

Novel Resonant Pole Inverter for Brushless DC Motor Drive System using Fuzzy Logic controller

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Abstract— The brushless dc motor (BDCM) has been widely used in industrial applications because of its low inertia, fast response, high power density, high reliability, and maintenance-free reputation. Brushless DC motors have a permanent-magnet rotor, and the stator windings are wound such that the back electromotive force (EMF) is trapezoidal. It therefore requires rectangular-shaped stator phase currents to produce constant torque. The Motors possess high torque/weight ratio, operate at very high speed, are very compact and are electronically controlled. The advantage of these motors is the removal of brushes, leading to eliminate many problems associated with brushes. BDCM drives have been focused on the motor control strategies. Nevertheless, most of these converter topologies employ the hard-switching technique which causes high switching losses and severe electromagnetic interference. Recently, a number of soft-switching techniques, providing zero-voltage switching (ZVS) or zero-current switching (ZCS) condition, have been successfully developed. This paper proposed the fuzzy logic and PI based speed control of brushless DC motor using soft-switching inverter Hence all switches work in zero voltage switching condition.

Index Terms: Brushless dc motor (BDCM), resonant pole inverter, soft switching, zero-current-switching (ZCS), zero-voltage switching (ZVS), Fuzzy logic controller, PI controller

I. INTRODUCTION

The Brushless DC (BLDC) motor is used for consumer and industrial applications owing to its compact size, controllability and high efficiency. The main limitation to the wider deployment of BLDC motors is the cost of the electronic controller including position sensors. Despite the technical capabilities of power electronics matching the requirements of electronic commutation, induction motors are often preferred due to lower cost. The BLDC motor has many advantages over the induction motor, including better efficiency and power factor. The BLDC motor is also easier to control especially in its trapezoidal configuration. BLDC motors can be divided into two types, sinusoidal back EMF and trapezoidal back EMF. This study utilizes a three phase BLDC motor with trapezoidal back EMF as shown in Figure 1.

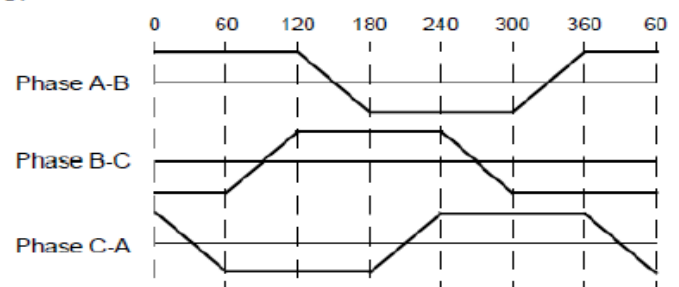


Figure. 1 Trapezoidal back EMF

Soft switching operation of the power inverter has attracted much attention in the recent decades. In electric motor drive applications, soft-switching inverters are usually classified into three categories, namely, resonant pole inverter, resonant dc link inverter, and resonant ac link inverter [1]. Resonant ac link inverter is not suitable to BDCM drivers. Resonant dc link inverter[2], [3] has disadvantages such as high voltage stress of the switches, high dc link voltage ripple, and large resonant inductor power losses. It is with discrete pulse modulation (DPM) control that it is hard to achieve real PWM control and will result in sub-harmonics. Several quasiparallel resonant dc link inverters were designed to solve these problems, but these

inverters require an additional main conduction path switch, which will increase the conduction power losses of the inverter [4], [5]. Other problems with the resonant dc link are such that whichever phase is needed to commutate, the dc link voltage is reduced to zero temporarily, which will affect the operation of other phases.

The structure of the resonant pole inverter [6]–[11] is shown in Fig. 2. Each resonant pole comprises a resonant inductor and a pair of resonant capacitors at each phase leg. These capacitors are directly connected in parallel to the main inverter switches in order to achieve zero-voltage switching (ZVS) condition. In contrast to the resonant dc link inverter, the dc link voltage remains unaffected during the resonant transitions. The resonant transitions occur separately at each resonant pole when the corresponding main inverter switch needs switching. Therefore, the main switches in the inverter phase legs can switch independently from each other and choose the commutation instant freely. Moreover, there is no additional main conduction path switch. Thus, the normal operation of the resonant pole inverter is entirely the same as that of the conventional hard switching inverter.

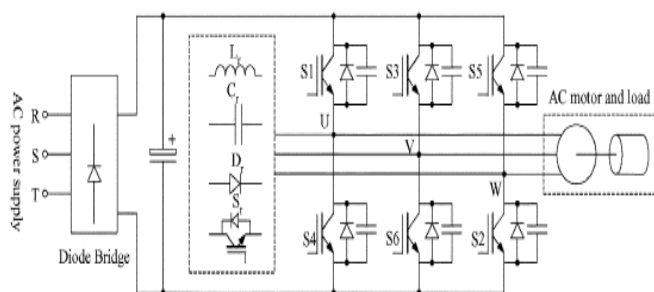


Fig. 2. Resonant pole inverter

The auxiliary resonant commutated pole (ARCP) inverter [6] and the ordinary resonant snubber inverter [7] provide a ZVS condition without increasing the device voltage and current stress. These inverters are able to achieve real PWM control. However, they require a stiff dc link capacitor bank that is center-taped to accomplish commutation. The center voltage of dc link is susceptible to drift that may affect the operation of the resonant circuit. The resonant transition inverter [8], [9] only uses one auxiliary switch, whose switching frequency is much higher than that applying to the main switches. Thus, it will limit the switching frequency of the inverter. Furthermore, the three resonant branches of the inverter work together and will be affected by each other.

Moreover, resonant pole inverters have been applied in induction motor drive applications. They are usually required to change two phase switch states at the same time to obtain a resonant path. It is not suitable for a BDCM drive system as only one switch is needed to change the switching state in a PWM cycle. The switching frequency of three upper switches (S1, S3, S5) is different than that of three lower switches (S2, S4, S6) in an inverter for a BDCM drive system. All the switches have the same switching frequency in a conventional inverter for induction motor applications. Therefore, it is necessary to develop a novel topology of soft-switching inverter and special control circuit for BDCM drive systems. This paper proposes a special designed resonant pole inverter that is suitable for BDCM drive systems and is easy to apply in industry. In addition, this inverter possesses the following

advantages: low switching power losses, low inductor power losses, low switching noise, and simple control scheme.

II . BRUSHLESS DC MOTOR

BDCM motors are one of the motor type's fast gaining popularity. They find applications in industries such as appliance, automotive, aerospace, consumer, medical and instrumentation. BDCM motors do not use brushes for commutation, instead they are electronically commutated. The stator of the BDCM motors consists of stacked steel laminations axially cut along the inner periphery. Though the stator resembles that of an induction motor, the windings distributed in a different manner. The rotor is made up of permanent magnets and consists of alternate north and south poles. Ferrite magnets are traditionally used to make permanent magnets. Rare earth alloy magnets are gaining popularity due to their high magnetic density per volume. An alloy of neodymium, ferrite and boron has been used of late to make permanent magnets.

A. BLDC MOTOR PRINCIPLE

BLDC motors are basically inside-out DC motors. In a DC motor the stator is a permanent magnet. The rotor has the windings, which are excited with a current. The current in the rotor is reversed to create a rotating or moving electric field by means of a split commutator and brushes. On the other hand, in a BLDC motor the windings are on the stator and the rotor is a permanent magnet. Hence the term insideout DC motor. Many motor types can be considered brushless; including stepper and AC-induction motors, but the term "brushless" is given to a group of motors that act similarly to DC brush type motors without the limitations of a physical commutator. To build a brushless motor, the current-carrying coils must be taken off the rotating mechanism. In their place, the permanent magnet will be allowed to rotate within the case.

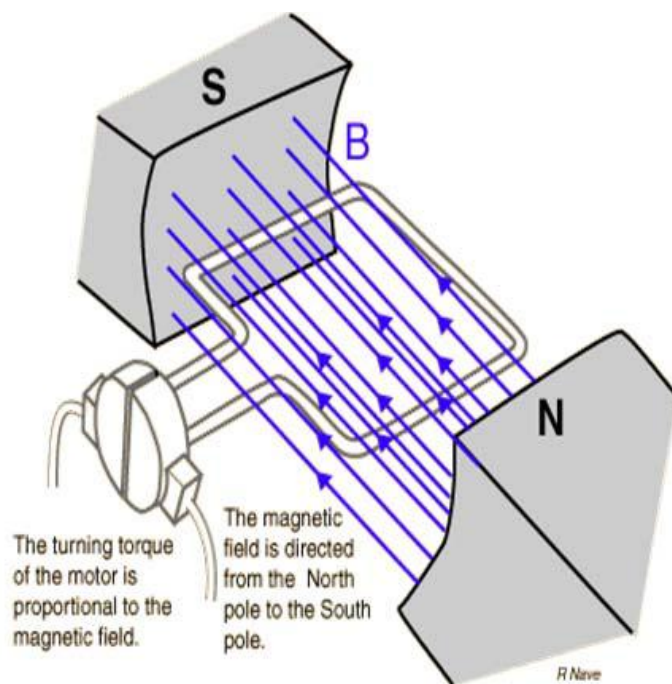


Figure 3. Basic operation of BLDC motor

From the various earlier works that on BLDC Motors, various types soft switching techniques, control strategies and different types of converter designs are used. Their applications, performances and their experimental results are also discussed as earlier work review. In this paper a soft switching of BLDC motor using IGBT is tried. Soft switching using IGBT gives low switching losses, higher efficiency, reduce torque ripples and improves speed as compared to hard switching.

III . SOFT SWITCHING

Traditional hard-switching inverters presented several problems during switching. During turn-on, the device current rises from zero to the load current with additional diode reverse recovery and stray capacitor charging and discharging currents on top of the load current. Typically, a current spike will occur, and the peak device power consumption is extremely high. During turn-off, the device voltage rises. Due to the leakage inductance in the loop, a voltage overshoot caused by $L di/dt$ will occur, and the device voltage will exceed the dc bus voltage. This voltage overshoot can be reduced by a good circuit layout and high frequency dc bus capacitors. The turn-off loss varies among different types of devices depending upon the turn-off delay and current fall time. The power MOSFET consumes least turn-off loss [2]. The insulated gate bipolar transistor (IGBT) turn-off loss also varies among different manufacturing processes and its associated minority carrier lifetime killing. Some ultrafast IGBTs may have low turnoff loss close to that of power MOSFETs. The bipolar junction transistors (BJTs), in general, have a long turn-off delay time and consequently, high switching losses. Another switching problem is the voltage rise and fall rate, di/dt . During turn-on, the voltage falls to zero when the opposite switch turns on. During turn-off, the voltage rises to the dc bus voltage with an overshoot.

A. REASONANT POLE INVERTER

The structure of the resonant pole inverter is shown in Fig.4. Each resonant pole comprises a resonant inductor and a pair of resonant capacitors at each phase leg. These capacitors are directly connected in parallel to the main inverter switches in order to achieve zero-voltage switching (ZVS) condition.

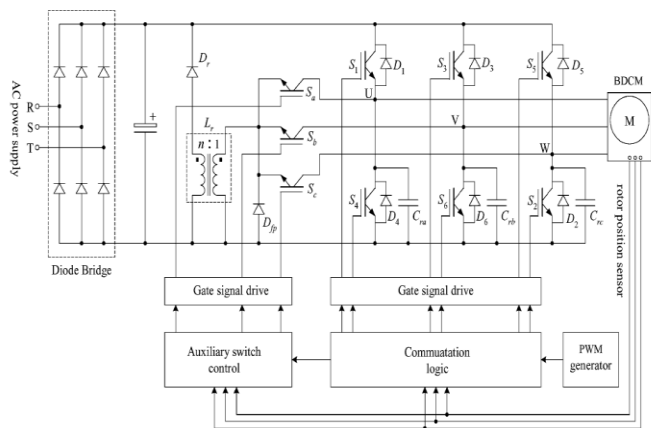


Fig. 4. Structure of resonant pole inverter for BDCM drive system.

In contrast to the resonant dc link inverter, the dc link voltage remains unaffected during the resonant transitions. The resonant transitions occur separately at each resonant pole

when the corresponding main inverter switch needs switching. Therefore the main switches in the inverter phase legs can switch independently from each other and choose the commutation period without restraint. Moreover, there is no additional main conduction path switch. Thus, the normal operation of the resonant pole inverter is entirely the same as that of conventional hard switching inverter.

IV. SPEED CONTROLLERS

Different types of speed controllers have been considered for BLDC motor drive. The speed error (ω_{re}) is computed and used as an input to the speed controller, which outputs torque value (T). This value of torque (T) is fed to the limiter and the final reference torque (T^*) is obtained from the limiter. The speed error at the n^{th} instant of time is given as:

$$\omega_{re}(n) = \omega_r(n)^* - \omega_r(n) \dots \dots \dots (1)$$

Where $\omega_r(n)^*$ reference speed at the n^{th} instant, $\omega_r(n)$: rotor speed at the n^{th} instant $\omega_{re}(n)$: speed error at the n^{th} instant.

A . DESIGN OF PI CONTROLLER

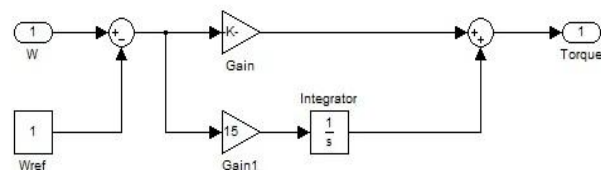


Fig 5. Design of PI controller

The value of proportional gain considered for the BLDC motor is 100 and the value of gain of integral control is 15. $K_i=15$ and $K_p=100$.

B . DESIGN OF FUZZY LOGIC CONTROLLER

Fuzzy logic controller is a rule-based controller. It consists of an input, processing and output stages. The input or fuzzification stage maps sensor or other inputs such as switches, thumbwheels and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output or defuzzification stage converts the combined result back into specific control output. The membership function is triangular, although trapezoidal and bell curves are also used, but the shape is generally less important than the number of curves and their placement. From three to seven curves are generally appropriate to cover the required range of an input value or the "universe of discourse" in fuzzy language. There are several different ways to define the result of a rule, but one of the most common and simplest is the "max - min" inference method, in which the output membership function is given by the truth value generated by the promise. The simulation diagram of fuzzy logic controller is shown in Figure.6. Fuzzy rule has a 7 x 7 decision table with two input variables and one output variable. The look up table for the input and output rules defined for seven linguistic variables (NB, NM, NS, ZE, PS, PM, PB) that stand for negative big, negative medium, negative small, zero, controller converges to the reference value, positive small, positive medium and positive big respectively are given in Table.1.

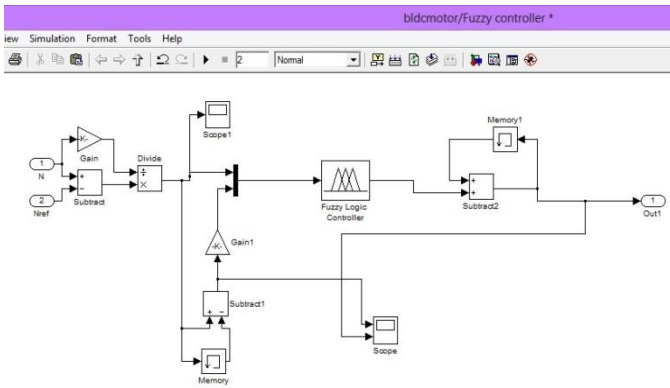


Fig. 6 Simulation diagram for fuzzy logic controller

Table .1. The Fuzzy Linguistic Rule Table

<i>ce</i>	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PL	PL	NM	Z	Z
NM	PL	PL	PL	PM	PS	Z	Z
NS	PL	PM	PS	PS	PS	Z	Z
Z	PL	PM	PS	Z	NS	NM	NL
PS	Z	Z	NM	NS	NS	NM	NL
PM	Z	Z	NS	NM	NL	NL	NL
PL	Z	Z	NM	NL	NL	NL	NL

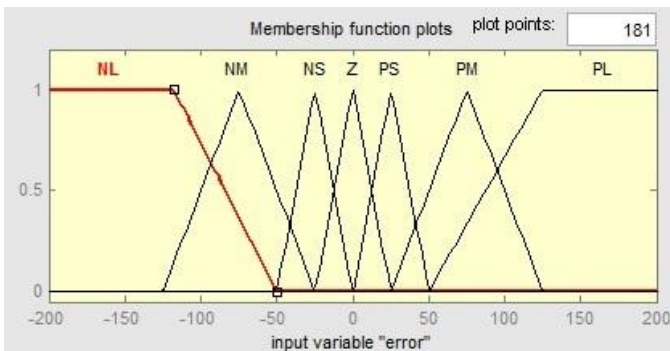


Fig. 7 The fuzzy structure of 'error', 'change in error', and 'output'

V. SIMULATION AND EXPERIMENTAL RESULTS

The proposed topology is verified by software simulation PSim. The dc link voltage V_s is 300 V, and the maximum load current is 25 A. The transformer turn ratio is 1:4, and the leakage inductances of the primary secondary windings are 6 microH and 24 microH, respectively. Therefore, the equivalent transformer inductance L_t is 7.5 microH. The resonant capacitance C_t is 0.047microF. The frequency of the PWM is 20 kHz.

In order to verify the theoretical analysis and simulation results, the inverter was tested by experiment. The test conditions are:

- 1) dc link voltage: 300 V;
- 2) power of the BDCM: 3.3 hp;
- 3) rated phase current: 10.8 A;
- 4) switching frequency: 20 kHz.

A .BLDC MOTOR WITHOUT CONTROLLER

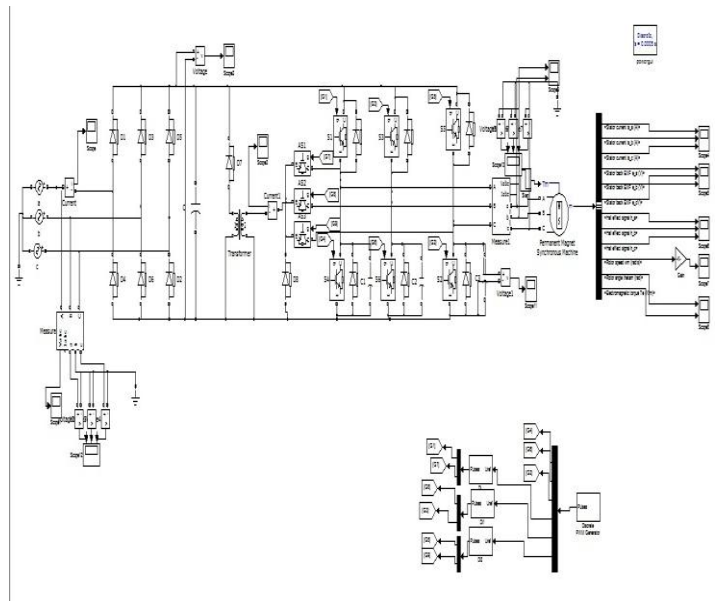


Fig 8. BLDC motor without controller

The Results of BLDC motor model without controller is shown below:

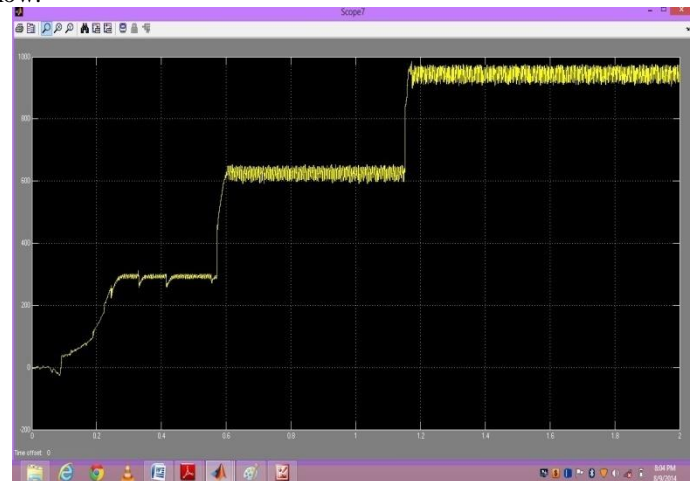


Fig 9. Speed response of BLDC motor without controller

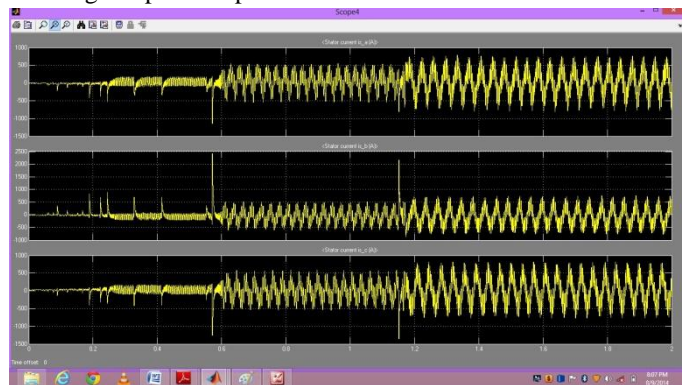


Fig 10. 3ph stator current of BLDC motor without controller

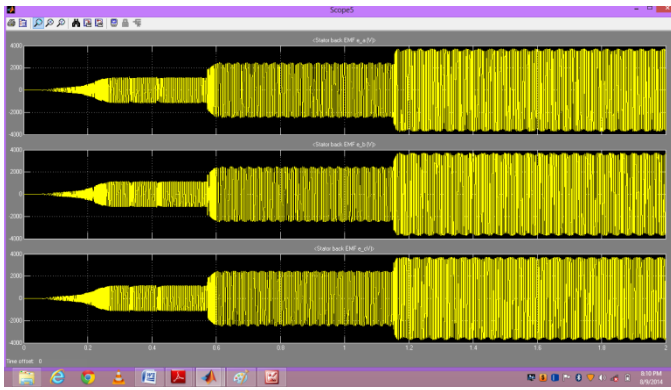


Fig 11. 3phase back EMF of BLDC motor without controller

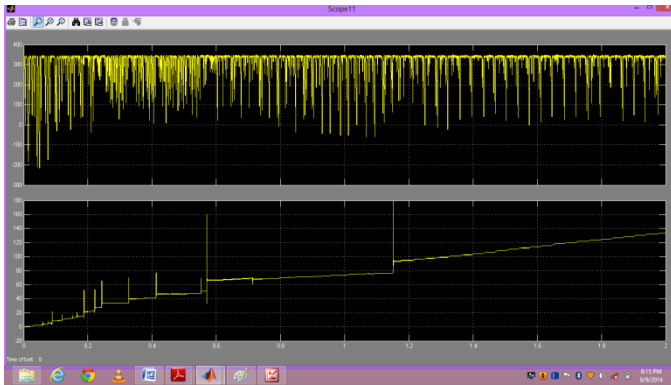


Fig 12. Resonance Voltage and current without controller

B .BLDC MOTOR WITH PI CONTROLLER

The simulation model of BLDC motor with PI controller is shown in fig 13.

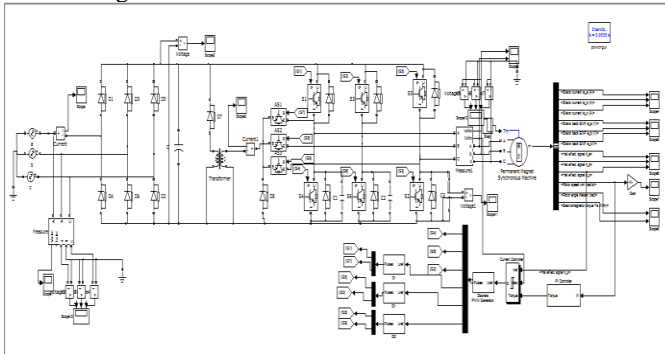


Fig 13. Simulation diagram of BLDC motor with PI controller
The simulation results of BLDC motor with PI controller is shown in fig.14 to fig17.

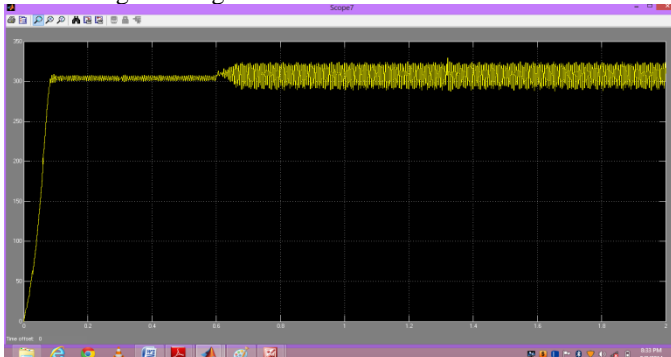


Fig 14. Speed response of BLDC motor with PI controller

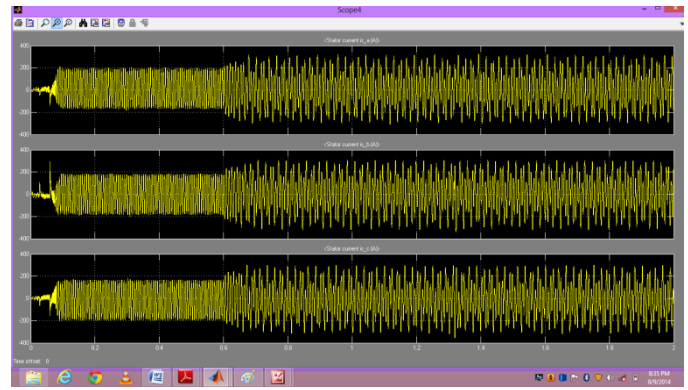


Fig 15. 3 ph stator current of BLDC motor with PI controller

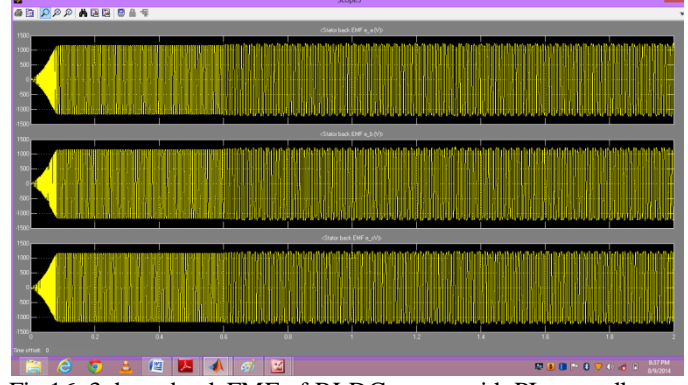


Fig 16. 3phase back EMF of BLDC motor with PI controller

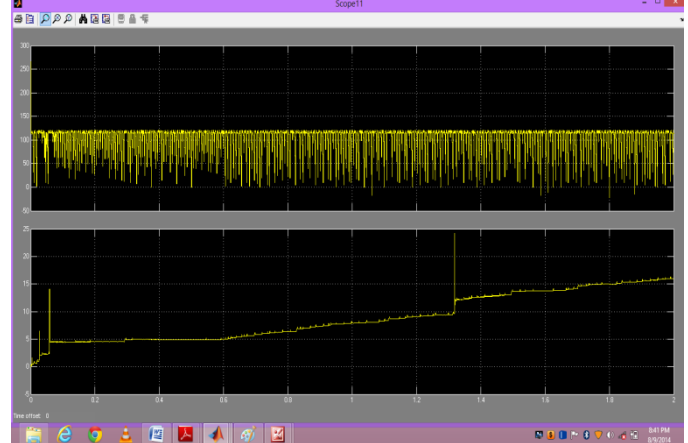


Fig 17. Resonance voltage and current with PI controller

C .BLDC MOTOR WITH FUZZY LOGIC CONTROLLER

The simulation model of BLDC motor with Fuzzy logic controller is shown in fig 18.

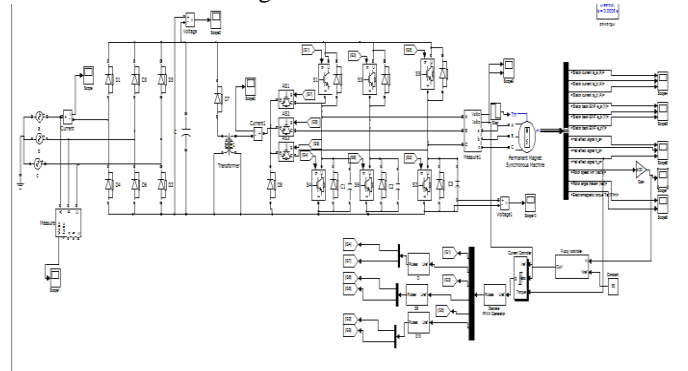


Fig 18. Simulation diagram of BLDC motor with fuzzy logic controller

The simulation results of BLDC motor with fuzzy logic controller is shown in fig.19 to fig 22.

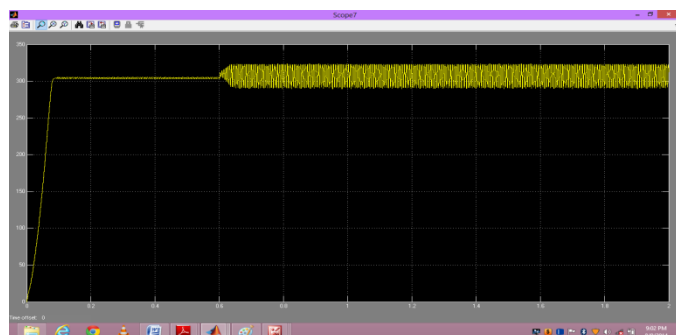


Fig 19. Speed response of BLDC motor with fuzzy controller

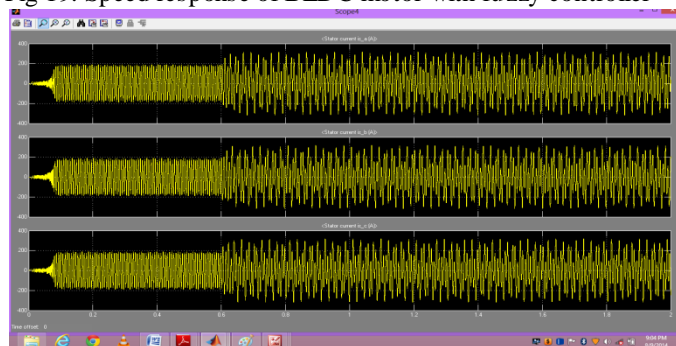


Fig 20. 3ph stator current of BLDC motor with fuzzy controller

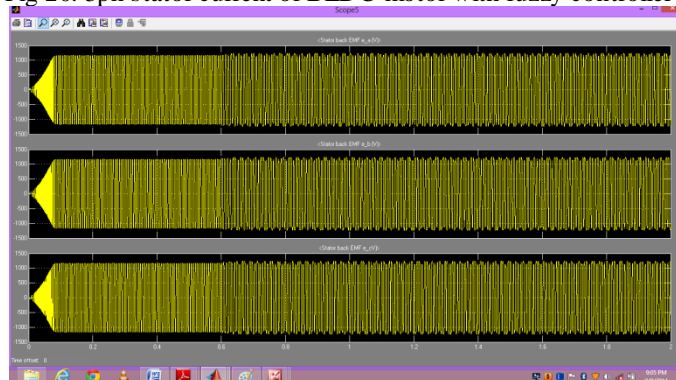


Fig 21. 3ph back EMF of BLDC motor with fuzzy controller

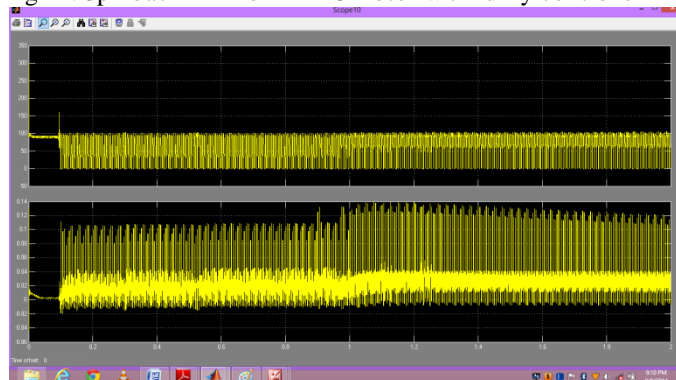


Fig 22. Resonance voltage and current with fuzzy controller

VI. CONCLUSIONS

The performance analysis of a specially designed Resonant pole inverter for brushless dc motor drive system without controller and With two types of speed controllers namely PI and fuzzy based controller is presented. The dynamic behaviour of the Drive system without controller and with both controllers are presented and compared for a speed operation. It is observed that the fuzzy Logic controller gives much better dynamic response for the System and is robust. From the results of proposed inverter Topology the following observations are also made. All the high switching frequency switches work under soft switching condition. Voltage stress on all the switches is so low and it is not greater than the dc

supply voltage .Very simple auxiliary switches control scheme is needed. Freewheeling diodes are turned off under zero current condition which greatly reduces the reverse recovery problem of the diodes. The normal operation of the inverter is entirely the same as that of the hard switching inverter.

The Resonance voltage and current without controller and with PI and fuzzy logic controller is compared and the resonance voltage and current with fuzzy logic controller is best suited according to the theoretical analysis of the resonance soft switching inverter.

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DC Link Voltage	V_{dc}	300 V
Base Speed	ω_b	1000 rpm
Armature Resistance	R_a	2.875 Ω
Armature Inductance	L_a	8.5 mH
Magnetic Flux Linkage	Φ	0.175 wb
No. of Poles	P	4
Moment of Inertia	J	0.89 m^2
Friction Coefficient	B	0.005 Nm.s