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Speed Control of SLqZSI FED PMBLDC Motor with Double-Loop Control

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Abstract: ***In this paper, a permanent magnet brushless DC motor drive using switched-inductor quasi z-source inverter is proposed. This drive system utilizes the advantages of both the PMBLDC motor and SL-qZSI and can be used in high power/medium power electric vehicles and any other adjustable drive applications. The BLDC (Brushless DC) motor is characterized by linear torque to current and speed to voltage. The speed and torque is controlled by adjusting the armature voltage applied. Desired level of speed performance can be achieved with Double loop control for the speed and torque control. Also, SLqZSI has numerous advantages like low capacitor voltage stress, low current stress on inductors, high voltage gain etc. Thus feeding a high boosted dc voltage to the inverter and obtaining a smooth operating performance and dynamic response of the drive is very fast. Maximum constant boost control method has been used to generate the switching signals for the inverter switches.***

Keywords: Switched Inductor Quasi Z source Inverter, BLDC Motor, Double Loop control, Boost factor

1. Introduction

According to various reports, cars and trucks are responsible for almost 25% of CO_2 emission and other major transportation methods account for another 12%. Nowadays, where fuel are on a shortage and the rising issues of global warming led the researchers for some alternative and one of the most discussed technology is the use of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell hybrid electric vehicles (FCHEVs), and electric vehicles (EVs) require power electronics and electrical machines to function. These devices allow the vehicle to use energy from the battery or inverter to assist in the propulsion of the vehicle, either on their own or in combination with an engine. Thus, implementation of Z-Source inverter with BLDC motor solves the purpose by utilizing superior qualities of Z-Source inverter and BLDC motor. The operation of BLDC motor is similar to DC motor, where speed is directly proportional to input voltage. Unlike the traditional voltage source inverters, it can utilize the shoot-through (ST) state to boost the input voltage, which improves the inverter reliability and enlarges its application field[1]. It can utilize the shoot-through (ST) state to boost the input voltage. Thus, the generation of high ac voltage made the motor to run at higher speed. The rotor current is sensed to limit the torque ripple which is required for quiet operation of the drive system. This paper investigates the input and output performance of BLDC motor drive system with close loop control of speed and torque.

2. Switched Inductor Quasi Z-Source Inverter

A newly proposed topology, which consists of two capacitors(C1 & C2), the inductors (L1,L2 & L3) and four diodes (D1,D2,D3 & D1n). And as the name suggests, it is a set of energy storing elements arranged in such a way to minimize the inrush current at starting up of the switches. Along with it, reduces the current strain on inductor and voltage stress on capacitors. Also reduces the passive components connection and improves system authenticity.

The main advantage of this arrangement is, the boost factor increases from 1/(1-2D) to (1+D)/(1-2D1-D2).[2]

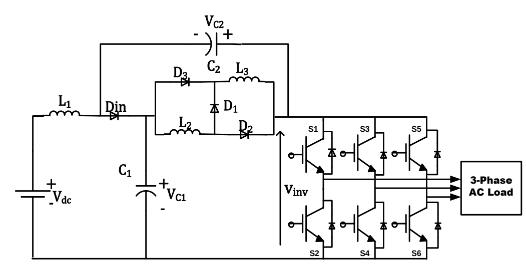

Figure 1: Switched Inductor Quasi Z-Source Inverter

The operating principle of SlqZSI is, it has an extra shoot-through state unlike the traditional inverter which enhances the boosting capability of the inverter.

The operating condition is divided into two states for analysis purpose (i) shoot- through state (ii) non shoot- through state. Fig. 5 shows the equivalent circuits of the proposed SL-qZSI. In the nonshoot-through state, the energy flows from the dc supply to the load through inductors L_1, L_2, and L_3 and capacitors C_1 and C_2 gets charged. And during the shoot-through state, capacitors C_1 and C_2 is feeding the energy to the inductors L_1 , L_2 , and L_3 and stores energy.

3. SLqZSI based BLDC Motor Drive System

Fig.2 shows the proposed model of SL-qZ source inverter based Permanent Magnet Brushless DC motor drive system. The dc

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input voltage is either buck/boosted as per the requirement of the motor drive. The boosted energy from the SLqZSI is feeded to the brushless dc motor.Basically two modes are there (a) commutation mode (b) non-commutation mode[3].

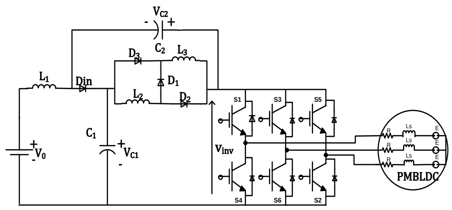

Figure 2: SL-qZSI based PMBLDC Motor

According to the operating principle of PMBDCM[4], only two phases conducts in the non-commutation state which is shown in fig 2.Thus in that only two switches(IGBT or the anti-parallel) conducts in different legs of the bridge in non shoot-through mode. While four devices are conducted in the shoot-through mode when it occurs in one phase leg shown in fig 2(c). When stator phase current flows from a-phase to b-phase. For getting the boost capability, shoot-through states are generated either by shorting one arm or two arm in the inverter. Consider that lower switches are arranged so as to short the bridge whereas upper switches perform the chopper operation. The operation of various modes can be explained by the fig 2.

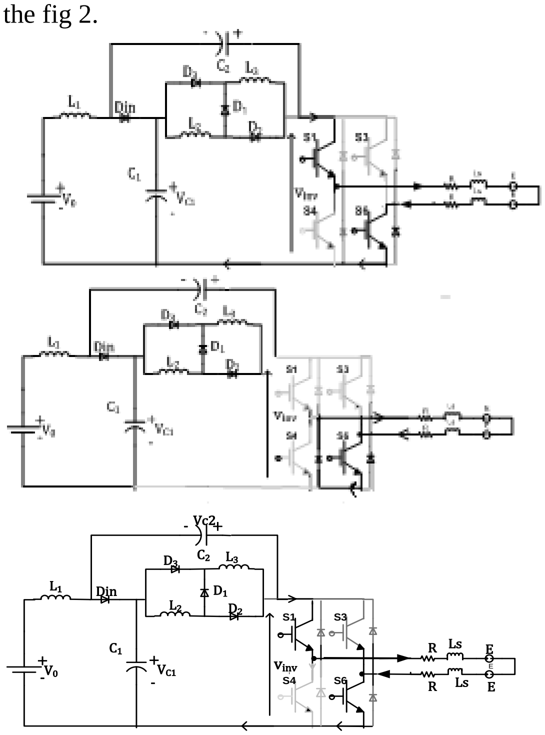

Fig. 3 Equivalent circuits during non – commutation stage (a) open state(b) active state (c) shoot – through

The operation differs in the phase commutation stage, where three phase conducts in all the three modes. In the non shoot-through mode, three devices conducts which is shown in fig 3(a) while five devices conducts when shoot-through occurs in one phase leg and seven devices may conduct when in shoot-through occurs in two phase leg. When the inverter output is in active state, the shoot-through states need to be inserted by giving gate pulse on the lower switch.

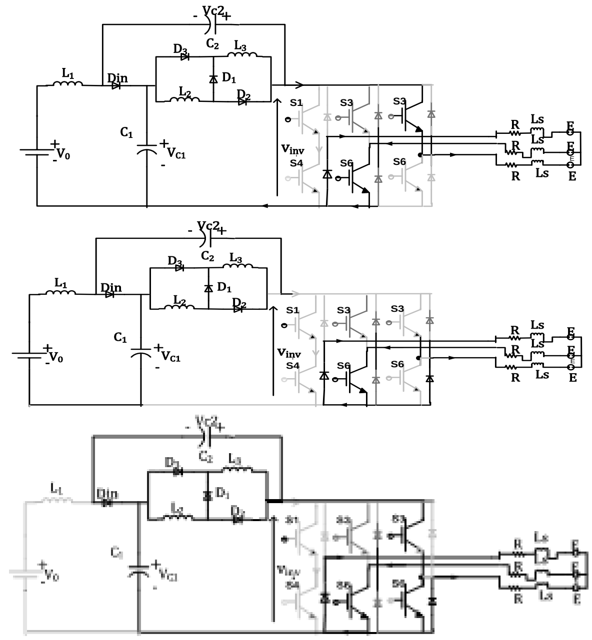

Figure 4: Equivalent circuit during phase commutation stage (a) open state(b) active state (c) shoot – through state.

The fig 3 below shows that when switches S1 and S6 conducts, the current flows from phase a to phase b, and simultaneously switch S4 conducts, which shorts the leg.

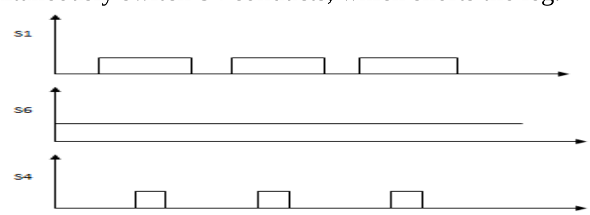

Figure 5: Gating pulse for Switch S1,S6 & S4

4. Proposed Model of Motor Drive System and its Control Strategy

The voltage buck/boost is done in accordance with a speed and current feedback system providing precise speed and torque control of the BLDC motor.

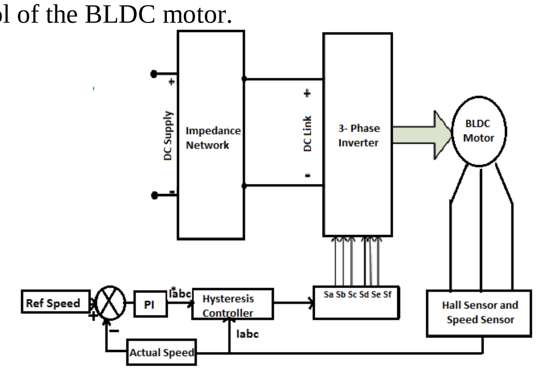

Figure 5: Proposed model of Motor Drive system

The control system consists of speed feedback system, a controller, PMBLDC motor, SLqZ-Source Inverter and a speed. The control system consists of speed feedback system, a controller, PMBDC motor, SLqZ-Source Inverter and a speed setting equipment.

The purpose is to achieve a constant speed and torque characteristics. Here, motor speed controller is designed such as to take a reference signal which represents the demanded speed and this reference signal compared with the rotor speed signal. Now the controller estimates the difference between both the signals which produces an error signal, which is fed to the PI controller. PI controller is the most popular controller, which computes and transmits a controller output signal in every sample time 'T' to the final control system i.e, motor drive system. It consists of proportional gain which generates a signal which is proportional to the input error and the integral action empower the controller to remove the offset. Thus the system becomes stable by making the steady state error to zero[5].The control system is properly designed for a precise control of speed and torque which makes it insensible to any disturbance and changes in the parameters[6]. P which is termed as proportional gain which generates a signal which is proportional to the input error and it correlates with present error whereas I is termed as integral action which empower the controller to remove the offset and I depends on the accrual of past errors, established by current rate of change. There are several methods for tuning a PI loop [7]. The PI Loop is tuned by various methods. The most productive Method is to develop a process model and then choosing the P, I values according to the dynamic model parameters[8]. Here in the proposed model, a feedback loop of speed signal and a feedback loop of current signal is used and is shown in Fig. 6 shown below.

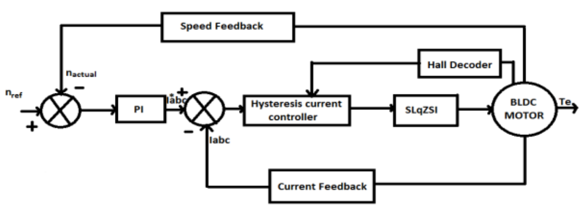

Figure 6: Block diagram of the proposed model with double-loop control

Thus the speed loop comprises of PI controller and the Current loop comprises of hysteresis current loop.

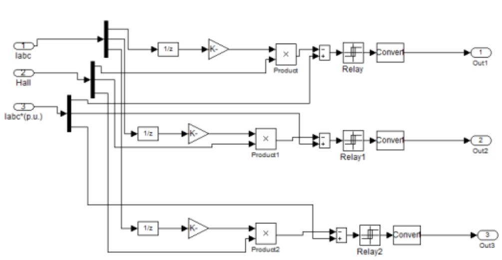

Figure 7: Hysteresis Current Controller

The control algorithm is very easy to understand and practically easy to implement. The hysteresis current controller works on basis of comparison of reference current level with the upper and lower level. The difference between upper level U_H and lower level U_L is called as the hysteresis band. The hysteresis band width is decided by the engineer on the basis of reference current level. And upper and lower level is calculated from this band. Thus, when the actual and reference signal difference will be above the upper level (U_H), controller generates a pulse which will be active low. As the load is inductive and the presence of freewheeling diode in the drive system, the current decreases. After then, the difference between actual and reference signal will be below the Lower level (U_L), controller generates a pulse which go to active high. Thus taking the current to the maximum and the shape of current will become rectangular which synchronize with the back emf. The current signal is chopped from the upper and lower bands[9].

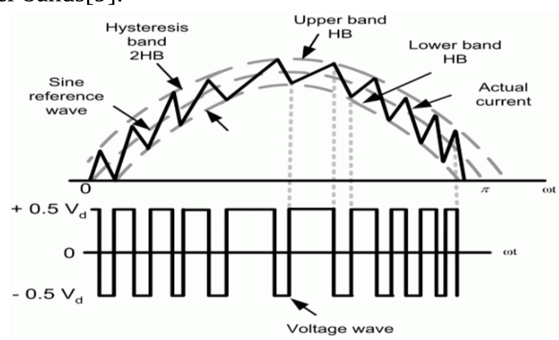

Figure 8: (a) Hysteresis band, (b) Switching pulse

Here the rotor position is sensed with the help of hall sensor and the signal from these hall sensor is used as the modulating signal for the PWM generation. The insertion of shoot-through is done by the use of combinational logic circuit. Maximum voltage gain can be achieved with this switching technique without introducing any lower order harmonics related to the output frequency [10]. Maximum constant boost control method is used for pulse generation and the shoot-through duty ratio is kept at D_0=0.75. By controlling the duty cycle of pulse width modulation (PWM) signal, the amplitude of applied voltage can be controlled, which in turn will control the speed of the motor.

5. Simulation Results & Discussion

To analyze the performance of proposed model of SLqZSI fed BLDC Motor drive system, simulation has been done in MATLAB/SIMULINK. The simulation has been done for two speed frames i.e, (i) constant speed frame and (ii) variable speed frame. The simulation parameters are mentioned in table.1 and 2 and the main simulation circuit performed in MATLAB is shown in fig.5. Also, maximum constant boost control technique has been used for this drive system with constant modulation index, M=0.67.

Case 1: Constant speed drive with low torque

The simulation is done keeping in view of the operation of hybrid EV's and at first performed for low speed and low torque.

Simulation Parameters for SL-QZSI fed BLDC Motor

DC Input Voltage		60V
Carrier Frequency		10KHz
Z-Source Parameters	L_1=L_2=L_3	0.5mH
	C_1=C_2	220uF
Load Torque 'T'(Nm)		4 Nm
Ref. speed 'N' (rpm)		2500
Kp		0.02
Ki		0.6
Hysteresis Band		0.4

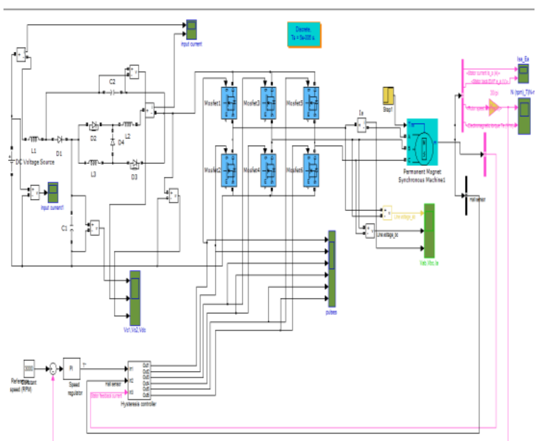

Figure 11 (a): MATLAB/SIMULINK model of the proposed method

We observed that the PI controller keeps the speed constant and hysteresis controller lower the torque ripple. So, the speed settles fast and it is reaching its desired speed within 0.4s and torque ripple is nearly 1%.

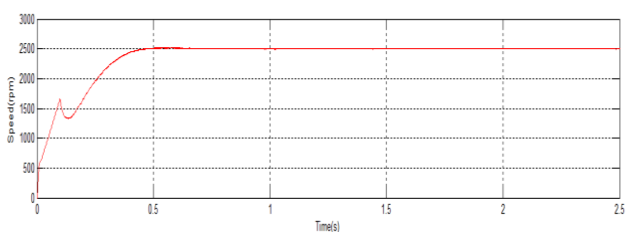

Figure 10 (a): Speed Characteristics

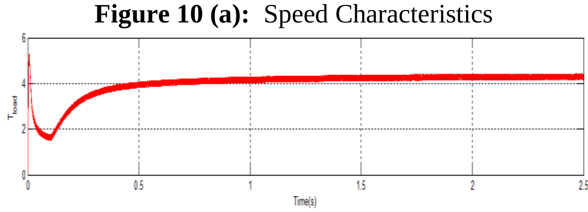

Figure 10 (b): Torque Characteristics

The stator phase current is 5 A which is also in fair limit which can be applied to the stator phase winding for safe operation.

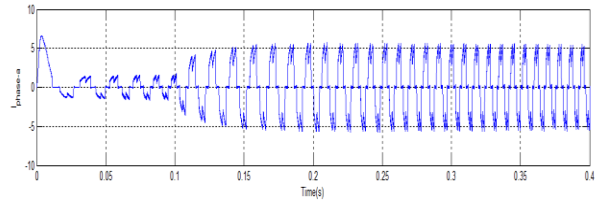

Figure 10 (c): Stator Phase-a current

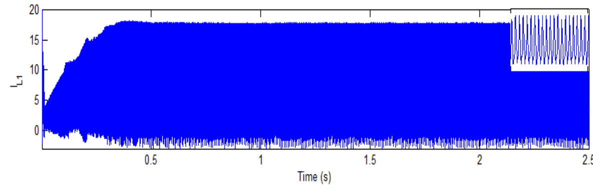

Figure 10 (d): Input current through L1

The input dc voltage is 60V but the injection of shoot- through keeps the capacitors to store the charge and which result in boosting the voltage to 420V in dc link. The voltage stress on capacitor is also less and can be utilized practically.

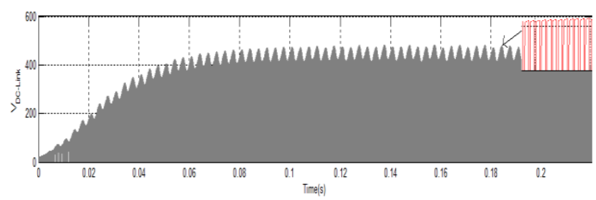

Figure 10 (e): Voltage across dc link

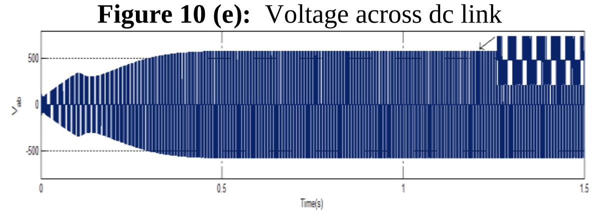

Figure 10 (g): Line Voltage Vab

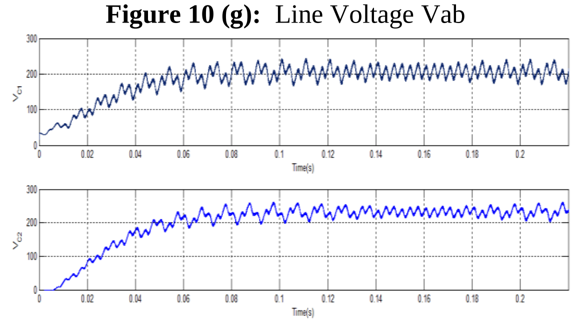

Figure 10 (f): Voltage across capacitors C1 & C2

Case 2: Variable speed drive with high toque

In auto-vehicles where speed frequently varies and torque should have high range. So, keeping in view of operation of auto-vehicles, the parameters have been set. Thus speed varies from 10000 to 15000 rpm and keeping the torque at 41 Nm, the control system keeps the speed constant and settles at new desired speed within 0.5 secs. Also the torque ripple is very low at 2.5%.

Simulation Parameters for variable speed in SL-QZSI fed BLDC Motor

Variable Input Voltage		0-650V
Carrier Frequency		10KHz
Z-Source Parameters	L1=L2=L3	0.5mH
	C1=C2	220uF
Load Torque		41 Nm
Ref. speed		15000-10000-12000 rpm
Kp		0.07
Ki		0.5
Hysteresis Band		0.4

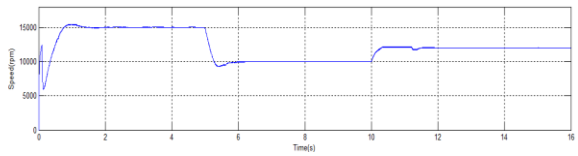

Figure 11 (a): Variable speed characteristics

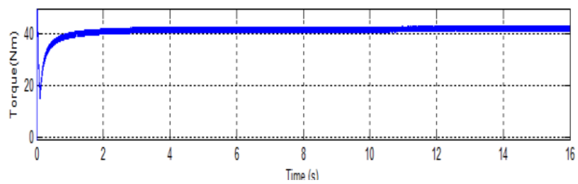

Figure 11 (b): Fixed torque characteristics

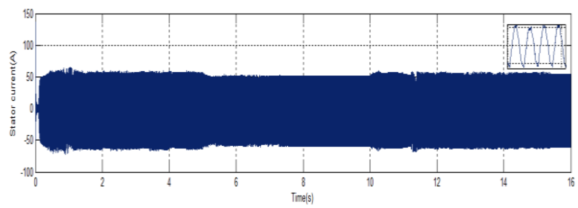

Figure 11 (c): Stator phase current

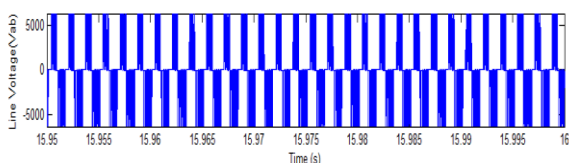

Figure 11 (d): Line Voltage Vab

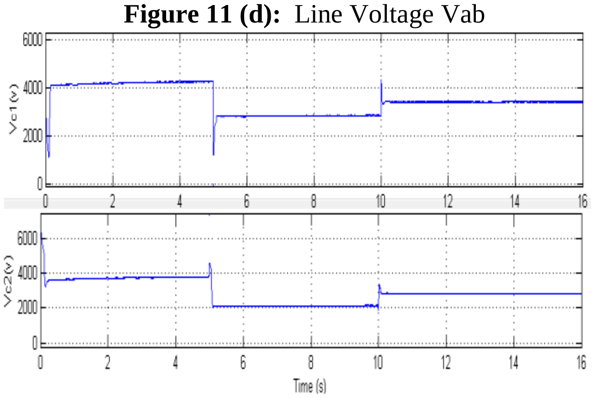

Figure 11 (f): Voltage across capacitors C1 & C2

From fig 11(a),it is observed that this drive system can attain the speed of 15000 within 1.2s and variation in speed is also achieved with a fast speed adjustment to the desired speed. The load torque is directly proportional to the stator current and as with high torque, the stator phase current reaches 50A.The dc link voltage is boosted to 8000V at starting and the voltage across the capacitor is 4000V. The above analysis clearly represents that it can supply heavy loads, when there is a need of high speeds and medium load torque. However, when this motor drive system is used with a load torque more than 70 Nm, then the efficiency decreases and reaches to 50%. When operating at high speed low torque, than the motor drive's efficiency reaches upto 85%.

6. Conclusion

This paper proposes a new model for speed control of SLqZSI fed BLDC motor. A new switching algorithm has been proposed for SL-qZSI with BLDC motor by sensing the rotor position through Hall sensors and controlling the speed and torque by designing double-loop control. As speed is increased the back EMF also increases. This increase in back EMF, results in a reduced torque. Inverter supplies a high voltage to the BLDC motor when it is required to drive high power load. SL-qZSI helps in increasing the back EMF to a value which is required for attaining the desired speed. Analysis shows that when the modulation index is at 0.83, boost factor is near to 5 times and it is the optimum operating point as the shoot-through current remains in the permissible range. The speed can vary from 0 to 15000 rpm rapidly and settling at desired speed within 1.4s. The control of speed is smooth and the efficiency at high speed low torque is more than 85%. It is basically a constant torque drive hence it can conclude that this drive is best suited for application which needs a variable range of high speed and constant medium/low load torque.

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