IMPLEMENTATION OF Z SOURCE INVERTER WITH FOUR SWITCH BLDC DRIVE FOR DOMESTIC APPLIANCES

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Abstract

This paper explains a design a control scheme for Brushless DC motor for domestic applications using ZSI. This drive uses four switches which reduces the cost of the drive. Here the ZSI is used for both inversion and boosting. This utilizes the inductors and capacitors and the shoot through states by gating on both the upper and lower switches in the same phase legs, to boost dc voltage without dc/dc converter. The inductors and capacitors can be optimally designed to lower the cost and size of the system. Since the Z-source inverter does not need dc-dc converter to boost voltage it can gain 2-3% in conversion efficiency. Because of no dead time, control accuracy and reduction in harmonics can be achieved.

Keywords Brushless DC motor (BLDC), converters, Z-source inverter, pulse width modulation, motion control.

I. INTRODUCTION

The BLDC Motors are becoming more popular in the domestic as well as industrial areas. Earlier to this conventional motor drive are used for the domestic appliances such as refrigerators and air conditioning systems. The conventional motors are having low efficiency and high maintenance. The BLDC Motor drives are known for higher efficiency and lower maintenance. The inverters used in the BLDC drive are using six switches. In this paper for BLDC drive ZSI is used and the number of switches used is also reduced. Hence the cost of the drive is also reduced and the switching losses are also reduced. This paper is organized as follows section II deals with the basics of BLDC Motor, section III with the basics of Z-source, Section IV deals ZSI control of BLDC Motor drives. Section V deals with the modeling of the Z source inverter. Section VI gives the simulation results and section VII gives the conclusion.

II. BASICS OF BLDC MOTOR

We have got a number of choices of motors for low cost application drives one among them is Brushless dc motor. According to the opinion of the design engineers the BLDC motor is the best for many applications, especially for low cost application drives.

Fig. 1. Stator of the BLDC Motor Outer rotor Inner rotor

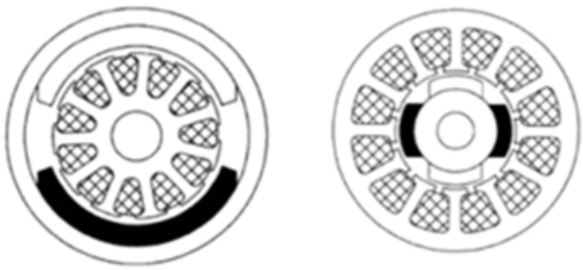


Fig. 2 Cross sectional view of the rotor of the BLDC Motor.

Fig 1 shows the stator of the BLDC Motor and Fig 2 shows the cross sectional view of the rotor of the BLDC Motor, which gives explanation of the stator, the rotor types namely the outer rotor and inner rotor construction. BLDC motors are gaining the importance because its merits such as

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

As the name indicates the BLDC motor do not have brushes, instead they are electronically commutated. Therefore the maintenance required is very less. Therefore they are widely used in the domestic as well as industrial applications. In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. The construction, working principle, characteristics and typical applications and the basic equations used for modeling of BLDC motors are explained. A BLDC motors tend to be more reliable, last longer, and be more efficient [1-3]. The back emf waveform of BLDC Motor is as shown in Fig.3

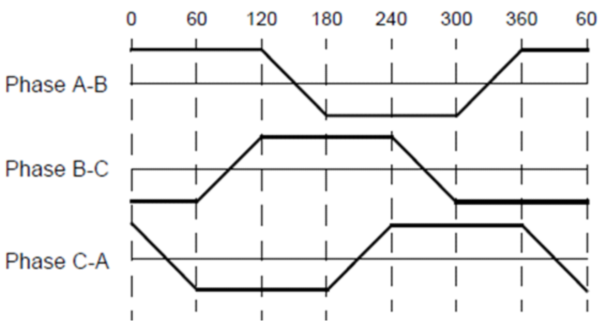


Fig. 3 Back emf waveform of BLDC Motor.

The equations of the BLDC Motor are given below. These equations are expressed in the phase reference frame (abc frame). Note that the phase inductance Ls is assumed constant and does not vary with the rotor position.

$$\frac{di_a}{dt} = [2V_{ab} + Vubbc - 3R_s i_a + \lambda\, p\, \omega_r (-2\,\phi'_a + \phi'_b + \phi'_c)]$$

$$\frac{di_b}{dt} = \frac{1}{3L_s}[-V_{ab} + V_{bc} - 3R_s i_b + \lambda\, p\, \omega_r (\phi'_a - 2\,\phi'_b + \phi'_c)]$$

$$\frac{di_c}{dt} = -\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right)$$

$$T_e = p\,\lambda\,(\phi'_a \cdot i_a + \phi'_b \cdot i_b + \phi'_c \cdot i_c)$$

where

Ψ'	–	is the electromotive force.
L_s	–	Inductance of the stator windings
R	–	Resistance of the stator windings
i_a, i_b, i_c	–	a, b and c phase currents
$\phi'_a, \phi'_b, \phi'_c$	–	a, b and c phase electromotive forces
V_{ab}, V_{bc}	–	phase to phase voltages
ω_r	–	Angular velocity of the rotor
λ	–	Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
P	–	number of pole pairs
T_e	–	Electromagnetic torque

Mechanical System

$$\frac{d}{dt}\omega_r = \frac{1}{j}(T_e - F\omega_r - T_m)$$

$$\frac{d\theta}{dt} = \omega_r$$

Where	J	Combined inertia of rotor and load
	F	Combined viscous friction of rotor and load
	θ	Rotor angular position
	T_m	Shaft mechanical torque

III. ABOUT THE Z-SOURCE INVERTER

The Z-source network is consists of two inductors and two capacitors. The Z-source network is the energy storage/filtering element for the Z-source inverter. It provides a second-order filter and is more effective to reduce the voltage and current ripples than capacitor or inductor used alone. Therefore, the value of the inductor and capacitor required will be lesser compared to the traditional inverters. When the two inductors (and) are small and approach zero, the Z-source network will reduces to two capacitors (and) in parallel and becomes a traditional V-source. Therefore, a traditional V-source inverter's capacitor requirements and physical size is the worst case requirement for the Z-source network. Considering the additional benefits provided by the inductors like filtering and energy storage, the Z-source network require less capacitance and smaller size compared to the traditional V-source inverter. Similarly, when the two capacitors (and) are small and approach zero, the Z-source network reduces to two inductors (and) in series and becomes a traditional I-source. Therefore, a traditional I-source inverter's inductor requirements and physical size is the worst case requirement for the Z-source network. Considering the filtering and energy storage capacity of the capacitors, the Z-source network should require less inductance and smaller size compared to the traditional I-source inverter [4].

IV. ZSI CONTROL OF BLDC MOTOR DRIVES

Typical inverter drive system for a three phase BLDC motor is shown in Fig-4

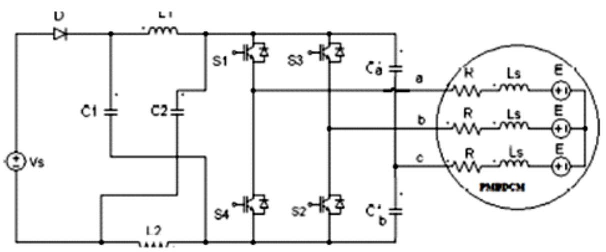


Fig. 4 Three phase drive system for BLDC Motor

According to the operation principle of BLDC motor, two phases are conducted in the non-commutation stages. Fig.4 shows equivalent circuits when the phase a and b windings are conducted, with the current flows from phase-a winding to phase-b winding. The shoot-through states can be generated via shorting either any one arm or both arms in the bridge. For ease of illustration, assume that the upper switches of the bridge operate in chopping modes, while the lower are used to short the bridge arms.

The broad-brush lines and arrows indicate the path and direction of the currents, respectively. From Fig.5 (a) and (b), only two semiconductor devices (MOSFET or the anti-parallel diode) in different arms of the bridge are conducted in the non-shoot-through modes. In the shoot-through modes, four devices are conducted, when the shoot-through occurs in one phase arm, as shown in Fig.5(c). and six devices may be conducted if the shoot-through occurs in two phase arm. In the phase commutation stage, the switch S1 is shut off, and the switch S5 is turned on at the same time. There are three devices conducted in the non-shoot-through modes, as shown in Fig.6 (a) and (b). While in the shoot-through modes, five devices may be conducted when the shoot-through occurs in one phase arm, as shown in Fig.6 (c). and seven devices may be conducted if the shoot-through occurs in two phase arms.

It is worth noting that, the shoot-through states should be generated by gating on the lower switch only when the inverter output is in 'active'state. For example,in Fig.5(c), the switches S1 and S2 are triggered to feed the phase a and b windings, the switch S4 is used to shorted the arm, and the sketch of gating signals to the switches S1, S2 and S4 can be seen in Fig. 6.

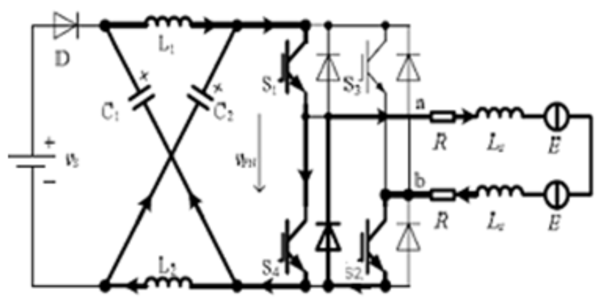


Fig. 5a Equivalent circuits during non–commutation stage - open state

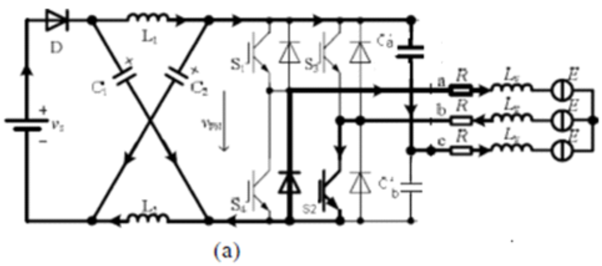


Fig. 5b Equivalent circuits during non-commutation stage - active state

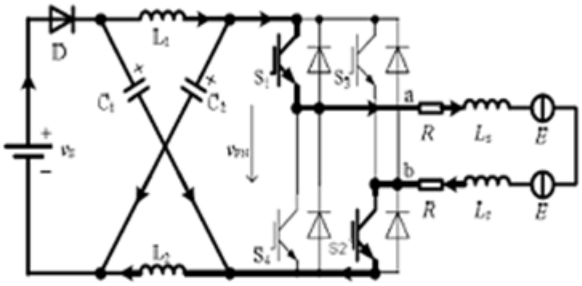
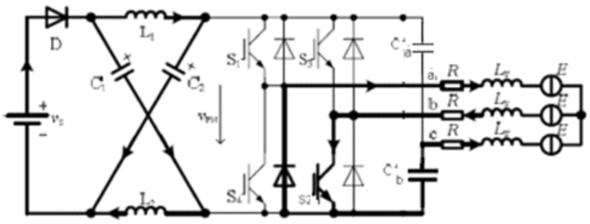


Fig. 5c Equivalent circuits during non–commutation stage - shoot – through



(b)

Fig. 6a Equivalent circuit during phase commutation stage - open state

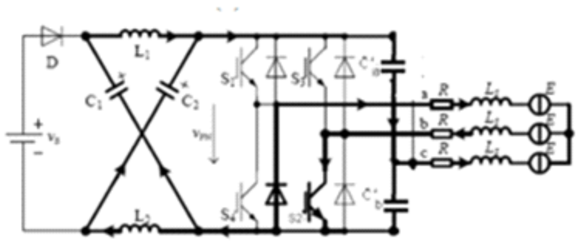


Fig. 6b Equivalent circuit during phase commutation stage - active state

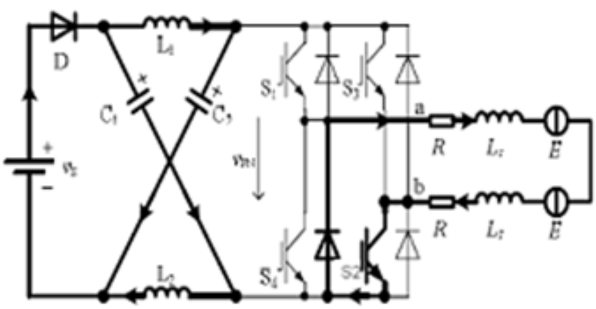


Fig. 6c Equivalent circuit during phase commutation stage - shoot-through state

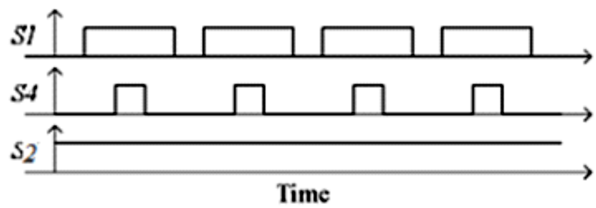


Fig. 7. waveform of the gate signals

Taking the duty ratio of S1 is D1 and the duty ratio of S4 is D4, the average output voltage of the inverter is [9]

$$V_0 = \frac{D_1 - D_4}{1 - 2D_4} \cdot V_3 \cdot$$

Where $0 < D_1 \cdot O < D_4 < 0.5 \cdot D_4 < D_1$

and $0 < \frac{D_1 - D_4}{1 - 2D_4} < \infty.$

The output voltage can be bucked and Boosted within a wide range. A straight line is used to control the shoot-through states. When the triangular waveform is lower than the straight line, the circuit turns into shoot through modes[5]. In paper [5] they have made the ZSI with six switches but in this paper I have proposed ZSI with four switches.

V. MODELING OF THE Z SOURCE NETWORK

Since the Z-source inverter is controlled with PWM signals, the switching states of the bridge should be considered in the modeling to describe the dynamics of the drive system. In Fig.4, the main circuit can be divided into two parts, one is the X-shape impedances network combined with the dc source, and the other is the three-phase inverter connected with the equivalent circuit of PMBDCM. So modeling of the z-source network is shown below in Fig.8.

A. MODELING OF THE IMPEDANCE SOURCE NETWORK

Generally, the Z-source network can operate in six possible states, in which three states are desired while the other three are undesirable. And the undesirable states can be avoided by choosing appropriate values of the inductors and capacitors of the impedance network [5]. It is supposed that only the three desired states are considered in the following analysis. The desired open state, active state and shoot-through state are illustrated in Fig.5 (a), (b) and (c), respectively. Assuming that the Z-source network is symmetrical, that is $L1 = L2 = L$, $C1 = C2 = C$, $iL1 = iL2 = iL$ and $VC1 = VC2 = VC$ [4].

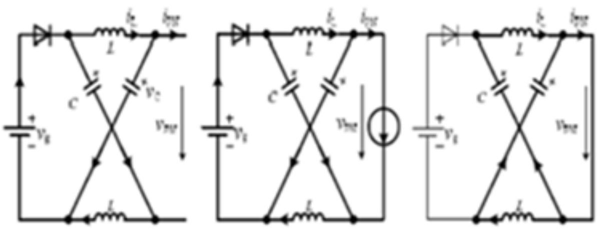


Fig. 8 Equivalent circuit of Z-source network in (a) open state (b) active state (c) shoot –through state.

B. Z-SOURCE NETWORK PARAMETERS

The values of the inductor and capacitor are decided by the design calculations. For designing the values we need to know the load specifications. The Specification of the load is as given below

1. 3-phase Brushless Dc motor,
2. Power - 5 kW, Speed - 2000rpm
3. Voltage – 40 V, Current - 1.80 A
4. Frequency - 50Hz

The design formulas will be given in forth coming paper. The purpose of the capacitor in the Z-source network is to absorb the current ripple and to maintain a fairly constant voltage so as to keep the output voltage sinusoidal. During shoot-through, the capacitor charges and the current through the capacitor equals to the current through the inductor. Therefore, the voltage ripple across the capacitors can be roughly calculated by

$$\Delta V_c = (I_{av} * T_0)/C$$

Where $\Delta V_c =$ Capacitor voltage during the conduction

$I_{av} =$ Average inductor current

$C =$ Required capacitance

$T_0 =$ Time [6-7].

C. Calculating power losses within the MOSFET

Power losses in the gate drive circuitry are negligibly small except at very high switching frequencies. The primary source of power loss is across the drain and the source, which can be divided in to two categories:

- Conduction loss
- Switching loss

Conduction loss: In the on-state, the MOSFET conducts a drain current for an interval T_{on} during every switching time-period T_s, with the switch duty-ratio *d=Ton/Ts*. Assuming a current *Io* during *dTs,* the average Power loss in the on-state resistance R*Ds(on)* of the MOSFET is:

$$P_{\text{cond}} = d\, R_{Ds\,(\text{on})}\, I_0^2$$

As pointed out earlier varies significantly with the junction temperature equal to 25 degree Celsius and data sheets often provide its value at the junction temperature equal to 120 degree Celsius. The conduction loss is highest at the maximum load on the converter when the drain current would also be at its maximum.

Switching loss: At high switching frequencies, switching power losses can be even higher than the conduction loss. The switching waveforms for the MOSFET voltage v*ds* and the current id, the corresponding to the Turn-on and Turn-off trajectories are shown in Fig-5. During each transition from ON to OFF and vice versa, the transistor has simultaneously high voltage and current, as shown in Fig-5.The instantaneous power loss p*sw(t)* in the transistor is the product of v*ds* and i*d* ,as plotted[5].The average value of the switching losses is given by

$$P_{sw} = \frac{1}{2} V_{\text{in}}\, I_0\, (t_{c,\,\text{on}} + t_{c,\,\text{off}})\, f_s$$

Where $t_{c,\,\text{on}} = t_{ri} + t_{fv}$

$t_{c,\,\text{off}} = t_{rv} + t_{fi}$

$P_{sw} =$ Power loss in switch

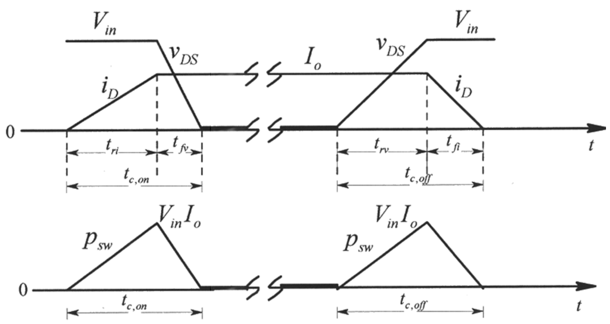


Fig. 9 MOSFET switching losses.

VI. SIMULATION RESULTS

The general existing closed loop control system of BLDC Motor is as shown in Fig.10

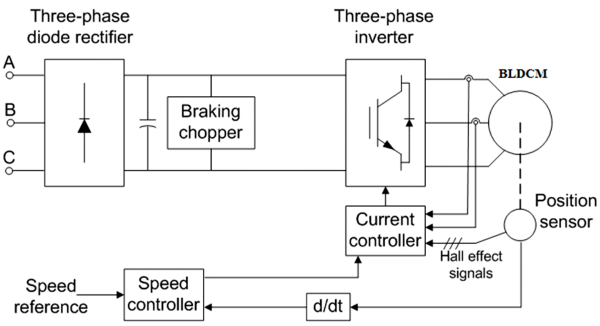


Fig. 10 Closed loop control system of BLDC Motor.

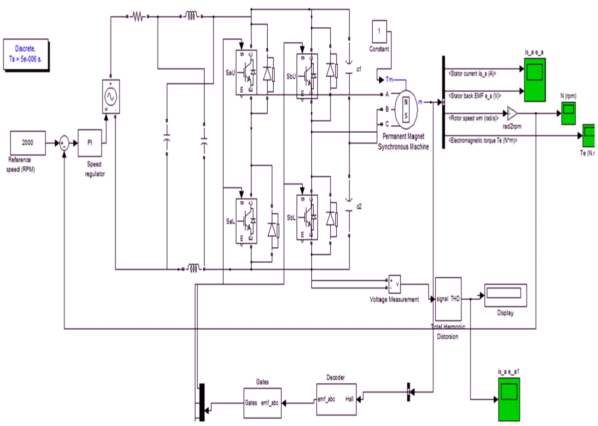


Fig.11 Simulation circuit of ZSI control scheme of BLDC Motor.

To assess the performance of the anticipated Z – source inverter for BLDC motor drive scheme, simulation model has been established using MATLAB software. The simulation circuit is shown in Fig. 10. The speed and current closed loop control is applied to control the PMBDCM, and simulation studies have been performed with and without shoot-through mode.

Fig.12 a. Photographic View of Hardware before connecting the Z-source

Fig.12 b. Photographic View of Hardware after connecting Z-source

Fig. 13-15 shows the simulation waveforms of the phase current *i*a, Electromotive force, rotor speed *n* and electromagnetic torque *T*e of the PMBDCM. Fig. 16 and 17 shows the waveform of the total harmonic distorsion in the existing system and proposed system.

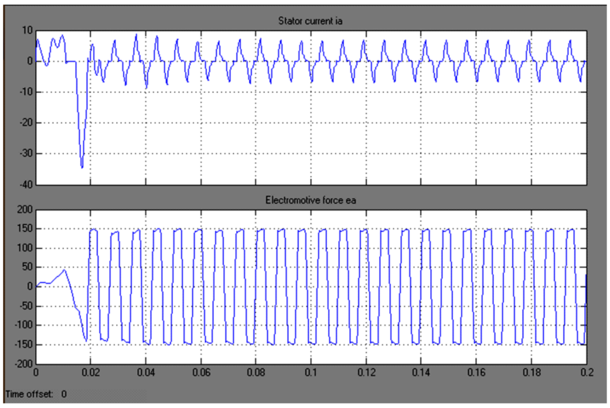


Fig. 13. waveform of stator current and electromotive force

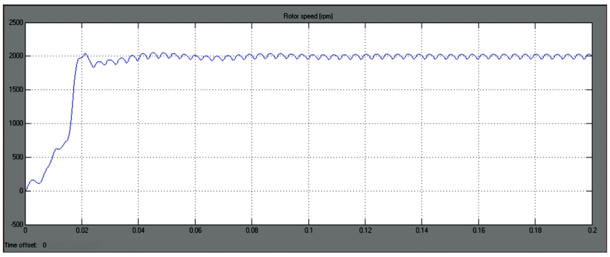


Fig. 14. waveform of Rotor speed

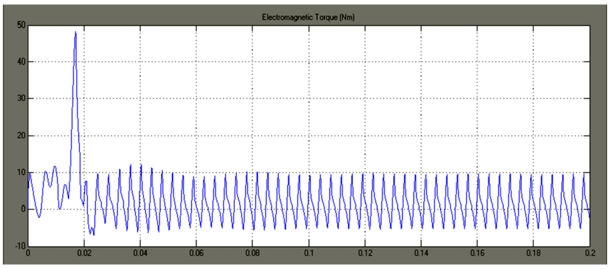


Fig. 15. waveform of Electromagnetic Torque

VII. CONCLUSION

A new ZSI control concept for BLDC machines has been introduced and experimentally verified. The objective of this paper is to develop a low cost controller for domestic applications. This paper has proposed a Z – source inverter based Brushless DC motor drive. This drive system has the advantages of both BLDCM and Z-source inverter. The system configuration, operation principle and control method have been analyzed in detail. Based on the equivalent circuits, the mathematical model has been established.

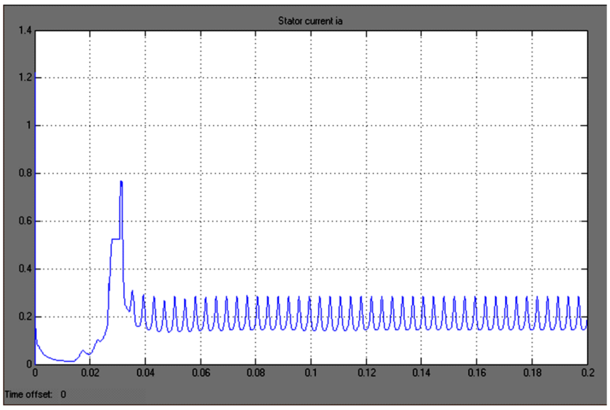


Fig. 16. waveform of Total harmonic distortion in existing system

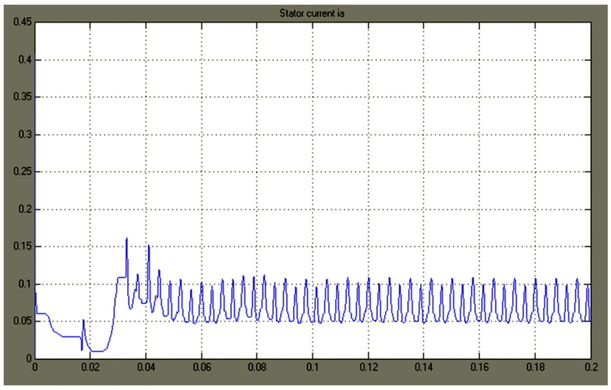


Fig. 17. waveform of total harmonic distortion in the proposed system

Simulation results have validated the preferred features as well as the possibility of the proposed drive system. Additionally, the shortcoming of switching loss has been discussed, and a possible improvement has been seen. Also in this paper, the four-switch inverter topology is studied to provide a possibility for the realization of low cost and high performance three-phase BLDC motor drive System.

Table 1

Rated power of the motor	5kw
Rated voltage of the motor	40v
Rated speed of the motor	2000 rpm
Inductors of Z-source inverter	$L1 = L2 = 500\ \mu H$
Capacitors of Z-source inverter	$C1 = C2 = 500\ \mu F$
Switching frequency	10KHz

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