

An analytical study of power factor correction employing a CUK converter-fed BLDC motor

¹K.Ramesh, ²Dr.K.Chandramouli, ³M.RamanaReddy, ⁴Bojanapalli Akhila

¹Associate Professor, ²Professor & HOD, ³Assistant Professor, ⁴UG Student, ^{1,2,3,4}Department of Electrical and Electronic Engineering, Vaageswari College of Engineering, Karimnagar, Telangana, India

ABSTRACT

Brushless dc motors (BLDC), which have excellent efficiency, a wide speed range, and low maintenance costs, are being employed in low-power appliances more and more often. This paper examines a power factor correction (PFC) based Cuk converter fed brushless DC motor or (BLDC) drive as a workable solution for low power applications. The speed of the BLDC motor may be controlled by adjusting the DC bus voltage of the voltage source inverter (VSI), which employs low frequency switching of VSI (electronic commutation of BLDC motor) for lower switching losses. Fundamental frequency switching has been employed to reduce the switching losses in the VSI by electrically commutating the BLDC motor. The implementation of two BLDC motor drive control approaches, one of which is based on PFC-CUK converter fed BLDCM drive and another one is Hysteresis current controller converter fed BLDC motor drive. Comparison has been made between the two control strategies is PI and HCC in terms of minimize Torque ripple, Power factor for different operating speeds. The proposed work has been implemented under MATLAB/Simulink environment.

Keywords: BLDC motor, BLDCM drive, PFC-CUK converters, fed brushless DC motor, power factor correlation

I. INTRODUCTION

A BLDC motor is a three-phase AC motor that features electronic commutation and feedback on the rotor position. Normally, a BLDC motor is implemented using a three phase inverter with six switches. The Hall Effect sensors offer information about rotor position. There are fewer switches and sensors as a result of the widespread usage of BLDC motors and their inherent advantages, such as high efficiency, high flux density, and optimal cost [1]. A novel design known as the Six Switches, Three Phase Inverter (SSTPI) is being researched for BLDC driving systems [2, 3]. Since fewer power electronic switches are required in this architecture, overall costs and losses are reduced [4, 5]. Using PWM when the voltage is inconsistent makes it challenging to reduce conducting currents. The current PWM schemes cannot be used for SSTPI.

Therefore, a new converter topology for three phase BLDC motor drive is to be developed. The Back EMF wave form of BLDC motor is trapezoidal in shape. And the stator current wave form is rectangular in shape. Hysteresis current control is employ to maintain the actual motor currents close to rectangular reference values [6, 7]. All through steady state analysis SSTPI fed BLDC motor is studied, the modeling, simulation and practical realization is to be explored. PI control is method of speed control of BLDC motor which reduces the steady state error to zero [8], PI controller does not respond to quick variation of speed and reaches the set point slowly. The PI controller can be easily implemented because simplicity and most common usage since long time [9]. In this paper, two control strategies for BLDC motor drive have been implemented. One of the control strategies is based on PFC-CUK converter fed BLDCM drive and another one is Hysteresis current controller converter fed BLDC motor drive and comparison is made between this two control strategies for different operating speeds. The performance of the BLDC motor with CUK converter for four switch VSI fed BLDCM motor is found to be quite effective due to improve power quality, less torque ripple and smooth control of speed of BLDC motor [10-12]. The CUK converter for six switches VSI fed BLDC motor drive system. The control scheme employs

hysteresis current control. For each phase of 3-hysteresis current controller, six power electronic switches are used and hence low cost and less switching losses and also reductions in torque ripple, as well as voltage stress and improved dynamic response. The variable DC output of bridge rectifier is fed to CUK converter. The output of the CUK converter is fed three leg VSI inverter which drives BLDC motor [13-14]. The power factor correction control scheme is based on the principle of current multiplier approach. This involves the presence of current loop inside speed control loop, in case of continuous conduction of the converter. The control loop starts with processing of speed obtained by comparing the actual, speed with the desired reference speed. The error is fed to the PI controller to obtain the reference torque and compared with actual torque of BLDC motor. The resultant torque error is multiplied with suitable constant and amplified in order to provide input to reference current block. The reference current is compared with phase a current which gives to hysteresis current control. The hysteresis current controller generates pluses for operation of three leg inverter and a rate limiter is introduced, which limits the current within specified limits [15].

II. SYSTEM CONFIGURATION

Figs.1 and .2 shows the PFC Cuk converter based VSI fed BLDC motor drive using a current multiplier and a voltage follower approach respectively.

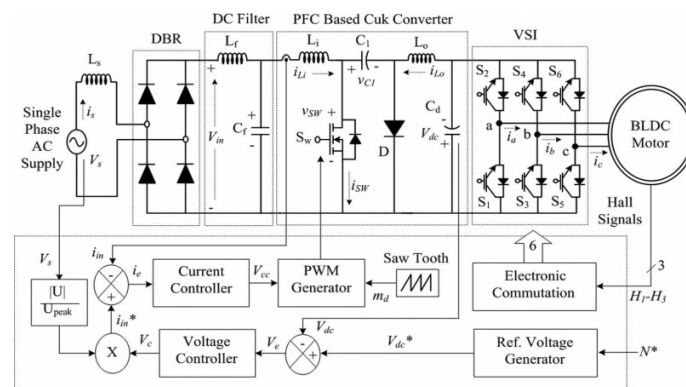


Fig.1. BLDC motor drive fed by a PFC Cuk converter using a current multiplier approach

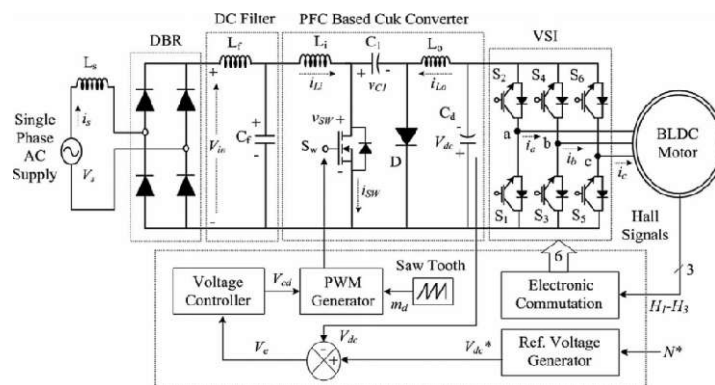


Fig.2.A BLDC motor drive fed by a PFC Cuk converter using a voltage follower approach.

A high frequency metal oxide semiconductor field effect transistor (MOSFET) is used in Cuk converter for PFC and voltage control whereas insulated gate bipolar transistor's (IGBT) are used in the VSI for its low frequency operation .BLDC motor is commutated electronically to operate the IGBT's of VSI in fundamental frequency switching mode to reduce its switching losses [13-14]. The PFC Cuk converter operating in CCM using a current multiplier approach is shown in Fig.1 i.e. the current flowing in the input and output inductors (L_i L_o), and the voltage across the intermediate capacitor (C_1) remains continuous in a switching period. Whereas, Fig.2 shows a

Cuk converter fed BLDC motor drive operating in DCM using a voltage follower Approach. The current flowing in either of the input or output inductor (L_i and L_o) or the voltage across the intermediate capacitor (C_1) become discontinuous in a switching period for a PFC Cuk converter operating in DCM. A Cuk converter is designed to operate in all three discontinuous conduction modes and a continuous conduction mode of operation and its performance is evaluated for a wide voltage control with unity power factor at AC mains [15].

III. OPERATION OF CUK CONVERTER IN DIFFERENT MODES

The operation of Cuk converter is studied in four different modes of CCM and DCM. In CCM, the current in inductors (L_i and L_o) and voltage across intermediate capacitor C_1 remain continuous in a switching period. Moreover, the DCM operation is further classified into two broad categories of discontinuous inductor current mode (DICM) and discontinuous capacitor voltage mode (DCVM). In DICM, the current flowing in inductor L_i or L_o becomes discontinuous in their respective modes of operation. While in DCVM operation, the voltage appearing across the intermediate capacitor C_1 becomes discontinuous in a switching period. Different modes for operation of CCM and DCM are discussed as follows.

CCM Operation:

The operation of Cuk converter in CCM is described as follows. Figs.3(a) and (b) show the operation of Cuk Converter in two different intervals of a switching period and Fig.3(c) shows the associated waveforms in a complete switching period.

Interval I: When switch S_{w1} turned on, inductor L_i stores energy while capacitor C_1 discharges and transfers its energy to DC link capacitor C_d as shown in Fig.3(a). Input inductor current i_{L_i} increases while the voltage across the intermediate capacitor V_{C_1} decreases as shown in Fig3(c).

Interval II: When switch S_{w1} turned off, then the energy stored in inductor L_o is transferred to DC link capacitor C_d , and inductor L_i transfers its stored energy to the intermediate capacitor C_1 as shown in Fig.3(b). The designed values of L_i , L_o and C_1 are large enough such that a finite amount of energy is always stored in these components in a switching period

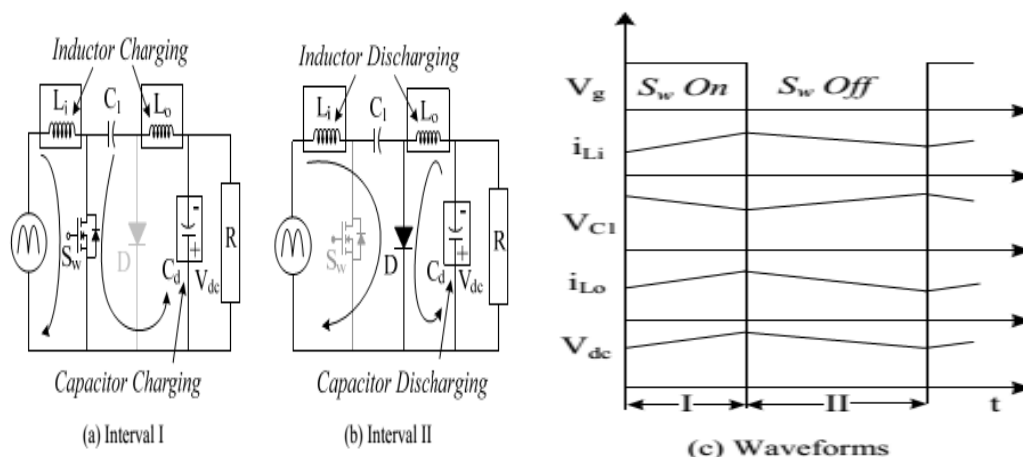


Fig.3. Operation of Cuk converter in CCM during (a-b) different intervals of switching period and (c) the associated waveforms

IV. DESIGN OF A PFC CUK CONVERTER

A PFC based Cuk converter fed BLDC motor drive is designed for DC link voltage control of VSI with power factor correction at the AC mains. The Cuk converter is designed for a CCM and three different DCMs. In DCM, any one of the energy storing elements L_i , L_o or C_1 are allowed to operate in discontinuous mode whereas in CCM, all these three parameters operate in continuous conduction. The design and selection criterion of these three parameters is discussed in the following section. The input voltage V_s applied to the DBR is given as,

$$V_s(t) = |V_m \sin(2\pi fL t)| = |220\sqrt{2} \sin(314t)| \text{ V} \quad (1)$$

Where V_m is the peak input voltage (i.e. $\sqrt{2}V_s$, V_s is the rms value of supply voltage), fL is the line frequency i.e. 50 Hz. The instantaneous voltage appearing after the DBR is as,

$$v(t) = |V_m \sin(\omega t)| = |220\sqrt{2} \sin(314t)| \text{ V} \quad (2)$$

Here represents the modulus function. The output voltage, V_{dc} of Cuk converter is given as

$$V_{dc} = D(1-D) / (t) \quad (3)$$

Here D represents the duty ratio. The instantaneous value of duty ratio, $D(t)$ depends on the Input voltage appearing after DBR, $V_{in}(t)$ and the required DC link voltage, V_{dc} .

Hence the instantaneous duty ratio, $D(t)$ is obtained by substituting (2) in (3) and rearranging it as,

$$D(t) = V_{dc} / (v(t) + V_{dc}) = V_{dc} / |V_m \sin(\omega t)| + V_{dc} \quad (4)$$

The Cuk converter is designed to operate from a minimum DC voltage of 40V ($V_{dc \text{ min}}$) to a maximum DC link voltage of 200V ($V_{dc \text{ max}}$). The PFC converter of maximum power rating of 350W (P_{max}) is designed for a BLDC motor of 251W (P_m) (full specifications given in Table I) and the switching frequency (f_s) is taken as 20kHz. Since the speed of the BLDC motor is controlled by varying the DC link voltage of the VSI, hence the instantaneous power, P_{inst} any DC link voltage (V_{dc}) can be taken as linear function of V_{dc} . Hence for a minimum value of DC link voltage as 40V, the minimum power is calculated as 70W.

TABLE I
SPECIFICATIONS OF A BLDC MOTOR

S.NO	PASRAMETERS	VALUES
1	No. of poles (P)	4 POLES
2	Rated power (PRATED)	251.3 W
3	Rated DC link voltage (VRSATED)	200V
4	Rated torque (TRATED)	1.2 N-M
5	Rated speed (NRATED)	2000 RPM
6	Back Emf constant (Kb)	78 V/KRPM
7	Torque constant (Kt)	0.74 N-M/A
8	Phase resistance (RPH)	14.56 Ω
9	Phase inductance (LPH)	25.71 mH
10	Moment of inertia (J)	1.3×10^{-4} N-M/-S ²

TABLE II
ELECTRONIC OUTPUT BASED ON THE HALL EFFECT SIGNAL

HALL SIGNALS			SWITCHING SIGNALS					
H1	H2	H3	Sa1	Sa2	Sb1	Sb2	Sc1	Sc2
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1

1	1	1	0	0	0	0	0	0
---	---	---	---	---	---	---	---	---

TABLE III

DESIGN PARAMETERS IN DIFFERENT MODES OF OPERATION

S.NO	SPECIFICATIONS	VALUES			
1	Supply voltage(Vs)	Rated:220v ,(Universal Mains:85-270v)			
2	DC Link Voltage(Vcd)	Rated:220v,(40v-200v)			
3	Power (P)	Rated:350w,(70w-350w)			
4	Switching frequency(fs)	20khz			
5	Operation	Li	Lo	C1	Cd
6	CCM	2.5Mh	4.3mH	0.66µF	220µF
7	DICM(Li)	100µH	4.3MH	0.66µF	220µF
8	DICM(Lo)	2.5Mh	70µH	0.66µF	220µF
9	DCVM(C1)	2.5mH	4.3mH	9.1nF	220µF

V.MATLAB/SIMULATION RESULTS

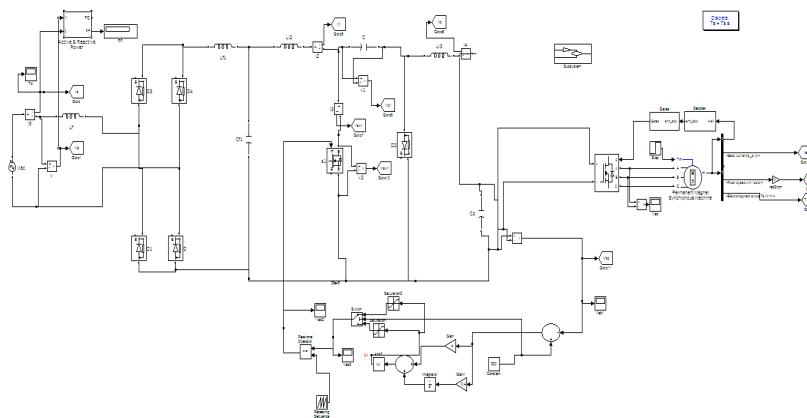


Fig.4. Simulation model of BLDC motor drive fed by a PFC Cuk converter using a multiplier approach

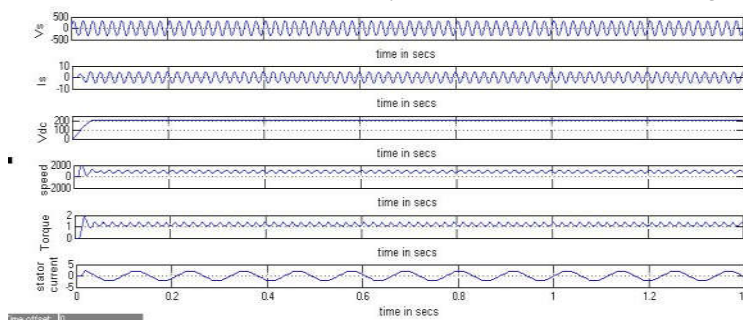


Fig.5.Simulation waveform for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the CCM

Performance of BLDC Motor Fed Cuk Converter Operating in the CCM:

The circuit configuration and control of the PFC Cuk converter operating in the CCM. The parameters selected for this converter to operate in the CCM are as follows: Input inductor $L_i = 2.5$ mH, output inductor $L_o = 4.3$ mH, intermediate capacitor $C_1 = 0.66$ μ F and dc-link capacitor $C_d = 2200$ μ F.

The performance of the proposed BLDC motor drive fed by a PFC Cuk converter operating in the CCM. The input inductor current i_{Li} , output inductor current i_{Lo} , and intermediate capacitor's voltage V_{C1} are continuous in operation while the supply current I_s is sinusoidal and in phase with the supply voltage v_s , which shows a 0.9306 PF at ac mains.

Simulation model of CUK-converter fed HCC BLDCM drive by using HCC:

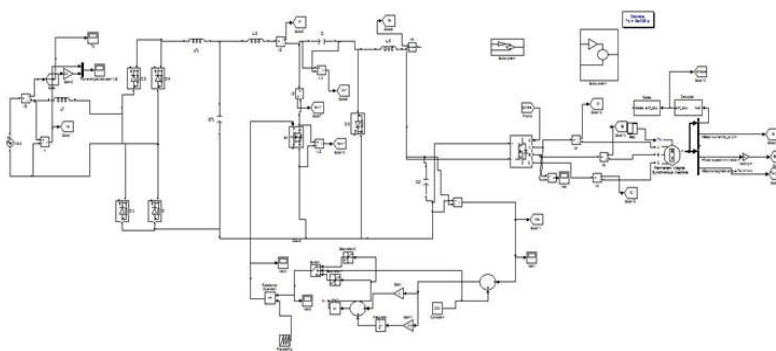


Fig.6. Simulation model of HCC based BLDC motor drive fed by a PFC Cuk converter.

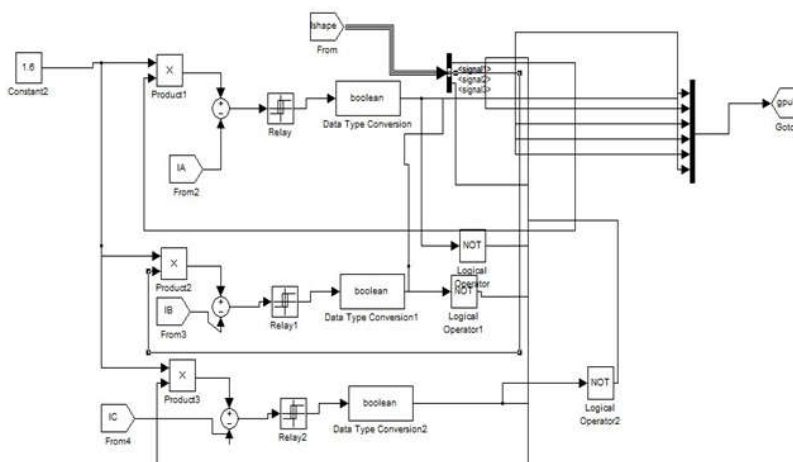


Fig.7. Control strategies for hysteresis current control

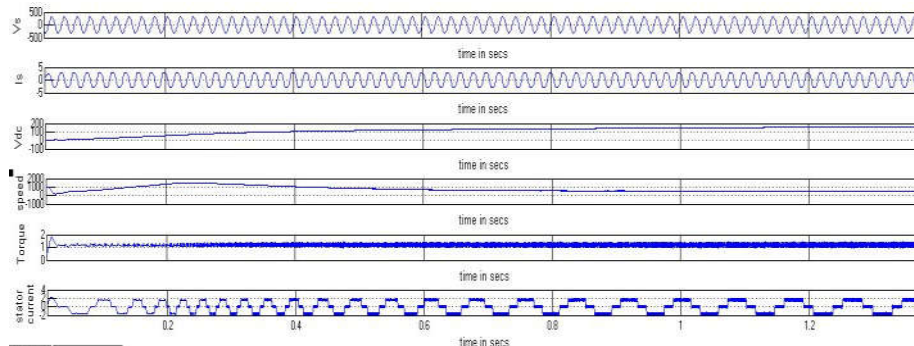


Fig.8.Simulation results for source voltage, current, dc link voltage, and speed, torque, stator Current of BLDC motor under hysteresis current control

Performance of HCC based BLDC Motor Fed Cuk Converter:

Finally, a best suited mode of Cuk converter operating in CCM has been selected for experimental verifications. By using HCC the power factor is improved from 0.9306 to 0.9994. The simulation model which is implemented in a modular manner with HCC under MATLAB environment allows dynamic characteristics such as phase currents, rotor speed, and mechanical torque ripple has been effectively reduced.

Performance details:

S.NO	BLDC MOTOR	POWER FACTOR
1	Fed CUK-converter	0.9306
2	fed CUK-Converter along with HCC	0.9994

CONCLUSION

A Cuk converter for VSI fed BLDC motor driving has been created for the production of low cost PFC motors for numerous low power equipment such as fans, blowers, water pumps, etc. By running the VSI in fundamental frequency switching mode, it is feasible to control the speed of the BLDC motor drive and lessen switching losses by regulating the DC link voltage of the VSI. Four different operating modes of the Cuk converter operating in CCM and DCM have been examined for the development of a BLDC motor drive with a unity power factor at the AC mains. The suggested hysteresis current controller system provides excellent resilience and flexibility when the system is perturbed. HCC results in an improvement of the power factor from 0.9306 to 0.9994. The simulation model which is implemented in a modular manner with HCC under MATLAB environment allows dynamic characteristics such as phase currents, rotor speed, and mechanical torque ripple has been effectively reduced.

REFERENCES

1. J. F. Gieras and M. Wing, Permanent Magnet Motor Technology—Design and Application. New York, NY, USA: Marcel Dekker, Inc, 2002.
2. C. L. Xia, Permanent Magnet Brushless DC Motor Drives and Controls. Beijing, China: Wiley, 2012.
3. Y. Chen, C. Chiu, Y. Jhang, Z. Tang, and R. Liang, "A driver for the single phase brushless DC fan motor with hybrid winding structure," IEEE Trans. Ind. Electron., vol. 60, no. 10, pp. 4369–4375, Oct. 2013.
4. S. Nikam, V. Rallabandi, and B. Fernandes, "A high torque density permanent magnet free motor for in-wheel electric vehicle application," IEEE Trans. Ind. Appl., vol. 48, no. 6, pp. 2287–2295, Nov./Dec. 2012.
5. X. Huang, A. Goodman, C. Gerada, Y. Fang, and Q. Lu, "A single sided matrix converter drive for a brushless DC motor in aerospace applications," IEEE Trans. Ind. Electron., vol. 59, no. 9, pp. 3542–3552, Sep. 2012.
6. W. Cui, Y. Gong, and M. H. Xu, "A permanent magnet brushless DC motor with bifilar winding for automotive engine cooling application," IEEE Trans. Magn., vol. 48, no. 11, pp. 3348–3351, Nov. 2012.
7. C. C. Hwang, P. L. Li, C. T. Liu, and C. Chen, "Design and analysis of a brushless DC motor for applications in robotics," IET Elect. Power Appl., vol. 6, no. 7, pp. 385–389, Aug. 2012.
8. T. K. A. Brekken, H. M. Hapke, C. Stillinger, and J. Prudell, "Machines and drives comparison for low-power renewable energy and oscillating applications," IEEE Trans. Energy Convers., vol. 25, no. 4, pp. 1162–1170, Dec. 2010.
9. N. Milivojevic, M. Krishnamurthy, A. Emadi, and I. Stamenkovic, "Theory and implementation of a

- simple digital control strategy for brushless DC generators,” IEEE Trans. Power Electron., vol. 26, no. 11, pp .3345– 3356, Nov. 2011.
10. T. Kenjo and S. Nagamori, Permanent Magnet Brushless DC Motors. Oxford, U.K.: Clarendon Press, 1985.
 11. J. R. Handershot and T. J. E Miller, Design of Brushless Permanent Magnet Motors. Oxford, U.K.: Clarendon Press, 2010.
 12. T. J. Sokira and W. Jaffe, Brushless DC Motors: Electronics Commutation and Controls. Blue Ridge Summit, PA, USA: Tab Books, 1989.
 13. H. A. Toliya t and S. Campbell, DSP-Based Electro mechanical Motion Control. New York, NY, USA: CRC Press, 2004.
 14. “Limits for harmonic current emissions (equipment input current ≤ 16 A per phase),” International Standard IEC 61000-3- 2, 2000
 15. N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications and Design. New York,NY, USA: Wiley, 2009.