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Torque ripple minimization of brushless DC motor using switched capacitor and spider-based controller.

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ABSTRACT

In BLDC motor,difference in current deviation of entering and leaving phase at the time of commutation causes torque ripple resulting in vibration and noise which restricts them to use for certain applications. This paper presents asimple controller based on bio inspired spider web algorithm for torque ripple reduction which can be used BLDC motor. Switched capacitor along with spider web-based controller are employed in the torque ripple reduction circuit. Spider web controller generates switching signals for inverter switches and for controlling the capacitor voltages. The potency of the proposed strategy is validated through the simulation of BLDC motor with spider-basedcontrollerandaswitchedcapacitor.

Index Terms: Spider web-based controller, switched capacitor, counter emf, Bio inspiredalgorithm.

I. INTRODUCTION

Brushless DC (BLDC) motors are progressively restoring brushed DC motors because of its high efficiency, longer life time,capability of trouble-free torque and high-speed possibility. In the past, there is a decline in the application of BLDC motor due to complexity and increased cost of motor controller required to operate these motors.Still, the controller cost has been moving downward in the last few years such that applications of BLDC motors have reached its peak. Measurement of rotor position is an important crucial process in driving BLDC motors. A slight incorrectness in position detection of BLDC motor can cause unsatisfactory output and in certain circumstances, it can bring about an overall failure in motor performance. A three-phase brushless DC motor needs three Hall effect sensors to measure the position of the rotor which is the effortless and highly familiar technique.

But brushless DC motors suffers from intrinsic torque ripples produced because of quasi square wave control of current resulting in pulsating movement and noise and are inappropriate for application where smooth torque is highly required. Since the brushless DC motor windings are also inductive in nature, there is a limitation for the controller circuit to give the desired performance at the time of commutation process which produces torque ripple.

A typical brushless DC motor drive system is shown in Fig 1. Consisting of a full bridgediode rectifier andthen a large electrolytic DC link capacitor which is fed to the inverter circuit [1].The lifetime of capacitor used in the DC link declines with operating temperature which makes them a frequent component of failure. It costs an approximately 12% cost of drive circuit of the motor and occupies about 15% of overall space in the printed circuit board of the motor driver. Many researches have pointed out several methods to solve such aproblem.

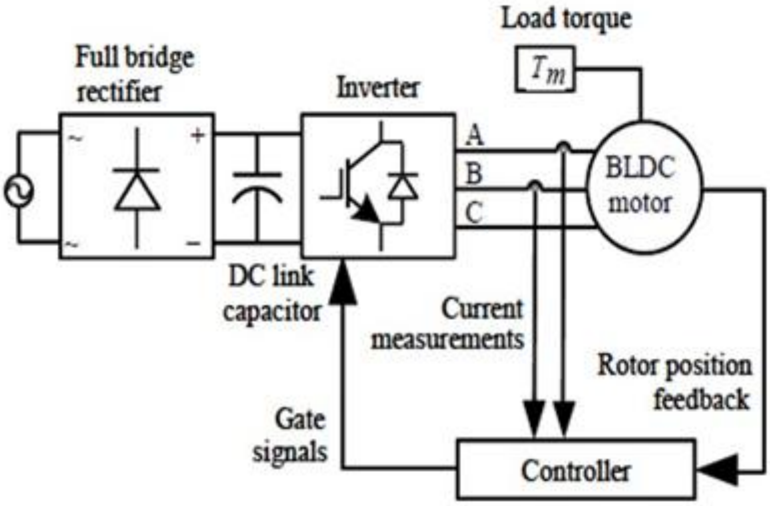

Fig. 1. Conventional BLDC drive system [1].

Torque ripple minimization method on the basis controlling a small valued capacitor is used[1]. The method used for controlling switch is simple, where additional components is not required. Since the response time of electronics is less, an 8% torque ripple is present. Phase resistance of BLDC motor is asymmetric,[2] which causes an imbalance in phase currents and rise in torque ripple. Online calculation of unbalanced resistances of windings of the motor is done using recursive least square algorithm. Stator resistances is measured which can be used to make up unbalanced resistance of windings of motor, which balances phase current and torque ripple is reducedto4%oftorquewithoutcompensation.Atorque ripple mitigate algorithm based on the one-cycle average torque control is used [3]. The algorithms have two major steps. The first step calculatesthe exact currentwaveform to obtain minimal ripple. The second steptakes observers to calculate the stator flux linkage and torque so that torque ripple reduces to 0.55Nm. During commutation and normal conduction period, the modes of the cuk converter can be changed by using a selector circuit [4] which minimizes torque ripple for the entire speed range. Cuk converter enters in to boost mode at the time of commutation and buck boost mode at the time of conduction. For regenerative braking and plug braking of BLDC motor, eight modulation patterns are used for both braking torque control and torque ripple reduction [5]. Through this method the torque gets smoothened and ripple rate is reduced to 13.6%. In case of BLDC motor with very small inductance for winding of the motor, a new converter topology is proposed [7] consisting of a multilevel inverter,a modified single-ended primary-inductor converter (SEPIC), and a voltage selector circuit. For efficient suppression of ripple, selector circuit regulates output voltage obtained from modified SEPIC converter at the time of commutation. A control strategy for ripple minimization in electromagnetic torque because of non-trapezoidal back emf for a four-phase brushless DC motor is included in [8]. To compensatefor the non-ideality of back emf waveforms, an online and estimated back emf method is employed to inject appropriate phase current [9]. This method uses same modulating mode both in conduction and commutation time and requires only a single current sensor. According to shortest commutation time, non-commutation phase modulation strategy is selected and DC voltage is adjusted by boost converter to reducetorque ripple. With this mechanism [10], commutation time can be controlled to integral multiples of PWM period and no additional circuit is required for detecting commutation time. In order to control the duty ratio of PWM signals, a new method to regulate the current is formulated [11] by calculating position of the rotor, counter emf and speed. PWM ON PWM pattern avoids diode freewheeling of inactive phase. Another configuration integrates [12] both modified SEPIC and a three-level neutral-point-clamped (NPC) inverter for minimization of torque ripple. Inorder to control the DC voltage, modified SEPIC converter is included at thefront end of three-level NPC inverter. This topology of hybrid converter is able to reduce torque ripple to 14.6%. Another work concerns [13] about controllability of braking torque along with commutation torque ripple reduction. Compares the speed range of eight unipolar modulation pattern where minimization of torque ripple and control of braking torque is possible. Thus, a combination of PWM ON, OFF PWM modulation pattern is used. In case of torque ripplethatare produced by non – sinusoidal EMF and cogging torque, Fourier analysis is done and a controller circuit obtained from internalmodelprinciple(IMP)isproposed[14].Thecontroller considers the changing behaviour of the velocity which can be easily applied to DSP controlled synchronous motor. Another incorporated control strategy[15]dealt with both commutation and conduction torque ripple minimization obtained from simple direct power control method. For reduction of both the ripples, an inner loop in which a three-phase voltage vector injection in PWM modulation is used for BLDC motor for getting the required waveforms of current to reduce torque ripple. Even though lots of work has been carried out to reduce torque ripple, it suffers from various disadvantages and difficulties especially related to cost. Hence it is very essential to find a solution to decline the torque ripple rate with reduced overallcost.

A bio inspired spider web controlling algorithm is used to produce switching pulses to inverter switches and controlling switches in BLDC motor drive for effective torque ripple reduction. The algorithm is called so, because it resembles the web building activity of the spider. This method adopts a small capacitor instead of large DC link capacitor, and no additional components are required which reduces the overall cost.

For the convenience, paper is divided into the following subsections as: operation of BLDC motor in section II, Analysis of torque and torque ripple reduction in sections III and IV respectively. Ripple reduction technique is verified through simulation and is given in section V.

II. OPERATION OF BLDCMOTOR

Three phase BLDC motors are operated by energizing two of the three electrical winding at a time (any two phases). Usu- ally only two switches in the six-step inverter, one belonging to the positive group and other belonging to negative group energizes any two phases at a time keeping switches of other phase in OFF state. Since small capacitor is used instead of a large DC link capacitor, strategy used here is controlling only one switch with a duty ratio and maintaining other switch in ON state for a particular value of hall sensor output.Switching sequence is given inTable I.

TABLE I
INVERTER SWITCHING SEQUENCE

Switching steps	**Hall sensor signals**				
	Ha	***Hb***	***Hc***	***ON State***	***Controlled***
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

Switches in the phases A, B, C of the six-step inverter are denoted as A1, A2, B1, B2, C1, C2 where subscript 1 and 2 represents upper and lower inverter leg respectively. The signals from hall effect are denoted as Ha, Hb, Hb. Switching signals for six inverter switches with hall signals are given in the Fig.2.

Considering the working of the brushless DC motor drive during step 2 switching sequence [20] as given in table I. Where switch B1 is controlled whereas switch C2 is kept in ON state. Fig 3 and 4 shows current path in the drive circuit

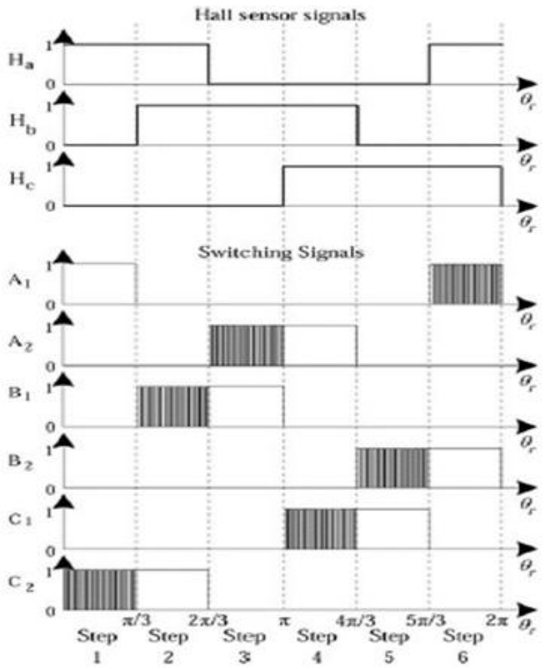

Fig. 2. Switching signals with hall sensor output [20].

of the motor during step 2. The operation of BLDC motor driveduringstep2resemblesbuckconverterasgivenin Fig 5. Thus, during all other steps in the working of drive circuit Of the motor, it can be pictured by a model resembling buck converter. As two of the phases are energized at a time, 'e' is line value of back emf, 'S' is the controlling switch, 'D' is the Freewheeling diode. V_{input} is the input voltage to the buck converter. 'R' and 'L' represents resistance and inductance of the winding of stator respectively.

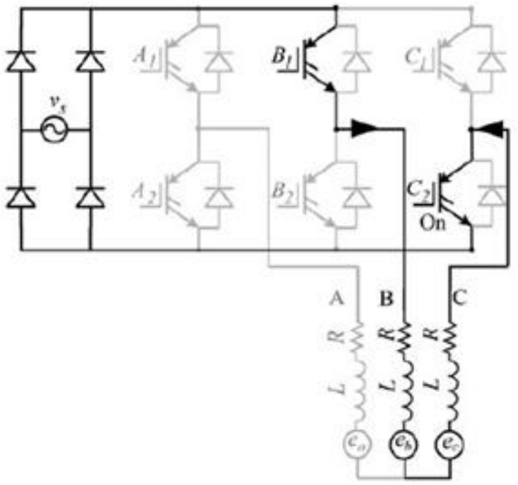

Fig. 3. Step 2 in the switching Sequence when B1 is ON [20].

From fig 5, applying Kirchhoff's voltage law to drive circuit of the motor during ON state and OFF state of the switch 'S' is

$$V_{input}\ (t) = 2i_m(t)R + 2(L - M)\frac{di_m(t)}{dt} + e(t) \qquad (1)$$

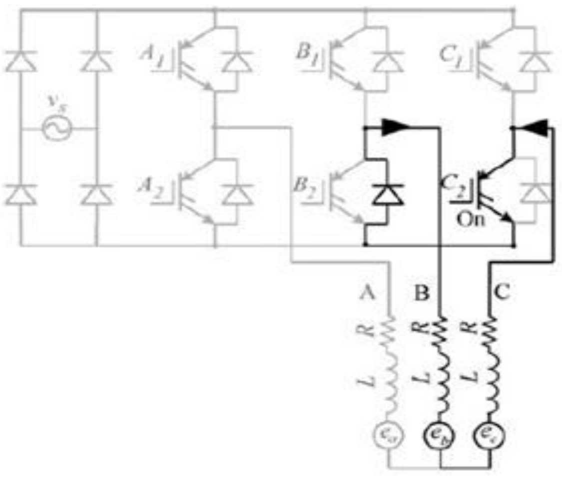

Fig. 4. Step 2 in the switching sequence when B1 is OFF [20].

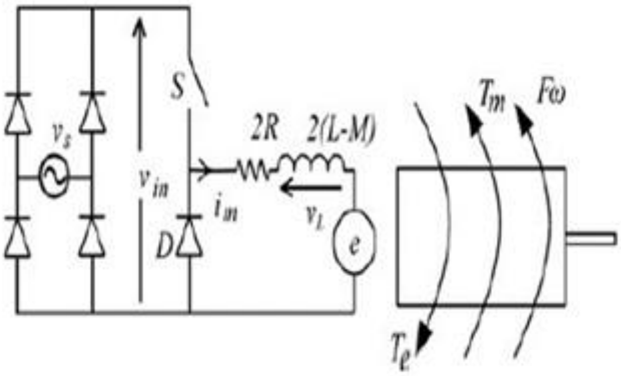

Fig. 5. Buck converter resembling model of brushless DC motor [20].

$$0 \quad = 2i_m(t)R + 2(L - M)\frac{di_m(t)}{dt} + e(t)(2)$$

Input voltage $V_{input}(t)$ is

$$V_{in}(t) = V_m sin|2\pi f t|$$

Where 'V_m' corresponds to peak amplitude of input voltage and 'f' is the supply frequency

III. TORQUEANALYSIS

Ideally counter emf of brushless DC motor is trapezoidal. Practically this trapezoidal counter emf is not obtainedbecause of disparity in the magnet used and variations in the design. But for the analysis, counter emf is assumed trapezoidal. i. e. commutationtorquerippleistakenintoconsideration. Consider the 120°region of back emf and its average value is taken as 'E'. As in the Fig. 6, rectified voltage is divided into two regions depending on the value of phase current. At the first region where back emf is lesser then rectified voltage, phasecurrentremainsatIrefitselfwhereasinregion2rectified voltage is lesser when compared to back emf, there is a dip in phase current or phase current is non-linear and uncontrollable which may produce uncontrollable torque. The time taken for region2islongerifbackemfishavinghighervalue.
From eqn. (1), (2) and (3)
On simplifying, expression for duty ratio D is

$$D(t) = \begin{cases} \frac{2I_{ref}\,R+E}{V_m\,|\sin(2\pi f t)|} & for\,region\,1 \\ 1 & for\,region\,2 \end{cases} \quad (4)$$

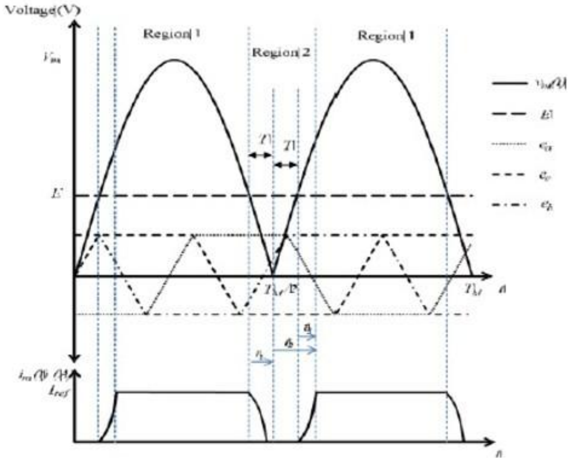

Fig. 6. Different regions of current in brushless DC motor drive [6].

IV. TORQUE RIPPLE REDUCTION IN BLDCMOTOR

Torque analysis reveals that torque ripple is produced in region 2 due to the nonlinearity and uncontrollability ofphase current. Such a disturbance in the motor may result in pulsating movement and errors in tracking particularly at low speeds which is not acceptable for certain applications. Thus, a torque ripple reduction technique using hybrid filter along with a control algorithm obtained from spider web building method isused.

The circuit consists of full bridge diode rectifier supplied with single phase AC followed by a series combination of small capacitor and a controlling switch connected across the rectifier. This combination is in input to the six-step inverter connected to the winding of the BLDC motor. In order to produce switching pulse to the controlling switch SDC and inverter switches, spider web-based controller algorithm is used. The circuit diagram showing ripple reduction technique for brushless DC motor is shown in Fig 7.

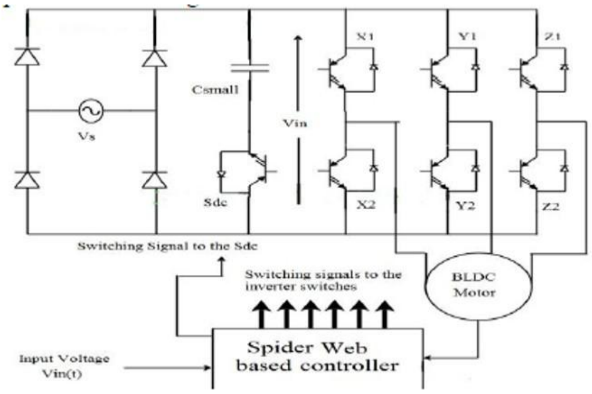

Fig. 7. BLDC motor with spider-based controller [6].

In region 1 of the rectified supply voltage, whereback emf is lesser when compared to rectified voltage, charging of capacitor takes place through anti-parallel diode of the switch SDC. The capacitor C_{small} cannot discharge naturally. So, the discharge can be induced by giving gating signals to the switch SDC. Sincethecapacitor discharges only during the region 2, energy stored in the capacitor is sufficient to retain phase current at I_{ref} so the phase current becomes controllable and linear and thereby torque ripple minimization. As a result, small capacitor C_{small} is enough when compared to DC link capacitor. Thus, the disadvantages associated with the usage oflargeDClinkcapacitorcanbeavoided.

A. Spider based controller algorithm

Biologically inspired algorithm is an arising proposal obtained from the basis of habitants and biological evolution of living things to find solution for complex scientific problems. One such algorithm resembling theweb buildingactivityof spider can be used for producing switching pulses for the switch SDC and inverter switches. To produce switching sequence given in the table I for the inverter switches, spider web controller [6] takes speed and hall sensor output as input signals in case of sensored BLDC motor. For generating pulse for the switch SDC, rectified voltage and back emf should be compared. Thus, the small capacitor used may get charged or discharged according to the state of rectified voltage and back emf. For the production of ripple free torque, capacitor must be discharged in region 2 to maintain phase current at I_{ref}. By the application of switching pulse to the switch SDC, dischargingcanbeinitiated.Thecapacitordischargesin region 2 only when it is sufficiently gets charged during the region 1.

During the web building activity of the spider, at first it forms a silky like fiber from its mouth. Resembling this activity, controller circuit is fed with rectified voltage and hall sensor output. There are two working modes for this controller.

Mode 1:

1. During this mode, input voltage is applied to the controller, readingitsvalueateverysecond.
2. Spider reaches zero crossing point of input voltage (resemblingthespideractivity of fixing the silkata point).
3. Spiderdetectsanotherlocationandlocatetothatpoint.
4. Moving back and forth between previous location and new location (by destroying previously created silky like fiber). This activity indicates the operation of controlling switch SDC.

Mode 2:

1. The spider is fed with a hall sensor output. Thus, it starts findingasuitablelocationforfixingthesilk.
2. After finding suitable place which implies the switch that belongs to the positive terminal of input voltage, silky fiber isfixedwhichmeansONprocessoftheinverterswitch.
3. Then it starts searching another suitable place to locate the fiber.
4. This suitable place indicates the switch that belongs to negative terminal of input voltage which do not belongs to the phase previously selected and thereby it fixes the silky fiber.
5. The forward and backward movement between newly found location and previous location implies controlling the inverterswitchwithadutyratio‘D’asgiveninswitching sequence.

V. RESULTS ANDDISCUSSION

BLDC motor with switched capacitor and spider-based controller is simulated using MATLAB/SIMULINK. The parameters of 250W, 6 pole, three phase brushless DC motor is given in Table II.

TABLE II
MACHINE PARAMETERS

Parameters	Values
Armature resistance per phase	0.0952
Armature inductance per phase	0.289mH
Torque constant	0.181Nm/A
Back emf constant	0.17Vs/rad

Fig.8 illustrates simulated waveforms for phase current in caseofBLDCmotorwithspider-basedcontrollerandswitched capacitor. With the use of spider-based controller, phase current becomes more uniform, less distorted and contains less ripples.

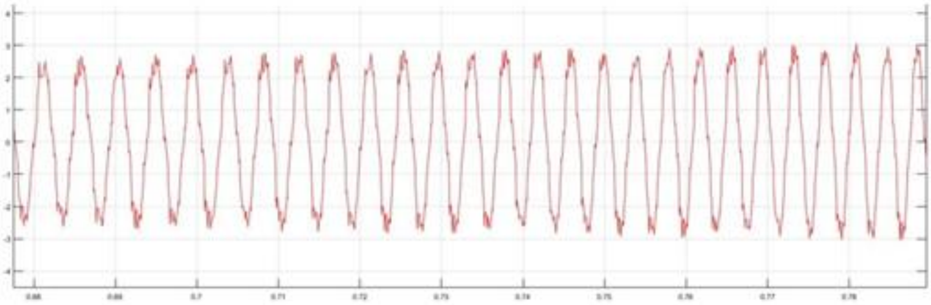

Fig. 8. phase current for brushless DC motor with spider web controller

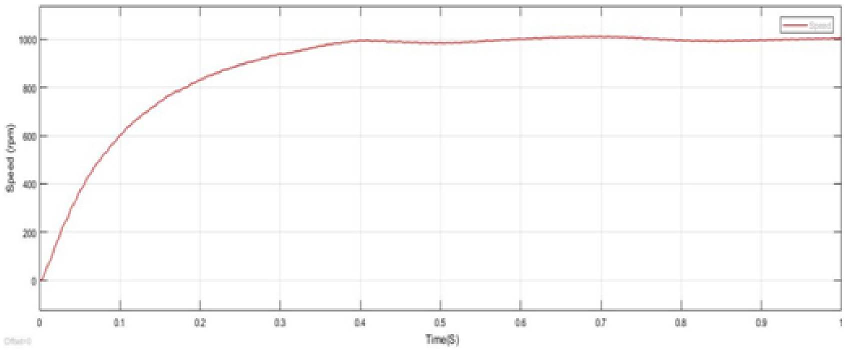

Fig. 9. Speed waveform of BLDC motor with spider-based controller

Torque waveform of brushless DC motor with spider- based controller is given in Fig. 10. Pink line indicates electromagnetictorqueandbluelineshowsloadtorque With spider-based controller torque becomes more smoothened and linear with torque ripple rate of only 11.2%. Simulation results validates the suitability of spider

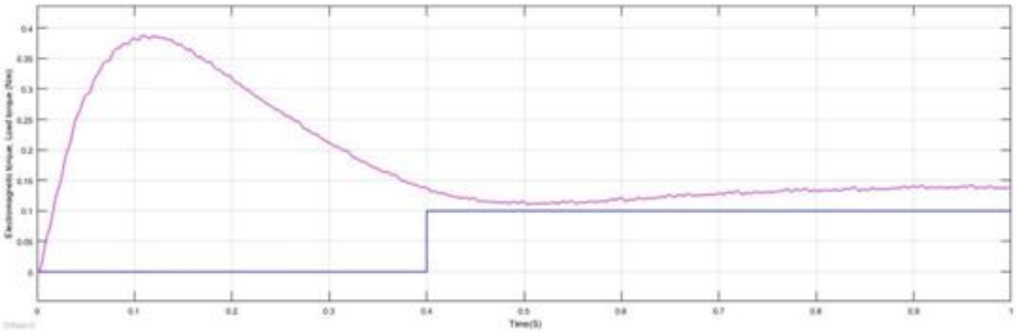

Fig. 10. Torque waveform of brushless DC motor with spider-based controller. Pink line indicates electromagnetic torque and blue line shows load torque of 0.1 Nm at 0.4s

web-based controller for reducing torque ripple of sensorless BLDC motor. This low-cost torque ripple reduction technique provides an effective BLDC motor drive for various applications.

VI. CONCLUSION

A simple and low-cost technique for minimizing ripple in the torque of BLDC motor is carried out using spider web- based controller and a voltage-controlledcapacitor. Torque ripple in BLDC motor inhibits them to utilize for various applications due to vibrations, noise etc. With the use of lesser number of components like a small capacitor and a controlling switch along with bio inspired spider web-based controller, a smooth torque waveform with reduced ripples are obtained. Thus, spider web controller, a least cost drive circuit of BLDC motor with minimized torque ripple can be obtained. Torque rippleobtainedwithspider-basedcontrolleriscomparablewith conventional BLDC motor with PI controller which reveals thatamuchsmoothertorqueisobtained.

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