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A Low Cost BLDC Motor Drive with Sensor Less Speed Estimation and Minimum Torque Ripple Powered from Photo-Voltaic Source Fed SL-QZS Inverter

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Abstract: In vector controlled drives speed or position sensor results in added cost and mounting sensors in motor case adds to mechanical complexity, motor vibration increases noise in sensing speed additional electronic circuits required. This study presents a speed sensor less control of BLDC motor drive fed from switched inductor quasi Z-source inverter powered from a photovoltaic source. A simplified Indirect Field Oriented Control (IFOC) is implemented in this drive for accurate speed control and minimizing torque ripple of BLDC motor. In this scheme, back-EMF estimation method is used for speed estimation in speed sensor less approach, implemented speed estimation method found to track speed changes continuously even with respect to varying load and system parameters. The estimated speed is used to originate rotor position and hall commutation signals are estimated from rotor angle since BLDC motor is an electronically commutated motor. The proposed speed sensor less scheme is simulated using MATLAB/simulink environment in order to verify the performance of drive. With minimum torque ripple and by operating at low voltage proposed drive exhibit high efficiency at low cost. A 24 V switched inductor quasi Z-source PV inverter fed BLDC drive is developed in hardware for experimental verification of proposed scheme.

Key words: Sensor less, simplified IFOC, SL-QZS inverter, torque, ripple, back-EMF

INTRODUCTION

Brushless DC motors researches on electronic commutation does not require mechanical brushes for commutation. But it requires continuous rotor position information for electronic commutation, hall effect position sensors are employed in BLDC motors for sensing rotor position. This tends to increase manufacturing cost of BLDC motors and also complexity in construction. BLDC motor shows greater performance than induction motors and brushed dc motors. It has high reliability and high efficiency compared to other motors, size of the BLDC motor is smaller compared to other motors of same power rating. It is preferred for high speed moderate power applications due to numerous advantages of BLDC motors researches are carried on developing BLDC motor drives based on improving performance and keeping cost. Sensor less BLDC motor drive created a great focus by Zhao *et al*. (2013) proposed a MRAS model reference adaptive system for sensor less speed estimation of BLDC motor. Sliding mode observers preferred for estimating speed over MRAS, it has less computation and does not involve tuning of pi controllers (Chi *et al*., 2009; Zheng and Li, 2016). Tawadros *et al*. (2014) used a back EMF estimation method for speed calculation. These speed estimation techniques are based on machine Mathematical model does require clear values of machine parameters and voltage and current at any instant of time for exact speed estimation. Sensor less approach reduces cost of the drive and efficiency of drive depends on proper computation.

Interfacing PV source for motor drives is a challenging task, motor draws peaky current from source extracting high power from PV suitable for motor drives using Mathematical modeling is shown by Rai *et al*. (2016). Maximum power point technique (Patel *et al*., 2016) used in this literature for extracting maximum power from PV source under parameters varying conditions. Zakzouk *et al*. (2016) used an incremental conductance based MPPT technique for high power extraction from PV compared to perturb and observe algorithm incremental conductance continuously track solar parameters variation including temperature, irradiance and give duty cycle command. Buck boost converters are used in high voltage drives for improving boost factor of PV source. Some research works proposed Z-source for voltage

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boosting and also extracting power from PV. Feyzi implemented a Z-source PV inverter for brushless dc motor drive with incremental conductance MPPT technique for power extraction. Quasi Z-source inverter has both boosting capability and high power extraction suitable for motor drives (Xia *et al*., 2015; Hosseini *et al*., 2010).

In vector controlled drives field oriented control FOC technique uses a speed sensor whereas in indirect field oriented control IFOC speed is estimated based on different speed estimation techniques (Taneja *et al*., 2014; Banerjee *et al*., 2015; Akkarapaka and Singh, 2014) without using speed sensors. In PMSM drive with sinusoidal back EMF IFOC is quite easy to apply (Zambada and Deb, 2010). But for non sinusoidal back EMF characteristic motors IFOC needs some modification. For tracking back EMF especially in BLDC motors having trapezoidal back EMF simplified IFOC scheme is proposed in this study. Ripples in torque of any motors reduces efficiency, enhances acoustic noise of motor decreases lifetime of motor. Various torque ripple minimization techniques have been discussed by Muralidhar and Aranasi (2014), Promthong and Konghirun (2013), De Castro *et al*. (2016), Prabhash and Vandana (2016) and Park *et al*. (2016) for brushless DC motor drives. In this study, photovoltaic source is designed based on Mathematical modeling and equivalent circuit of PV panel, incremental conductance based MPPT technique is adopted for power extraction from PV source. Instead of going for boost converters switched inductor quasi Z-source inverter is used which has boosting functionality.

MATERIALS AND METHODS

Main objective of proposed scheme is sensor less control of BLDC motor mitigating torque ripple at high efficiency. There are various speed estimation methods based on machine modeling in the proposed scheme back EMF estimation is used. It involves back EMF calculation by relation between machine voltage and current with back EMF. After estimation of back EMF maximum value of back EMF is calculated then electrical speed of motor is obtained from equation relating flux constant and back EMF and by dividing by number of pole pair electrical speed of motor can be converted into mechanical speed. A simplified IFOC scheme is used for motor control which uses a PI speed regulator. Then, reference current is calculated and by means of hysteresis current controller gating pulses for switches in inverter is generated. In implemented IFOC scheme for improving current and torque performance of motor a hall signal command is

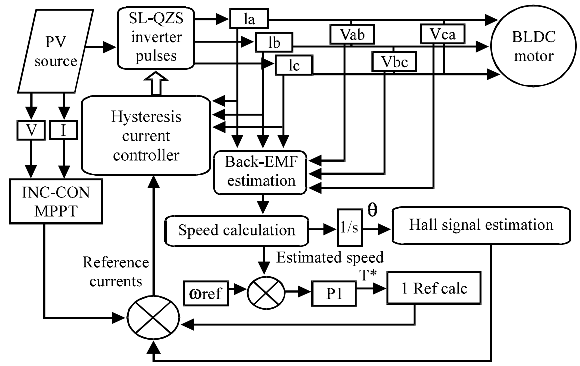

Fig. 1: Block diagram of proposed system

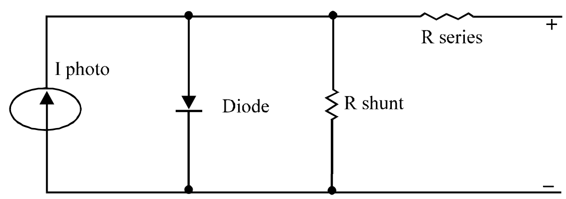

Fig. 2: PV source equivalent circuit

generated from current rotor position of motor. Rotor can be obtained from estimated speed of motor. Then hall signal is modulated by reference current value obtained from PI speed regulator. PI controller will give reference torque of motor which can be utilized to obtain reference current. A PV source is used to power SLQZS inverter, Incremental conductance MPPT algorithm is employed to extract maximum power at any instant from PV source. Figure 1 shows overall block diagram of proposed PV powered SLQZSI fed BLDC motor drive.

PV Model: A single diode equivalent circuit based photovoltaic model is used in this scheme since it is simple for implementing has high reliability and easy adjustment of parameters when interfacing with power converters in comparison with multi diode model. Rai *et al*. (2016) proposed a PV source of single diode with series and parallel resistance combinations included in equivalent circuit which is shown in Fig. 2. Proposed photovoltaic Model is designed by following equation and its interfaced with dynamic single diode equivalent circuit as:

$$I_{Photo} = N_P\left\{I_{photo} - I_0\left\{\exp\left(\frac{qv_{PV}}{nN_sKT}\right)\right\}\right\} \quad (1)$$

where in above Eq. 1 current and voltage of photovoltaic array is denoted by I_{PV} and V_{PV}, respectively short circuit current of photovoltaic array and saturation current are

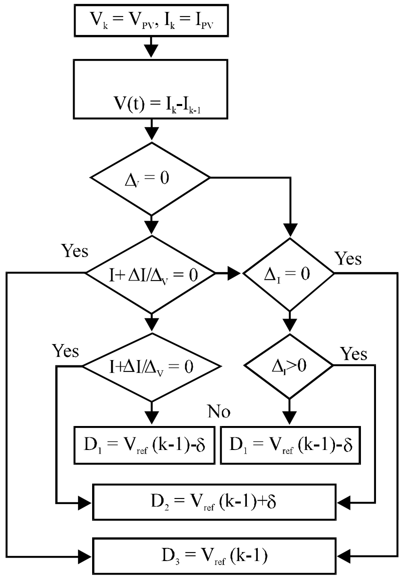

Fig. 3: Flowchart of incremental conductance MPPT algorithm

denoted by l_{ph} and l_0, respectively. Coulomb constant (q) (1.602×10^{-19}) and Boltzmann constant (k) (1.38×10^{-23}J/K) are applied for derivation of photovoltaic current (l_{PV}).

In order to extract maximum solar power from solar array a MPPT (Maximum Power Point Tracking) is applied widely in modeling of photovoltaic source as by Patel *et al*. (2016). Actual voltage and current in Eq. 1 is replaced by V_{MP} and l_{MP} is obtained by using incremental conductance method as:

$$I_{MP} = N_P\left\{I_{photo}\text{-}I_0\left\{\exp\left(\frac{qv_{MP}}{nN_sKT}\right)\right\}\right\} \quad (2)$$

The power and current characteristic of photovoltaic array is explained on every P_{Photo}-V_{Photo} characteristic can be extracted every operating point for photovoltaic array is called maximum power point tracking by MPPT controller (Patel *et al*., 2016).

The incremental conductance Maximum Power Point Tracking (MPPT) (Zakzouk *et al*., 2016) scheme is introduced to extract maximum power from PV source as shown in Fig. 3. V_k, l_k are the temporary voltage and current of photovoltaic array. Current voltage and current value of photovoltaic array is represented as V_{k-1} and l_{k-1}, $l+(\Delta l/\Delta V)$ V is expressed as dP/dV. The duty cycle values are calculated from output voltage reference V_{ref} and also calculated by comparing various if conditions using incremental conductance method as shown in Fig. 3.

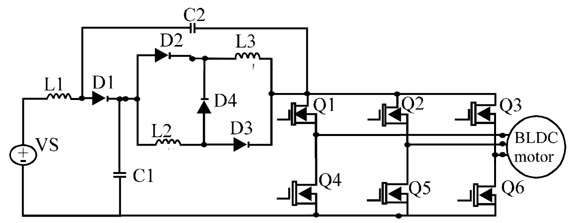

Fig. 4: Circuit diagram of SLQZSI FED BLDC motor drive

Switched inductor quasi Z-source inverter: The power circuit diagram of switched inductor quasi Z-source inverter fed BLDC motor drive is shown in Fig. 4. The switched inductor quasi Z-source inverter is derived from conventional quasi Z-source inverter by adding two inductors and three diodes to the main circuit. It has overcome demerits shown by quasi Z-source inverter; it reduces the high starting inrush current which makes it suitable for motor control applications. High voltage gain can be achieved with the help of SLQZSI in comparison with QZSI even by choosing less value and size of passive elements. SLQZSI has continuous DC input current, lower peak overshoot current during shoot through time and reduced voltage stress on capacitors in switched inductor quasi Z-source network.

Mode of operation: Conventional Z-source inverter has 2 zero vectors and 6 active vectors, the SLQZS inverter has extra 2 zero vectors in addition to 6 active and 2 zero vectors.

Shoot through state: During this mode energy is not transferred from source to load through inverter. This is done by turning one upper and lower switch of same leg of the inverter. During this mode inductors are charged through DC source. Boosting of input voltage corresponds to this mode of operation, still this mode is operated for short duration of time. This can discharge the source quickly hence for continuous operation of inverter shoot through mode is operated in much lesser time every cycle.

Non-shoot through state: During this mode DC source energy and energy store in the inductor is transferred to load and capacitors start to charge. The 6 active vectors of inverter can be realized during this mode of operation. In this mode, upper and lower switches of same leg of inverter are not turned on simultaneously.

Control scheme using simplified IFOC: In the proposed simplified indirect field oriented control scheme initial part is to estimate speed of BLDC motor, back EMF estimation

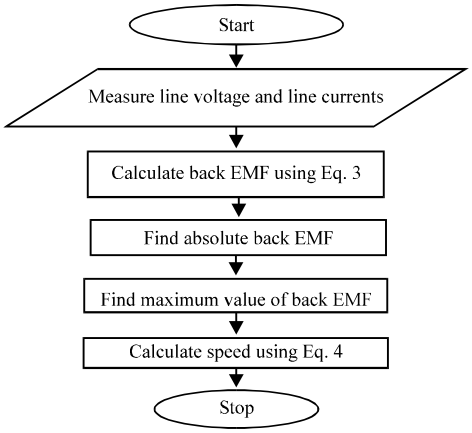

Fig. 5: Flow chart of proposed speed estimation method

method is employed to estimate speed it is explained in detail in following study. PI controller is used as speed regulator in this scheme after estimating speed error between speed reference and estimated speed is given as input to pi controller and pi response is reference torque. The reference current is computed from the value of reference torque using its relation from Eq. 6. Then from estimated speed rotor position in form of angle can be obtained using simple integral operator. Hall signal of BLDC motor is to be computed from the rotor angle information which is then product with computed reference current for feeding to hysteresis current controller for gating signal generation. Incremental conductance algorithm to extract maximum power from photovoltaic source is implemented and duty cycle command from MPPT algorithm modulates reference current value calculated.

Back EMF estimation: Flow chart of the proposed back EMF based speed estimation method is shown in Fig. 5. For calculating back EMF 3 phase voltage and currents from inverter to BLDC motor have to be sensed. Then line voltages and line currents should be calculated from sensed values. From BLDC motor machine Mathematical modeling equation back EMF can be calculated for all 3 phases and absolute value of back EMF is obtained. Then for proper speed estimation maximum value of back EMF is computed and by using Eq. 3 mechanical rotor speed can be the calculated:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3)$$

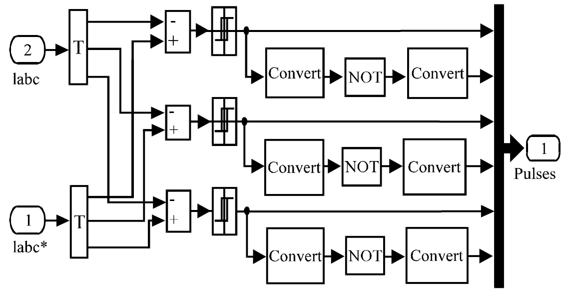

Fig. 6: Hysteresis current controller

$$\omega_r = \frac{E_{max}}{2\times p\times flux} \quad (4)$$

$$\theta = \int \omega_r \; dt \quad (5)$$

$$I_{ref} = \frac{T_{ref}}{2\times p\times flux} \quad (6)$$

Where:

V_a, V_b, V_c = The phase voltages
I_a, I_b, I_c = The phase currents
e_a, e_b, e_c = The back EMF of BLDC motor
ω_r = The rotor speed of BLDC motor
p = The number of pole pairs
Flux = The flux linkage established by magnets
θ = The rotor angle or position of rotor
T_{ref} = The obtained from pi speed regulator

Current controller: Current controller will work properly only when we define two bands correctly viz. Upper hysteresis band and lower hysteresis band of relay. Current error between actual and reference current is fed as input to hysteresis current controller, the controller will produce a high pulse if error is within the band limit otherwise it will produce a low pulse and switches will be turned off when current error exceeds specified band limit. Figure 6 shows implementation of hysteresis current controller for three phase switched inductor quasi Z-source inverter fed BLDC motor drive. Hysteresis band limit should be kept at a very lesser value if higher value is chosen switching frequency of output pulse will be higher it leads to high switching losses of power electronic switching device used. The hysteresis controller employed is based on single band for high performance of inverter double hysteresis bands are used.

RESULTS AND DISCUSSION

Figure 7 shows simulink implementation of PV powered SLQZS inverter fed BLDC motor drive. Table 1

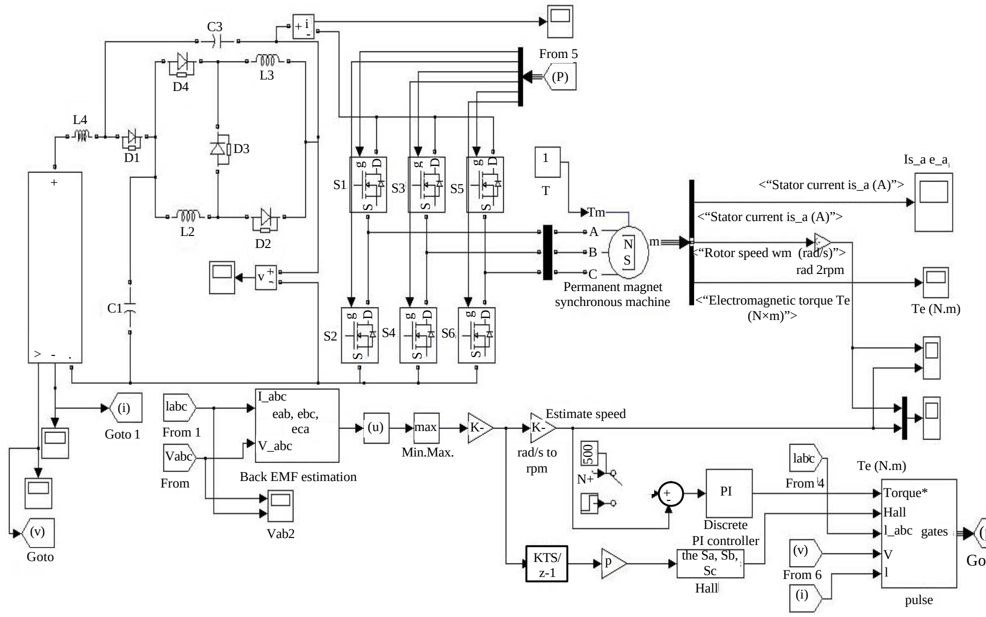

Fig. 7: MATLAB implementation of proposed sensor less BLDC motor drive

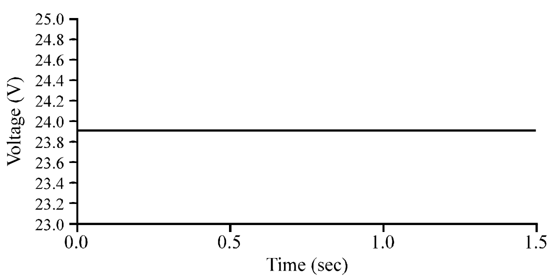

Fig. 8: Photovoltaic output voltage

Table 1: Simulation parameters

Names	Ranges
Motor parameters	
Stator resistance (Rs)	0.7 Ω
Stator inductance (Ls)	2.72 mH
Rotor speed	500 rpm
Flux linkage	0.019099 V.s
Poles	4
Torque constant	0.15279 N.m/A
Circuit parameter	
Impedance source inductors (L_1, L_2, L_3)	0.1, 1, 1 mH
Impedance source capacitors (C_1, C_2)	1000 µF
DC-link voltage V_{DC}	24 V
PV specifications	
Voltage	24 V
Current	6.4 A
Power	150 W

shows simulation parameters applied in proposed circuit, PV specifications and BLDC motor parameters. PV source is modeled from its corresponding circuit and Mathematical equation containing solar parameters like temperature, irradiance, open circuit voltage, short circuit

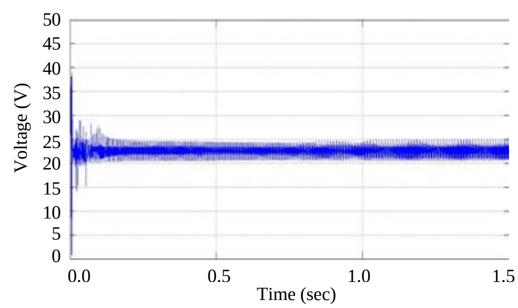

Fig. 9: DC link voltage waveform

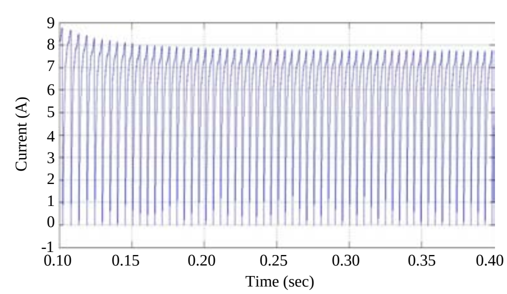

Fig. 10: DC link current waveform

current. PV output power is then fed to SL-QZS Inverter to drive BLDC motor. Figure 8-11 show plot of PV response, DC link voltage and current waveforms, r-phase voltage wave form of inverter output.

In sensor less approach speed is estimated by back EMF estimation method, 3 phase voltage and currents are sensed and using machine Mathematical modeling back

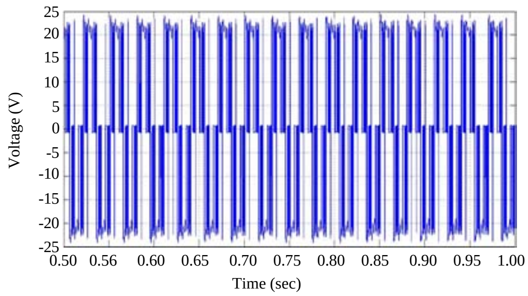

Fig. 11: R phase voltage waveform of BLDC motor

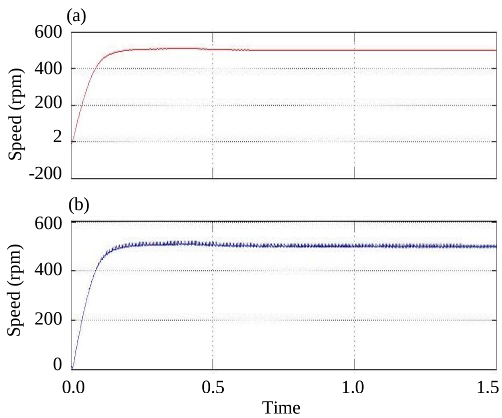

Fig. 12: Speed response from speed measurement and estimated speed: a) Speed from sensor and b) estimated speed

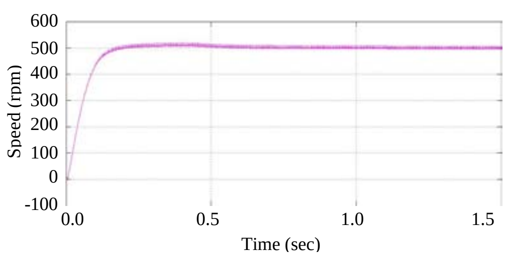

Fig. 13: Speed response of BLDC motor

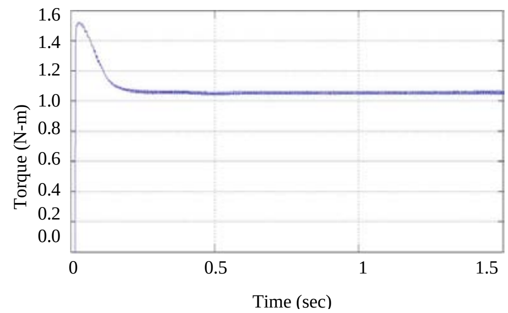

Fig. 14: Electro-magmetic torque waveform

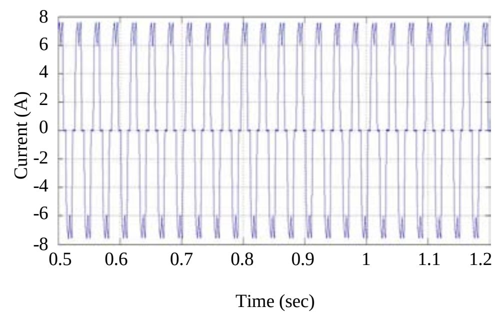

Fig. 15: Stator current waveform of BLDC motor

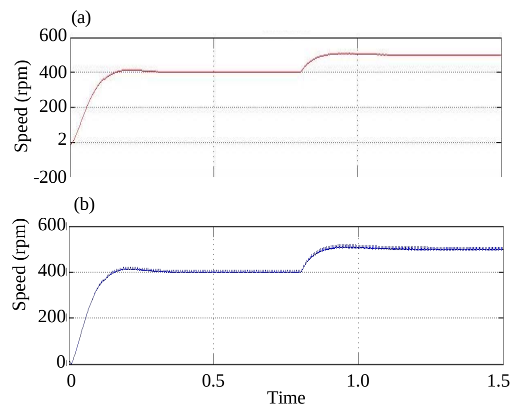

Fig. 16: a) Speed response from speed measurement and b) estimated speed for step change of speed reference at t = 0.8 sec

EMF is estimated. Then using relation between back EMF and electrical speed of motor speed is estimated and mechanical rotor speed can be calculated. Then error between estimated speed and reference speed is given as input to PI controller to generate reference torque. Then reference torque is converted to reference current. From estimated speed rotor position is derived and hall signal is estimated based on rotor angle. Reference current is multiplied with estimated hall signal and fed to hysteresis current controller along with actual current for pulse generation. The response of proposed drive under loaded conditions for a speed reference of 400 rpm is given from Fig. 12-15. Plot of BLDC motor speed estimated and actual, electro-magnetic torque and stator current is shown. From results we can observe that estimated speed is equal to actual speed at all instants of time even under varying load command and at different reference speeds. The BLDC motor response for proposed drive under varying speed command is shown from Fig. 16-19. At t = 0.8 sec reference speed command is changed from 400-500 rpm corresponding speed, electro-magnetic torque and stator current plot is given below which verifies robustness of the proposed drive for the varying system parameters.

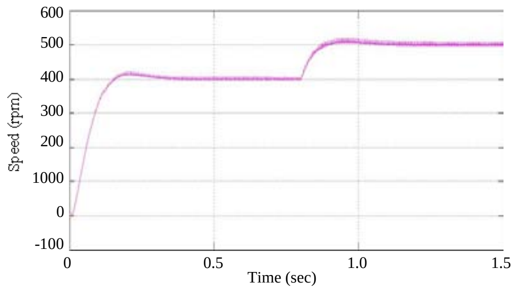

Fig. 17: Speed response of BLDC motor for step change of speed reference at t = 0.8 sec

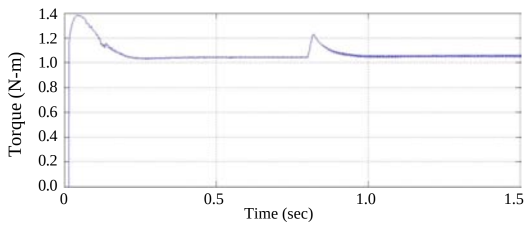

Fig. 18: Electromagnetic torque waveform for varying speed reference (Nm)

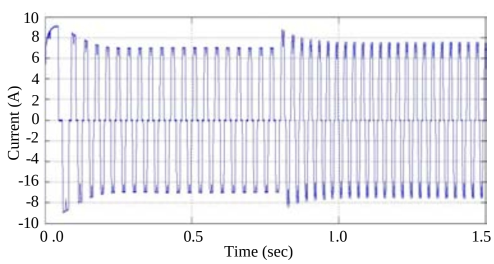

Fig. 19: Stator current waveform for varying speed reference

Experimental results: The PV powered switched inductor quasi Z-source inverter fed BLDC motor drive shown in Fig. 3 is implemented in hardware for experimentally verifying the advantages of proposed scheme. SL-QZS inverter is controlled using ds PIC33FJ32MC202 digital signal controller platform and results are presented in this study. Conventional 6 switch inverter circuit is implemented using power MOSFET IRF 840 and for driving these MOSFET's 8-pin opto coupler TLP-250 IC is used. Power from solar panel will charge a 24 V, 1.3 Ah battery with the help of a charge controller and acts as a source for SLQZS inverter drive.

In hardware circuit parameters used in the simulation was followed and there is no deviation in voltage specifications used. Experimental setup of proposed scheme is shown in Fig. 20. Experimental performance of the proposed drive is shown from Fig. 21-25 and the experimental results validate the simulation results and also verify the proposed scheme in a real time of environment.

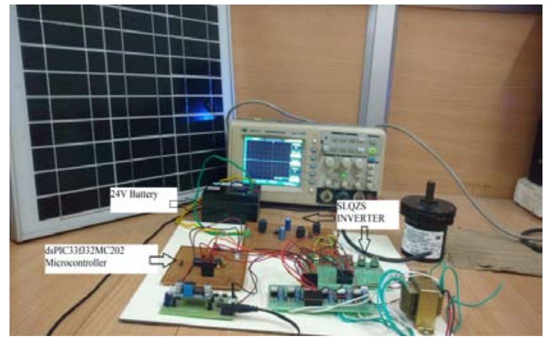

Fig. 20: Experimental setup of proposed drive

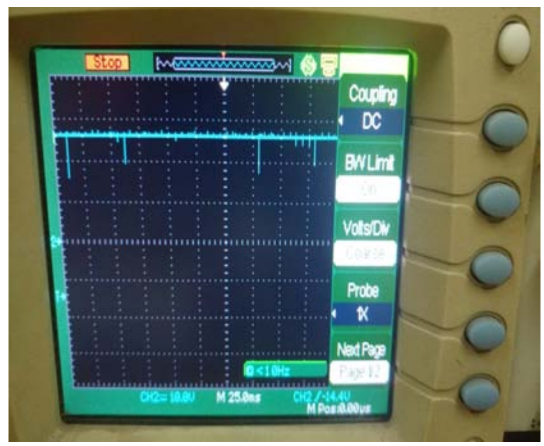

Fig. 21: DC link voltage of inverter

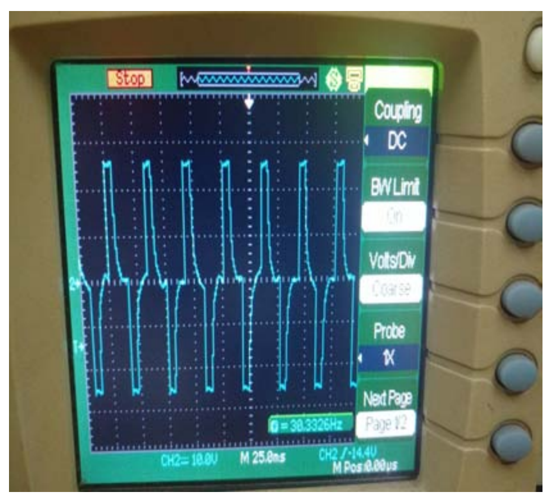

Fig. 22: R phase voltage of inverter

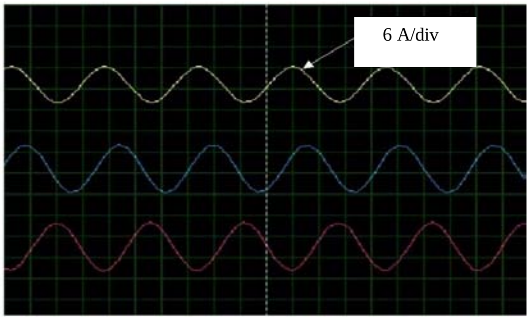

Fig. 23: Combined 3 phase current response of BLDC motor

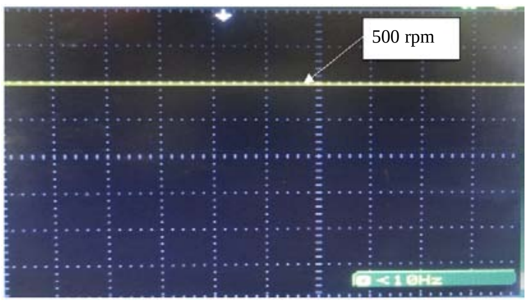

Fig. 24: Experimental speed response (rpm)

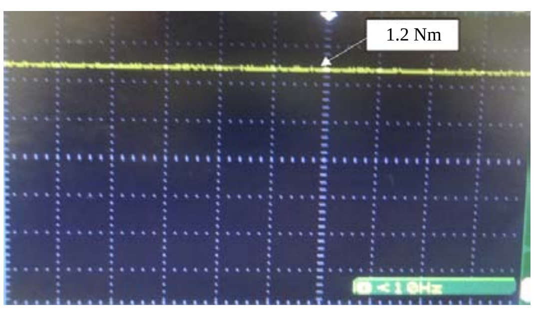

Fig. 25: Experimental electromagnetic torque response (Nm)

CONCLUSION

Speed sensor less control of Brush Less DC (BLDC) motor by using back EMF estimation method proposed in this study is simulated in MATLAB Software and a 24 V hardware setup of drive is implemented for experimental validation. BLDC motor is fed from a PV powered switched inductor quasi impedance source inverter, the SLQZSI has certain merits over conventional quasi Z-source inverter. It avoids high starting in rush current, operates at less value of passive components and it has continuous DC link current. From results, we can inference that speed estimated from proposed scheme is equal to measured speed in all conditions. The robustness of simplified IFOC control scheme is tested under varying speed references at full load and response of controller under speed tracking is great and does not have overshoot, settling time is reasonably less even with conventional PI controller. The proposed control scheme produces smooth electro-magnetic torque wave form and does not contain ripple components. The current response of proposed drive still holds the original characteristics of BLDC motor maintaining trapezoidal shape. The performance of the proposed sensor less BLDC motor drive fed from PV powered SLQZSI is experimentally verified using developed hardware and performance of drive in hardware was shown in previous study.

REFERENCES

Akkarapaka, A.K. and D. Singh, 2014. The IFOC based speed control of induction motor fed by a high performance Z-source inverter. Proceedings of the 2014 International Conference on Renewable Energy Research and Application (ICRERA'14), October 19-22, 2014, IEEE, Milwaukee, Wisconsin, ISBN:978-1-4799-3796-7, pp: 539-543.

Banerjee, T., J. Bera and G. Sarkar, 2015. Parameter estimation of three phase induction motor using gravitational search algorithm for IFOC. Proceedings of the Conference on Michael Faraday IET International Summit 2015, September 12-13, 2015, IET, Kolkata, India, ISBN:978-1-78561-186-5, pp: 607-610.

Chi, S., Z. Zhang and L. Xu, 2009. Sliding-mode sensorless control of direct-drive PM synchronous motors for washing machine applications. IEEE. Trans. Ind. Appl., 45: 582-590.

De Castro, A.G., W.C. Pereira, T.E. Almeida, C.M.D. Oliveira and J.R. Monteiro et al., 2016. Improved finite control-set model-based direct power control of BLDC motor with reduced torque ripple. Proceedings of the 12th IEEE International Conference on Industry Applications (INDUSCON'16), November 20-23, 2016, IEEE, Curitiba, Brazil, ISBN:978-1-5090-5128-1, pp: 1-6.

Hosseini, S.H., F. Nejabatkhah, S.K.M. Niapoor and S. Danyali, 2010. Supplying a brushless dc motor by z-source PV power inverter with FL-IC MPPT. Proceedings of the 2010 International Conference on Green Circuits and Systems (ICGCS'10), June 21-23, 2010, IEEE, Shanghai, China, ISBN:978-1-4244-6876-8, pp: 485-490.

Kim, T.S., B.G. Park, D.M. Lee, J.S. Ryu and D.S. Hyun, 2008. A new approach to sensorless control method for brushless DC motors. Intl. J. Control Autom. Syst., 6: 477-487.

Muralidhar, J.E. and P.V. Aranasi, 2014. Torque ripple minimization and closed loop speed control of BLDC motor with hysteresis current controller. Proceedings of the 2nd International Conference on Devices Circuits and Systems (ICDCS'14), March 6-8, 2014, IEEE, Combiatore, India, ISBN:978-1-4799-1354-1, pp: 1-7.

Niapoor, S.K.M., S. Danyali and M.B.B. Sharifian, 2010. PV power system based MPPT Z-source inverter to supply a sensorless BLDC motor. Proceedings of the 1st Conference on Power Electronic and Drive Systems and Technologies (PEDSTC'10), February 17-18, 2010, IEEE, Tehran, Iran, ISBN:978-1-4244-5944-5, pp: 111-116.

Park, J., Y. Kwak, Y. Jo, J. Bae and D.H. Lee, 2016. Torque ripple reduction of BLDC motor using predicted current control. Proceedings of the 2016 IEEE Conference and Expo on Transportation Electrification Asia-Pacific (ITEC Asia-Pacific'16), June 1-4, 2016, IEEE, Busan, South Korea, ISBN:978-1-5090-1273-2, pp: 407-411.

Patel, H., M. Gupta and A.K. Bohre, 2016. Mathematical modeling and performance analysis of MPPT based solar PV system. Proceedings of the International Conference on Electrical Power and Energy Systems (ICEPES'16), December 14-16, 2016, IEEE, Bhopal, India, ISBN:978-1-5090-2477-3, pp: 157-162.

Prabhash, V. and P. Vandana, 2016. PV fed BLDC motor using zeta converter with minimized torque ripple for water pumping. Proceedings of the 2016 International Conference on Emerging Technological Trends (ICETT'16), October 21-22, 2016, IEEE, Kollam, India, ISBN:978-1-5090-3752-0, pp: 1-6.

Promthong, S. and M. Konghirun, 2013. Sensorless control of BLDC motor drive with 150° conducting mode to minimize torque ripple. Proceedings of the International Conference on Electrical Machines and Systems (ICEMS'13), October 26-29, 2013, IEEE, Busan, South Korea, ISBN:978-1-4799-1445-6, pp: 1004-1009.

Rai, A., B. Awasthi, A. Dixit and C.K. Dwivedi, 2016. Modeling of solar photovoltaic module and study parameter variation effect using MATLAB-Simulink. Proceedings of the 2016 International Conference on Control, Computing, Communication and Materials (ICCCCM'16), October 21-22, 2016, IEEE, Allahbad, India, ISBN:978-1-4673-9085-9, pp: 1-6.

Taneja, L., S. Kumar and R. Kumar, 2014. Current regulated induction motor drive with IFOC. Proceedings of the 2014 IEEE 6th India International Conference on Power Electronics (IICPE'14), December 8-10, 2014, IEEE, Kurukshetra, India, ISBN:978-1-4799-6047-7, pp: 1-5.

Tawadros, M., M. Nagrial and J. Rizk, 2014. Sensorless control of brushless DC motors using virtual back EMF mapping projection. Proceedings of the 2014 International Conference on Electrical Machines (ICEM), September 2-5, 2014, IEEE, Berlin, Germany, ISBN:978-1-4799-4389-0, pp: 903-907.

Xia, K., L. Shen, B. Dong, Y. Zeng and S.S. Ge, 2015. Research of four-switch three-phase BLDC motor control scheme based on quasi Z-source converter. Proceedings of the 18th International Conference on Electrical Machines and Systems (ICEMS'15), October 25-28, 2015, IEEE, Pattaya, Thailand, ISBN:978-1-4799-8806-8, pp: 1-6.

Zakzouk, N.E., M.A. Elsaharty, A.K. Abdelsalam, A.A. Helal and B.W. Williams, 2016. Improved performance low-cost incremental conductance PV MPPT technique. IET. Renewable Power Gener., 10: 561-574.

Zambada, J. and D. Deb, 2010. Sensorless field oriented control of a PMSM. MCs Thesis, Microchip Technology, Chandler, Arizona.

Zhao, Y., W. Qiao and L. Wu, 2013. Model reference adaptive system-based speed estimators for sensorless control of interior permanent magnet synchronous machines. Proceedings of the 2013 IEEE Conference on Transportation Electrification and Expo (ITEC'13), June 16-19, 2013, IEEE, Detroit, Michigan, ISBN:978-1-4799-0146-3, pp: 1-6.

Zheng, C. and Y. Li, 2016. Sensorless speed control for brushless DC motors system using sliding-mode controller and observers. Proceedings of the 8th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC'16) Vol. 1, August 27-28, 2016, IEEE, Hangzhou, China, ISBN:978-1-5090-0769-1, pp: 216-220.