An Integrated Inverter Output Passive Sinewave Filter for Eliminating Both Common and Differential Mode PWM Motor Drive Problems

Todd Shudarek
Director of Engineering
MTE Corporation
Menomonee Falls, WI USA
todd.shudarek@mtecorp.com

Tin Luu
R&D Product Engineer
MTE Corporation
Menomonee Falls, WI USA
tin.luu@mtecorp.com

***Abstract*—An integrated output filter that eliminates motor problems due to the PWM waveforms in both common mode and differential mode operation is proposed. The filter includes a three phase inductor constructed with tricore laminations with six mutually coupled windings. The windings possess differential mode inductance and proportionally very large common mode inductance characteristics. The single integrated inductor with the capacitors creates a low pass filter with additional band stop attenuation near the switching frequency in both common mode and differential mode operation. The filter voltage transfer functions are derived. A prototype was constructed and test results presented. Simulation results correlated well with the prototype test data. The prototype filter reduced the differential mode THVD to 4.6% while the common mode voltage near the PWM switching frequency was reduced by 90%.**

Keywords— common mode voltage; differential mode voltage; passive filter

I. INTRODUCTION

PWM (Pulse-width modulation) inverter systems are used throughout industry. They are used on variable-speed drives to power motors. Companies have benefited from these low cost and efficient drive systems. There have been challenges to reduce the negative effects of the differential and common mode voltages that these inverter systems produce. Many users are much less familiar with the common mode voltages produced by a PWM inverter that can result in high peak voltages and currents to ground, especially when long cables are used. Many of the problems associated with common mode voltages and currents are by nature not easy to locate. The common mode effects are associated with difficult to define parasitic parameters of cables and motors. They can cause erratic behavior of control systems. Sometimes a ground fault error will occur and prevent the drive from starting. At the most catastrophic level, ringing of the common mode voltages and currents can cause premature failure of the motor bearings, motor windings, and cables [1]. Applications with lead lengths under about 305 meters can benefit from a *dV/dt* filter that includes both differential mode and common mode impedance with damping matched to the cable surge impedance. These filters reduce reflection of both differential mode and common mode traveling waves [2, 3]. A common solution to common mode and differential mode filtering, when very long motor lead lengths are required, is to use a typical sinewave filter with an isolation transformer. The typical sinewave filter reduces the differential mode harmonics, while the drive isolation transformer removes most of the common mode voltage through galvanic isolation. This is a very cost effective solution when the system voltage is different than the motor voltage, since a transformer is required for operation. But when the drive isolation transformer is not required to adjust voltage, it can be a costly alternative. The cost of the transformer can be as much as the drive itself. Alternative filter solutions to essentially eliminate PWM common mode and differential mode harmonics have been proposed [4, 5]. These options have multiple filter sections that address the common mode and differential mode filtering separately. These solutions are more costly than the integrated proposed filter and the results can be inconsistent. This paper proposes an integrated filter solution that includes both differential and common mode filtering. This paper also performs an analysis of the filtering solution. An experimental filter system, based on the proposed solution, is built and tested with a motor application.

II. BASIC STRUCTURE OF PROPOSED FILTER

A. Proposed Filter Circuit and Components

The circuit of the proposed filter is shown in Fig. 1. Capacitors C_{D1}, C_{D2}, and C_{D3} are solely for differential mode filtering. Capacitors C_{C1}, C_{C2}, and C_{C3} are in a wye connection to ground and provide common mode capacitance. C_{D1}, C_{D2} and C_{D3} are very large in comparison to C_{C1}, C_{C2} and C_{C3}, and only slightly alter the differential mode filter tuning. The six inductor coils are on one tricore inductor core structure [6-8].

B. Coils of the Tricore Inductor

Each of the coils is magnetically coupled to the other five coils [8]. Fig. 2 shows the position of each of the inductor coils on a tricore lamination core structure. Since L_{L1}, L_{L2} and L_{L3}, (line coils) and L_{S1}, L_{S2}, L_{S3} (shunt coils) are symmetrical, only the four unique mutual inductances M_{LL}, M_{SS}, M_{LSO} and M_{LS}

are shown. The symmetry can be used to determine the locations of the remaining mutual inductances.

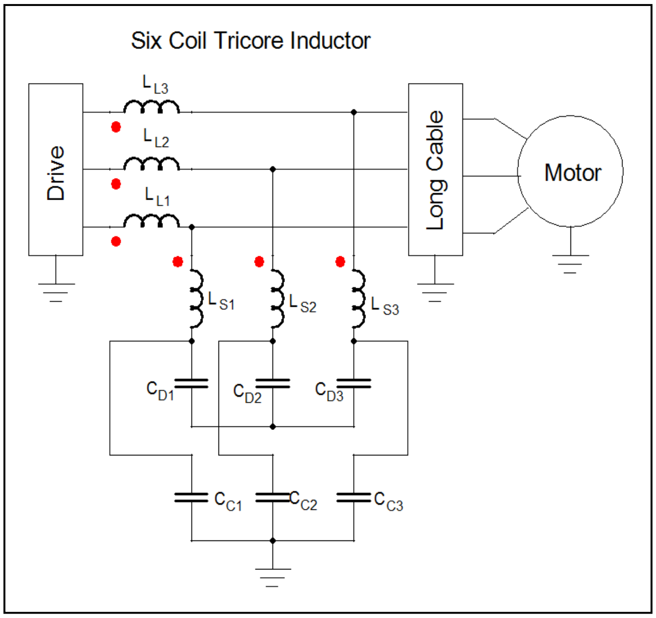

Fig. 1. Circuit of proposed filter

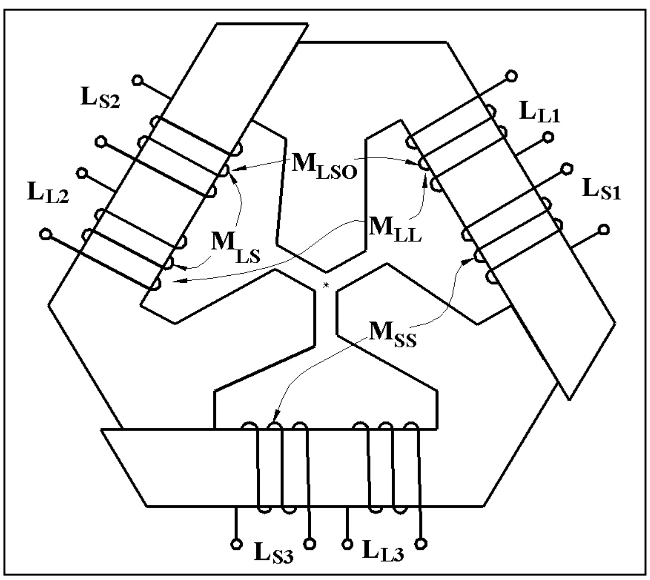

Fig. 2. Inductor coil positions and mutual inductances

III. THEORETICAL ANALYSIS OF PROPOSED FILTER

A. Simplified Common Mode Filter Equivalent Circuit

A simplified common mode equivalent circuit of the filter in Fig. 1 is shown in Fig. 3. The three input terminals are shorted together. C_{D1}, C_{D2} and C_{D3} are removed from the equivalent circuit because they are each at the same voltage potential at both terminals. C_{C1}, C_{C2} and C_{C3} all have the same value of C_C. L_{L1}, L_{L2} and L_{L3} all have the same self-inductance values defined as L_L. L_{S1}, L_{S2}, and L_{S3} all have the same self-inductance value of L_S. The source current I, is equally divide between the three phases. The mutual inductances are defined as shown in Fig. 2. A single KVL loop is used around the outside of the schematic starting at the source then proceeding clockwise.

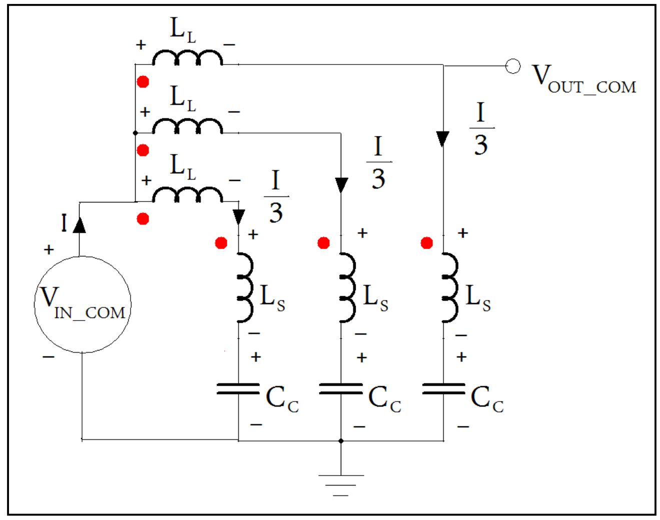

Fig. 3. Simplified common mode equivalent circuit

B. Common Mode Transfer Function

The Fig. 3 is used to write the equation

$$0 = V_{IN\_COM}(s) - L_S s(I(s)/3) - M_{LL}s(I(s)/3) - M_{LL}s(I(s)/3) - M_{LS}s(I(s)/3) - M_{LSO}s(I(s)/3) - M_{LSO}s(I(s)/3) - L_S s(I(s)/3) - M_{SS}s(I(s)/3) - M_{SS}s(I(s)/3) - M_{LS}s(I(s)/3) - M_{LSO}s(I(s)/3) - M_{LSO}s(I(s)/3) - (1/C_C s)(I(s)/3) \qquad (1)$$

Note that after each voltage drop in (1) across the self-inductance there are five mutual inductance voltage drops that follow. Solving for $I(s)$ results in (2)

$$I(s) = (3sV_{IN\_COM}(s)C_C)/[1+s^2C_C(L_L+L_S+2M_{LL}+4M_{LSO}+2M_{LS}+2M_{SS})] \qquad (2)$$

The $V_{OUT\_COM}(s)$ is calculated by multiplying the impedance of L_S, and each of the associate five mutual inductances and C_C with one third of $I(s)$. The result for $V_{OUT\_COM}(s)$ is in (3)

$$V_{OUT\_COM}(s) = [L_S s+M_{SS}s+M_{SS}s+M_{LS}s+M_{LSO}s+M_{LSO}s+(1/C_C s)] * (I(s)/3) \qquad (3)$$

Dividing both sides of (3) by $V_{IN}(s)$ and simplifying results in the common mode voltage transfer function (4).

$$V_{OUT\_COM}(s)/V_{IN\_COM}(s) = [1+s^2C_C(L_S+2M_{LSO}+M_{LS}+2M_{SS})]/[1+s^2C_C(L_L+L_S+2M_{LL}+4M_{LSO}+2M_{LS}+2M_{SS})] \qquad (4)$$

C. Simplified Differential Mode Filter Equivalent Circuit

A simplified filter differential mode equivalent circuit of the filter in Fig. 1 is shown in Fig. 4.

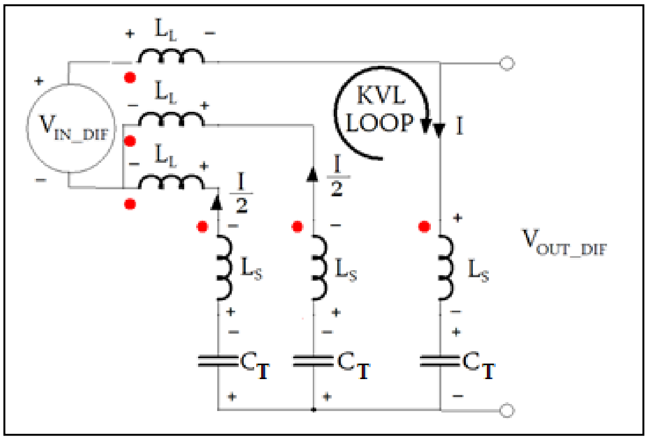

Fig. 4. Simplified differential mode equivalent circuit

The two input terminals and output terminals are shorted together for differential mode circuit analysis. C_{D1}, C_{D2} and C_{D3} are paralleled with C_{C1}, C_{C2}, and C_{C3} respectively, with the parallel value of C_T. L_{L1}, L_{L2}, and L_{L3} all have the same self-inductance value defined as L_L. L_{S1}, L_{S2}, and L_{S3} all have the same self-inductance value defined as L_S. The source current I, is equally divided between two of the paralleled equal circuit branches. The mutual inductances are as defined as shown in Fig. 2. A single KVL loop is used in Fig. 4, starting at V_{IN_DIF} and proceeding clockwise.

D. Differential Mode Transfer Function

The Fig. 4 is used to write the equation as follows:

$$0 = V_{IN\_DIF}(s) - L_L sI(s) + M_{LL}s(I(s)/2) + M_{LL}s(I(s)/2) - M_{LS}s(I(s)/2) + M_{LSO}s(I(s)/2) + M_{LSO}s(I(s)/2) - L_S sI(s) + M_{SS}s(I(s)/2) + M_{SS}s(I(s)/2) - M_{LS}sI(s) + M_{LSO}s(I(s)/2) + M_{LSO}s(I(s)/2) - (1/C_D s)I(s) - (1/C_D s)(I(s)/2) - L_S s(I(s)/2) + M_{SS}sI(s) - M_{SS}s(I(s)/2) + M_{LSO}sI(s) - M_{LS}s(I(s)/2) - M_{LSO}s(I(s)/2) - L_L s(I(s)/2) + M_{LL}sI(s) - M_{LL}s(I(s)/2) - M_{LS}s(I(s)/2) + M_{LSO}sI(s) - M_{LSO}s(I(s)/2) \quad (5)$$

The solution for $I(s)$ is:

$$I(s) = (2V_{IN}(s)C_D s)/3[1+s^2C_D(L_L+L_S-M_{LL}-2M_{LSO}+2M_{LS}-2M_{SS})] \quad (6)$$

Multiply $I(s)$ in (6) by the impedance of the self-inductance of L_S, five associated mutual inductances and the capacitance to calculate $V_{OUT\_DIF}(s)$.

$$V_{OUT\_DIF}(s) = [-L_S s+0.5M_{SS}s+0.5M_{SS}s-M_{LS}s+0.5M_{LSO}s+0.5M_{LSO}s-(1/C_D s)] * I(s) \quad (7)$$

Substituting C_D and C_C in for C_T, normalizing, simplifying and solving for $V_{OUT\_DIF}(s)/V_{IN\_DIF}(s)$ results in the following:

$$V_{OUT\_DIF}(s)/V_{IN\_DIF}(s) = [1+s^2(C_D+C_C)(L_S-M_{LSO}+M_{LS}-M_{SS})]/[1+s^2(C_D+C_C)(L_L+L_S-M_{LL}-2M_{LSO}+2M_{LS}-M_{SS})] \quad (8)$$

E. Filter Design Example

An example filter is designed with the system parameters in Table I. The filter design parameters are shown in Table II. The inductance parameters were determined by using a finite element Ansoft Maxwell magnetics program.

TABLE I. TEST SYSTEM PARAMETERS

System Voltage	480 V
Fundamental frequency	60 Hz
PWM carrier frequency	2 kHz
Motor rating	50 HP
Cable type	4 AWG shielded
Cable length	305 meters
Filter rating	55 A

TABLE II. FILTER PARAMETERS

L_L	Line self-inductance	22.09 mH
L_S	Shunt self-inductance	480.8 uH
M_{LL}	Mutual inductance line-line	21.28 mH
M_{SS}	Mutual inductance shunt-shunt	460.8 uH
M_{LSO}	Mutual inductance line-shunt on different coils	3.13 mH
M_{LS}	Mutual inductance line-shunt on the same coils	3.25 mH
C_D	Differential mode capacitance	48.0 uF
C_C	Common mode capacitance	0.570 uF

The common mode and differential mode voltage transfer function were calculated using (4), (8) and Table II.

$$V_{OUT\_COM}(s)/V_{IN\_COM}(s) = (1+6.2*10^{-9}s^2)/(1+4.85*10^{-8}s^2) \quad (9)$$

$$V_{OUT\_DIF}(s)/V_{IN\_DIF}(s) = (1+6.5*10^{-9}s^2)/(1+5.07*10^{-8}s^2) \quad (10)$$

The plot of both the differential mode and common mode transfer functions are shown in Fig. 5 and Fig. 6, respectively.

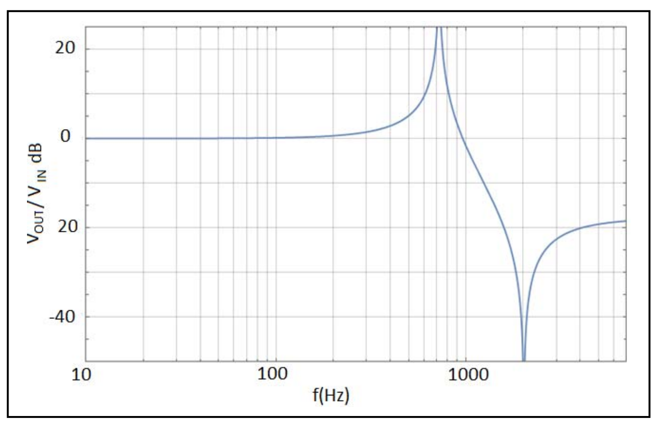

Fig. 5. Differential mode voltage transfer function

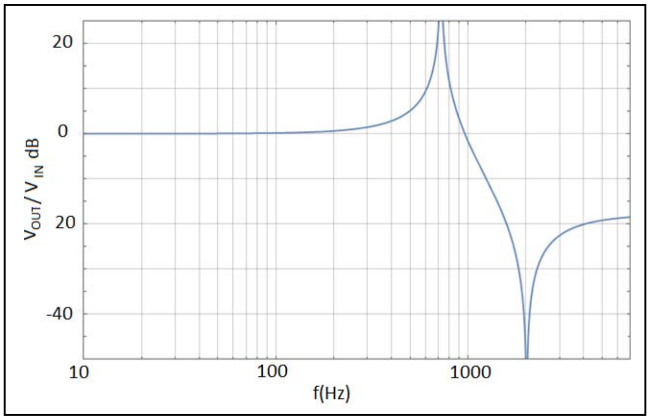

Fig. 6. Common mode voltage transfer function

The filter, both common mode and differential mode, is designed to have a pole near 700Hz. If the drive output voltage does not include harmonics near the resonant frequency, the internal equivalent resistance within the tricore inductor is usually enough, and no discrete damping resistance is required. A zero in the transfer function, for both common mode and differential mode, was placed near 2000Hz, the dominant PWM frequency.

IV. SIMULATION RESULTS

A completed filter topology simulation system comprises of a two level IGBT conventional inverter, a tricore inductor, three differential mode capacitors, three common mode capacitors, and 50 HP load motor. The system is simulated using Ansoft Simplorer as shown in Fig. 7.

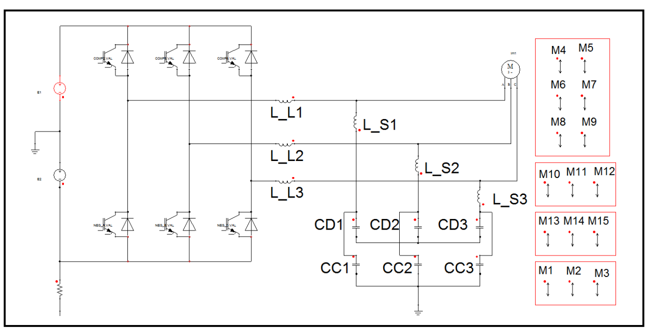

Fig. 7. Simulation system of common mode and differential mode filter

The tricore inductor in Fig. 7 has

-Self-inductance of three input coils (L_L1, L_L2 and L_L3)

-Self-inductance of three shunt coils (L_S1, L_S2 and L_S3)

-Mutual inductance between input coils (L_L1 and L_L2, L_L2 and L_L3, L_L3 and L_L1)

-Mutual inductance between shunt coils (L_S1 and L_S2, L_S2 and L_S3, L_S3 and L_S1), mutual inductance between input coils and shunt coils (L_L1 and L_S1, L_L1 and L_S2, L_L1 and L_S3, L_L2 and L_S1, L_L2 and L_S2, L_L2 and L_S3, L_L3 and L_S1, L_L3 and L_S2, L_L3 and L_S3)

Fifteen mutual inductance values are modeled in the boxes of Fig. 7. The total six self-inductance values are the values of the coils L_L1, L_L2, L_L3, L_S1, L_S2 and L_S3. The simulation is based on the parameters of Table I and Table II. The line to line voltages of the inverter output and motor terminals are shown in Fig. 8 and Fig. 9, respectively.

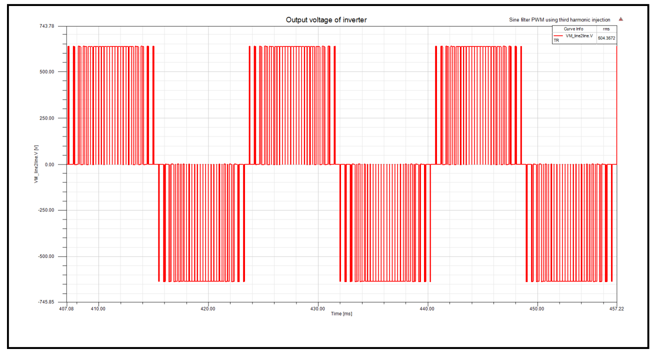

Fig. 8. Inverter output line to line voltage (504V RMS)

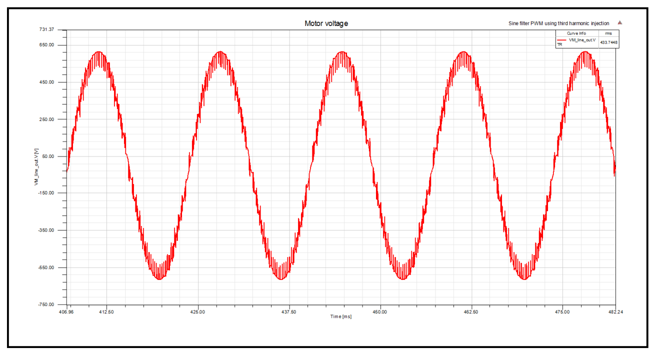

Fig. 9. Line to line motor voltage (434V RMS)

The spectral of motor voltage with THVD of 4.5% is shown in Fig. 10

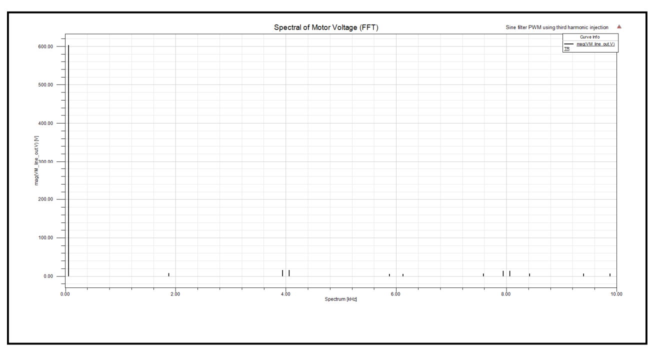

Fig. 10. The Spectral of motor voltage (THVD 4.5%)

The inverter output and motor currents are shown in Fig. 11 and Fig. 12, respectively. The magnetic flux density of input coil and the harmonic spectrum of the magnetic flux density are shown in Fig. 13 and Fig. 14, respectively.

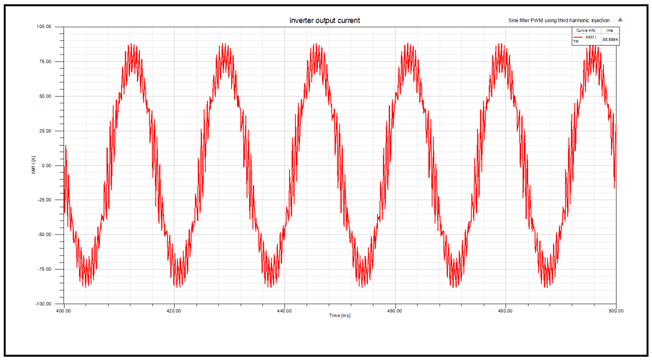

Fig. 11. Inverter output current (55.5A)

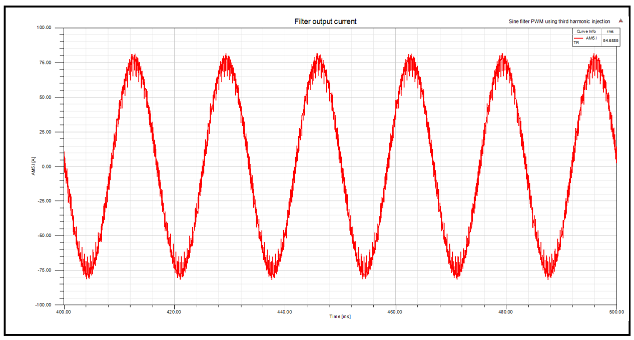

Fig. 12. Motor current (54.7A)

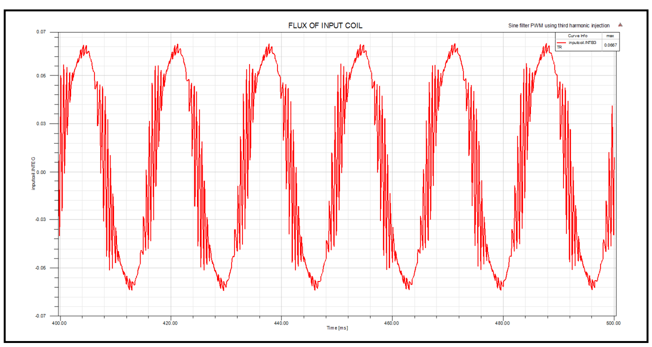

Fig. 13. Coil magnetic flux density

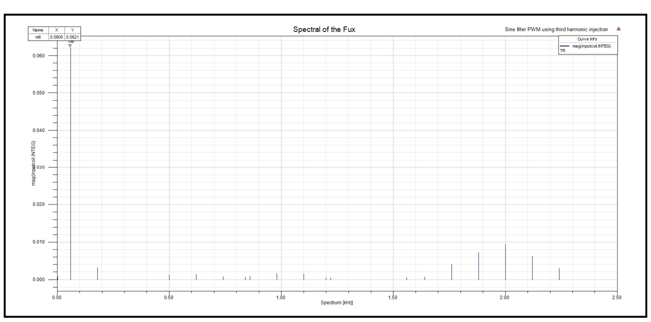

Fig. 14. Harmonic spectrum of the coil magnetic flux density

The magnetic flux density and its harmonic spectrum are useful design parameters for inductors. The common mode voltage both before and after using the filter topology are shown in Fig. 15 and Fig. 16.

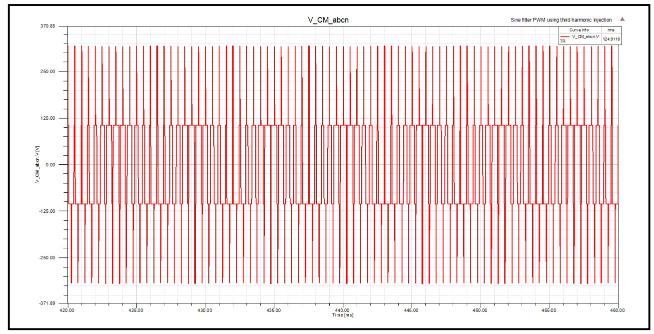

Fig. 15. Common mode voltage without proposed filter (125V RMS)

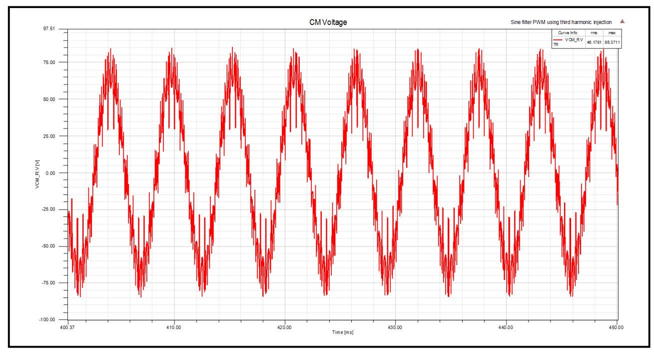

Fig. 16. Common mode motor voltage with proposed filter (46V RMS)

V. EXPERIMENTAL RESULTS

Experimental results were obtained using the system parameters in Table I and filter parameters in Table II. The laboratory conducted two experiments both with and without the filter topology. The experimental filter is shown in Fig. 17.

Fig. 18 and Fig. 19 show the differential mode voltage both without and with the filter, respectively. Without the filter, the differential mode line to line voltage is a typical output inverter waveform with high THVD. The motor line to line voltage with the filter topology has a sinusoidal waveform. The peak voltage was 1660V without the filter, and with the filter THVD was 4.6%.

Fig. 20 and Fig. 21 show the common mode voltage without and with the filter. The peak common mode voltage was reduced from 643V to 228V. The PWM switching harmonics at 2 kHz were reduced by 90%. Most of the remaining common mode voltage was the third harmonic at 180 Hz which is present from the six-pulse rectifier converter portion of the drive.

Fig. 22 and Fig. 23 show the common mode currents with and without the filter. The motor common mode current was reduced from 16.7A peak to 3.5A peak. The total common mode filter capacitor current was 4.9A peak. This capacitor current was well below the motor common mode current of 16.7A without the filter.

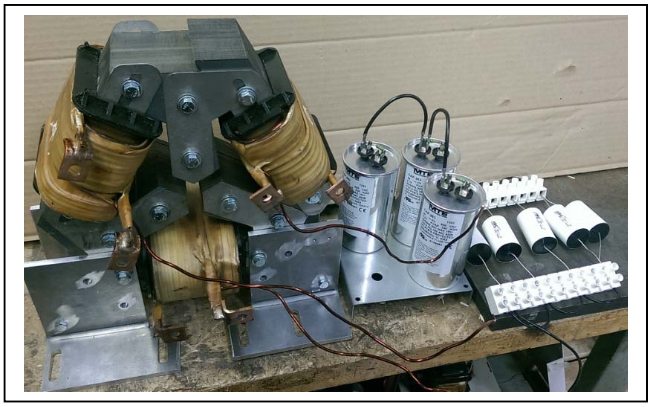

Fig. 17. Experimental filter

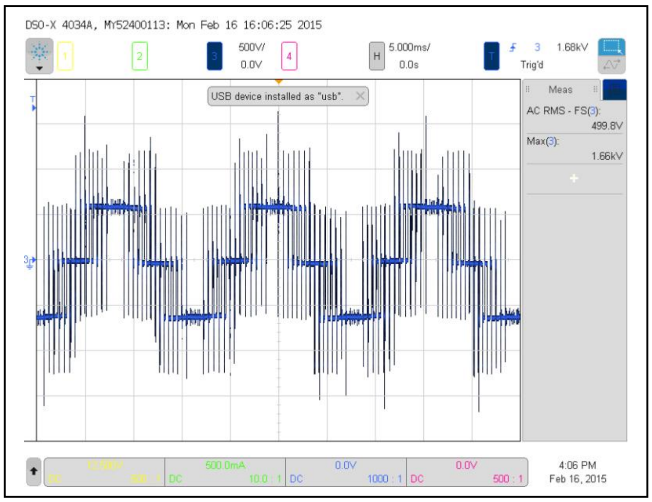

Fig. 18. Motor differential mode voltage without the proposed filter

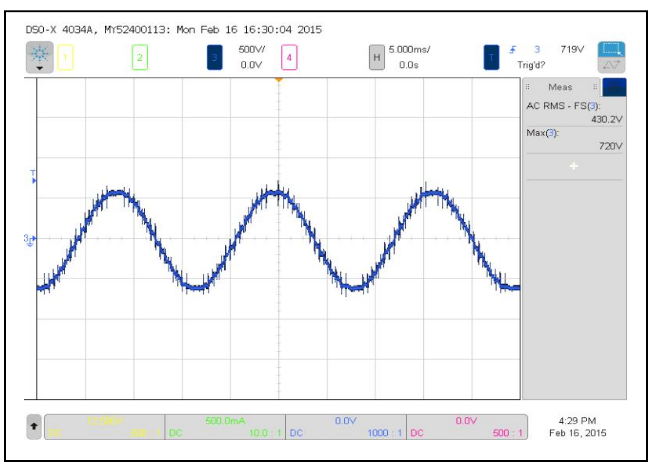

Fig. 19. Motor differential mode voltage with the proposed filter

The experimental result in Fig. 18 shows that the motor voltage without the filter is around 500V and the peak voltage is 1660V. Fig. 19 shows the motor voltage with the filter is around 430V and the peak voltage is 720V.

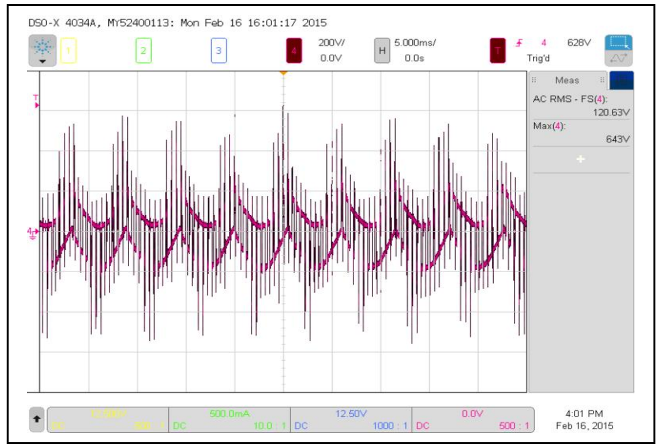

Fig. 20. Motor common mode voltage without the filter

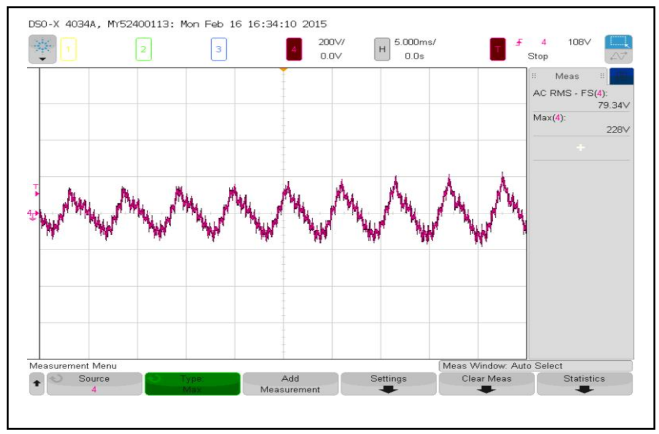

Fig. 21. Motor common mode voltage with the proposed filter

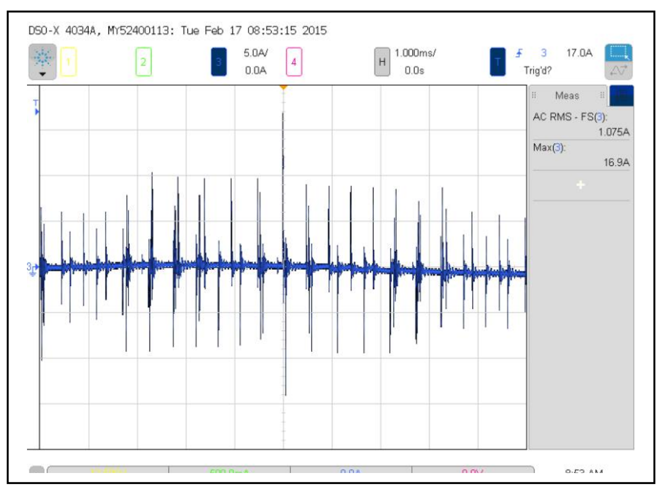

Fig. 22. Motor common mode current without the proposed filter

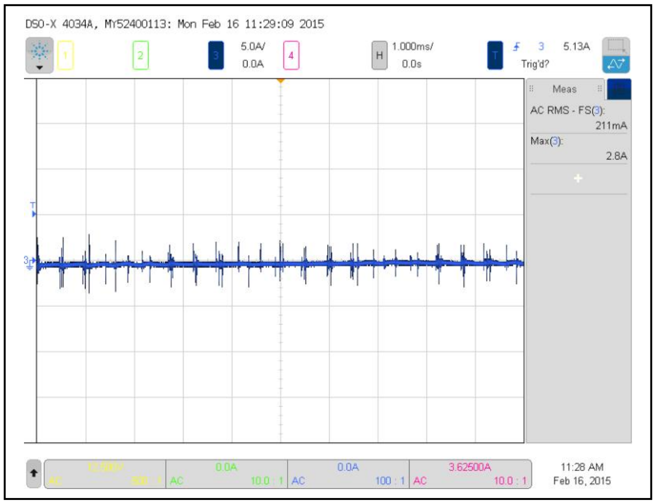

Fig. 23. Motor common mode current with the proposed filter

Fig. 22 shows that the common mode peak current without the filter is 16.7A and common mode peak current with the filter is 2.8A. Fig. 23. Fig. 24 show the common mode motor and capacitor currents, respectively.

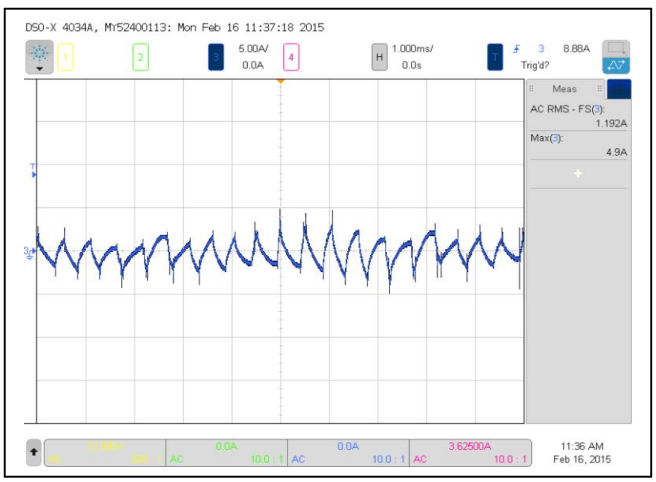

Fig. 24. Common mode capacitor current with the proposed filter

VI. CONCLUSION

The modeling and analysis of an integrated inverter output passive sinewave filter for eliminating both common and differential mode has been presented. The transfer functions of common mode and differential mode equations also have been verified and demonstrated in a very simple form.

The filter has separate common mode and differential mode filtering voltage transfer functions that can be independently analyzed. It has been shown that these transfer functions can be set to the ideal condition of being practically identical.

Through analysis and simulation, experimental results of the prototype have shown that the proposed filter is capable of reducing the differential mode THVD to less than 5%. It is also proven to reduce the common mode detrimental high frequency voltage harmonics by more than 90%.

The performance of the integrated filter has been evaluated with a 480V 50HP motor drive system with a switching frequency of 2 kHz. Experimental results obtained in the laboratory confirm the validity of the simulation model developed in this paper.

REFERENCES

[1] T. A. Shudarek, "Understanding Adjustable Speed Drive Common Mode Problems and Effective Filter Solutions", MTE Corporation, 2015.

[2] R. M. Tallam, G. L. Skibinski, T. A. Shudarek and R. A. Lukaszewski, "Integrated Differential-Mode and Common-Mode Filter to Mitigate the Effect of Long Motor Leads on AC Drives." 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, 2010, pp.838-845.

[3] "The dV Sentry. The future is here.", Retrieved October 28, 2016, from http://www.mtecorp.com/products/dv-sentry-dvdt-filters/

[4] A. L. Julian, T. A. Lipo, D. M. Divan, "Method and apparatus for reducing common mode voltage in multi-phase power converters," U.S. Patent 5 852 558, December 22, 1998.

[5] X. Chen, D. Xu, "A Novel Inverter-Output Passive Filter for Reducing Both Differential- and Common Mode *dv/dt* at the Motor Terminals in PWM Drive Systems," *IEEE Trans. Ind, Electron.,* vol. 54, no. 1, pp. 419-425, Feb. 2007.

[6] T. A. Shudarek, "Common Mode Differential Mode Three Phase Reactor," U.S. Patent 7 768 373, August 3, 2010.

[7] T. A. Shudarek, "Adjustable Integrated Combined Common Mode and Differential Mode Three Phase Inductors and Methods of Manufacture and Use Thereof," Patent application number 14/513056, October 13, 2014.

[8] T. A. Shudarek, J. P. Mertes, "Drive Output Harmonic Mitigation Devices and Methods and Use Thereof," U.S. Patent 9 083 234, July 14, 2015.