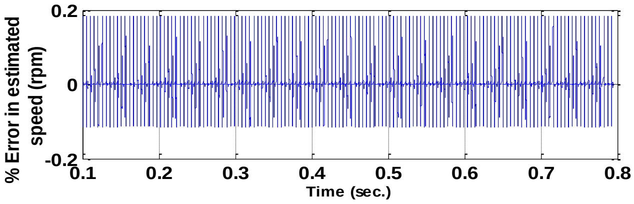
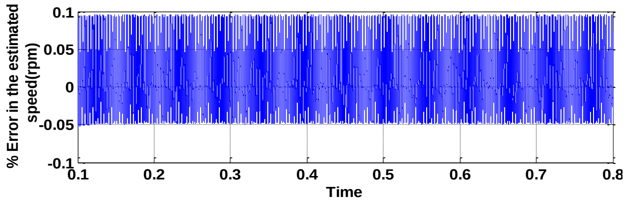
G. Percentage Steady state error between actual and estimated speed with direction:

The percentage error using proposed method obtained based on the reference speed, has been shown in Fig.20.



(a)



(b)

Figure20 (a) Percentage error in the estimation of speed with speed reference of 2000 rpm. (b) Percentage error with input reference speed of 5000 rpm.

Fig. 20 (a) shows the forward motoring case for speed reference of 2000 rpm with Kalman gains K1=1x10^4 and K2 =-3.5x10^7 while the reference speed of drive is 2000 rpm and 0.5 Nm load torque. Fig.20 (b) represents the percentage error in the estimation of the speed with input reference speed of 5000 rpm.

H. Effiecency Versus Load Torque

The efficiency versus load torque plot for the solid state hall sensor based control as well as for sensorless control using U-function based Virtual Hall sensor has been shown in Fig.21. The reference speed has been given 3000 rpm. It has been observed in simulation study that the sensorless control through U-function based virtual hall sensors perform better than actual solid state hall sensor based control at higher load torques. The bifurcation in efficiency plots starts from 6 Nm load torque for the drive parameters selected as per Table.2.

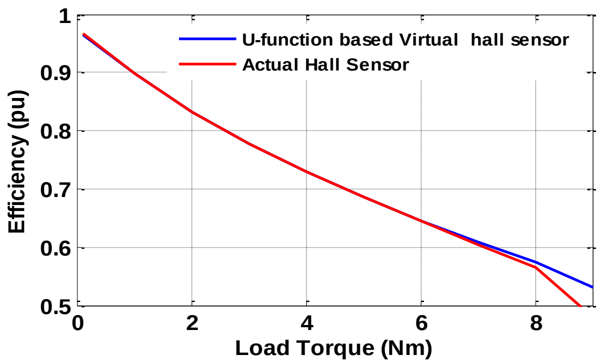


Figure 21. Plot of efficiency versus load torque for actual and U-fucntion based virtual hall sensor control reference speed of 3000 rpm.

CONCLUSION

In the proposed work, a Direction Independent U-function based sensorless commutation technique has been introduced for brushless DC motor. The exact estimated speed value with direction information was used as feedback for current control loop as well as in U-functions. The line to line back EMF estimated out of unknown input observer has been used for speed magnitude calculation. The U-function based virtual hall sensor signals are more sensitive at starting and reversal instants. The positions are stable as solid state hall sensors. At starting, the system with feedback may give unstable results, so for 0.0001 seconds time the feedback is not given to current control loop, so as to lead the system in reference direction. The method has been observed to be self-sustainable in the condition of the load disturbance, vibration and step load variations when using proposed technique with speed and load proportional current control. It has been observed that for higher observer gain obtained with corresponding Eigen values, the position estimation and speed estimation error reduce to very low value and remain constant. Percentage estimation error at steady state is limited to 0.1 to 0.2 %. Proposed method has provided excellent tracking of reference speed and torque. It works for all four quadrants with positive as well as negative reference torque and speed. The proposed sensorless system is completely free of actual (hall or encoder based) speed and position feedback and works only on estimated line to line back EMFs. The proposed method has higher efficiency at higher loads than the actual hall sensor base control.

REFERENCES

[1] M.V.Kesava Rao, Department of Electrical technology, IISc Bangalore, "Brush Contact Drops in DC machines", Accepted 25-6-1934, Bangalore Press.

[2] Y.S. Jeon, H.S. Mok, G.H. Choe, D.K. Kim, J.S. Ryu, "A New Simulation Model of BLDC Motor with Real Back EMF waveform", 7 th workshop on Computers in power Electronics , 2000 (COMPEL 2000), page 217-220.

[3] Padmaja yedmale, "Brushless DC (BLDC) Motor Fundamentals", AN885, 2003 Microchip Technology.

[4] J. R. Frus and B. C. Kuo, "Closed-loop control of step motors using waveform detection," in Proc. Int. Conf. Stepping Motors and Systems, Leeds, U.K., 1976, pp. 77–84.

[5] S. Tara , Syfullah Khan Md "Simulation of sensorless operation of BLDC motor based on the zero cross detection from the line voltage" International Journal of Advanced Research in Electrical Electronics and Instrumentation Engineering, vol 2, issue 12 , December 2013, ISSN 2320-3765.

[6] R. L. Lin, M.T. Hu, S.C. Chen, and C.Y. Lee, "Using phase-current sensing circuit as the position sensor

for brushless DC motors without shaft position sensor," IEEE Conf. Digital Object Identifier, Vol. 1, pp. 215-218, Nov. 1989.

[7] S. Ogasawara and H. Akagi, "An approach to position sensorless drives for brushless DC motors", IEEE Trans. On Industry Applications vol.27, no.5 pp.928-933, 1991.

[8] C. G. Chen, T. H. Liu, M. T. Lin, and C. A. Tai, "Position control of a sensorless synchronous reluctance motor," IEEE Trans. Digital Object Identifier, Vol. 51, Issue 1, pp. 15-25, Feb. 2004.

[9] K. Iizuka, H. Uzuhashi, and M. Kano, "Microcomputer control for sensorless brushless motor," IEEE Trans. on Industry Applications, vol. 27, pp. 595-601, 1985.

[10] K. Iizuka, H. Uzuhashi, M. Kano, T. Endo, and K. Mohri, "Microcomputer Control for Sensorless Brushless Motor, Industry Applications," IEEE Trans, vol. IA-21, pp. 595-601, 1985.

[11] J.C. Moreira, "Indirect sensing for rotor flux position of permanent magnet AC motors operating over the wide speed range", IEEE trans. on Industry Applications, vol. 32, no. 6, pp. 1394-1401, 1996.

[12] H. G. Yee, C. S. Hong, J. Y. Yoo, H. G. Jang, Y. D. Bae, and Y. S. Park, "Sensorless drive for interior permanent magnet brushless DC motors," Proc. of IEEE International Conf. on Electric Machines and Drives, 18-21, pp.TD1/3.1-3.3, 1997.

[13] J. S. Kim, and S. K. Sul, "New approach for high-performance PMSM drives without rotational position sensors," IEEE Trans. Power Electronics, Vol. 12, pp. 904-911, Sep. 1997.

[14] J. Shao, D. Nolan, and T. Hopkins, "A novel direct back EMF detection for sensorless brushless DC(BLDC) motor drives," 17th Annual IEEE Applied Power Electronics Conference and Exposition, Vol. 1, pp. 33-37, Mar. 2002.

[15] G. J. Su and J. W. Mckeever, "Low cost sensorless control of brushless DC motors with improved speed range," IEEE Trans. on Power Electronics, vol. 19, pp. 296-302, 2004.

[16] Q. Jiang, C. Bi, and R. Huang, "A new phase delay-free method to detect back EMF zero crossing points for sensorless control of spindle motors," IEEE Trans. Magn., vol. 41, no. 7, pp.2287-2294, 2005.

[17] Y. Kang, S. B. Lee, and J. Yoo, "A microcontroller embedded AD converter based low coast sensorless technique for brushless dc motor drives," IEEE Conf. Industry Applications, Vol. 3, pp. 2176-2181, Oct. 2005.

[18] C. G. Kim, J. H. Lee, H. W. Kim, and M. J. Youn, "Study on maximum torque generation for sensorless controlled brushless dc motor with trapezoidal back EMF," IEE Proceedings of Electric Power Applications, Vol.152, Issue 2, pp. 277-291, Mar. 2005.

[19] J. Shao, "An improved microcontroller-based sensorless brushless DC (BLDC) motor drive for automotive applications". IEEE Trans. Ind. Appl. 42(5): 1216- 1222 (2006).

[20] Yushui, Yugang Xin, Weicheng Zhang, "An improved BEMF Detection Method for sensorless BLDC motor" IEEE international conference in Industrial technology, ICIT 2008.

[21] P. Damodharan and Krishna Vasudevan, "Sensorless Brushless DC Motor Drive Based on the Zero-Crossing Detection of Back Electromotive Force (EMF) from the Line Voltage Difference", IEEE Trans on energy conversion, vol. 25, no. 3, September 2010.

[22] Lai Y.-S. Lin Y.-K., "A unified approach to zero crossing point detection of back EMF for Brushless DC motor drives without current and hall sensors". IEEE Trans. Power Electron. 26(6), 2011).

[23] J.X. shen ,Z.Q. Zhu and D. Howe, "sensorless flux weakening control of permanent magnet brushless machine using third harmonic back EMF", IEEE transactions on Industry applications, vol 40 no 6 pp. 1629-1636, 2004.

[24] T.M. Jahns, R.C. Becerra, and M. Ehsani, "Integrated current regulation for a brushless ECM drive" ,IEEE trans. on power Electronics, Vol No. 6, No.1, pp 118-126, 1991.

[25] H.R Anderson and J.K. Pedersen, "Sensorless ELBERFELD control of brushless DC motors for energy optimized variable speed household refrigerators," EPE confrec,vol.1, pp. 314-318, 1997.

[26] J. X. Shen, K. J. Tseng, "Analyses and Compensation of Rotor Position Detection Error in Sensorless PM Brushless DC Motor Drives," IEEE Trans. Energy Conversion, vol. 18, no. 1, pp. 87-93,March 2003.

[27] Fakham H, Djemai M, Busawon K. "Design and practical implementation of a back-EMF sliding-mode observer for a brushless DC motor", IET Electr. Power Appl. 2008;2(6):353–61.

[28] R. Wu and G. R. Slemon, "A permanent magnet motor drive without a shaft sensor," IEEE Transactions on Industry Application, vol. 27, pp. 1005–1011, Sept. /Oct. 1991.

[29] N. Ertugrul and P. Acarnley, "A new algorithm for sensorless operation of permanent magnet motors," IEEE Trans. Ind. Applicat., vol. 30, pp. 126–133, Jan./Feb. 1994.

[30] J. S. Kim, and S. K. Sul, "New approach for high-performance PMSM drives without rotational position sensors," IEEE Trans. Power Electronics, Vol. 12, pp. 904-911, Sep. 1997.

[31] Jium –Ming Lin , Ming –Chang Lin, Hsin –Ping Wang, "LEQG/LTR controller design with extended kalman filter for sensorless brushless DC

driver.”,Computer. Methods Applied Mechanical Engineering 190(2001) pp.5481-5494, Elsevier.

[32] Ki- hong Park, tae-Sung Kim, Sung-Chan Ahn, Dong-Seok Hyun, “Speed Control of High Performance Brushless DC Motor drives by load Torque Estimation”, 34th IEEE Power Electronics Specialist Conference, 2003 PECS 03, pp. 1677-1681.

[33] Tae-Sung Kim,Byong –Gun Park, Dong-Myung Lee, Ji-su Ryu and Dong –Seok Hyun, “A new Approach to sensorless control method for brushless DC Motors”, International Journal of Control Automation and Systems, vol. 6 No.4 PP 477-487, August 2008.

[34] S.A.KH. Mozaffari Niapour, M. Tabarraie , M.R. Feyzi, “Design and analysis of speed-sensorless robust stochastic L_∞-induced observer for high-performance brushless DC motor drives with diminished torque ripple” Energy Conversion and Management, 64 (2012) 482–498.

[35] S.A.KH. Mozaffari Niapour, M. Tabarraie , M.R. Feyzi, “A new robust speed sensorless control strategy for high performance brushless DC motor drives with reduced torque ripple”, Control Engineering Practice(Elsevier), 24(2014), 42-54.

[36] Tae-Hyung Kim ,M. Ehsani, “Sensorless control of BLDC motors from near zero to high speeds”, IEEE Transactions on Power Electonics , ISSN 0885-8993,vol 19, No. 6, p.1635-1645, Nov 2004.

[37] Umesh Kumar Soni and Ramesh Kumar Tripathi, “Novel Back EMF Zero Difference Point Detection Based Sensorless Technique for BLDC Motor”, Proceedings of IEEE 18th Annual International Conference on Industrial Technology, ICIT 2017, 22-25 March 2017, Toronto, Canada, pp.330-335.

[38] Umesh Kumar Soni and Ramesh Kumar Tripathi,”Novel Estimated back EMF ZDP based sensorless controlled BLDCM using Unknown Input Observer”, Proc. of International Seminar on Intelligent Technologies and Its Applications, pp. 121-126, Indonesia, 28-29 August, 2017.

[39] Mitesh B. Ashtik, Pragnesh Bhatt, Bhavesh R. Bhljia, “ Analysis of Sensorless Control of brushless DC motor using unknown input observer with different gains”, Journal of Electrical Engineering, Vol. 68(2017) no. 2, pp.99-108.

[40] U. K. Soni and R. K. Tripathi, "Direction independent U-function based sensorless control of BLDC motor," *2017 IEEE International Conference on Industrial and Information Systems (ICIIS)*, Peradeniya, Sri Lanka, 2017, pp. 1-6.