Abstract—This paper presents a design of ZSI control scheme for Brushless DC motor for domestic applications. This drive can operate with four switches which reduces the cost of the drive. In this paper we are using the ZSI which is used for both inversion and boosting. The impedance network 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. Z-source inverter does not need dc-dc converter to boost voltage in the circuit, so it can gain 2-3% in conversion efficiency. Because of no dead time, control accuracy and reduction in harmonics can be achieved.

Index Terms—brushless DC motor (BLDC), converters, Z-Source inverters, 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 the 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

Fig. 1 shows the cross sectional view of the BLDC Motor, which explains 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. 2.
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 $L_s$ is assumed constant and does not vary with the rotor position.

$$\frac{di_a}{dt} = \frac{1}{3L_s} [2V_{ab} + V_{bc} - 3R_i i_a + \lambda \omega_r (-2\Phi'_a + \Phi'_b + \Phi'_c)]$$

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

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

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

Where

- $\Phi'$ 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
- $\omega_r$ - Angular velocity of the rotor
- $\lambda$ - 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
- $\theta$ - Rotor angular position
- $T_m$ - Shaft mechanical torque

IV. ZSI CONTROL OF BLDC MOTOR DRIVES

Typical inverter drive system for a three phase BLDC motor is shown in Fig. 3.

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. 4 (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. 4(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. 5 (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. 5(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. 4(c), the switches $S_1$ and $S_2$ are triggered to feed the phase a and b windings, the switch $S_4$ is used to shortened the arm, and the sketch of gating signals to the switches $S_1$, $S_2$ and $S_4$ can be seen in Fig. 6.

\[ V_0 = \frac{D_1 - D_4}{1 - 2D_4} V_i, \quad \text{where} \quad 0 < D_1, \quad 0 < D_4 < 0.5, \quad D_4 < D_1 \quad \text{and} \quad 0 < \frac{D_1 - D_4}{1 - 2D_4} < \infty. \]

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.1, 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. 7.

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 \( L_1 = L_2 = L,\ C_1 = C_2 = C,\ iL_1 = iL_2 = iL \) and \( vC_1 = vC_2 = vC \). [4]

\[ \Delta V_c = \frac{(I_{av} \cdot T_0)}{C} \]

Where \( \Delta V_c \) = Capacitor voltage during the conduction
\( I_{av} \) = Average inductor current
\( C \) = Required capacitance
\( T_0 \) = Time

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 into 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 \( d = T_{on}/T_s \). Assuming a constant \( I_0 \) during \( dT_s \), the average Power loss in the on-state resistance \( R_{DS(on)} \) of the MOSFET is:

\[ P_{cond} = d \cdot R_{DS(on)} \cdot I_0^2 \]

As pointed out earlier \( R_{DS(on)} \) 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 \( i_d \) is 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 \( p_{sw} \) in the transistor is the product of \( v_{ds} \) and \( i_d \), as plotted[5]-[6]. The average value of the switching losses is given by

\[ P_{SW} = \frac{1}{2} V_{in} I_0 (t_{c,on} + t_{c,off}) f_s \]

Where \( t_{c,on} = t_{ri} + t_{rv} \)
\( t_{c,off} = t_{riv} + t_{fi} \)
\( P_{SW} \) = Power loss in switch

VI. SIMULATION RESULTS

The general existing closed loop control system of BLDC Motor is as shown in Fig. 9 [7].

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. 12-14 shows the simulation waveforms of the phase current $i_a$, Electromotive force, rotor speed $n$ and electromagnetic torque $T_e$ of the PMBDCM. Fig. 15. a and b shows the waveform of the total harmonic distortion in the existing system and proposed system.

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. 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>
<thead>
<tr>
<th>TABLE I.</th>
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<tbody>
<tr>
<td>Rated power of the motor</td>
<td>5kw</td>
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<tr>
<td>Rated voltage of the motor</td>
<td>40v</td>
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<tr>
<td>Rated speed of the motor</td>
<td>2000 rpm</td>
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<tr>
<td>Inductors of Z-source inverter</td>
<td>L1=L2=500μH</td>
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<tr>
<td>Capacitors of Z-source inverter</td>
<td>C1=C2=500μF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10KHz</td>
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</table>

REFERENCES

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