Minimization of Harmonics, Vibrations and Acoustic Pressure in BLDC Motor Drive Using Variable Inductor Filter

[1]Parag S. Chaudhari, [2]Sanjaykumar L. Patil
[1] [2] College of Engineering, Pune, India
[1] electrlengr@gmail.com,[2] slp.instru@coep.ac.in

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Abstract:
Harmonics with corresponding vibrations and its alleviation is very essential for high rating and high-performance Brushless DC (BLDC) motor drives. BLDC motor drives have substantiated an increasing demand for various automobile as well as industrial applications in recent times. Due to wide frequency range, these drives are most suited for variable speed drive applications. For longevity of motor drive system and to improve overall drive performance, harmonics and accompanying vibrations mitigation plays a vital role. High frequency current ripples can result in significant damage to the motor winding insulation and bearings. This paper proposes a servo controlled innovative inductor filter scheme which reduces current harmonics, which helps to reduce resulting torque ripples over complete speed range (and hence over wide frequency range) of BLDC Motor. Reduction in torque ripples result in minimization of motor structural vibrations and acoustic pressure. The strategy is implemented on a three phase 2 kW, 48 V, inverter fed BLDC motor drive using TI's DSP TMS320F2812 controller followed by simulation using MATLAB / Simulink. For accurate instant position of variable inductor, a position control for DC servomotor with curve fitting technique is used. Experimental results confirm the potency of the proposed strategy. The current harmonics and corresponding motor vibrations are compared for performance of BLDC motor drive with and without the variable inductor filter.

Keywords: *BLDC motor, speed control, variable inductor filter, harmonics and vibration reduction, acoustic pressure reduction.*

I. INTRODUCTION

Brushless DC motors are the first choice in today's era and are capturing the industry due to its unique features of fast dynamic response, high efficiency, high torque to weight ratio, long service life. BLDC motors has low loss, clean type actuator as the sparking due to brushes and the losses because of commutation are removed completely, which widens its area of application in the field of automation, Defense, aerospace and drones' applications, etc. [1], [2]. In the brush-less DC motor an electronic servo system replaces the mechanical commutator, with hall effects sensors embedded on stator, or angle encoders which identify the angle of rotor and s determine the switching pattern for the inverter.

Now-a-days there are methods to identify the position of the rotor without the hall effect sensors. [3], [4], [5] in which the back emf un-energized coils to infer rotor position, is calculated.

A. Review Stage

Various strategies for BLDC Motor control are discussed in this paragraph. DSP based advanced controllers are also employed to manage the torque and speed. A four-quadrant operation suitable for electric traction is presented in [5]. A speed controller for BLDC motor comprising of phase locked loop is deployed in [6]. However, these schemes lack high dynamic control of torque required for many industrial applications. In [7], line current feedback is

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used for current controlled modulation where as an advance angle calculation is implemented in [8] to enhance the torque to current ratio of a BLDC motor. For a trapezoidal BLDC motor, digital control strategy drive using FPGA is implemented in [7], [8] where as digital control strategy using dSPACE is presented in [8].

B. Torque Ripple

To reduce torque ripples in BLDC motor drive, various strategies employed are as presented in this paragraph. In [9]

duty cycle of PWM is regulated by a current control rule generated from the wave function of back emf which eliminates the free-wheeling of the diode for inactive phase and reduces resulting torque ripples. In [10], non-uniformity in back emf waveform is reduced by feeding appropriate phase currents for compensation using back emf estimation method which reduces torque ripple. In [11], discrepancy times of two commutated phase currents throughout the commutation intervals are equalized to reduce torque ripple. In [12], momentarily controlled source voltage is applied to the inverter, which limits phase currents reducing the switching current ripples by using hysteresis current controller.

C. Harmonics

To minimize power harmonics various strategies implemented are as under. The motor is susceptible to electromagnetic interference [13]. A combined RLC filter with LC trap filter, tuned for the required switching frequency is proposed in [14], reduces the switching harmonies in PMSM drive considerably. Harmonic noises and torque ripples in a permanent magnet synchronous motor (PMSM) drive are reduced by implementing an active filter topology [15]. A review of various Power Factor Corrector (PFC) converter topologies for BLDC motor drive is presented in [16] which improves power factor along with reduction in harmonics and torque ripples. Converter topology based on single ended primary inductance converter (SEPIC) [17] without using voltage or current sensors for driving a BLDC motor is proposed. This paper works on reducing the lower order harmonics and improvement in power factor.

D. LC Filter

Various strategies using LC Filters are employed for three phase inverters. An LC filter proposed in [18] minimizes transient current, which in turn reduces inverter stack size whereas LC filter is proposed in [19] reduces at the output of inverter. A flatness-based control (FBC) of three phase *dv/dt* inverters with LC filter provides sine wave with less THD in output voltage [20].

E. Vibrations

All above factors and strategies generate a lot of noise and vibrations in motor structure, thus weakening the winding insulation, damaging the motor bearing and reducing life of motor. It has been observed that the stator excitation by electronic commutation in BLDC motor drives generate acoustic noise which aggravate mechanical resonances in the structure of motor [21] – [23]. PMSM motor speed variations are reduced by implementing feed forward compensation method in which the harmonics present in the dq-control signals are suppressed using Fourier transform and repetitive control [24] - [27]. A novel algorithm for alignment of the encoder with motor to minimize the amplitude of vibrations during start up is presented in [28], EMI is an added issue explained in [29]. In [30], electronic commutation pattern is altered to avoid reinforcing of mechanical resonances, which significantly reduces pure tone acoustic noise caused due to mechanical resonances. In [31], analysis of the vibration and acoustic noise caused by electromagnetic torque ripples in BLDC motor drive after application of sinusoidal waveform is presented.

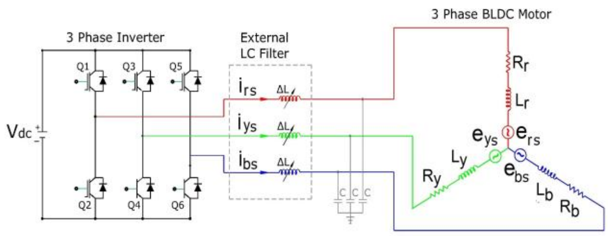

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Fig. 1 Circuit diagram of BLDC motor drive with proposed filter

All these strategies discussed for control BLDC Motor drive, torque ripple minimization, harmonics and motor vibration reduction, involve complex control hardware and cost in effect. Lot of research has already been carried out for torque ripple minimization of BLDC motor drive by limiting current ripples, whereas less attention is given to studies on harmonics associated vibrations and acoustic noises. Methods to reduce torque ripples are important because reduction in torque will reduce corresponding motor vibrations and acoustic noise. Therefore harmonics, torque ripples, mechanical vibrations and corresponding acoustic noise in BLDC motor drive are co-related to each other. In this paper, a new motorized variable inductor filter strategy with curve fitting technique is proposed to reduce harmonics as well as vibrations and acoustic pressure in a trapezoidal type BLDC Motor drive to enhance overall performance of the system. Variable inductor filter is connected in between inverter output and motor input.

II. Mathematical model of proposed system

Simplified circuit for BLDC motor drive along with variable inductor and fixed capacitor is shown in Fig. 1. Three phase inverter feeds power to BLDC motor (P. S. Chaudhari et al., 2016).

$$\begin{bmatrix} V_{rs} \\ V_{ys} \\ V_{bs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{rs} \\ i_{ys} \\ i_{bs} \end{bmatrix} + \begin{bmatrix} L_{rr} & L_{ry} & L_{rb} \\ L_{yr} & L_{yy} & L_{yb} \\ L_{br} & L_{by} & L_{bb} \end{bmatrix} \begin{bmatrix} i_r \\ i_y \\ i_b \end{bmatrix} + \begin{bmatrix} e_{rs} \\ e_{ys} \\ e_{bs} \end{bmatrix} \quad (1)$$

where, R_s = per phase stator winding resistance, L = inductance of respective phases. M = mutual inductance. V_{rs}, V_{ys}, V_{bs} are respective phase voltages. i_{rs}, i_{ys}, i_{bs} are respective phase currents and Peak induced emfs in stator winding.

$$E_p = N\phi_a\omega_m = \lambda_p\omega_m \quad (2)$$

Where, ϕ_a = respective stator flux, $N\phi_a = \lambda_p$ and ω_m is maximum frequency in rad/s.

$$L_{rr} = L_{yy} = L_{bb} = L \quad (3)$$

$$L_{ry} = L_{yr} = L_{rb} = L_{br} = L_{yb} = L_{by} = M \quad (4)$$

Substituting [2], [3] and [4] in [1], externally added inductor is ΔL_{ext} as a part of proposed filter and for balanced stator phase currents

$$i_{rs} = i_{ys} + i_{bs} = 0 \quad (5)$$

$$\begin{bmatrix} V_{rs} \\ V_{ys} \\ V_{bs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{rs} \\ i_{ys} \\ i_{bs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L + \Delta L_{ext} - M & 0 & 0 \\ 0 & L + \Delta L_{ext} - M & 0 \\ 0 & 0 & L + \Delta L_{ext} - M \end{bmatrix} \begin{bmatrix} i_r \\ i_y \\ i_b \end{bmatrix} + \begin{bmatrix} e_{rs} \\ e_{ys} \\ e_{bs} \end{bmatrix} \quad (6)$$

The electromagnetic torque is

$$T_e = \frac{e_{rs}i_{rs} + e_{ys}i_{ys} + e_{bs}i_{bs}}{\omega_m} \quad (7)$$

The instantaneous induced emfs are given by

$$e_{rs} = f_{rs}(\theta_r)\lambda_p\omega_m\,;\ e_{ys} = f_{ys}(\theta_r)\lambda_p\omega_m \text{ and } e_{bs} = f_{bs}(\theta_r)\lambda_p\omega_m \quad (8)$$

Where, $f_{xs}(\theta_r)$ is induced emf position dependent function in phase x, where, $f_{rs}(\theta_r)$, $f_{ys}(\theta_r)$, $f_{bs}(\theta_r)$ = position dependent function in the induced emf in respective phases.

The electromagnetic torque equation becomes the dynamics of BLDC motor drive is represented as

$$J\frac{d\omega_m}{dx} = T_e - T_L - B\omega_m \quad (9)$$

III. Proposed variable inductor filter scheme for brushless DC motor drive

BLDC motor drive coupled to a proposed variable inductor filter is as shown in Fig. 2. Depending on the voltage to be controlled, a control signal for the SCR module of converter is provided from DSP. Variable inductor filter is connected in between the output of inverter and BLDC motor. A Texas make controller TMS 320F2812 is used for controlling action of the drive. A fixed value capacitor is selected as a part of LC filter through various iterations to maintain voltage level. Further the inductance of variable inductor filter varies according to the rotor speed as per the curve fitting algorithm given to the controller. Motor and generator set-up as shown in Fig. 5(a,b) is kept on soft rubber pads so that vibrations can be noted accurately. The current and voltage harmonics are recorded with and without proposed filter for verifying effect of variable inductor filter. Vibration pattern as well as acoustic pressure is measured for various speeds.

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A. Selection of variable inductor

A servo controlled variable inductor selected would be such that whose value could be able to vary as per the supply frequency (rotor speed) of motor. The option for this is to use either multi tap inductor or variable inductors (H. -S. Kim et al., 2011; T. G. Habetler et al., 1999). A capacitor of appropriate value for suitable operating voltage has to be selected. Factors such as line voltage, back EMF, line current should be considered while designing filters. The current rating of the selected inductor should be 20 % more than the maximum output current of the inverter or the rated current of the BLDC motor. Care should be taken for selection of inductor so that the inductor doesn't get saturated. The inductor attenuates the current ripples resulting from the switching action of inverter. In this paper a second order LC filter is used. The motor inductance makes the system a third order LCL filter. The values of the motor resistance per phase are 0.11Ω and inductance per phase is 0.045 H for motor frequency 400Hz. The value of external inductor to be added in the motor circuit is decided on the basis of upper and lower cut off frequency of the LC filter.

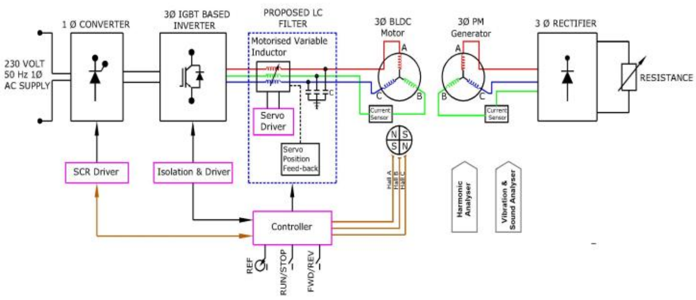

Fig. 2 Block diagram of the proposed scheme

Transfer function of the proposed filter is as given below.

$$\frac{V_o(s)}{V_i(s)} = \frac{(2\pi f_c)^2}{s^2 + 2\xi(2\pi f_c)s + (2\pi f_c)^2} \quad (10)$$

Where cut-off frequency is f_c and ξ is a damping factor.

$$\omega_n = 2\pi f_c \text{ and } f_c = \frac{1}{2\pi\sqrt{LC}} \quad (11)$$

Quality factor Q is given by

$$Q = \frac{1}{2\xi} \quad (12)$$

The inverter current is given by [25], [26],

$$i_{inv} = \frac{\sqrt{2}\omega_f C_f V}{\sqrt{1-\xi_c^2}} e^{-\xi_c \omega_f t} \sin\left(\omega_f \sqrt{1-\xi_c^2}\, t\right) \quad (13)$$

Value of motor resistance per phase is 0.16Ω and inductance per phase is 0.025H. Motor frequency is 400 Hz. Considering increment of 0.005H is steps till it reaches to 0.110 H.

$$L_{Filter} = L_{Motor} + L_{External} \quad (14)$$

B. Variable Inductor Position Control

Position control of a variable inductor is selected as per the value of the inductance required which is to be set with respect to the motor speed/frequency. As mentioned in Eq. no. 20, it is to be noted that the filter inductance as the addition of motor inductance and externally added inductance. Along with insertion of external inductance manually in the motor circuit, a relation in between external inductance to be added versus motor speed/frequency is obtained which is shown in Fig. 3.

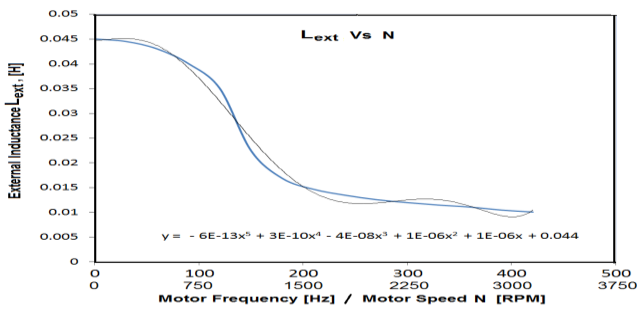

Fig. 3 External Inductance to be added in motor circuit

The same is represented by following equation obtained by curve fitting technique.

$$L_{ext} = -6\times10^{-13} f^5 + 3\times10^{-10} f^4 - 4\times10^{-8} f^3 + 1\times10^{-6} f^2 + 1\times10^{-6} f + 0.0444 \quad (15)$$

The data of the equation is provided to the controller for achieving the exact value of inductance by position control of motor geared with variable inductor. Flowchart for shaft angle setting for servo-controlled inductor corresponding to motor frequency is shown in Fig. 4.

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IV. SIMULATION OF THE PROPOSED SYSTEM

Simulation of the complete system is carried out in MATLAB Simulink. The motor data as specified in Table II is used.

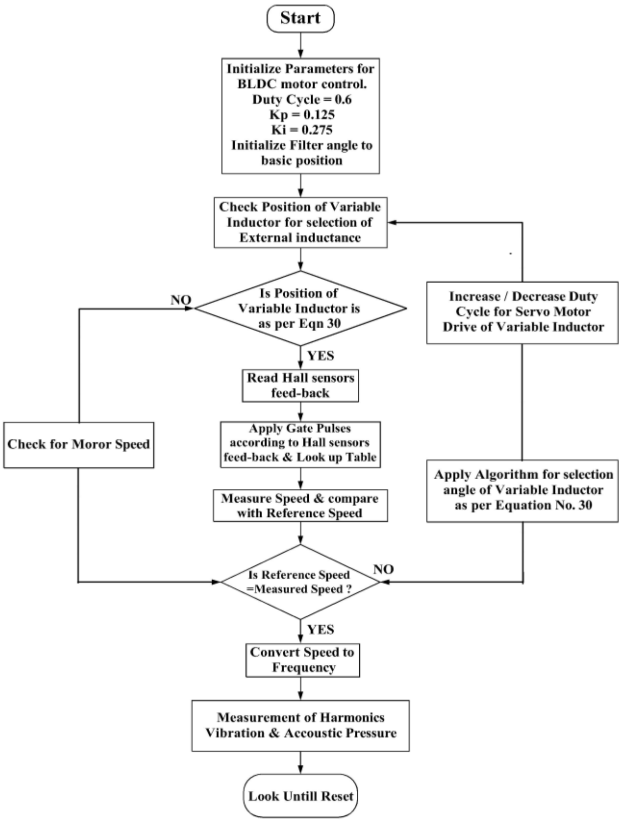
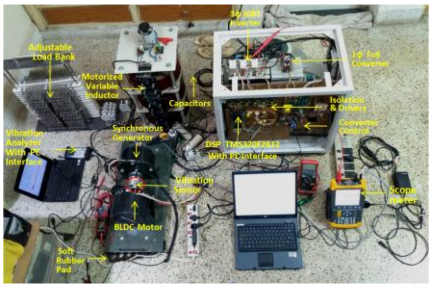


Fig. 4 Flowchart for shaft angle setting of servo-controlled inductor corresponding to motor frequency

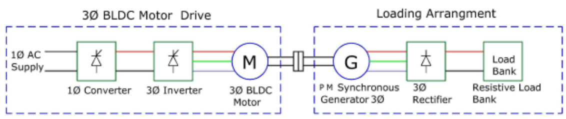
The three-phase inductor of variable filter is incorporated by adding external three phase inductor in between three phase inverter and BLDC motor connections. The value of three phase inductor is fed as per the curve shown in Fig. 3 for a particular speed and frequency. Various readings like line current, line current THD and torque are obtained as per the requirement with and without implementation of the proposed variable inductor filter. Fig. 6 shows, simulated line current, transient and steady state response of line current and transient and steady state response of electromagnetic torque at a certain load with and without proposed filter, respectively. Considerable improvement is observed in transient response with first and second overshoots are reduced. This ensures reduction in torque ripples during starting of the BLDC motor which assures minimization of the motor vibrations at start. Improvement in steady state response of both current and torque is noted.

V. HARDWARE VALIDATION OF THE PROPOSED TOPOLOGY AND EXPERIMENTAL RESULTS

Experimental results are shown in Fig 7 and 8. Experimental results with and without proposed filter for motor supply frequency 151 Hz (speed 1132 rpm) are shown in Fig. 7, whereas for motor supply frequency 254 Hz (speed 1905 rpm) are shown in Fig. 8. Fig. 7a, Fig. 7b and Fig. 8a, Fig. 8b shows line current waveforms and respective line current percentage THD, with and without proposed variable inductor filter for 151 Hz and 254 Hz motor frequency, respectively.



(a)



(b)

Fig. 5 Drive with variable inductor filter (a) Experimental setup (b) Load testing arrangement

Fig. 7c, Fig. 7d and Fig. 8c, Fig. 8d shows the with and without proposed variable inductor filter for 151 Hz and 254 Hz motor frequency, respectively. The line current percentage THD reduced after implementation of the filter. The reduction in power losses with increase in efficiency of system helps to avoid use of oversize components, making system more compact.

Fig. 7e, Fig. 7f and Fig. 8e, Fig. 8f Fig. 7g, Fig. 7h and Fig. 8g, Fig. 8h shows vibration spectrum with and without proposed variable inductor filter for 151

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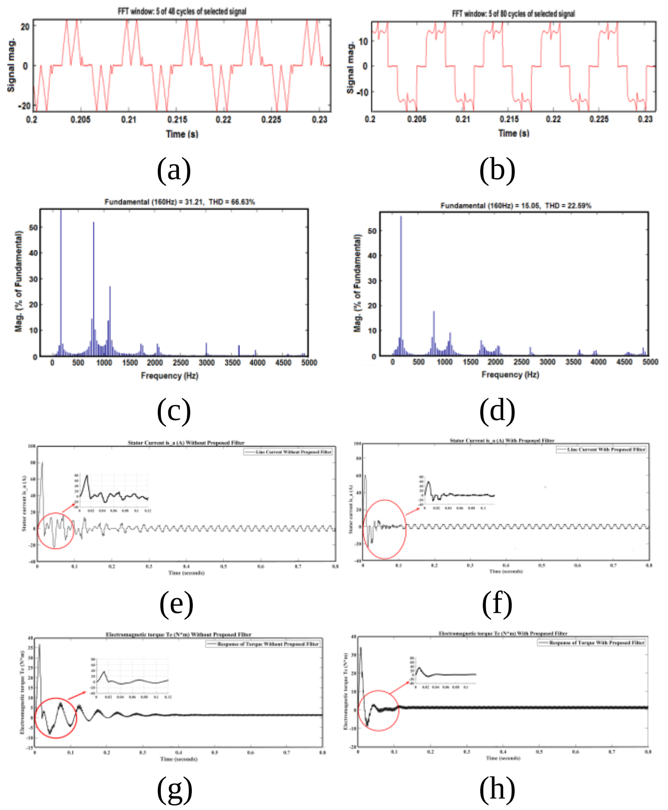
Hz and 254 Hz motor frequency respectively. The motor and generator set-up as shown in Fig. 5a is kept on soft rubber pads so that vibrations pattern can be noted accurately.

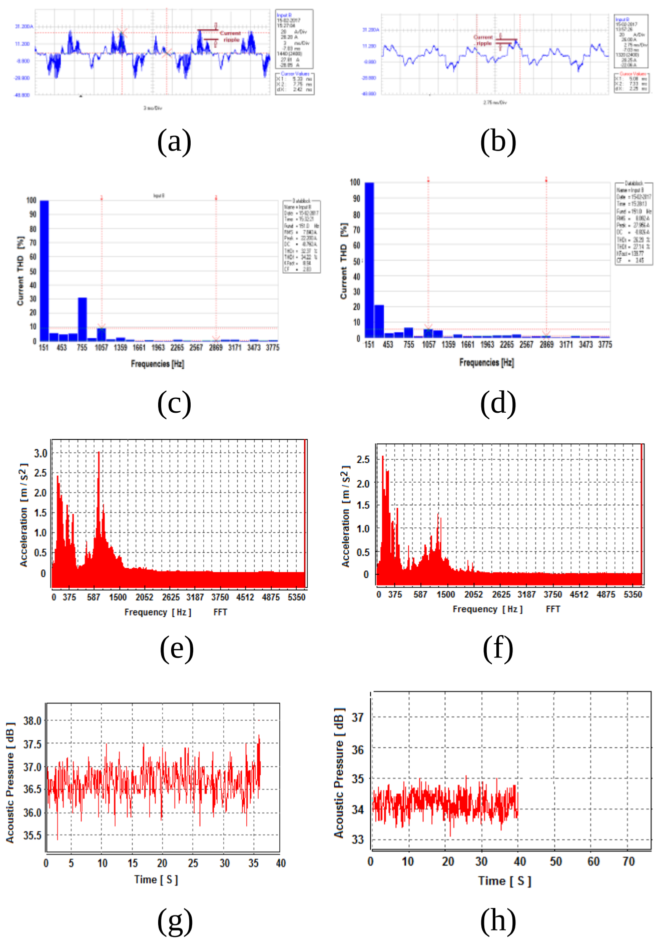
To note the readings a higher end vibration analyzer is used. In both the cases of speed that is transient as well as steady state, reduction in vibrations is noted. A microphone of sound analyzer is positioned near to motor and generator set-up as shown in Fig. 5a so that acoustic pressure can be note accurately. In both the cases of speed that is during starting of motor as well as at stable speed, reduction in acoustic pressure is observed.

Fig. 10(a,b,c) shows reduction in motor current THD, reduction in motor vibrations standstill to rated speed condition of BLDC motor and reduction in acoustic pressure over the complete speed ranges, respectively.



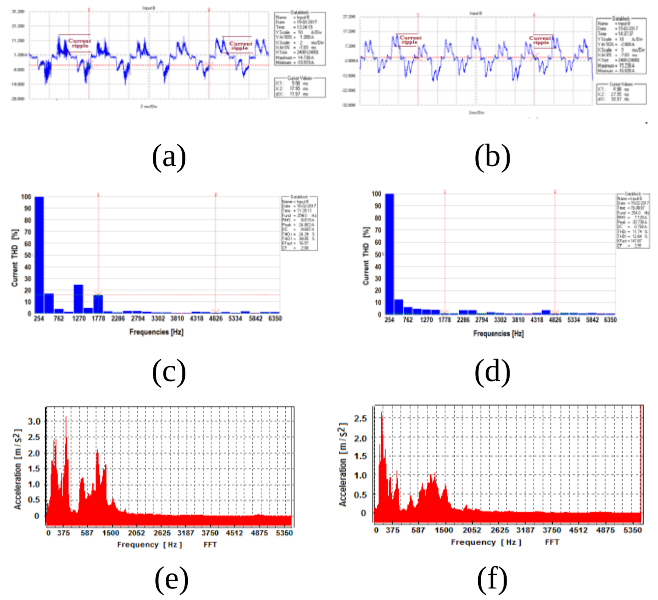
(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 6 Simulation results without and with proposed filter: (a) Line current (21 Ap-p, 160Hz, 1200rpm); (b) Line current (21 Ap-p, 160Hz, 1200rpm); (c) Line current THD 66.63%; (d) Line current THD 22.59%; (e)&(f) Transient response of line current; (g)&(h) Transient response of torque



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 7 Experimental results with and without proposed filter for motor supply frequency 151Hz, Speed 1132rpm: (a)&(b) Line current; (c) Line current THD 32.37%; (d) Line current THD 26.20%; (e)&(f) Vibration spectrum; (g)&(h) Acoustic pressure



(a) (b) (c) (d) (e) (f)

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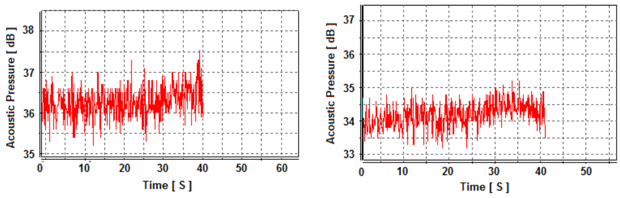
This is the important feature of the proposed filter which ensures reduction in torque ripples which ensures reduction in motor vibrations and acoustic pressure.



(g) (h)

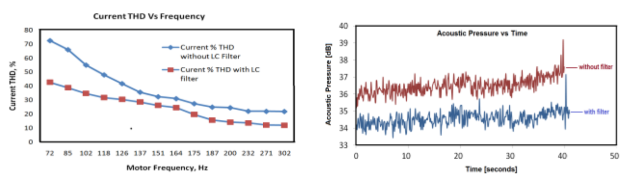
Fig. 8 Experimental results with and without proposed filter for motor supply frequency 254Hz, Speed 1905 rpm: (a)&(b) Line current; (c) Line current THD 32.37%; (d) Line current THD 26.20%; (e)&(f) Vibration spectrum; (g)&(h) Acoustic pressure

Motor Frequency f (in Hz)	I_{THD} Without Filter (%)	I_{THD} With Filter (%)	Vibrations Without Filter m/s^2	Vibrations With Filter m/s^2	Sound Without Filter dB	Sound With Filter dB
70	72.50	42.70	1.84	1.52	35.23	34.18
85	66.11	38.80	2.42	1.94	36.45	34.89
118	48.00	31.73	3.06	0.42	36.82	34.75
138	36.30	28.60	1.23	0.67	36.91	34.55
160	32.44	26.60	1.15	0.65	37.10	34.12
175	27.40	19.69	2.04	0.68	36.94	34.78
186	24.92	17.39	2.26	0.88	37.15	34.68
200	24.26	15.94	1.58	1.05	37.38	34.97
232	22.60	13.46	1.44	0.92	37.45	34.88
270	28.40	12.14	0.75	0.56	37.53	34.68
302	21.40	11.80	0.55	0.25	38.44	34.45
330	27.30	10.90	0.25	0.22	38.68	34.95

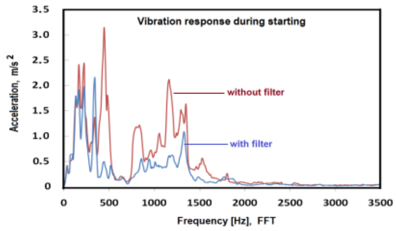
Table 1. Improvement in current THD, vibrations and acoustic pressure (sound) due to proposed filter

Parameter	Value
BLDC motor	Three phase
Motor type	Trapezoidal
Motor rating	2000 Watt
Motor Speed(N)	3000 rpm
Rated voltage (V_{ab})	48 Volt
Rated line Current(I_a)	26 A
Power factor(pf)	0.92
Rated torque (T_e)	6.52 Nm
Inertia (J)	0.048Kg-m^2
Torque constant (K_t)	0.21 Nm/A
Resistance (R_{ph})	0.16 Ω/phase
Inductance (L_{ph})	0.025H /Phase
Back emf constant K_b	1.25 V/(rad/s)
Frictional coefficient	0.001 Nm/rad/s
Number of poles (P)	16

Table 2. BLDC motor parameters



(a) (b)



(c)

Fig. 9 Flowchart for Shaft angle setting of servo-controlled inductor corresponding to motor frequency

VI. Conclusion

In this paper, a new un-attempted concept for reduction in harmonics, vibrations and acoustic pressure in a BLDC motor drive over its complete speed range is presented. For that rotary variable inductor used whose inductance varies according to the speed of the motor. The value of external inductance decreases as speed increases and at rated speed it is zero.

To control variation of the inductor and motor operation, a DSP based algorithm is used. Performance of the BLDC motor is studied from stand still to the rated speed. The proposed scheme effectively reduces current harmonics from the motor supply, and improves overall performance of the trapezoidal type BLDC motor drive by reducing torque ripples, motor vibrations and acoustic pressure in the motor over complete speed range. Nature of the current waveform seen to be improved along with improvement in line current percentage THD after implementation of the proposed filter.

Considerable improvement in transient response of motor current is observed. The first and second overshoots are clearly seen to be reduced. The simulation and experimental results show that for a specified frequency and voltage band, overall 22.47 % reduction in line current THD is achieved which assist to reduce torque ripples up to 10 % in effect. Because of this, overall 8.81% reduction in motor vibrations and 6.54 % reduction in acoustic pressure is noted. Reduction in harmonic content aids in minimization of EMI.

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Improvement in line current percentage THD assure reduction in power losses with increase in efficiency of the system. It also helps to avoid use of oversize components, making system more compact. The developed filter finds

VII. REFERENCES

[1] R. Krishnan, Electric motor drives: modeling, analysis, and control. Prentice Hall, 2001.

[2] S. M. Shakouhi, M. Mohamadian, and E. Afjei, “Torque ripple minimization control method for a four-phase brushless DC motor with non-ideal back-electromotive force”, IET Electric Power Applications, vol. 7, no. 5, pp. 360 - 368, 2013.

[3] B. K. Bose, Power electronics and motor drives: advances and trends. Academic press, 2010.

[4] I. Janpan, R. Chaisricharoen, and P. Boonyanant, “Control of the brushless DC motor in combine mode”, Procedia Engineering, vol. 32, pp. 279 - 285, 2012.

[5] D. K. Kim, K. W. Lee, and B. I. Kwon, “Commutation torque ripple reduction in a position sensorless brushless DC motor drive”, IEEE Transactions on Power Electronics, vol. 21, no. 6, pp. 1762 - 1768, 2006.

[6] M. Masmoudi, B. El Badsi, and A. Masmoudi, “DTC of B4-inverter-fed BLDC motor drives with reduced torque ripple during sector-to-sector commutations”, IEEE Transactions on Power Electronics, vol. 29, no. 9, pp. 4855 - 4865, 2014.

[7] S. B. Ozturk, W. C. Alexander, and H. A. Toliyat, “Direct torque control of four-switch brushless DC motor with non-sinusoidal back EMF”, IEEE Transactions on Power Electronics, vol. 25, no. 2, pp. 263 - 271, 2010.

[8] S. B. Ozturk and H. A. Toliyat, “Direct torque and indirect flux control of brushless DC motor”, IEEE/ASME Transactions on Mechatronics, vol. 16, no. 2, pp. 351 - 360, 2011.

[9] B.-K. Lee, T.-H. Kim, and M. Ehsani, “On the feasibility of four switch three-phase BLDC motor drives for low cost commercial applications: topology and control”, IEEE Transactions on Power Electronics, vol. 18, no. 1, pp. 164 - 172, 2003.

[10] C. S. Joice, S. Paranjothi, and V. J. S. Kumar, “Digital control strategy for four quadrant operation of three phase BLDC motor with load variations”, IEEE transactions on Industrial Informatics, vol. 9, no. 2, pp. 974 - 982, 2013.

[11] C.-T. Pan and E. Fang, “A phase-locked-loop-assisted internal model adjustable-speed controller for BLDC motors”, IEEE Transactions on Industrial Electronics, vol. 55, no. 9, pp. 3415 - 3425, 2008.

[12] J. Karthikeyan and R. D. Sekaran, “Current control of brushless dc motor based on a common dc signal for space operated vehicles”, International Journal of Electrical Power and Energy Systems, vol. 33, no. 10, pp. 1721 - 1727, 2011.

[13] C. Shin, C. Choi, and W. Lee, “Advance Angle Calculation for improvement of the torque-to-current ratio of brushless dc motor drives”, Energy Procedia, vol. 14, pp. 1410 - 1414, 2012.

[14] A. Sathyan, N. Milivojevic, Y.-J. Lee, M. Krishnamurthy, and A. Emadi, “An FPGA-based novel digital PWM control scheme for BLDC motor drives”, IEEE transactions on Industrial Electronics, vol. 56, no. 8, pp. 3040 - 3049, 2009.

[15] F. Rodriguez and A. Emadi, “A novel digital control technique for brushless DC motor drives”, IEEE transactions on Industrial Electronics, vol. 54, no. 5, pp. 2365 - 2373, 2007.

[16] J. Fang, H. Li, and B. Han, “Torque ripple reduction in BLDC torque motor with nonideal back EMF”, IEEE transactions on Power Electronics, vol. 27, no. 11, pp. 4630 - 4637, 2012.

[17] I. Kim, N. Nakazawa, S. Kim, C. Park, and C. Yu, “Compensation of torque ripple in high performance BLDC motor drives”, Control Engineering Practice, vol. 18, no. 10, pp. 1166 - 1172, 2010.

[18] D.-H. Lee and J.-W. Ahn, “A current ripple reduction of a high-speed miniature brushless direct current motor using instantaneous voltage control”, IET electric power applications, vol. 3, no. 2, pp. 85 - 92, 2009.

[19] V. Vaiyapuri and S. Jeevananthan, “Hybrid converter topology for reducing torque ripple of bldc motor”, IET Power Electronics, 2017.

[20] K. Gulez, A. A. Adam, and H. Pastaci, “Torque ripple and EMI noise minimization in PMSM using active filter topology and field-oriented control”, IEEE Transactions on Industrial Electronics, vol. 55, no. 1, pp. 251 - 257, 2008.

[21] Y. Sozer, D. A. Torrey, and S. Reva, “New inverter output _lter topology for PWM motor drives”, IEEE Transactions on Power Electronics, vol. 15, no. 6, pp. 1007 - 1017, 2000.

[22] B. Singh and S. Singh, “Single-phase power factor controller topologies for permanent magnet brushless dc motor drives”, IET power electronics, vol. 3, no. 2, pp. 147 - 175, 2010.

[23] T. Gopalarathnam and H. A. Toliyat, “A new topology for unipolar brushless dc motor drive with high power factor”, IEEE Transactions on Power Electronics, vol. 18, no. 6, pp. 1397 - 1404, 2003.

[24] H.-S. Kim and S.-K. Sul, “A novel filter design for output LC filters of PWM inverters”, Journal of Power Electronics, vol. 11, no. 1, pp. 74 - 81, 2011.

[25] T. G. Habetler, R. Naik, and T. A. Nondahl, “Design and implementation of an inverter output LC filter used for dv/dt reduction", Applied Power Electronics Conference and Exposition, vol. 2, pp. 1279 - 1284, IEEE, 1999.
[26] A. Houari, H. Renaudineau, J.-P. Martin, S. Pierfederici, and F. Meibody-Tabar, “Flatness-Based Control of Three-Phase Inverter with Output LC Filter”, IEEE Transactions on Industrial Electronics, vol. 59, no. 7, pp. 2890 - 2897, 2012.
[27] M. Brackley and C. Pollock, “Analysis and reduction of acoustic noise from a brushless dc drive”, Industry Applications Conference, 1999, Thirty-Fourth IAS Annual Meeting, Conference Record of the 1999 IEEE, vol. 2, pp. 888 - 893, IEEE, 1999.
[28] S. Hattori, M. Ishida, and T. Hori, “Vibration suppression control method for PMSM utilizing repetitive control with auto-tuning function and Fourier transform”, Industrial Electronics Society, 2001, IECON01, The 27th Annual Conference of the IEEE, vol. 3, pp. 1673 - 1679, IEEE, 2001.
[29] C. Concari, G. Franceschini, and A. Toscani, “Vibration-less alignment algorithm for incremental encoder-based BLDC drives”, Electric Power Systems Research, vol. 95, pp. 225 - 231, 2013.
[30] L. Jianjun, X. Yongxiang, and Z. Jibin, “A study on the reduction of vibration and acoustic noise for brushless dc motor”, Electrical Machines and Systems, ICEMS 2008, International Conference, pp. 561 - 563, IEEE, 2008.
[31] P. S. Chaudhari, S. Patil, S. K. Pandey, and S. Sinha, “Performance analysis of bldc motor on sinusoidal and square wave supply”, Power Electronics, Drives and Energy Systems (PEDES), 2016 IEEE International Conference, pp. 1 - 6, IEEE, 2016.