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Analysis of Commutation Torque Ripple Suppression Strategy for Brushless DC Motor using NIBFE with SEPIC

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ABSTRACT: This paper is based on Analysis of Commutation Torque Ripple Suppression Strategy for Brushless DC Motor using NIBFE with SEPIC. BLDC Motor are used by many applications as it has high starting torque, high efficiency, high power density. There are no brushes and commutator present in BLDC motor. Commutation happens every 60 degrees. Commutation is done with help of electronic switches of Inverter. Hall sensors placed in Stator are used to sense position of rotor. In commutation period torque ripple is produced due to phase current which is not undergoing commutation. The commutation torque ripple cause vibration and noise, could reduce high performance operation of BLDC motor. By maintaining noncommutation phase current steady in commutation period torque ripple can be reduced. In this Project work NIBFE fed BLDC motor is compared with SEPIC converter fed BLDC motor using Proposed control strategy. NIBFE called as Non inductive boost front end formed using Diode, MOSFET and capacitor. A Closed loop feedback controller circuit with Switching sequence is used to generate PWM gate pulse for Inverter and converter Switch. By selecting proper Switching Vectors in Noncommutation and Commutation period have reduced Commutation Torque Ripple. The components are simulated in MATLAB 2019b Software and Simulation results of Open and Closed loop of NIBFE compared with SEPIC Converter with Proposed method is presented.

KEYWORDS: NIBFE, SEPIC Converter, BLDC Motor, Commutation torque ripple reduction, Hall sensors, Switching Vectors.

I. INTRODUCTION

BRUSHLESS DC motors know as BLDC Motor has been used by many applications due to high torque density, simple structure. A Maximum of 50% average torque will be torque ripple which is produced in commutation process, Torque ripple occurs when phase current control is lost in commutation period.[1]. The major problem of BLDC Motor is commutation torque ripple that cause noise and vibration which minimize high-performance operation [1][2]. BLDCM usually operates in two phase conduction mode during non commutation period and three phase conduction mode during commutation Period. Two different modulation methods are used in commutation period depending upon motor speed [8][11]. Three phase modulation method is used for high speed.[9]. During both commutation and noncommutation period two phase modulation mode where PWM are modulated in non commutating phase simplifies modulator design [10]. Three segment modulation strategy is used to minimize commutation torque ripple which divides each PWM period into three segments and analyse duration of each segment based on both constant noncommutation phase current and reduced commutation time.[9] Before and after commutation average voltage of noncommutated phase should be kept steady [10]. At high speed range to minimize commutation torque ripple DC to DC converter is added to input side which would adjust average voltage of inverter during the commutation period.[4][9] Analysis shows noncommutation phase in low-speed region and modulation in outgoing phase in highspeed region are selected. When machine operates at low speed range with PWM technique torque ripple can be reduced.[5][7]. It is not possible to reduce torque ripple at high speed with PWM scheme at rated condition due to limited DC source voltage of Inverter. The SEPIC converter is employed to adjust the voltage required in commutation period, where DC source and SEPIC converter are selected to supply motor during noncommutation and commutation periods. [3][4]. A Cuk converter is used to reduce commutation torque ripple [6], to regulate voltage two operation



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modes are employed during noncommutation and commutation period. Since more inductors and power switches are required in DC–DC converters, can increases size and cost of motor drive system [6] [9].

II. PROPOSED METHODOLOGY

In this project work commutation torque ripple reduction strategy using Switching Vectors is Proposed. Input DC voltage is given to Converter which converts DC to DC. Converter for comparison used are NIBFE and SEPIC. NIBFE is noninductive boost front end. SEPIC converter is Single ended primary inductor converter formed as capacitor and inductor connected in between boost converter. Output is fed to Inverter which is fed to BLDC motor and Closed loop feedback controller circuit having proper switching sequence pattern used to generate PWM gate signal pulses for six inverter switches and converter switch. The commutation torque ripple can be reduced by keeping noncommutation phase current steady in commutation period.



Fig. 1 Block diagram of converter fed Brushless DC Motor



Fig. 2 Proposed control strategy of NIBFE fed BLDC motor drive in Closed loop

In closed loop operation of NIBFE fed VSI fed BLDC motor and SEPIC fed VSI fed BLDC motor using Proposed control strategy. Reference speed and actual speed are compared and error obtained is given to Speed PI controller and next to current PI controller, Noncommutation duty cycle d1,d2 is obtained given to Noncommutation block. Commutation period duty cycle dcmt is obtained given to Commutation block. Period Judgement block checks if Commutation period select Commutation modulation method (Table 3) and Noncommutation period select Noncommutation method (Table 4). Depending upon the switching sequence PWM gate pulses are



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obtained fed to 6 Inverter switches and NIBFE capacitor or SEPIC converter switch. The equations and parameters used for NIBFE and SEPIC converter is shown below.

C = 2300MF Capacitor NIBFE Parameter L1 = L2 = 1mH, C1=C2= 4000MF, Duty cycle 0.4 SEPIC Parameter

NIBFE

SEPIC converter



Vo = Vi*D/(1-D) $L1 = D*Vi/(fs*\Delta IL1)$ $L2 = (1-D)*Vo/(fs*\Delta IL2)$ $C1 = \Delta Idc/(fs*\Delta VC1)$ $C2 = Idc/(fs*\Delta VC2)$

d1, d2 - duty cycle of non commutation period dcmt - duty cycle of commutation period.

Where Vi,Vo Input and Output Voltage L1, L2 Inductors C1, C2 Capacitor D- duty cycle

Mathematical modelling using equations and parameter of Brushless DC motor (BLDC Motor).



$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_v \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L - M & 0 & 0 \\ 0 & L - M & 0 \\ 0 & 0 & L - M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$
(1)

where Va,Vb,Vc are stator phase voltages, R stator resistance per phase, ia,ib,ic stator phase currents, L self-inductance of each phase,M mutual inductances between phases, ea,eb,ec phase back electromotive forces

$$V_{a} = i_{a}R + L\frac{di_{a}}{d_{t}} + e_{a}$$
$$V_{b} = i_{b}R + L\frac{di_{b}}{d_{t}} + e_{b}$$
$$V_{c} = i_{c}R + L\frac{di_{c}}{d_{t}} + e_{c}$$

We assume back EMF ea,eb,ec have trapezoidal shape are displaced by 120 degree.

(2)

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$$e_{a} = \omega_{m}\lambda_{m} f_{as}(\theta_{r})$$

$$e_{b} = \omega_{m}\lambda_{m} f_{bs}(\theta_{r})$$

$$e_{c} = \omega_{m}\lambda_{m} f_{cs}(\theta_{r})$$
ere com angular rotor speed in radians per seconds λ m flux linkage for

where ω m angular rotor speed in radians per seconds, λ m flux linkage, θ r rotor position in radian and fas(θ r) ,fbs(θ r), fcs(θ r) trapezoidal functions have same shape as ea,eb,ec with maximum magnitude of ±1 phase displaced by 120. Electromagnetic toque and Motion equation

$$T_{e} = \left[e_{a}i_{a} + e_{b}i_{b} + e_{c}i_{c}\right] / \omega_{m}$$

$$J \frac{d\omega_{m}}{dt} + B\omega_{m} = (T_{e} - T_{l})$$
(5)

where J moment of inertia, B friction coefficient, Tl load torque, ωm angular velocity. The electrical rotor speed and position is shown where p number of poles pairs

$$\frac{d\theta_r}{dt} = \frac{p}{2}\omega_n$$

Torque ripple is calculated where Thigh is maximum torque and Tlow is minimum torque

$$K_{\rm rT} = \frac{T_{\rm high} - T_{\rm low}}{T_{\rm high} + T_{\rm low}} \times 100\%$$

The Commutation Torque ripple reduction of Brushless DC motor using Proposed control strategy in Closed loop use four Switching Vectors namely two main Vectors (Vm0,Vm1) and two auxiliary Vectors (Va0,Va1). Hall signals for each sector and current conduction phases are shown.

	$V_{ m m0}$	$V_{ m m1}$	$V_{\rm a0}$	V_{a1}	
	$\mathbf{S}_{p\mathrm{H}} \; \mathbf{S}_{n\mathrm{L}} \; \mathbf{S}_{7}$	$\mathbf{S}_{p\mathrm{H}} \ \mathbf{S}_{n\mathrm{L}} \ \mathbf{S}_{7}$	$\mathbf{S}_{p\mathrm{H}} \ \mathbf{S}_{n\mathbb{L}} \ \mathbf{S}_{7}$	$\mathbf{S}_{p\mathrm{H}} \; \mathbf{S}_{n\mathrm{L}} \; \mathbf{S}_{7}$	
4 , 2 , 1	1 1 0		0 1 x		
5, 6, 3	1 1 0	1 1 1	1 0 x	000	

"1" is ON; "0" is OFF; "x" is ether ON or OFF. The switches not listed in the table are OFF. Table. 1. Current conduction phases

H _a H _b H _c	101	100	110	010	011	001
Sector	5	4	6	2	3	1
(<i>p</i> , <i>n</i>)	(a,b)	(a,c)	(b,c)	(b,a)	(c,a)	(c,b)

"H_a," "H_b," and "H_c" are denoted as the Hall signals of three phases. Table. 2. Four Switching Vectors used in Proposed method

For each Sector Modulation control strategy for Commutation and Noncommutation period the switching sequence required to generate PWM gate pusles for 6 Inverter switches and Converter switch are shown.

States	Sector								
Status	5	4	6	2	3				
$d_{ m cmt}$	\mathbf{S}_{6}	\mathbf{S}_1	S_2	S_3	S_4	S_5			
1	\mathbf{S}_1	S_2	\mathbf{S}_3	S_4	S_5	\mathbf{S}_6			
1	S								

Sector	$U_{\rm ref} \leq U$	$U_{\rm cap} < U$	$U_{ m cap} {<} U_{ m ref}$			
	$S_{\rho H}$	S_{nL}	S_7	$\mathbf{S}_{p\mathbf{H}}$	S_{nL}	S_7
4, 2, 1	d_1	1	0	4	4	0
5, 6, 3	1	d_1	0	a_2	a_2	0

"1" is ON; "0" is OFF. The switches not listed in the table are OFF.

Table. 4. Noncommutation period Modulation control strategy

Table. 3. Commutation period Modulation control strategy

(7)

(6)

(3)



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Se	ector	-	Noncommutation Strategy					Commutation Strateg			
1	2	3	Vm0	Va0	S7	Vm0	Va1	S7	Vm1	Va0	S7
4	5	6	d1	1-d1	0	d2	1-d2	0	dcmt	1-dcmt	1

Table. 5. Switching scheme of Proposed control strategy

The main Vector will be chopped with duty cycle, auxiliary vector is chopped with 1-duty cycle and converter switch is ON only during commutation period.

III. EXPERIMENTAL RESULTS

The proposed control system using NIBFE fed BLDC motor and SEPIC fed BLDC motor is simulated using Matlab and results of Open and Closed loop are obtained. A 100V DC voltage is given as input to NIBFE (duty cycle 0.2) and SEPIC converter (duty cycle 0.4). No load Torque of 0Nm is applied to BLDC motor. Gate signals given to inverter switches are generated from hall signals produced from Hall sensor pass through Logic and decoder circuit convert it as PWM Gate pulse in case of Open loop.

Simulation of NIBFE fed VSI fed BLDC motor whole system in Open Loop is shown in Fig 3.



DC-NIBFE- VOLTAGE SOURCE INVERTER- BRUSHLESS DC MOTOR IN OPEN LOOP

Fig. 3 Simulation of NIBFE fed VSI fed BLDC motor whole system in Open Loop



Fig. 4 NIBFE waveform of Input, Output, Capacitor Voltage



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Fig. 6 Waveform of Inverter Voltage and Motor Stator current, back EMF, Hall signal

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Fig. 7 Waveform of Electromagnetic Torque , Speed, Load Torque of BLDC motor

NIBFE output voltage is 100V. Back-Emf of BLDC Motor are 120 degree displaced have trapezoidal waveform of magnitude of 87.26V. Stator current have quasi square waveform of magnitude 7A. Back EMF is proportional to Speed. stator current is proportional to Torque. There is small ripple in Torque waveform due to ripple in stator current. At no load torque Speed of motor is 5600rpm.



Fig. 8 Waveform of Motor Electromagnetic Torque

Simulation of SEPIC converter fed VSI fed BLDC motor whole system in Open Loop is shown in Fig 9. Input voltage of 100V is given to SEPIC converter with duty cycle 0.4. SEPIC output is fed to Voltage source inverter fed to BLDC motor.



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Fig. 9 Simulation of SEPIC fed VSI fed BLDC motor whole system in Open Loop





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Fig. 13 Waveform of Electromagnetic Torque, Speed, Load Torque of BLDC motor

SEPIC converter with duty cycle 0.4 have reduced the output voltage step down to 67.98V when input of 100V is given. Here SEPIC converter work as Buck. SEPIC converts DC to DC. Back-Emf waveform have magnitude of 74.43V. Stator current have magnitude 7.54A. At no load torque Speed of motor is 4776rpm. There is torque ripple which is measured by using equation (8).



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Fig. 14 Waveform of Motor Electromagnetic Torque

Simulation of NIBFE fed VSI fed BLDC motor whole system in Closed Loop with Proposed control strategy is shown in Fig 15.

A 100V DC voltage is given as input to NIBFE and SEPIC converter. No load Torque of 0Nm is applied to BLDC motor. Gate signals given to inverter switches and converter switch are generated from closed loop feedback controller with Proposed control strategy.



Fig. 15 Simulation of NIBFE fed VSI fed BLDC motor whole system in Closed Loop



Fig. 16 Closed loop feedback controller.



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Fig. 17 NIBFE waveform of Input, Output, Capacitor Voltage



Fig. 19 Waveform of Inverter Voltage



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Fig. 20 Waveform of Stator current, back EMF, Hall signal of BLDC motor

In closed loop of NIBFE fed BLDC shows Back-Emf of magnitude of 86.57V. Stator current of magnitude 5A. At no load torque Speed of motor is 5555rpm.



Fig. 21 Waveform of Electromagnetic Torque , Speed, Load Torque of BLDC motor

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Fig. 22 Waveform of Motor Electromagnetic Torque

Simulation of SEPIC fed VSI fed BLDC motor whole system in Closed Loop with Proposed control strategy is shown.



Fig. 24 SEPIC converter waveform of Input, Output, Capacitor Voltage



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Fig. 26 Waveform of Stator current, back EMF, Hall signal of BLDC motor

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Fig. 27 Waveform of Electromagnetic Torque , Speed, Load Torque of BLDC motor



Fig. 28 Waveform of Motor Electromagnetic Torque

In closed loop of SEPIC converter fed BLDC shows Back-Emf of magnitude of 74.21V. At no load torque, Speed of motor is 4762rpm. In BLDC motor initially there will be some torque, Speed will increase and attain steady state where electromagnetic Torque will be same as load torque under steady state.

Result analysis shows commutation torque ripple of NIBFE fed BLDC motor in Closed loop is further reduced to 42.22% than SEPIC fed BLDC motor 74.68%. By using Switching Vectors as per Proposed strategy method have reduced commutation torque ripple.



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NIBFE	Open Loop	Closed Loop		
Torque Ripple %	127.9%	42.22%		
Torque Ripple	2.15	0.76		
Thigh	2.45	1.28		
Tlow	-0.3	0.52		
SEPIC	Open Loop	Closed Loop		
Torque Ripple %	122. 22%	74.68%		
Torque Ripple	1.8	1.18		
Thigh	2	1.38		
Tlow	-0.2	0.2		

Fig. 29 Torque Ripple analysis of Open and Closed loop using NIBFE and SEPIC converter

IV. CONCLUSION

In this Project work commutation torque ripple reduction strategy is proposed. Simulation of NIBFE fed BLDC motor and SEPIC fed BLDC motor with proposed method is done. By using proper switching sequence of Switching Vectors in Commutation and Non commutation period, NIBFE fed BLDC motor and SEPIC fed BLDC motor have reduced the Commutation Torque Ripple with Proposed Control Method Strategy in Closed Loop. Advantage of NIBFE is it has less components and no inductors present can reduce system size and cost.

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