# Reduction of Torque Ripple in Brushless DC Drive by Using Capacitor Switching with fuzzy controller

**M Bhargava Kumar [1], C Prashanth Sai [2], U Padmaja [3]**

[1] PG Scholar, Dept.of Electrical Engineering, JNTUA College of Engineering, Anantapur, Andhra Pradesh, India.
[2] Lecturer, Dept.of Electrical Engineering, JNTUA College of Engineering, Anantapur, Andhra Pradesh, India.
[3] PG Scholar, Dept.of Electrical Engineering, JNTUA College of Engineering, Anantapur, Andhra Pradesh, India.

## ABSTRACT

Brushless DC (BLDC) motors have been gaining attention from different Industrial and domestic appliance manufacturers, because of their high power density, high efficiency, low cost and easy maintenance. Brushless DC motors are having a major problem with ripple in torque. The brushless DC drive without capacitor has more ripple to reduce that ripple by using a torque ripple compensation technique based on an actively controlled small capacitor is proposed for brushless dc motor. In proposed compensation technique, capacitor is used in uncontrollable region for the brushless dc motor drive, which is discontinuous current region nothing but uncontrollable region. The proposed brushless dc motor drive of small capacitor is charging in controllable region through diode switch. The small capacitor is discharge in uncontrollable region through controlled switch. This paper presents a three-phase BLDC motor with low cost drive to be driven without DC link capacitor. The proposed technique uses an electronic commutation and operates the machine exclusive of the intermediate DC link capacitor. The designing of Brushless DC motor drive system along with PI controller and fuzzy controller to reduce torque ripple by using MATLAB / SIMULINK and simulated results indicate that the total harmonic distortion of the machine is better than existing techniques.

**Keywords**: Brushless DC drive, Torque ripple compensation, uncontrollable region, controllable region, and harmonics.

## I. INTRODUCTION

Permanent Magnet Synchronous (PMS) motors and Brushless DC (BLDC) motors are becoming more useful in industrial applications and home appliance because of their high reliability, efficiency and low cost and maintenance compared to other motors. BLDC and PMS motors are now designed with high power densities, these causes the increasing their popularity in applications such as airspace applications and mobile coolers. Therefore, BLDC motors have becoming more popular for industrial applications where efficiency, compact and cost effective factors are considered.

PMS motors needs continuous rotor position information for their operation and a significant computational time is required to improve the motor Performance by controlling the rotor. By using rotor position, BLDC motors are commutated electronically and the rotor position information can be obtained by using position sensors. Hall Effect sensors or back EMF sensing technique is used to obtain the rotor position of BLDC motor for every 60 electrical degrees.

The Brushless DC motor drive consists of a diode bridge rectifier and a large electrolytic capacitor with a converter fed rotor for rotor position information. The Brushless DC motor drive with fixed capacitor circuit as shown in fig.1. The main function includes, bus voltage stabilization, ripple current conduction due to switching events, etc. The intermediate DC link capacitor used in indirect conversion topologies, requires a large space for its installation, which results in increasing its weight and occupying place.

Usually, a large electrolytic capacitor is employed to support the intermediate DC link voltage. The lifetime and properties associated with the capacitor are affected by the ambient temperature. The electrolytic capacitor is bulkier in size and weight, and its lifetime is severely affected by the operating temperature. Thus, the inclusion of the capacitor reduces the reliability of the motor drive, particularly in hot or cold environments such as in heating, ventilation, and air conditioning applications. In automotive applications, one of the major problems is the exuberant and barbarous temperatures they have to withstand, under hood, which during the summer months would reduce their life.

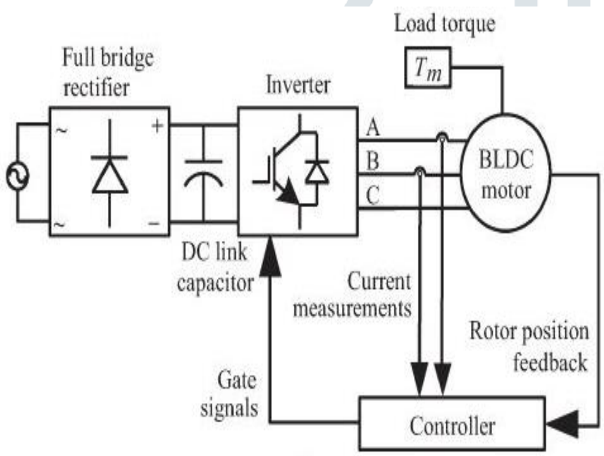


**Figure 1**. Brushless dc motor drive with fixed capacitor.

Furthermore, the type of dielectric material, the ambient temperature and the storage temperature are the most significant aging factors for an electrolytic capacitor mainly in hot or cold environments viz. heating, ventilation and air conditioning applications. So the inclusion of the capacitor in the circuit decreases the overall converter reliability, as it is the most vulnerable component amongst the other in the circuit. Moreover, electrolytic capacitor technology is relatively stable, and the price is governed only by the cost of materials.

If without the DC link capacitor, the rectified mains supply is directly applied to the drive. The Brushless DC motor drive without capacitor as shown in fig.2. The absence of DC link capacitor causes to reduce the overall cost of the motor drive but at the expense of harmonics in torque, which are inevitable and expected to be around zero crossing points of the supply. Without DC link capacitor have more ripple at rectifier output. The ripple will exhibit at inverter side also in the form of total harmonic distortion. The torque ripple is more due to large total harmonic distortion. This torque ripple reduces the system reliability and efficiency.

Torque pulsations/ripple in BLDC motors brought about by the deviation from ideal conditions are either related to the design factors of the motor or to the power inverter supply, thereby resulting in non-ideal current waveforms. Undesirable torque pulsation/ripple in the BLDC motor drive causes speed oscillations and excitation of resonances in mechanical portions of the drive, leading to acoustic noise and visible vibration patterns in high-precision machines. BLDC motor torque pulsations produce noise and vibration in the system. Due to this the BLDC motor drives have low efficiency, high maintenance, less life and high noise.

Such ripple and discontinuities are not preferred in some applications, which require a constant torque output. Moreover, discontinuities in the torque result in vibrations and acoustic noise in the motor drive. Those vibrations can cause undesirable stresses on the mountings and bearings, raising reliability concerns of the motor drive system. In addition, the average torque produced by a motor drive without the DC link capacitor is lower in comparison to a motor drive with stiff DC link. As a solution, a torque ripple compensation technique based on an actively controlled small capacitor is proposed and illustrated in Fig. 3.

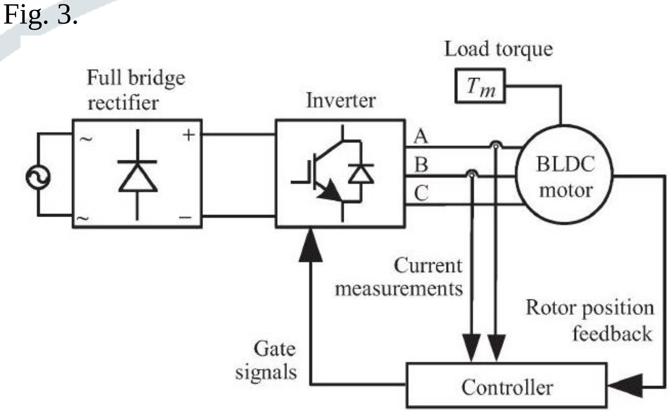


**Figure 2**. Brushless DC motor drive without capacitor circuit.

| Step | Hall sensor output | | | Switch is in on state | Controlled switch |
|---|---|---|---|---|---|
| | Ha | Hb | Hc | | |
| **1** | 1 | 0 | 0 | A1 | C2 |
| **2** | 1 | 1 | 0 | C2 | B1 |
| **3** | 0 | 1 | 0 | B1 | A2 |
| **4** | 0 | 1 | 1 | A2 | C1 |
| **5** | 0 | 0 | 1 | C1 | B2 |
| **6** | 1 | 0 | 1 | B2 | A1 |

The proposed technique of brushless DC motor have high efficiency, less maintenance, long life, less noise, less cost of the drive, size and weight of the drive reduces.

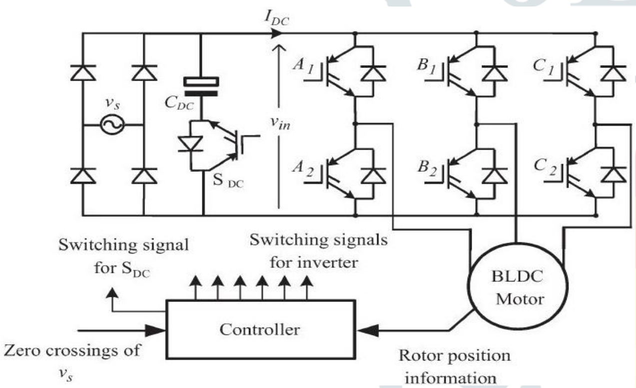


**Figure 3.** Proposed technique for torque ripple compensation.

## II. MATHEMATICAL MODEL

In the proposed BLDC motor drive, a switching algorithm, which is based on single switch control while keeping the other switch in ON state for the entire switching interval, is employed. The switch that remains in ON state provides a freewheeling path to the inductive current while the controlled switch in OFF state. The switching states are tabulated in Table I with rotor position information obtained by Hall Effect sensors. The outputs of Hall Effect sensors, denoted by Ha, Hb, and Hc, and the switching signals are illustrated in Fig.4 with the position of the rotor, denoted by θr, in electrical radians. Switches of the phase legs A, B, and C of the inverter are represented by A1, A2, B1, B2, C1, and C2, where subscripts 1 and 2 denote the upper and lower switches of each phase leg of the inverter, respectively.

**Table 1:** Switching algorithm

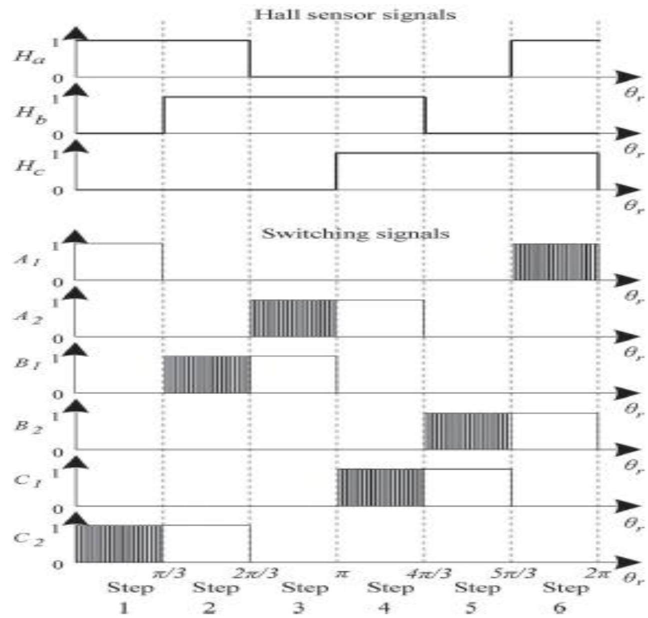


**Figure 4.** Hall sensor signals and switching signals.

The operation of the motor drive during all other steps of the switching algorithm can be represented by the same buck converter model. Since two phases are lumped together, e(t) represents the line-to-line back EMF (V), and S and D in Fig.5 represent the controlled switch and freewheeling diode, respectively.

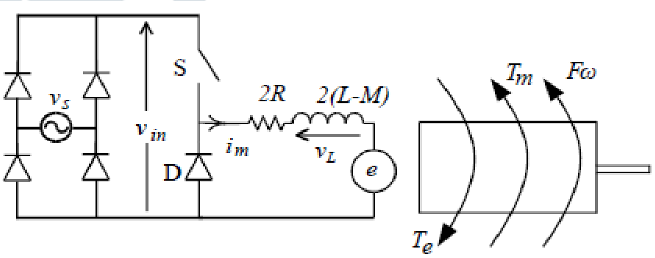


**Figure 5**. Buck converter based model of the motor drive.

From Fig. 6, we have to derive the equation of voltage and current equation are derived is illustrated in [1]. Generally, BLDC motor drives have trapezoidal back EMF, due to the harmonics the ideal trapezoidal back EMF is not trapezoidal back EMF. The average value of trapezoidal back EMF is represented as E. If reduce the harmonics to get ideal trapezoidal back EMF. For the reduction of higher order harmonics it takes computational complexity.

The motor drive without DC link capacitor of the rectifier output wave form and phase current as shown in Fig. 6. Form Fig. 6 the phase current is discontinuous in uncontrollable region, constant current in controllable region.

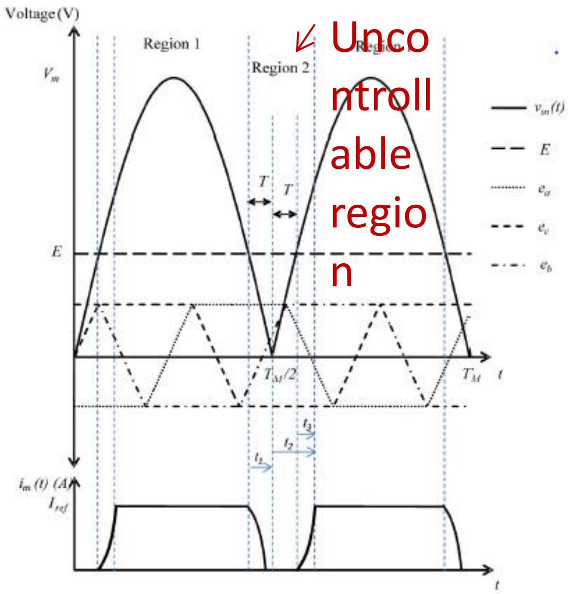


**Figure 6.** Controllable and uncontrollable regions of current of the brushless dc motor drive at steady state.

Form Fig. 6 the non-linear phase current in uncontrollable during region 2. Similarly the electromagnetic torque also non-linear in uncontrollable region during region 2. The non-linear torque will cause vibrations and acoustic noise in the motor drive. Those vibrations can cause undesirable stresses on the mountings and bearings, raising reliability concerns of the motor drive system.

Times T and $T_M$ are defined as the interval for $V_{in}(t)$ to reach E from 0 V and the period of the input mains voltage.

$$T = \frac{\sin^{-1}\left(\frac{E}{V_m}\right)}{2\pi f} \quad (1)$$

Where, $V_m$ and f are the peak value of supply voltage (V) and the frequency (Hz) of input supply voltage, respectively. Current $i_m(t)$ is derived as a piecewise function of time during region 2. Consequently, the generated torque by the motor can also be represented as a piecewise function. The following variables in time are defined to express $i_m(t)$ as a piecewise function, and, thus, to reduce the complexity in expressions.

$$t_1 = t - \left(\frac{T_M}{2} - T\right) \quad (2)$$

$$t_2 = t - \left(\frac{T_M}{2}\right) \quad (3)$$

$$t_3 = t - \left(\frac{T_M}{2} + T\right) \quad (4)$$

From above duration of time the phase current equations are derived and equations are

$$i_m(t_1) = -\frac{E\,t_1^2}{4(L-M)T} + I_{ref}\,, \quad (6)$$

$$i_m(t_2) = \frac{E\,t_2^2}{4(L-M)T} - \frac{E\,t_1}{2(L-M)} - \frac{E\,T}{4(L-M)} + I_{ref}\,, \quad (7)$$

$$i_m(t_3) = -\frac{E\,t_3^2}{4(L-M)T}\,, \quad (8)$$

These three equations are to maintain the constant current in uncontrollable region and also to reduce the torque ripple. The $i_m(t_1)$ is discontinuous before the zero crossing of$v_{in}(t)$. The $i_m(t_2)$ is continuous in uncontrollable region. The $i_m(t_3)$ is discontinuous after the zero crossing of$v_{in}(t)$.

## III. TORQUE RIPPLE COMPENSATION

To minimize the torque ripple by using controlling techniques are Modified PWM control techniques, DC Bus Voltage Control, Current control based techniques, Torque Control Techniques, Phase Conduction Methods, Compensation and other techniques.

The propose compensation method is torque control technique. The torque control technique is to compensate the torque ripple. The compensation method is a small capacitor $C_{DC}$ is connected in series with antiparallel diode with controlled switch $S_{DC}$ like MOSFET, IGBT and BJT. The small capacitor is charging in controllable region through diode switch in propose brushless dc motor drive. The small capacitor is discharge in uncontrollable region through controlled switch. From fig. 6. The phase current is discontinuous in uncontrollable region only. In uncontrollable region the capacitor is discharges through controlled switch. The stored energy is supplied to the drive in uncontrollable region. This will reduce the ripple in current similarly the torque ripple also reduces. The selection capacitor based on the formula of

$$C_{DC} = \frac{2TI_{avg}}{V_m - E} \quad (9)$$

The controlling switch is controlled in uncontrollable region. The uncontrollable region is estimated by $E > v_{in}$. This region the controlled switch is continuously in ON position only. Form Fig. 3. The controller is PI controller is used. This PI controller is also having so much of total harmonic distortion in phase current in brushless dc motor drive. Further extension the PI controller is replaced with fuzzy controller. The fuzzy controller gives less total harmonic distortion that improves the total harmonic distortion.

## IV. SIMULATION AND RESULT

The design of brushless dc motor drive without capacitor by using the MATLAB/simulation from fig. 7. The rectifier does not require any gate pulse because of full bridge diode rectifier. The inverter requires triggering pulses with closed loop signal only. The triggering pulses can be taken from the hall signals. The pulse generation for the inverter logic circuit diagram as shown in fig. In the process of pulse generation the PI controller and FUZZY controllers are used. In the simulation drive circuit the parameter values are as shown in the table II. The phase current THD comparison result with PI and fuzzy controller as shown in table 3.

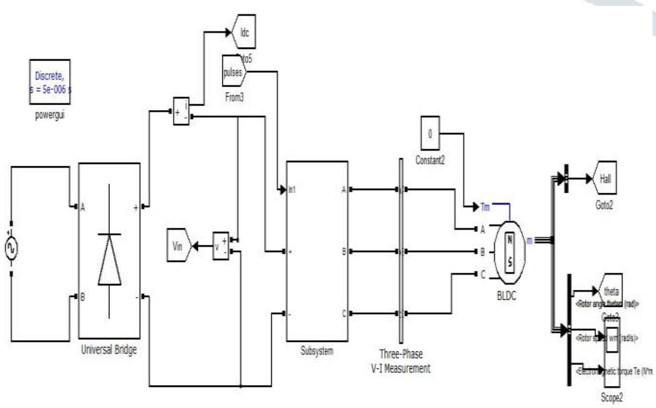


**Figure 7**. Simulation of brushless dc motor drive without capacitor.

**Table 2.** Drive parameters

| Parameter | Value |
|---|---|
| Resistance (R) | 3 |
| L-M | 15mH |
| J | 0.0024 $kgm^2$ |
| Back EMF | Trapezoidal |
| Frequency | 50 HZ |
| Capacitor | 4.7 µF |
| Electrolytic capacitor | 150 µF |

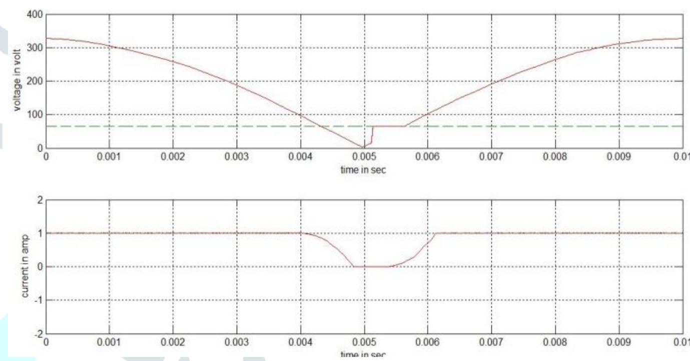


**Figure 8.** The voltage and current wave form of the BLDC drive without capacitor.

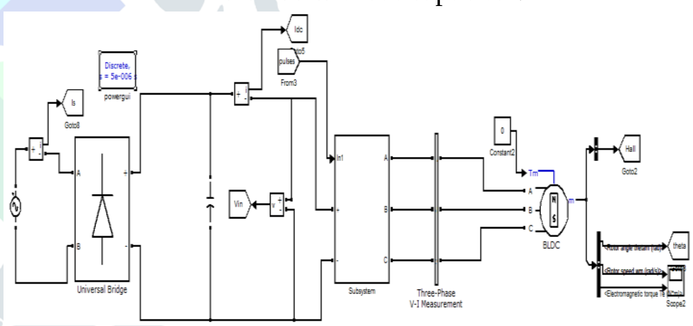


**Figure 9.** Simulation of BLDC motor drive with capacitor.

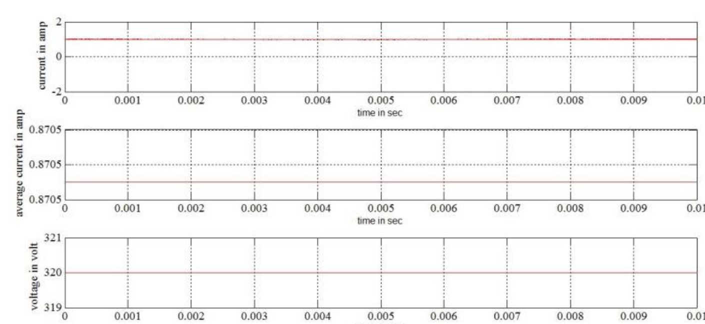


**Figure 10**. Current and voltage wave forms of the BLDC drive with fixed dc link capacitor.

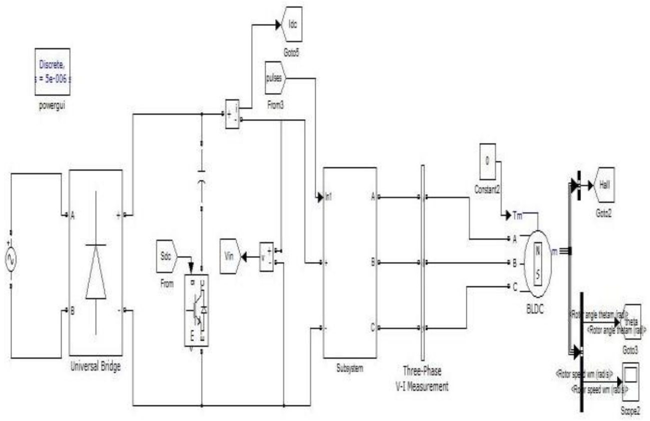


**Figure 11**. Simulation of the BLDC motor drive with capacitor switching.

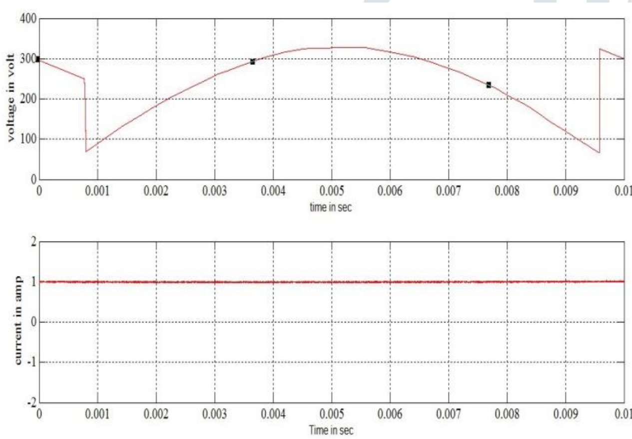


**Figure 12.** Voltage and current wave form of BLDC drive with capacitor switching.

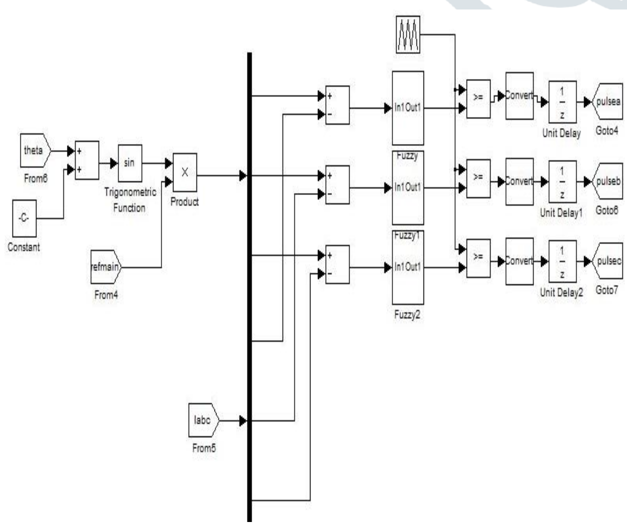

**Figure 14**. Generation of pulses with FUZZY controller.

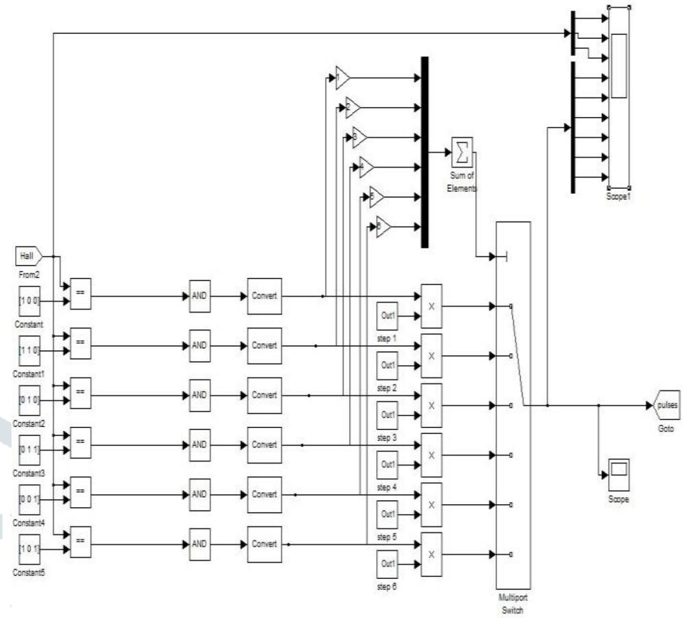

**Figure 13**.generation of controlling and switching pulses by using hall signals.

**Table 3.** THD comparison results

| | Conventional converter with stiff link | Converter without compensation | Converter with compensation |
|---|---|---|---|
| **PI** | 171.4% | 114.3% | 110.6% |
| **FLC** | 139.9% | 113.98% | 101.4% |

## V. CONCLUSIONS

A fuzzy logic controller (FLC) has been employed for torque ripple compensation of BLDC motor drive and analysis of results of the performance of a fuzzy controller is presented. The simulation of the complete drive system is described in this thesis. Effectiveness of the drive is established by performance prediction over a wide range of operating conditions. A performance comparison between the fuzzy logic controller and the conventional PI controller has been carried out by simulation runs confirming the validity and superiority of the fuzzy logic controller for implementing the fuzzy logic controller to be adjusted such that manual tuning time of the classical controller is significantly reduced. The performance of the BLDCM drive with reference to PI controller, FLC controller verified with conventional PI controller using simulation. Fuzzy logic controller improved the performance of BLDC Drive of the fuzzy logic controller.

## VI. REFERENCES


[1] H. K. Samitha Ransara and U. K. Madawala, "A torque ripple compensation of a low cost BLDC motor drive," IEEE Trans. On Industrial electronics., vol. 62, no. 10, pp. 6171–6182, oct. 2015.

[2] H. K. Samitha Ransara and U. K. Madawala, "A technique for torque ripple compensation of a low cost BLDC motor drive," in Proc. IEEE ICIT, Feb. 2013, pp. 222–227.

[3] H. K.Samitha Ransara and U. K. Madawala, "A low cost brushless DC motor drive," in Proc. 6th IEEE Conf. ICIEA, Jun. 2011, pp. 2723–2728.

[4] R. Krishnan, Electric Motor Drives, Modeling, Analysis, and Control. Englewood Cliffs, NJ, USA: Prentice-Hall, 2001.

[5] R. Krishnan, *Permanent Magnet Synchronous and Brushless DC Motor Drives*. Boca Raton, FL, USA: CRC Press, 2010.

[6] J. F. Gieras, *Permanent Magnet Motor Technology—Design and Applica-tions*. Boca Raton, FL, USA: CRC Press, 2010.

[7] V. Sankaran, F. Rees, and C. Avant, "Electrolytic capacitor life testing and prediction," in *Conf. Rec. 32nd IEEE IAS Annu. Meeting*, Oct. 1997, vol. 2, pp. 1058–1065.

[8] H. K.Samitha Ransara and U. K. Madawala, "A low cost brush-less DC motor drive," in *Proc. 6th IEEE Conf. ICIEA*, Jun. 2011, 2723–2728.

[9] Z. Zhu, L. Wu, and M. M. Jamil, "Distortion of back-EMF and torque of PM brushless machines due to eccentricity," *IEEE Trans. Magn.*, vol. 49, no. 8, pp. 4927–4936, Aug. 2013.

[10] R. Carlson, A. A. Tavares, J. P. Bastos, and M. Lajoie-Mazenc, "Torque ripple attenuation in permanent magnet synchronous motors," in *Conf. Rec. IEEE IAS Annu. Meeting*, Oct. 1989, vol. 1, pp. 57–62.

[11] T. R. England, "Unique surface-wound brushless servo with improved torque ripple characteristics," *IEEE Trans. Ind. Appl.*, vol. 24, no. 6, 972–977, Nov./Dec. 1988.

[12] D. Kim, K.-W. Lee, and B.-I. Kwon, "Commutation torque ripple re-duction in a position sensorless brushless DC motor drive," *IEEE Trans. Power Electron.*, vol. 21, no. 6, pp. 1762–1768, Nov. 2006.

[13] Y. A.-R. I. Mohamed and E. F. El-Saadany, "A current control scheme with an adaptive internal model for robust current regulation and torque ripple minimization in PMSM vector drive," in *Proc. IEEE IEMDC*, May 2007, vol. 1, pp. 300–305.

[14] S. V. Tewari and B. I. Rani, "Torque ripple minimization of BLDC motor with un-ideal back EMF," in *Proc. 2nd ICETET*, Dec. 2009, 687–690.

[15] H. L. Zhang and L. W. Qu, "A new torque control method for torque ripple minimization of BLDC motors with un-ideal back EMF," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 950–958, Mar. 2008.

[16] K.-Y. Nam, W.-T. Lee, C.-M. Lee, and J.-P. Hong, "Reducing torque ripple of brushless DC motor by varying input voltage," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 1307–1310, Apr. 2006.

[17] C.-S. Berendsen, G. Champenois, and A. Bolopion, "Commutation strate-gies for brushless DC motors: Influence on instant torque," *IEEE Trans. Power Electron.*, vol. 8, no. 2, pp. 231–236, Apr. 1993.

[18] 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 Trans. Power Electron.*, vol. 25, no. 2, pp. 263–271, Feb. 2010.