ANALYSIS OF TRAPEZOIDAL CONTROL OF SENSORLESS BLDC MOTORS

Muhammad Salim Butt, Fahim Gohar Awan
Faculty of Electrical Engineering, University of Engineering and Technology Lahore
salimbutt@uet.edu.pk, fawan@uet.edu.pk

ABSTRACT— *In this paper we have investigated the working of a sensor-less brush-less DC (BLDC) motors using PI controller techniques. The hardware implementation will be executed using a dsPICDEM MCLV, board especially designed to generate any type of 3-phase waveforms. For the dynamic control of speed and torque of a Sensor-less BLDC motor we will use MPLAB IDE and DMCI (Data Monitor Capture Interface). This study will demonstrate that a sensor-less BLDC work without mechanical sensors and contactors, which results in increased reliability, low cost operation and reduced wear and tear.*

Keywords: Brush-less DC motors, artificial neural networks, PI controller, Data Monitor and Control Interface

INTRODUCTION

In the distribution system around 90 percent loads are inductive and the largest participation in this load is electric motors. Motors are the essential and major component of an industry. Previously it was conventional to use induction motors in the industry due to their low manufacturing and maintenance costs, and easy to operate. For many applications reluctance motors and hysteresis motors have replaced induction motors. Then servo motors created their demand in industry. Now-a-days BLDC motors are greatly used in industry and for home appliances, due to their highly efficient operation, control, low maintenance cost and small size as compared to the traditional motors. Just like a three-phase synchronous motor, a three-phase sensor-less BLDC consists of 3 windings displaced at 120 degrees. Unlike the rotor of a synchronous motor which is supplied DC power, a BLDC is provided with permanent magnet. A DC voltage to the stator winding instead of AC is applied, but this DC is applied through an inverter in trapezoidal shape. In $3-\varphi$ BLDC motors, at any instance of time, only $2-\varphi$ out of three carries current with the help of 6-step commutation by restricting the conduction time to only 120o. This results in 3rd phase free for back EMF sensing. Thus commutation sequence is detected by this floating phase zero crossing. Owing to the reason that there are no carbon brushes to energize electromagnets, this is called brush-less motor. Switching is done electronically, so there is no need of commutators. The duty cycle, phase sequence and frequency to operate the BLDC is controlled by three-phase inverter consisting of generally six switches, depending entirely on the position of the rotating magnet. Two phases of the inverter are kept alive while a third phase remains in floating condition with the 120^{o} electrical displacement in each phase. To create the maximum torque switching is done at 60^{o} to keep the current in-phase with the back EMF. The rectangular wave of current in BLDC and trapezoidal waveform in back EMF create constant speed and torque for fair range of load.

A Hall-effect sensor is used to determine the position of the rotor, such that switching sequence is maintained. Previously proximity sensors were also used but these are not used currently due to cost of the sensors: also the motor size become large due to these sensors. Thus, overall the motor becomes dependent on these sensors. So the solution of this problem led to the introduction of sensor-less BLDC motors. A sensor-less motor provides us the freedom from all the mechanical sensors. However, at the same time we need very high speed micro-controllers or DSP boards to control speed and torque with high accuracy. The BLDC motor always operates in a region where we require a certain speed and torque: for this purpose we can use low cost controllers. For very high speed operation of motors we need very precise controllers such that their efficiency is not affected. The need of the hour is to use such a controller that can produce exact wave shape that is required to run a BLDC motor. To drive sensor-less BLDC motors, two algorithms are mostly used; Kalman-filter and artificial neural network (ANN). Recently modeling of BLDC motor is done in MATLAB SIMULINK.

In this paper, we perform all the experiments to evaluate the efficiency of sensor-less BLDC motor under different loads with the Microchip Board dsPIC33FJ32MC204 [1], using pulse width modulation (PWM) mode, Real time data monitor (RTDM) and tool available in MPLAB IDE Data monitor and capture interface (DMCI) [2] for digital motor control. For the measurement of load on the BLDC we have used a standard Permanent magnet DC generator. We have performed hardware based experiments in line with previously done PI (proportional and integrator) closed-loop simulations in MATLAB SIMULINK. In the next section we will analyze the dynamic performance of a BLDC motor under different load conditions, its torque and speed relations at maximum and minimum loads and its efficiency under varying speed and torque. There will also be a comparison between open-loop and closed-loop operation of BLDC under PI controllers. These simulated results will then be verified with experimental outcomes.

BLDC Motor Control

The digital filtering algorithm based on majority function is implemented with Digital Signal Controller dsPIC works by filtering the Back-Electromotive Force (BEMF). The voltage waveform along with the current waveform of each phase is detected through filters and thus given to the commutation. This complete work is done in the following steps [3], [4], [5], (i) "Sampling trapezoidal BEMF signals using the dsPIC Analog-to-Digital Converter (ADC). (ii) Reconstructing the Motor Virtual Neutral Point. (iii) Comparing the trapezoidal BEMF signals to the reconstructed motor virtual neutral point to detect the zero crossing points (iv) Filtering the signals coming from the comparisons using a majority function filter. (v) Commutating the motor driving voltages. And (vi) the control loop".

The six-step (Trapezoidal) commutation for energizing of the phases in motor for a complete cycle can be easily explained with the help of Figure 1 where each phase is displaced to 120 degrees from the other. The arrows point the direction of the current whereas the numbers show the time interval [6],

[7], [8]. The sequence of Step commutation is defined in Table 1.

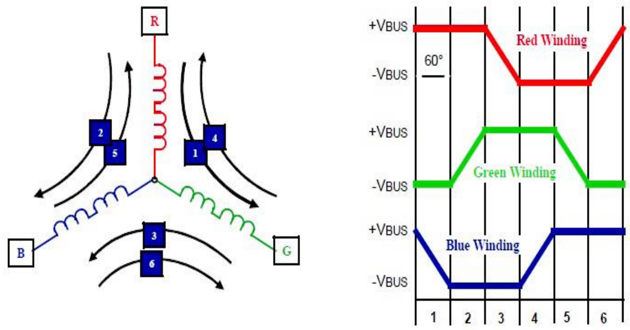

Figure 1: Six-step (Trapezoidal) commutation

Table 1. Step Commutation

Step #	Red	Green	Blue
1	+ ve	- ve	Open
2	+ ve	Open	- ve
3	Open	+ ve	- ve
4	- ve	+ ve	Open
5	- ve	Open	+ ve
6	Open	- ve	+ ve

One complete cycle of waveform corresponds to one complete revolution of the rotor. Where there are more poles of the motor the two complete cycles of the voltage waveform produce one revolution as defined in

$$RPM\_mech = \frac{2RPM\_elec}{no.of\ motor\ poles}. \qquad (1)$$

When voltage is applied to any phase of the armature, back-EMF is generated whose polarity is always opposite to the input voltage. This back-EMF depends on the number of turns of the armature winding, Speed of the rotation field and Magnetic flux density [9].

$$BEMF = NlrB\omega, \qquad (2)$$

where r is the internal radius of the rotor, l is length of the rotor, B is the rotor magnetic field, ω is the angular velocity and N is the number of windings per phase.

The sensing of back-EMF is important for triggering the motor. Once the back-EMF is sensed to operate motor, the exact rotor position can be located. The general purpose Back-EMF zero crossing technique is shown in Figure 2 [10], [11]. This technique is selected because of its applicability on a wide range of the motors, its connection configuration both as star or delta, and its speed control application in both closed and open loop.

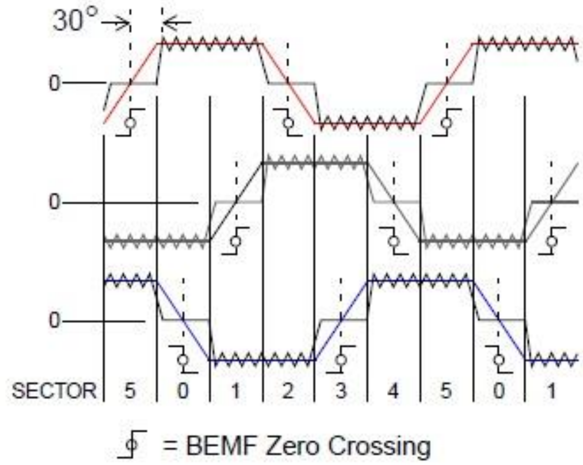

Figure 2: Back-EMF Zero Crossing Timing Diagram

Simulation and experimental Results

The simulation model of BLDC is developed in Simulink MATLAB in *SimPowerSystems* Library within MATLAB Simulink. The simulation model of the sensor less BLDC developed in MATLAB is shown in Figure 3. Here Motor reference speed is set at = 3000 rpm, Torque is applied on the motor at time = 0.2 sec with sensor-Less Brush-less PI control. Voltage increases as the torque is increased to maintain the speed of the motor as shown in Figure 4. Since current is directly proportional

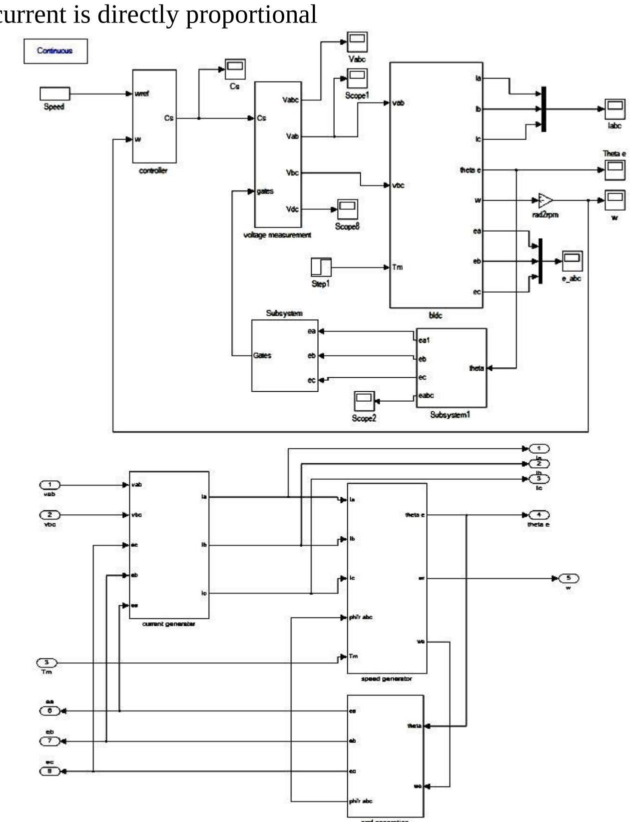

Figure 3: Block Diagram of sensor less BLDC

to the torque so it increases as shown in Figure 5. As torque on motor is increased, the amplitude of this control signal increases to maintain the speed. The magnitude of this control signal depends upon the Proportional and Integrated (PI) controller as shown in Figure 6. When torque is applied motor speed reduces, but it restores due to the closes loop PI controller. Graph in Figure 7 shows that the Speed dip on the application of torque.

For experimental verification, a 24V DC generator is used as a load with a rheostat. Ultimately, this will apply loaf to the Brush-less DC motor. The characteristics of the DC generator are given in Table 2.

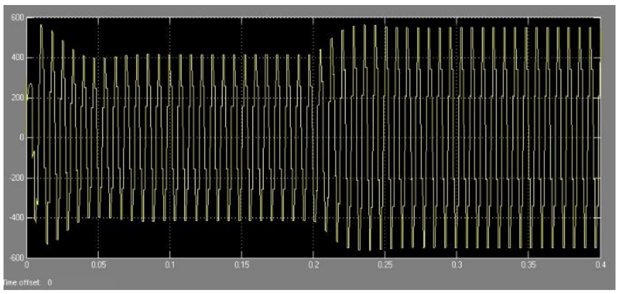

Figure 4: Voltage of a single phase

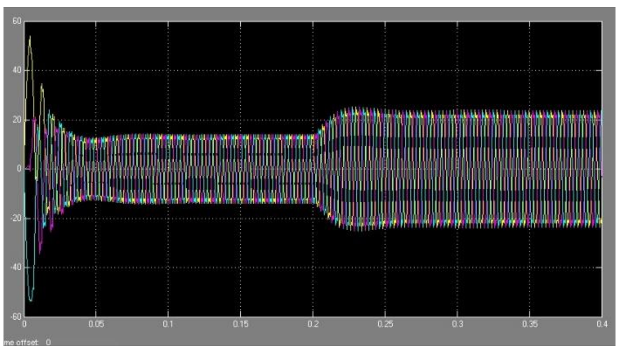

Figure 5: Three Phase Current

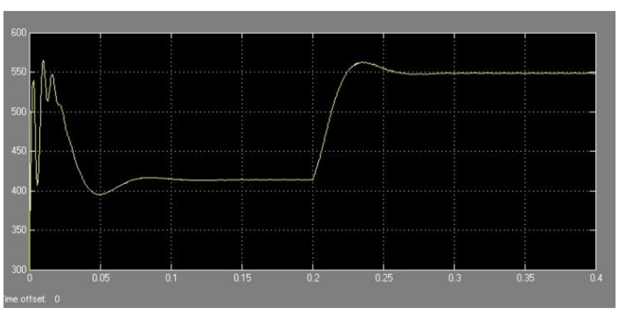

Figure 6: Control signal waveform

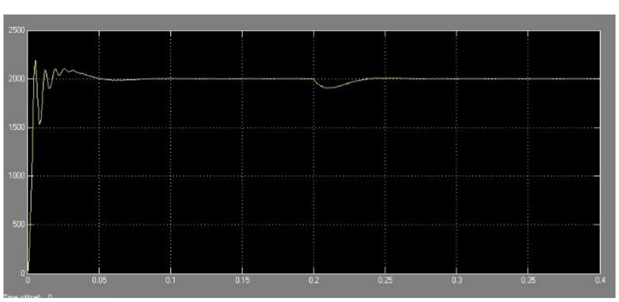

Figure 7: Speed of BLDC at 0.2 sec on application of torque

All tests are performed at 3000 rpm and system as well as generator efficiency alone is calculated so that exact Brush-less DC motor efficiency can be calculated. The DC generator is acting as break control unit for the Brush-less Motor. DC generator and Brush-less motor is mechanically coupled with each other for all the tests set. The outcome of this set of values are shown in various graphs as shown in Figure 8 (a) – 8 (e).

Table 2. Generator Characteristics

P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	Efficiency of System	Efficiency of GEN
260	19.1	0.5	9.55	3.67	73.67
264	18.8	0.6	11.28	4.27	74.27
269	18.7	0.7	13.09	4.87	74.87
275	18.5	0.8	14.8	5.38	75.38
280	18.3	1	18.3	6.54	76.54
284	17.9	1.3	23.27	8.19	78.19
288	17.4	1.6	27.84	9.67	79.67
293	16.4	2.1	34.44	11.75	81.75
297	16.2	2.4	38.88	13.09	83.09
300	15	2.9	43.5	14.5	84.5
310	13.2	3.3	43.56	14.05	84.05

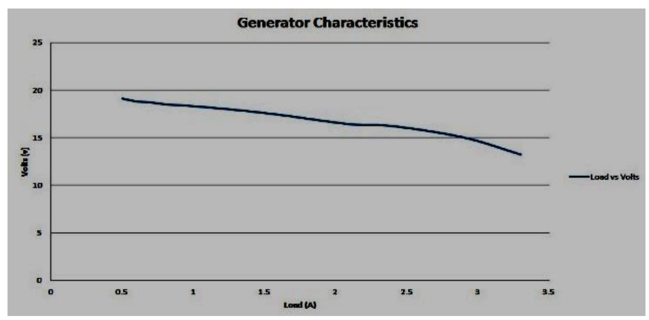

Figure 8 (a): Load vs Terminal Voltage

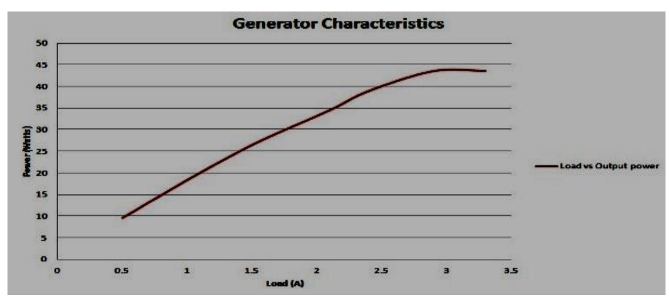

Figure 8 (b): Load vs Output Power (Watts)

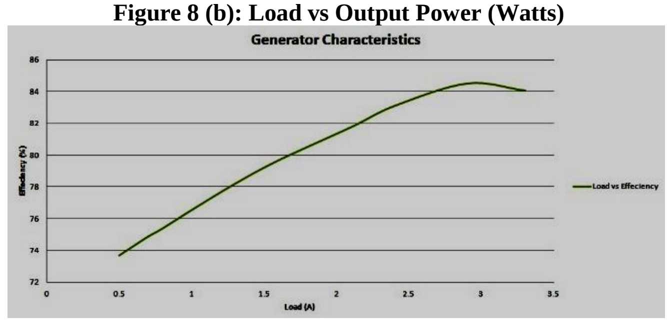

Figure 8 (c): Load vs Efficiency

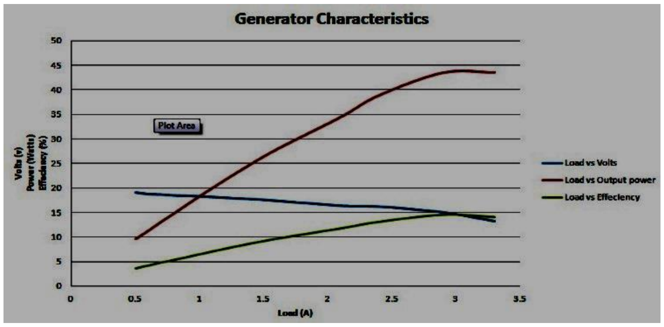

Figure 8 (d): Efficiency of Whole System

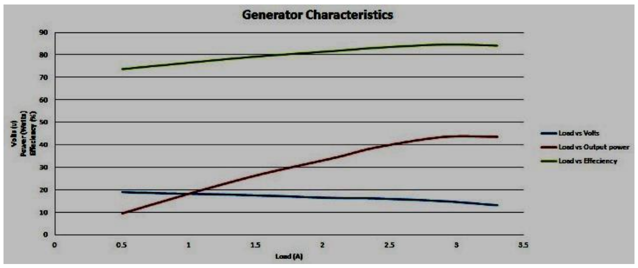

Figure 8 (e): Efficiency of DC Generator alone

Once the generator is standardized the break control unit is established. By increasing the generator current we can apply more load to the motor. In this setup we have a speed measuring device (Tachogenerator). So we can measure speed and torque at any time on the application of the load. The experiment is divided into two parts Open loop Characteristics of BLDC and Closed loop Characteristic of BLDC. In open loop mode the Brush-less motor is controlled without any sensors. Moreover, once the speed is set, on applying any load this speed can vary. All the results are tabulated in Table 3 to calculate the speed regulation of Sensor-less Brush-less DC motor and shown in Figure 9 (a) – 9 (e).

In closed loop mode Sensor-less Brush-less DC motor operates with the closed loop circuit. Once the reference speed is set the PI controller in DSPic will adjust the parameters accordingly. When the PI button is "ON" on the DMCI window, the motor operates in close loop mode. The Kp and Ki parameters were determined using the HURST (Brush-less) MOTOR sensors shipped

Table 3. Generator Characteristics

P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	RPM	Rad/S	Torque x 10^2 (Nm)	Efficiency of motor only
16	21.2	0	0	3440	360.24	0	0
33	18.3	1.002	18.3366	3237	338.98	0.054	75.57
35	18.2	1.07	19.474	3220	337.2	0.058	75.64
36	18	1.159	20.862	3210	336.15	0.062	77.95
38	17.8	1.26	22.428	3190	334.06	0.067	79.02
40	17.6	1.36	23.936	3170	331.96	0.072	79.84
42	17.3	1.48	25.604	3152	330.08	0.078	80.96
44	17.2	1.62	27.864	3127	327.46	0.085	83.33
47	16.8	1.77	29.736	3100	324.63	0.092	83.27
49	16.5	1.928	31.812	3067	321.18	0.099	84.92
52	16.1	2.109	33.9549	3045	318.87	0.106	85.3
55	15.7	2.29	35.953	3002	314.37	0.114	85.37
58	15.3	2.46	37.638	2976	311.65	0.121	84.89
63	14.7	2.8	41.16	2922	305.99	0.135	85.33
67	14.2	3.04	43.168	2880	301.59	0.143	84.43
73	13.4	3.46	46.364	2818	295.1	0.157	83.51
83	12.4	4	49.6	2720	284.84	0.174	79.76
93	11.1	4.64	51.504	2616	273.95	0.188	75.38
101	10.1	5.2	52.52	2550	267.04	0.197	72

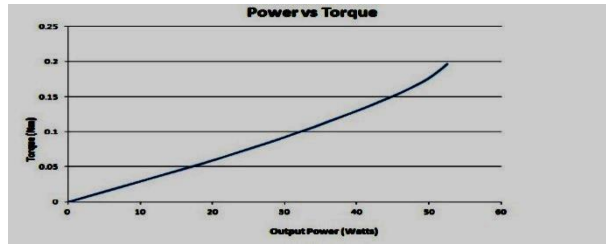

Figure 9 (a): Output power vs Torque

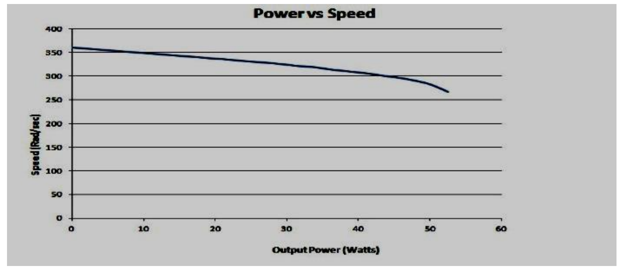

Figure 9 (b): Output power vs Speed (rad/sec)

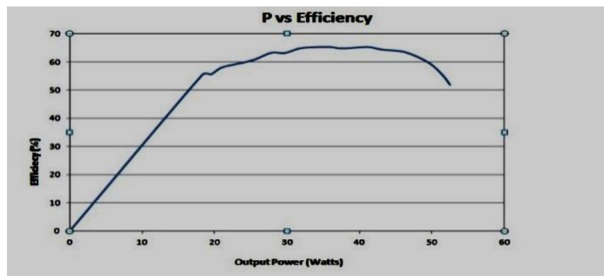

Figure 9 (c): Output power vs Efficiency (percentage)

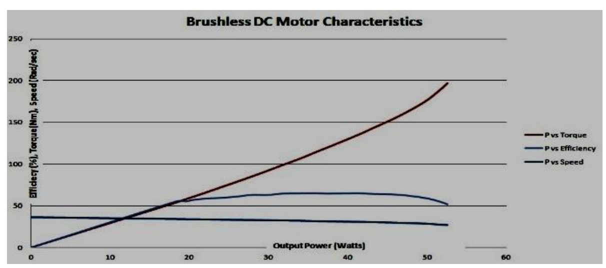

Figure 9 (d): Complete Characteristics of whole System

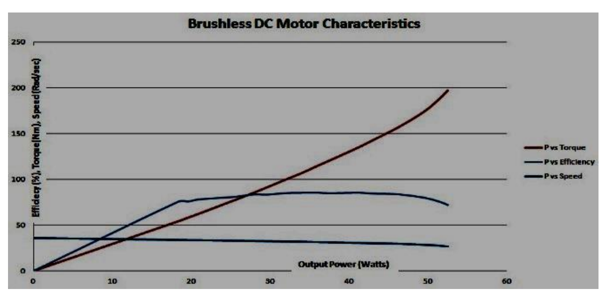

Figure 9 (e): Characteristics of BLDC motor only

with the MCLV board. These values should be modified according to the motor and load characteristics. The duty cycle of the input voltage waveform is kept at 66% to 100%.

The tabulated data in Table 4 and Figure 10 (a) – 10 (e) demonstrate that on any load the speed of the Brush-less motor will remain constant. The speed is controlled by the DMCI (Data monitor and Capture Interface) facility of

MPLab IDE. By switching ON or OFF the PID controller we can change the operation of motor. Data is collected on run time and motor speed is adjusted by comparing the reference signal. From the curves in Figure 10, it is observed that in open loop operation of sensor-less brush-less DC motor, control the speed regulation is quite good. And when motor is operated in closed loop configuration the speed remains constant for any torque and load requirements.

Table 4. Generator Characteristics

V_{out} (V)	I_{out}(A)	P_{out}(W)	Torque x 1000	Speed	rad/sec x .1	P_{in}(W)	Efficiency
15.2	0	0	0	2503	262.11	10	0
13.9	0.784	10.9	0.042	2503	262.11	22	69.55
13.7	0.932	12.77	0.049	2504	262.22	24	73.21
13.6	1.015	13.8	0.053	2504	262.22	25	75.2
13.5	1.08	14.58	0.056	2504	262.22	26	76.08
13.4	1.22	16.35	0.062	2505	262.32	29	76.38
13.2	1.34	17.69	0.067	2506	262.43	30	78.97
13	1.49	19.37	0.074	2506	262.43	33	78.7
12.8	1.73	22.14	0.084	2507	262.53	36	81.5
12.5	1.95	24.38	0.093	2507	262.53	40	80.95
11.5	2.4	27.6	0.105	2508	262.64	49	76.33
11.3	3.16	35.71	0.136	2508	262.64	61	78.54
10.4	4.1	42.64	0.162	2508	262.64	80	73.3

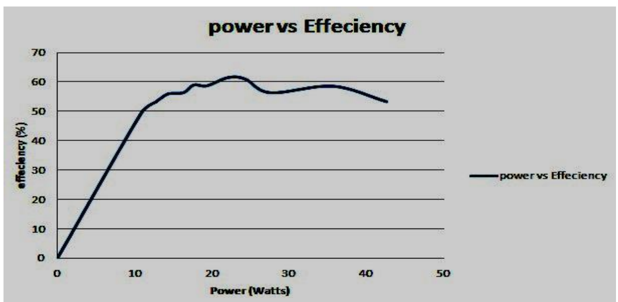

Figure 10 (a): Output power vs Efficiency (percentage)

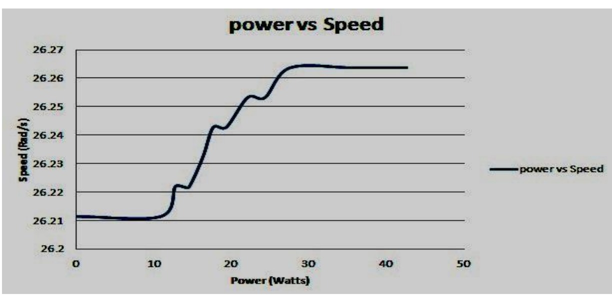

Figure 10 (b): Output power vs Speed (rad/sec)

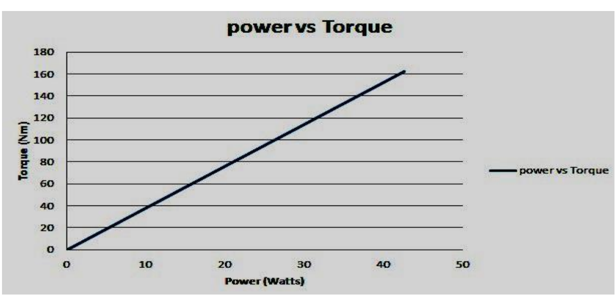

Figure 10 (c): Output power vs Torque

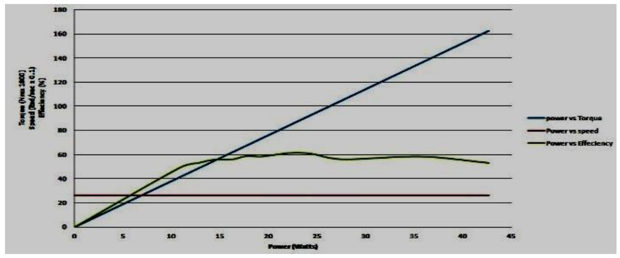
Figure 10 (d): Complete Characteristics of whole System

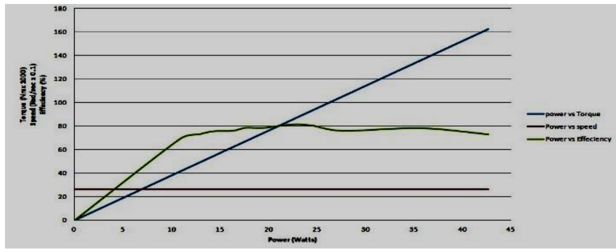
Figure 10 (e): Characteristics of BLDC motor only

All the work is done on dsPIC33FJ32MC204 Microchip Board. It comes with the facility of real time data monitoring (RTDM). The software is capable of capturing data through serial port. This facility is called Data monitor and Capture interface DMCI. Through this the motor speed can be adjusted and motor can be configured in an open or closed loop. Voltage as well as current waveforms can be captured during the motor operation. In this way motor can be completely analyzed by measuring its harmonics by any image processing technique of that curves. The program interface can also be seen through the Figure 11. First bar adjusts the speed of the motor. Second bar adjusts the Proportional parameters and third bar adjusts the intergraded parameters to remove the steady state error. This interface does not provide Differential controller because the motor is always in loaded condition so the speed overshoot is meaningless. Only proportional controller serves the need of removing the error from the reference signal. All this is done in PIC DSP Board through its signal processing.

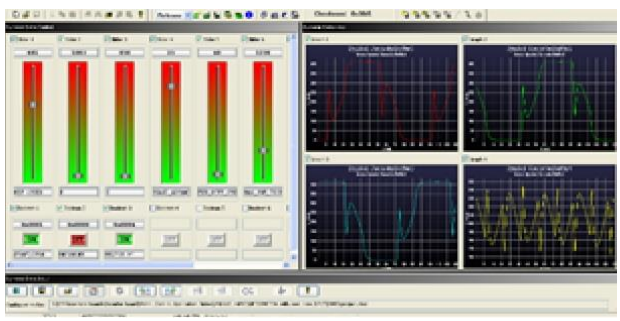
Figure 11: MPlab IDE real time DMCI

Here we have some waveforms of the phase voltage and the currents through DMCI (data monitor and capture interface). This is the three phase voltage waveform. This plot is the combination of three curves taken separately showing the phase voltage. Another thing that is notable and very important is the voltage waveform dip in each cycle that shows the rotor position. The frequency of the voltage waveforms describes the speed of the motor. To increase the speed of the motor we have to increase the frequency. But ,

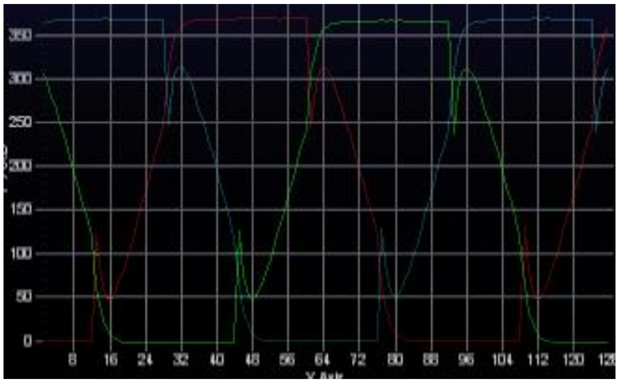

Figure 12: Three phase voltage waveform

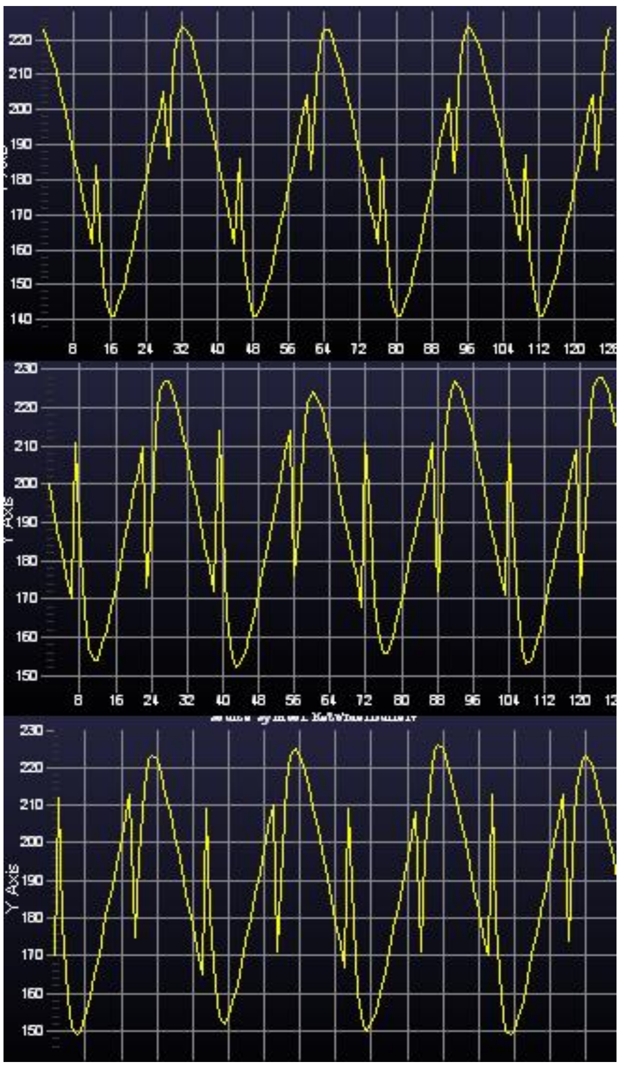

Figure 13: Current waveform at three different loads increasing from top to bottom

when load is applied and motor speed is reduced, PIC board increases the duty cycle of the input voltage waveform. As the torque requirement of the motor is increased, the increment in duty cycle increases the current in the armature which does not disturb the speed of the motor. The voltage waveforms are shown in Figure 12.

As any Brush-less DC motor is a three phase motor and each phase is position trapezoidal. In any operation sum of all three currents of each phase are equal and that is zero. So there is no unbalancing in currents of Brush-less DC motor control. The current waveforms as shown in Figure 13 are taken at different loads. 1) at no load. 2) at half load. 3) at full load. So these currents are directly proportional to the torque. And when load is increased the current waveform is distorted producing more harmonics. That is why when motor runs at high torque its sound become noisy.

CONCLUSION

In this paper, we have investigated the working of BLDC motors and demonstrated that Sensor-less Brush-less DC motor control is an efficient method that can be applied on any type of application, either industrial application or domestic application. In industry, it has greatly replaced the induction and servo motor due to its high precise speed controlling. Moreover, it is compact in size. With the help of simulations and practical experiments we conclude that Sensor-less Brush-less DC motor control gives us high flexibility and control over our desired results.

ACKNOWLEDGMENT

The authors would like to thank personnel in the Machines Laboratory Electrical Engineering Department, UET Lahore for their kind cooperation and constructive suggestions.

REFERENCES

[1]. http://www.microchip.com/"dsPIC33FJ32MC204 Family Data Sheet". (Available online)

[2]. Microchip Technology Inc. "Real-Time Data Monitor User's Guide" (DS70567)

[3]. Zeng, Li, and Zicheng Li. "An approach to position sensorless control system for brushless DC motor." In *Information Engineering and Computer Science (ICIECS), 2010 2nd International Conference on*, pp. 1-4. IEEE, 2010.

[4]. Varatharaju, V. M., B. L. Mathur, and K. Udhayakumar. "ANFIS based controllers and modeling simulation of PMBLDC motor and drive system." In*Sustainable Energy and Intelligent Systems (SEISCON 2011), International Conference on*, pp. 518-522. IET, 2011.

[5]. Lita, Adrian, and Mihai Cheles. "Sensorless BLDC control with back-EMF filtering using a majority function." *Microchip Technology Inc* (2008).

[6]. Zhongwei, Wang, Liu Haiting, and Zhao Xueping. "Simulation analysis of BLDC motor three step starting." In *Control, Automation and Systems Engineering (CASE), 2011 International Conference on*, pp. 1-6. IEEE, 2011.

[7]. Baluta, Gheorghe, and Marius Olariu. "Numerical simulation of BLDC electrical drive systems closed-loop control and sensorless control." In *2014 International Conference and Exposition on Electrical and Power Engineering (EPE)*. 2014.

[8]. Rajesh, T. S., and K. D. Joseph. "Sensorless operation of current controlled BLDC drive with phase lag compensation." In *Power Signals Control and Computations (EPSCICON), 2014 International Conference on*, pp. 1-5. IEEE, 2014.

[9]. D. Lenine, B.R. Reddy and S.V. Kumar, “Estimation of speed and rotor position of bldc motor using extended kalman filter”. In *International Conference on Information and Communication Technology in Electrical Sciences*, pages 433-440, 2007

[10]. Torres, Daniel. "Sensorless BLDC control with back-EMF filtering using a majority function." *Microchip Technology* (2008).

[11]. Ungurean, A., V. Coroban-Schramel, and I. Boldea. "Sensorless control of a BLDC PM motor based on If starting and Back-EMF zero-crossing detection." *Optimization of Electrical and Electronic Equipment (OPTIM), 2010 12th International Conference on*. IEEE, 2010.