + V_{30}}{3} + V_{0_g} \quad (9)$$

In this inverter three out of six IGBT switches are conducting at any given time. The six switching states provide voltage to the motor and alternate between one top switch with two bottom switches on and two top switches with one bottom switch on.

The summation of the voltage at the inverter AC terminals with respect to the DC link mid-point '0' can be expresses as

$$V_{a0} + V_{b0} + V_{c0} = \pm \frac{V_{dc}}{2} \quad (10)$$

The PWM inverter and motor configuration without an AC filter can experience over voltages due to reflections at the motor terminals which can be attributed to the high voltage dv/dt [7]. This voltage may be approximately twice the amount of voltage seen at the inverter terminals given in equation (10). Therefore the motor terminal voltage with respect to DC link mid-point '0' can be expressed as follows.

$$V_{10} + V_{20} + V_{30} = \pm V_{dc} \quad (11)$$

[One top and two bottom switches on or vice versa]
Instantaneous common mode voltage can be expressed as

$$V_{cm}(inst) = \left[\pm \frac{Vd_c}{3} + V_{0g} \right] \quad (12)$$

IV. COMMON MODE VOLTAGE WITH AN AC FILTER

Shows an R-L-C connected between the inverter and the induction motor with connection between the filter neutral 'N' to the DC link mid-point '0' is shown in Fig. 5. This configuration suppresses the high line to line dv/dt voltage (differential mode). The reduction of differential mode dv/dt helps to alleviate the stresses on the motor windings and also suppresses the voltage reflection along the three phase line. With a proper design of the R-L-C filters, all high frequency switching noise is attenuated and provides a differential mode output of nearly sinusoidal line to line voltage at fundamental frequency for the system.

Since the R-L-C filter supplies near sinusoidal voltage to the induction motor the filter output stage voltages (V'_{1g}, V'_{2g}, and V'_{3g}) can be equated to the induction motor terminals voltages, V_{1g}, V_{2g} and V_{3g}. Therefore the common mode voltage at the motor terminals can be expresses as follows.

$$V_{cm} = \frac{V_{1g} + V_{2g} + V_{3g}}{3} = \frac{V'_{1g} + V'_{2g} + V'_{3g}}{3} \quad (13)$$

The voltage relationship between the inverter terminal voltages and the output of the AC filter can be also expressed as

$$V_{ag} - V'_{1g} = L_f \frac{di1}{dt} \quad (14)$$

$$V_{bg} - V'_{2g} = L_f \frac{di2}{dt} \quad (15)$$

$$V_{cg} - V'_{3g} = L_f \frac{di3}{dt} \quad (16)$$

Adding equations (14), (15) and (16) results in

$$(V_{ag} + V_{bg} + V_{cg}) - (V'_{1g} + V'_{2g} + V'_{3h}) = L_f \frac{d(I_a + I_b + I_c)}{dt} \quad (17)$$

$$I_a + I_b + I_c = 0$$

equation (17) becomes

$$(V_{ag} + V_{bg} + V_{cg}) = (V'_{1g} + V'_{2g} + V'_{3g}) \quad (18)$$

Substituting equation (18) into equation (13) Vcm yields

$$V_{cm} = \frac{V_{ag} + V_{bg} + V_{cg}}{3} \quad (19)$$

Each inverter terminal voltages from equation (19) (V_{ag}, V_{bg} and V_{cg}) can also expressed as the sum of its terminal voltage with respect to the DC link mid-point '0' plus the voltage from the mid-point '0' with respect to the system ground.

$$V_{ag} = V_{a0} + V_{0g} \quad (20)$$

$$V_{bg} = V_{b0} + V_{0g} \quad (21)$$

$$V_{cg} = V_{c0} + V_{0g} \quad (22)$$

Substituting equations (20), (22) and (23) in equation (19) yields.

$$V_{cm} = \frac{V_{a0} + V_{b0} + V_{c0}}{3} + V_{0g} \quad (23)$$

By combining the equations (10) and (23) The instantaneous common mode voltage (V_{cm}) for an induction motor an inverter system with R-L-C results in

$$V_{cm}(inst) = \left[\pm \frac{V_{dc}}{6} + V_{0g} \right] \quad (24)$$

[one top and two bottom switches on or vice versa]

V. AC FILTER DESIGN

The present set up is for low speed high torque applications of motor. The motor is designed to work at 11.5Hz with a speed of 319 rpm using V/F control method. The R-L-C filter is designed for a cut-off frequency of 11.5Hz to 159Hz.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (25)$$

VI. EXPERIMENTAL RESULTS

The temperature of stator windings of three phase induction motor with control of speed by voltage/frequency technique using microcontroller has been studied. The temperature is recorded without any filter between the inverter and induction motor.

The temperature of stator windings after introducing an AC filter for two different cut-off frequencies, by selecting proper values to L-R-C filter is also measured. Since the rise in temperature in induction motor is high at low frequency hence the ratings of the induction motor reduced to 95V/11.5Hz. (V/F) to maintain constant torque.

The Experimental Setup is:
V = 95V
F = 11.5Hz
Speed = 319 rpm
Torque load = 0.477Nm
C_1=C_2=1000mF/450VDC

VII. CONCLUSION

The stator temperature of three phase induction motor is experimentally studied with and without AC filter at the output of the inverter (Fig.6-8). In this experiment we are studying only temperature effects on induction motor, hence the use of an R-L-C filter with its neutral connected to DC link mid-point '0' proved to be advantageous for the induction motor and magnetic bearing system by reducing the common mode (CM) and differential mode (DM) noise without affecting the motor control. Noise in the motor system caused by the DC to AC inverter high dv/dt switching is reduced by designing the values of the R-L-C filters between 11.5Hz to 159 Hz. Voltage stress and voltage doubling effect at the motor terminals have been considerably reduced, which reduces the temperature in the stator windings of three phase induction motor.

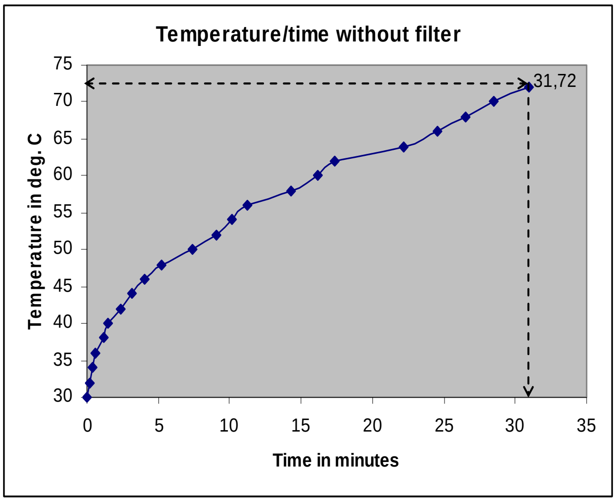

Fig. 6: Temperature/time curve without filter.

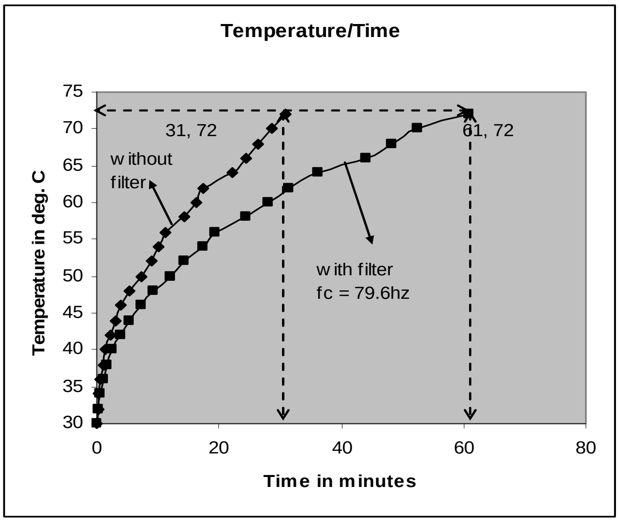

Fig. 7: Selecting L_f = 90mH, C_f = 100 μF, f_c = 79.6Hz.

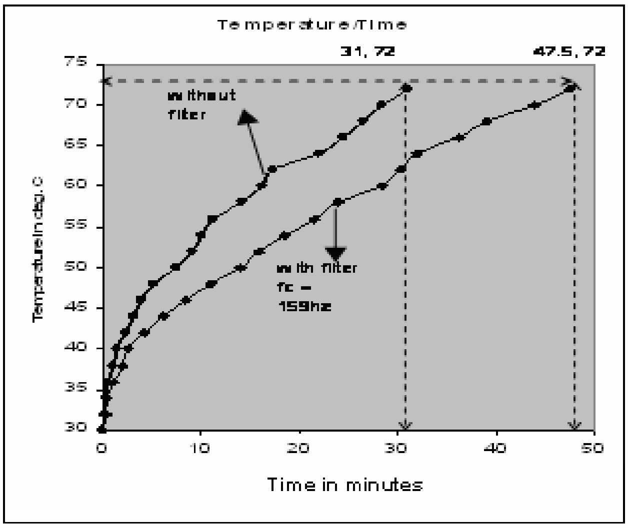

Fig. 8: Selecting L_f = 90 mH, C_f = 100 μF, f_c =159 Hz.

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BIOGRAPHIES

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