Proceedings of 2014 RAECS UIET Panjab University Chandigarh, 06 - 08 March, 2014

Torque Ripples Control and Speed Regulation of Permanent Magnet Brushless dc Motor Drive using Artificial Neural Network

Niraj Kishore
Electrical & Electronics Engg. Deptt.
Lovely Professional University,
Jalandhar, India
kishoreniraj3@gmail.com

Surbhi Singh
Electrical & Electronics Engg. Deptt.
Shobhit University,
Meerut, India
surbhisinghkkr@gmail.com

***Abstract*— This paper presents a torque control of Permanent magnet Brushless DC (PMBLDC) Motor Drive using Artificial Neural Network (ANN) for low torque ripples. Conventional BLDC Motor produces high ripples in electromagnetic torque and it is not directly controlled. The motor may lead to component loss as well as bearing failure due to vibrations caused by high torque ripples. The main drawback with the conventional Brushless dc motor drives (BLDCMD) is high torque ripples and the speed of BLDCMD is reduced under transient and dynamic state of operating condition. This drawback is reduced using with the proposed control technique. In this proposed control technique the speed of the BLDCMD is regulated by the PI controller and the torque ripple is reduced by the ANN. Complete simulation of the conventional BLDCMD is done in MATLAB Simulink.**

Keywords*— *Artificial Neural Network (ANN); Permanent magnet Brushless DC motor drive (PMBLDC); direct current (DC); MATLAB Simulink.

I. Introduction

Brushless dc motor drives (BLDCMD) are preferred as small horsepower control motors due to their high efficiency, silent operation, compact form, reliability and low maintenance. Therefore, the BLDC motor is widely used in computers, household and industrial products and automobiles. However, the BLDC motor has a disadvantage of high cost compared with the direct current (DC) motor because it is necessary to use an inverter and controller to remove brushes of DC motor [1]. Brushless dc motor drive (BLDCMD) with trapezoidal back-EMF have been widely used due to their high power density and easy control method. Moreover, basic trapezoidal brushless dc motors make it possible to use a single dc-link current sensor to regulate the phase current flowing through two motor phases. When 120^0 rectangular stator current control is performed based on a single current sensor as shown in Fig. 1, commutation torque ripples usually occur due to the loss of exact phase current control during the phase current commutation intervals. As for brushless dc motor drives with three phase current sensors, many research regarding commutation torque ripple have been carried out [2].

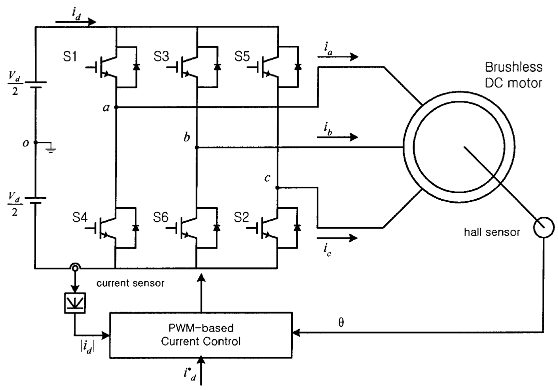


Fig. 1. Basic configuration of trapezoidal permanent magnet brushless dc motor drives

II. Permanent Magnet Brushless Dc Motor Drives

PMBLDC motors are one of the motor type's fast gaining popularity. They find applications in industries such as automotive, aerospace, consumer, medical and instrumentation. PMBLDC motors do not use brushes for commutation, instead they are electronically commutated. The stator of the PMBLDC motors consists of stacked steel laminations axially cut along the inner periphery. Though the stator resembles that of an induction motor, the windings are distributed in a different manner. The rotor is made up of permanent magnets and consists of alternate north and south poles. Traditionally ferrite magnets are 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 to make permanent magnets [3].

A. BLDC Motor Principle

A brush less dc motor is defined as a permanent synchronous machine with rotor position feed back. The brushless motors are generally controlled by using a three phase bridge power semiconductor. A rotor position sensor is required by the motor for starting and for providing proper commutation sequence to turn on the power devices in the bridge inverter. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason as it is an electronic motor. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator brush arrangement, thereby, making a BLDC more rugged as compared to a DC motor [4].

III. MATHEMATICAL MODEL OF BLDC MOTOR DRIVES [5,6,7,8]

The flux distribution in a PM brushless dc motor is trapezoidal; therefore, the *d-q* rotor reference frame model developed for the PM synchronous motor is not applicable. It is prudent to derive a model of the PMBDCM in phase variables for a given non-sinusoidal flux distribution. The derivation of this model is based on the assumptions that the induced currents in the rotor due to stator harmonic fields are neglected and that iron and stray losses are also neglected. Damper windings are not usually a part of the PMBDCM damping is provided by the inverter control. Fig. 3 equivalent circuit of BLDC Motor [9]

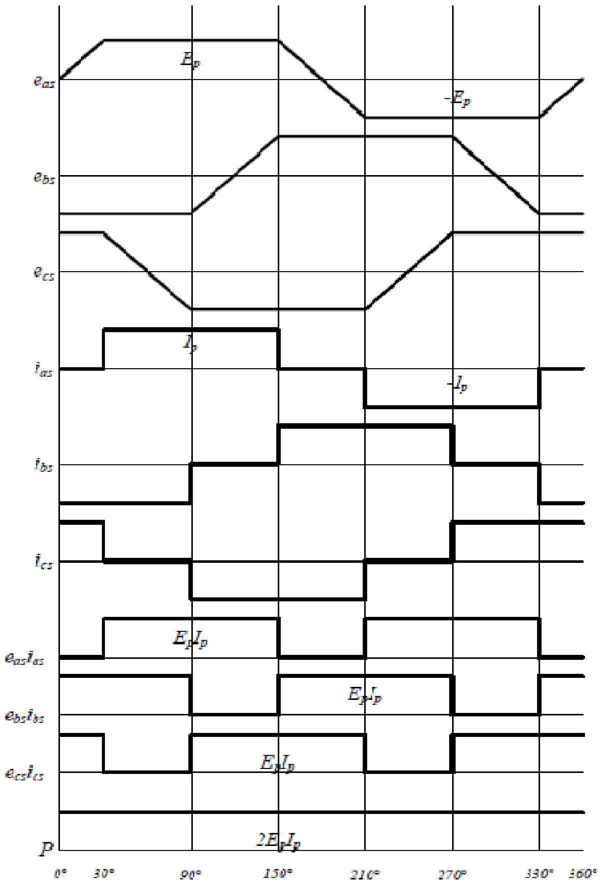


Fig. 2. PM Brushless dc motor waveforms

The derivation procedure is valid for any number of phases although this motor is considered to have three phases. The coupled circuit equations of the stator windings in terms of motor electrical constants are

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + P \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{1}$$

where R_s is the resistance of stator per phase, which is assumed to be equal for all three phases. The induced emfs e_{as}, e_{bs} and e_{cs} are all assumed to be trapezoidal, as shown in Fig. 2, where E_p is the maximum value, derived as

$$\left.\begin{aligned} E_P &= (Blv)N \\ &= N(Blr\omega_m) \\ &= N\Phi_a\omega_m \\ &= \lambda_p\omega_m \end{aligned}\right\} \tag{2}$$

where N is the total number of conductors in series per phase, v is the velocity, l is the length of the conductor, r is the radius of the rotor bore, ω_m is the angular velocity, and B is the flux density of the field in which the conductors are placed.

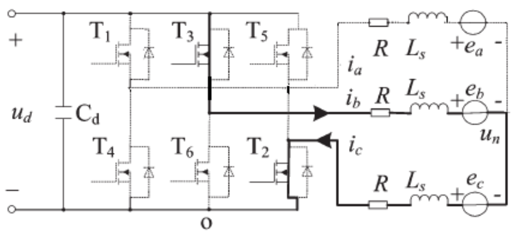


Fig. 3. Equivalent circuit of BLDC Motor

This flux density is solely due to the rotor magnets. The product (Blr), denoted as Φ_a has the dimensions of flux and is directly proportional to the air gap flux, Φ_g

$$\left.\begin{aligned} \Phi_a &= Blr \\ &= \frac{1}{\pi}B\pi lr \\ &= \frac{1}{\pi}\Phi_g \end{aligned}\right\} \tag{3}$$

Note that the product of flux and number of conductors in series has the dimension of flux linkages and is denoted by λ_p. Since this is proportional to phase *a* flux linkages by a factor of $\frac{1}{\pi}$, it is hereafter referred to as modified flux linkages.

The following are obtained if there is no change in the rotor reluctance with angle because of a nonsalient rotor and assuming three symmetric phases:

$$\left.\begin{aligned} L_{aa} = L_{bb} = L_{cc} = L; \\ L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M(H) \end{aligned}\right\} \tag{4}$$

Substituting equations (3) and (4) in equation (1) gives the PMBDC motor drive model as

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} +$$

$$\begin{bmatrix} (L-M) & 0 & 0 \\ 0 & (L-M) & 0 \\ 0 & 0 & (L-M) \end{bmatrix} P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \quad (5)$$

The stator phase currents are constrained to be balanced, i.e., $i_{as} + i_{bs} + i_{cs} = 0$, which leads to the simplification of the inductance matrix in the model as.

The electromagnetic torque is given by

$$T_e = [e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs}]\frac{1}{\omega_m}\ (Nm) \quad (6)$$

The instantaneous value of induced emf can be written from Figure 2 and equation (2) as

$$e_{as} = f_{as}(\theta_r)\lambda_p\omega_m \quad (7)$$

$$e_{bs} = f_{bs}(\theta_r)\lambda_p\omega_m \quad (8)$$

$$e_{cs} = f_{cs}(\theta_r)\lambda_p\omega_m \quad (9)$$

where the functions $f_{as}(\theta_r), f_{bs}(\theta_r)\ and\ f_{cs}(\theta_r)$ have the same shape as e_{as}, e_{bs}, and e_{cs} with a maximum magnitude of ± 1. The induced emfs do not have corners so sharp, as is shown in functions of trapezoidal, but round edges. The emfs are the result of the linkages of flux derivatives and the linkages of flux are the continuous functions. Fringing also makes the flux density functions smooth with no abrupt edges. Then the electromagnetic torque is

$$T_e = \lambda_p \begin{bmatrix} f_{as}(\theta_r)i_{as} + \\ f_{bs}(\theta_r)i_{bs} + f_{cs}(\theta_r)i_{cs} \end{bmatrix} (Nm) \quad (10)$$

It is significant to observe that the phase-voltage equation is identical to the armature voltage equation of a dc machine. This is one of the reasons for calling this machine the PM brushless dc machine. The equation of motion for a simple System with inertia J, friction coefficient B and load torque T_l is

$$J\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \quad (11)$$

and position and electrical rotor speed are related by

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \quad (12)$$

The system in state-space form by combining all the relevant equations is

$$\dot{x} = Ax + Bu \quad (13)$$

where $x = [i_{as}\ i_{bs}\ i_{cs}\ \omega_m\ \theta_r]^t$

$$A = \begin{bmatrix} -\frac{R_s}{L_1} & 0 & 0 & -\frac{\lambda_p}{L_1}f_{as}(\theta_r) & 0 \\ 0 & -\frac{R_s}{L_1} & 0 & -\frac{\lambda_p}{L_1}f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\frac{R_s}{L_1} & -\frac{\lambda_p}{L_1}f_{cs}(\theta_r) & 0 \\ -\frac{\lambda_p}{L_1}f_{as}(\theta_r) & -\frac{\lambda_p}{L_1}f_{bs}(\theta_r) & -\frac{\lambda_p}{L_1}f_{cs}(\theta_r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & -\frac{P}{2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & \frac{1}{L_1} & 0 & 0 \\ 0 & \frac{1}{L_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad L_1 = L - M; \quad u = [v_{as}\ v_{bs}\ v_{cs}\ T_l]^t$$

The state variable θ_r, rotor position is required so as to have the functions $f_{as}(\theta_r),\ f_{bs}(\theta_r)\ and\ f_{cs}(\theta_r)$ which can be realized from a stored table. This completes the modeling of the PMBDC motor drives [10,11].

IV. CONVENTIONAL PMBLDC MOTOR DRIVES MODEL

AC7 block of SimPowerSystem library models a brushless DC motor drive with a braking chopper for a 3HP motor. The permanent magnet synchronous motor (with trapezoidal back-EMF) is fed by a PWM voltage source inverter, made by using Universal Bridge Block. PI regulator is used by the speed control loop to produce the torque reference for the current control block. The three reference motor line currents are computed by the current control block, in phase with the back electromotive forces, corresponding to the torque reference and then feeds the motor with these currents using a three- phase current regulator. Fig. 4 shows block diagram of conventional PMBLDC motor drives [12,13].

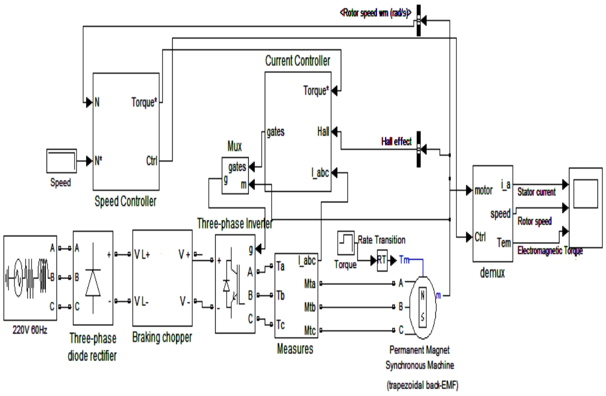


Fig. 4. Block diagram of conventional permanent magnet brushless dc motor drives (PMBLDC).

V. PROPOSED TECHNIQUE

A. *Principles of Artificial Neural Networks*

Artificial neural networks use a dense interconnection of computing nodes to approximate functions which are nonlinear. A neuron is constituted by each node which performs the multiplication of its input signals by constant weights, sums up the results and maps the sum to a nonlinear activation function *g;* the result is then transferred to its output. The neural network trainng is shown in fig. 6. **A** feed forward **ANN** is organized in layers: an input layer, an output layer and one or more hidden layers. A MLP consists of an input layer, many hidden layers, and an output layer. Node *i*, also called a neuron, in a MLP network is shown in Fig. 5. It includes a summer and a nonlinear activation function *g* [14].

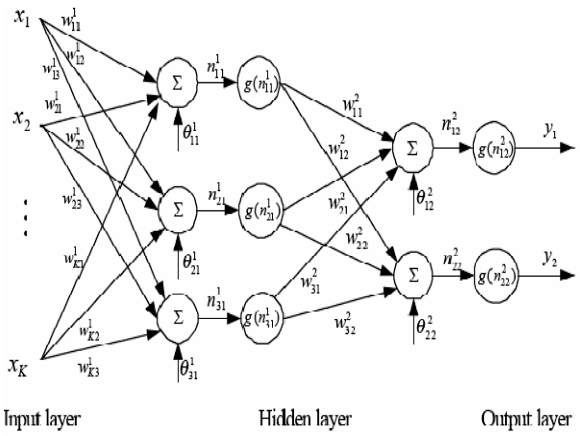


Fig. 5. A multilayer perceptron network with one hidden layer

The inputs x_k, $k = 1...K$ to the neuron are multiplied by weights w_{ki} and summed up together with the constant bias term θ_i. The resulting $i\ n$ is the input to the activation function *g*. The activation function was originally chosen a sigmoid function [14].

$$y_i = g_i = g\left(\sum_{i=1}^{N} w_{ji}x_j+\theta_i\right) \qquad (14)$$

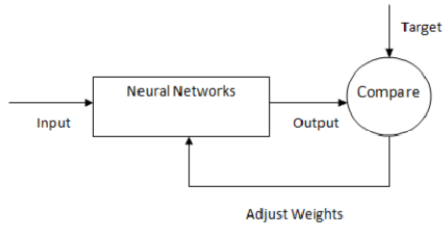


Fig. 6. Neural network training.

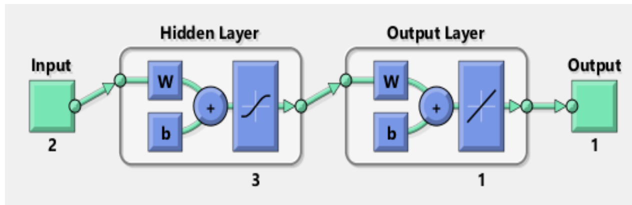


Fig. 7. Neural Network architecture for DTC of a BLDC motor

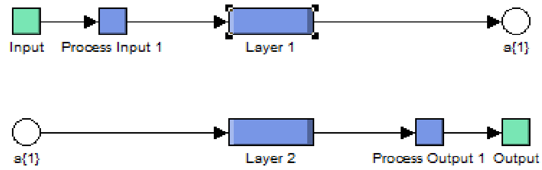


Fig. 8. Block Layer1 and Layer2

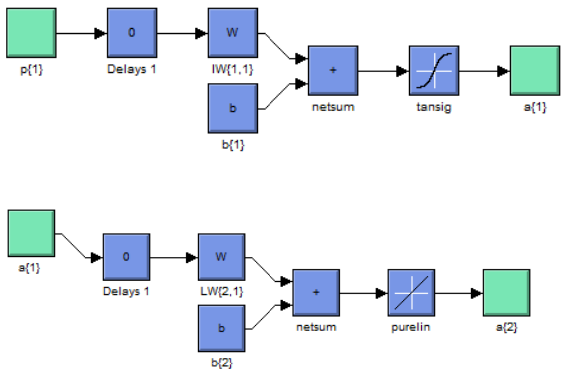
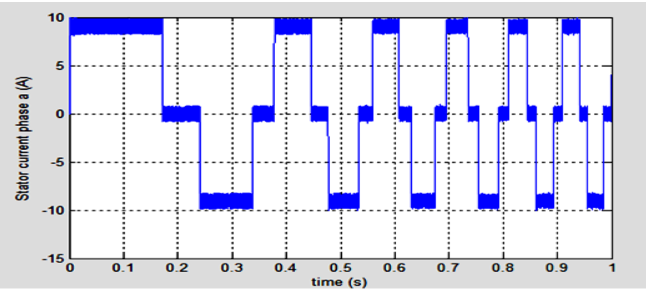


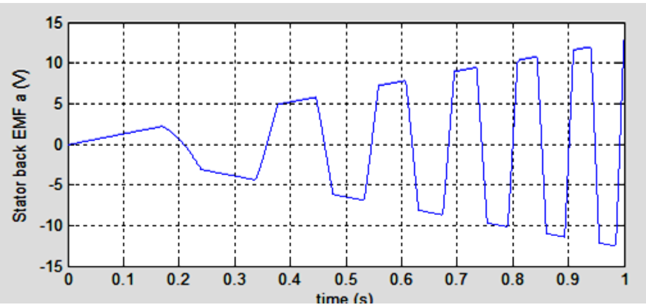
Fig. 9. Open Simulation Block of Layer1 and Layer2

VI. SIMULATION RESULTS

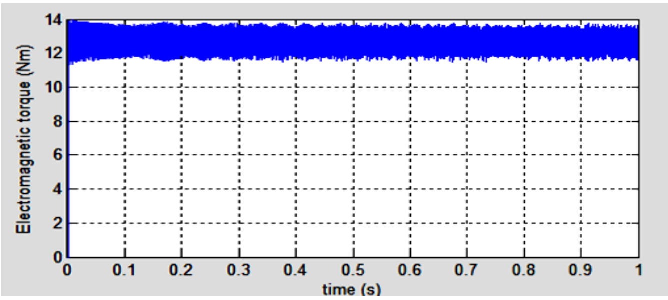
The simulation results from the conventional and Proposed ANN based PMBLDC motor drives MATLAB models are obtained for 3hp PMBLDC motor drives where VSI input DC link voltage is 220V. The parameter values of PMBLDC motor are shown in Table I. The simulation results of conventional and proposed Artificial Neural Network (ANN) are shown in Fig. 10 and Fig. 11, respectively. By comparing the results of electromagnetic torque waveforms achieved through Conventional permanent magnet Brushless DC Motor Drive (PMBLDC) and Artificial neural network (ANN) based Permanent Magnet Brushless DC Motor Drive (PMBLDC) is peak-to-peak ripples of 13.8 – 12.5 Nm (2.3 Nm) in Conventional PMBLDC motor drive and 13.5 – 12 Nm (1.5 Nm) in Proposed ANN based PMBLDC motor drives as shown in Table II. Reduction in current has also been observed in the proposed ANN based PMBLDC motor drives.



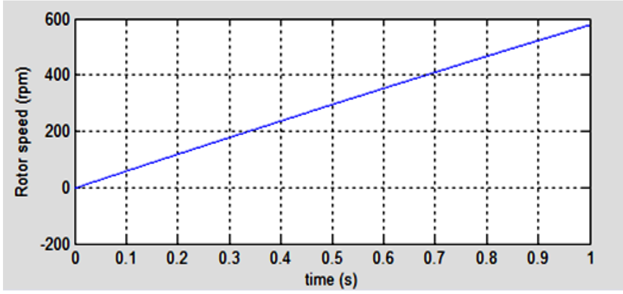
(a)



(b)

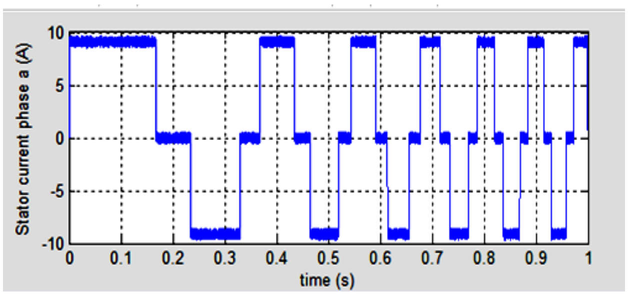


(c)

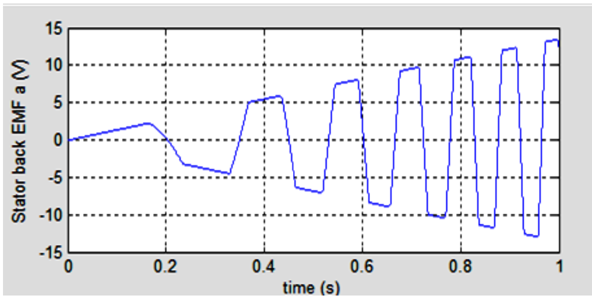


(d)

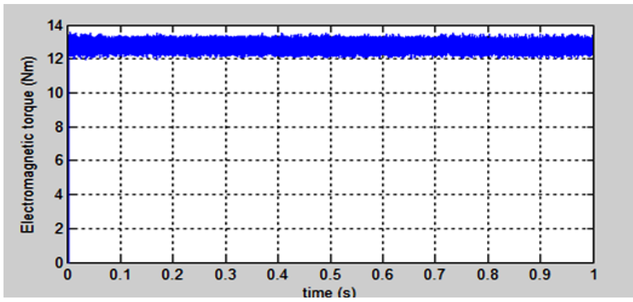
Fig. 10. Simulation results of conventional 3hp PMBLDC motor drives (a) Phase *a* Current (b) Phase *b* Emf (c) Electromagnetic torque (d) Speed



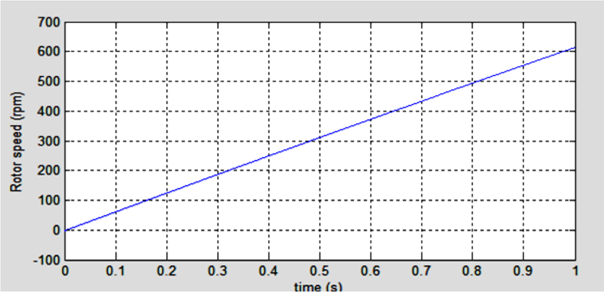
(a)



(b)



(c)



(d)

Fig. 11. Simulation results of Proposed ANN based PMBLDC motor drives (a) Phase *a* Current (b) Phase *b* Emf (c) Electromagnetic torque (d) Speed

TABLE I. PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVE PARAMETER OF 3HP

Parameters	**Nominal values**
Resistance (R)	0.2Ω
Inductance (L)	8.5mH
Inertia (J)	0.89Kgm^2
Friction	0.005Nms
Frequency (F)	50Hz
Voltage (V)	220V
Speed	1650RPM

TABLE II. COMPARISON BETWEEN CONVENTIONAL AND ANN BASED BLDCM DRIVES

S.No.	**Parameter**	**Conventional**	**Proposed ANN PMBLDC Motor Drives**	**Remarks**
1	Torque Ripples	2.3 Nm	1.5 Nm	Reduced
2	Speed	Same	Same	Same
3	Current	Same	Reduced	Reduced
4	Emf	Same	Same	Same

VII. CONCLUSION

Proposed techniques are used here for minimizing the torque ripples in PMBLDC motor drives from the control side. Control techniques used here for minimizing pulsating torque can apply advanced methods, depending on the accurate information of machine parameters. In conclusion, the demand in PMBLDC motor is to produce a PMBLDC drive with smooth operation to suit any application where needed. Proposed ANN technique reduce torque ripples associated to machine control and drives that could be minimized through different control techniques. Suppression of the ripples basically depends on the controller part of the drive system, and the techniques that can be used entail a variety of configurations to be arranged. Some techniques require hardware modification or add-on stages, whereas other schemes are algorithm-based techniques. Despite the number of techniques that have been reported for minimizing pulsating torque production, the effective solution mainly depends on the application limitation and applied controller.

REFERENCES

[1] K. Y. Nam, W. T. Lee, C. M. Lee & J. P. Hong, “Reducing torque ripple of brushless DC motor by varying input voltage”, *Magnetics, IEEE Transactions on*, vol. 42, no. 4, pp 1307-1310, Apr. 2006.

[2] R. Carlson, M. Lajoie-Mazenc & J. C. D. S. Fagundes, “Analysis of torque ripple due to phase commutation in brushless DC machines”, *Industry Applications, IEEE Transactions on*, vol. 28 no.3, pp 632-638, May/Jun 1992.

[3] P. Sreekala & A. Sivasubramanian “Speed control of brushless DC motor with PI and fuzzy logic controller using resonantpole inverter”, In *Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES* pp. 334-339, IEEE Dec. 2011.

[4] Y. Murai, Y. Kawase, K. Ohashi, K. Nagatake & K. Okuyama, “Torque ripple improvement for brushless DC miniature motors”, *Industry Applications, IEEE Transactions on*, vol. 25, no.3, pp 441-450, May/Jun 1989.

[5] J. H. Song & I. Choy, “Commutation torque ripple reduction in brushless DC motor drives using a single DC current sensor”, In *Power Electronics IEEE Transaction on*,vol. 19, no. 2, pp 312- 319, Mar. 2004.

[6] T. C. Siong, B. Ismail, S. F. Siraj, M. F. N Tajuddin, N. S. Jamoshid & M. F. Mohammed “Analysis of fuzzy logic controller for permanent magnet brushless DC motor drives”, In *Research and Development (SCOReD), 2010 IEEE Student Conference on* pp. 436-441, IEEE Dec. 2010.

[7] M. F. Z. Abidin, D. Ishak and A. H. A.Hassan, “A Comparative Study of PI, Fuzzy and Hybrid PI Fuzzy Controller for Speed Control of Brushless DC Motor Drive”, In *Computer Applications and Industrial Electronics International Conference on,* pp 189-194, 2011.

[8] D. K. Kim, K. W. Lee & B. I. Kwon, “Commutation torque ripple reduction in a position sensorless brushless DC motor drive”, *Power Electronics, IEEE Transactions on*, vol. 21 no. 6, pp 1762-1768, Nov. 2006.

[9] M. Ashabani, A. K. Kaviani, J. Milimonfared & B. Abdi “Minimization of commutation torque ripple in brushless DC motors with optimized input voltage control”, In *Power Electronics, Electrical Drives, Automation and Motion, 2008. SPEEDAM 2008. International Symposium on* pp. 250-255, IEEE Jun. 2008.

[10] W. A. Salah, D. Ishak & K. J. Hammadi “Minimization of torque ripples in BLDC motors due to phase commutation-a review”, *Przegląd Elektrotechniczny*, vol. 87, no. 1, pp. 183-188, 2011.

[11] R. Arulmozhiyal & R. Kandiban, “Design of Fuzzy PID controller for Brushless DC motor”, In *Computer Communication and Informatics (ICCCI), 2012 International Conference on*, pp. 1-7. IEEE Jan. 2012.

[12] M. Singh & A. Garg, “Performance evaluation of BLDC motor with conventional PI and fuzzy speed controller”, In *Power Electronics (IICPE), 2012 IEEE 5th India International Conference on* pp. 1-6. IEEE, Dec. 2012.

[13] M. S. Kalavathi & C. Reddy “Performance evaluation of classical and fuzzy logic control techniques for brushless DC motor drive”, In *Power Modulator and High Voltage Conference (IPMHVC), 2012 IEEE International* pp. 488-491. IEEE Jun. 2012.

[14] Meziane, R. Toufouti S., and H. Benalla. “Direct Torque control for induction motor using intelligent techniques”, In *Journal of Theoretical and Applied Information Technology*, 2007 vol no. 3 pp. 35-44.