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A Comparative study of Torque Ripple Reduction in BLDC Motor using Various Converters

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Abstract : *The BLDC (Brushless DC) motor has high power efficiency, high torque to weight and inertia ratio, high dynamic response, high reliability and simple control. Due to the availability of these features the BLDC motor is used in wide range of applications like air conditioners, air coolers, freezers etc. This paper presents a comparative study of the various torque ripple techniques in Brushless DC motor using various converters. So, in order to improve the performance of these motors the ripples in the electromagnetic torque have to reduced.Various research works have been taken out to minimize the torque ripple reduction in BLDC motors. Various cases of simulation studies were carried out.*

Keywords -*Brushless direct current motor (BLDCM), dc-bus voltage control, modified single-ended primary-inductor converter, 3-level diode clamped multilevel inverter (3-level DCMLI), torque ripple.*

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I. INTRODUCTION

BRUSHLESS DIRECT CURRENT MOTOR (BLDCM) is a type of permanent magnet synchronous motors. They are driven by DC voltage, but current commutation is achieved by solid-state switches. The commutation instant is determined by the rotor position which is detected either by position sensors or by sensor less techniques. The BLDC drives are becoming more popular due to its high power efficiency, high torque to weight and inertia ratios, high power density, high dynamic response, high reliability, compact size and simple control. In such motors, winding currents are switched by power electronics, rather than by mechanical commutators. BLDCMs offer high power density, reliability and efficiency. How-ever, typical motors, driven by either rectangular or sine wave currents, exhibit torque pulsations or ripple. At high speeds, torque ripple is mostly filtered out by the rotor inertia. How-ever, at low speeds the torque ripple produces noticeable effects which create undesirable speed variations, and cause inaccuracies in motion control. In general, torque in permanent-magnet (PM) synchronous motors is developed mainly by:

1. Mutual torque
2. Cogging torque

The torque is greatly affected by the motor's structure. For example, imperfections of the motor geometry give rise to harmonics, which are multiples of six times the motor speed, in the mutual torque. Another example is the cogging torque, which can be greatly reduced by skewing the magnets relative to the stator slotting. In the past years two general approaches have been proposed in order to reduce torque ripple. One approach is to improve the motor's geo-metrical structure. The second approach is to control the winding currents, in order to overcome the disturbances.

Typically a BLDC motor is an electronically commutated motor. It has three phase distributed winding on the stator, which is made up of stacked steel lamination and permanent magnet on rotor. Depending upon the application requirements the permanent magnets on rotor is either in surface mounted type or buried type. As the name indicates it has no brushes for commutation. The BLDC motor is powered with the help of VSI or CSI. Based on rotor position obtained by rotor position sensors like hall sensors, resolvers or optical encoders, the power electronic switches are commutated. The shape of the generated back EMF in these motors is depends on stator construction. In BLDC motors, the generated back EMF is in trapezoidal shape and in PMSM the generated back EMF is in sinusoidal wave shape. Depending upon the rotor position, the stator windings are energized by rectangular current waveforms which are displaced with 120 degree.

Due to enormous applications of BLDC motors in industries as well as household applications, the performance of these motors are considered to be quite significant. Normally the generated back EMF waveform is not ideal in these motors because of its manufacturing limitation and design consideration of magnetic materials. The back EMF waveform is departed from its original shape. As said earlier, the BLDC motor is an electronically commutated motor, due to commutation of power electronic switches the generated electromagnetic torque containing ripple in its waveform. This torque ripple produces noise which degrades the performance of the motor and complicates the speed-control characteristics especially at low speed. So commutation torque ripple produced by diode freewheeling in an inactive phase are the research hotspot in recent years.

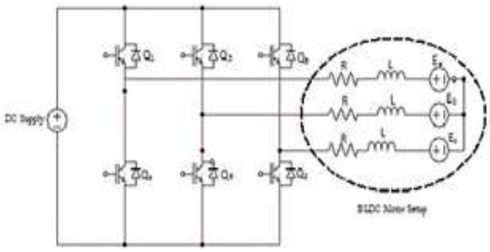

Fig.1. Circuit diagram of BLDC Motor

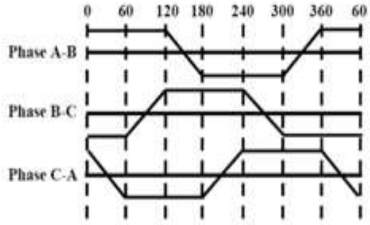

Fig.2. Trapezoidal Back EMF

Li et al. have presented a method for position sensor less control of high-speed BLDC motors with low inductance and non-ideal back electromotive force (EMF) in order to improve the reliability of the motor system of a magnetically suspended control moment gyro (MSCMG) for space application.

Calson et al. analyzed that the ripple in the generated torque due to phase commutation is related to the energizing phase current and varies with speed. To minimize the torque ripple in BLDC motor two levels of the control scheme is proposed for stator current. The first method employs the position sensor to determine the phase sequence of the rectangular current signals and the moment of current commutation from one phase to another phase and the other method controls the energizing current amplitude by PWM switching of the inverter

Zhang et al. analyze commutation torque ripple and proposed that the ripple in the electromagnetic torque is minimized by regulating the DC link voltage with the help of buck converter as front end converter of the VSI. With the help of buck converter, the supply voltage is step down and fed to the VSI which results in minimum amount of ripple in the load torque. PWM_ON switching pattern is a better choice for commutation of VSI. The proposed method effectively reduced the torque spikes and dips, but it doesn't consider the bandwidth of the buck converter, so it is suitable at the low speed range only.

Another major reason for torque ripple in BLDC motor is due to diode freewheeling current in inactive phase. This was analyzed with different modulation techniques for commutation torque ripple and while considering the power dissipation PWM_ON_PWM is the better modulation method. Fang et al. proposed novel automatic current control method for torque ripple minimization in gyro/BLDC motor drive. The non-linearity in the back EMF was considered as a control function for current control and PWM_ON_PWM modulation method is used for commutation which minimizes the torque ripple due to the diode freewheeling in inactive phase.

Now-a-days several artificial intelligence based control algorithms are proposed to minimize the torque ripple with non-linearity in the back EMF waveform. In harmonic injection method the ripple in the generated electromagnetic torque due to back EMF harmonics are eliminated. But this method ignores the higher order Fourier series terms used for harmonics calculations because of its complexity and time-consuming calculations also it is more complicated for real time implementation due to its harmonics calculation.

Torque control in multiphase BLDC motor can be achieved with the help of inequality constraints via Kuhn-Tucker theorem which leads to copper loss and torque ripple reductions. But the inequality constraints require feedback sensors like high resolution encoders and torque transducer which increase the overall cost of the system. In direct torque and indirect flux control method, the flux and torque estimations are carried out with the help of Clarke and Park transformations. But these transformations are more time consuming because of the difficulty in accuracy of the parameter estimations.

II. Torque Ripple Reduction Technique In Bldcm Drive Motors

Normally the BLDC motor is powered by either VSI or CSI. The two level inverter produces square wave output with harmonic distortions in its waveform, which results in total harmonic distortions (THD) in the output. Due to these effects the ripples are created in the output electromagnetic torque and distortion in the trapezoidal back EMF waveform. Conventionally controlled rectifier with large value of inductor in series act as a current source which increase the overall cost of the system as well as the system looks so bulky.

When the level of the output voltage is increased, the harmonic content gets reduced. The waveform is in staircase shape. The distortions in the stator current as well as the electromagnetic torque get reduced with high levels. These causes the generated electromagnetic torque contains minimum ripple in its waveform. Also the two level inverter is not suitable for high power applications but the multilevel inverter is suitable for high power applications by increasing the level of the output voltage.

2.1 Two Level Multi-Level Inverter

A comparative analysis between two level inverter and multilevel inverter with different modulation techniques are carried out and the results are depicted as graphical view in Figure 3(a)-3(d). From the graphical representation, it was clear that the multilevel inverter is the best choice for motors. The performance and efficiency of the motor is increased with the help of increasing the output levels of the inverter. Even though increasing the number of levels results in more number of switches and the control will be more complicated, which is often a limitation for the use of the multilevel inverter, better quality of load torque is considered to be the outcome of the MLI fed BLDC motor.

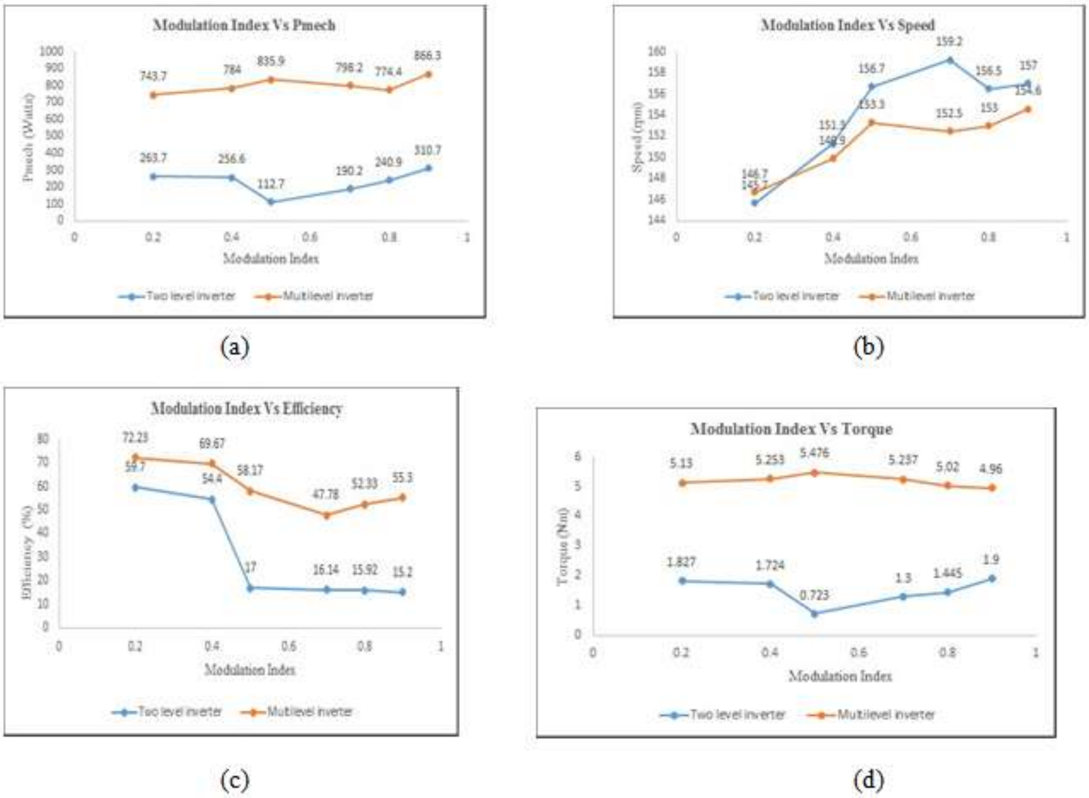

Figure 3. Comparative analysis of (a) P_{mech} , (b) efficiency, (c) Speed and (d) torque of the two level and multilevel inverter

2.2. Diode Clamped Multilevel Inverter

The single phase five level diode clamped multilevel inverter is shown in Figure 4. The voltage stress on the power device is limited with the help of the diodes is the major concept of these inverters. The three phase inverter output voltage shares common DC bus voltage and it is divided for five level with the help of the capacitors. The voltage across each capacitor and switches is Vdc which is same as the supply voltage. So there is no possible for high voltage stress across devices. Each leg as consist of switches, clamping diodes, freewheeling diodes and also capacitors. It is also named as neutral clamped inverter. The major drawback of these inverter is DC link voltage unbalancing. The components required for n-level inverter is:

a) Voltage sources: (n-1)
b) Switching devices: 2(n-1)
c) Diodes: (n-1)*(n-2)

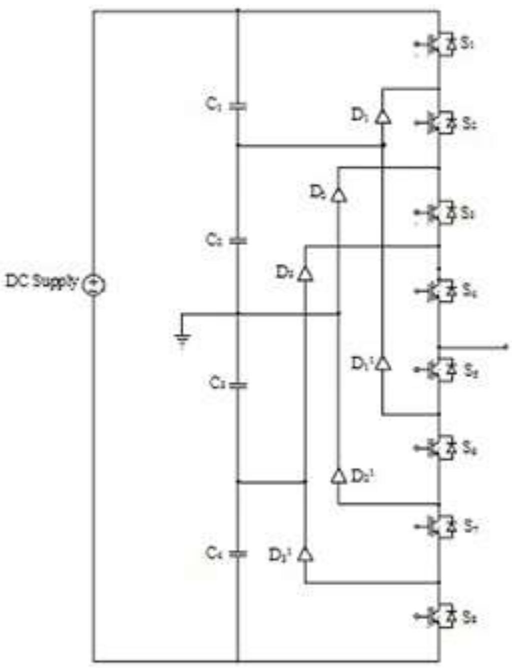

Fig.4: Diode Clamped Multilevel Inverter

The switching pattern for five level diode clamped multilevel inverter is shown in Table 1.

Table 1. Switching States for 5-level DCMLI Voltage Switching States

Sl.No	Voltage	Switching States							
		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	Vdc/2	1	1	1	1	0	0	0	0
2	Vdc/4	0	1	1	1	1	0	0	0
3	0	0	0	1	1	1	1	0	0
4	-Vdc/4	0	0	0	1	1	1	1	0
5	- Vdc/2	0	0	0	0	1	1	1	1

In the look up table '1' represents that the corresponding switch is in ON position and '0' represents that the switch is in OFF condition. At an instant four switches are in ON position. The upper arm switches are commutated at maximum positive voltage and the lower arm switches are commutated at negative maximum value. At fundamental frequencies, it is more efficiency.

2.3 Flying Capacitor Multilevel Inverter

The circuit configuration of this inverter is similar to the neutral point clamped converter but it requires high numbers of auxiliary capacitors which is shown in Figure 5. It doesn't require any clamping diodes. As the name indicates, the common DC bus voltage is divided into five level with the help of flying capacitors. The main advantages of this converter is it doesn't require any filters for high level and active and reactive power flow is possible in both directions. But the control of the system is complicated when the output level is increased. The components required for n-level inverter is:

a) Main capacitors : (n-1)

b) Auxiliary capacitor : (n-1)*(n-2)/2

The look up table for these inverters are similar to that of neutral point clamped multilevel inverter. The only difference is absence of the clamping diodes.

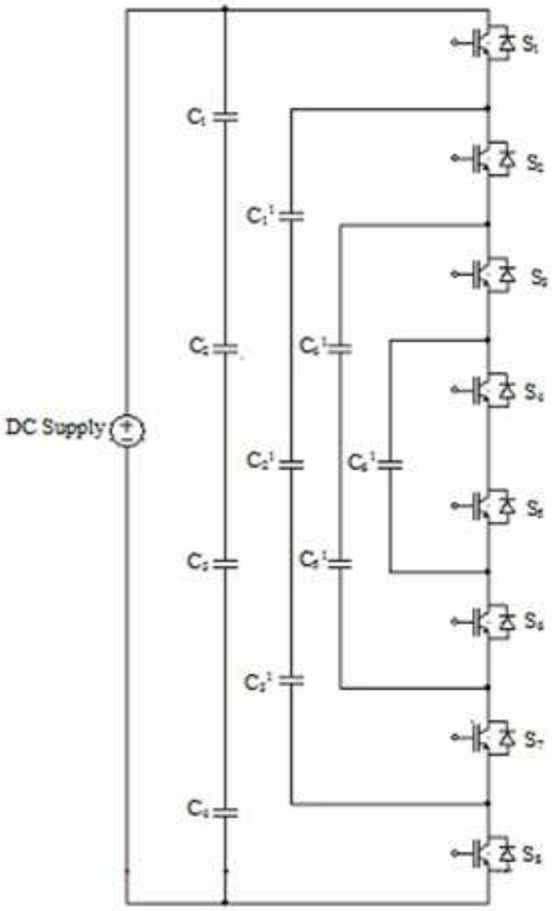

Figure 5. Flying Capacitor Multilevel Inverter

2.4 Cascaded H-Bridge Multilevel Inverter

The cascaded H-bridge multilevel inverters are built with series connection of H-bridge inverter with separate DC sources. As the name indicates H-bridge inverters are cascaded with each other to produce staircase waveform. When the level gets increased the number of inverters cascaded is also increased. It doesn't needs any clamping diodes and flying capacitors. For three phase configuration, the cascaded converters can be linked either in star connection or delta connection. Compare to other topologies, it uses less components which results in minimum amount of switching losses. The control of these inverter is also simple. But it requires isolated DC sources for the power conversion, which limits its use. For n-level inverter the number of switching device required is 2(n-1) per leg [30]. The circuit configuration of single phase five level inverter and its output voltage waveform is shown in Figure 6 and Figure 7 respectively. The switching states for five level inverter is shown in Table 2.

Table 2. Switching States for 5-level CHBMLI

Switches Turn ON	Voltage Level
S_1, S_2	$+V_{dc}$
S_1, S_2, S_5, S_6	$+2V_{dc}$
S_4, D_2, S_8, D_6	0
S_3, S_4	$-V_{dc}$
S_3,S_4,S_7,S_8	$-2V_{dc}$

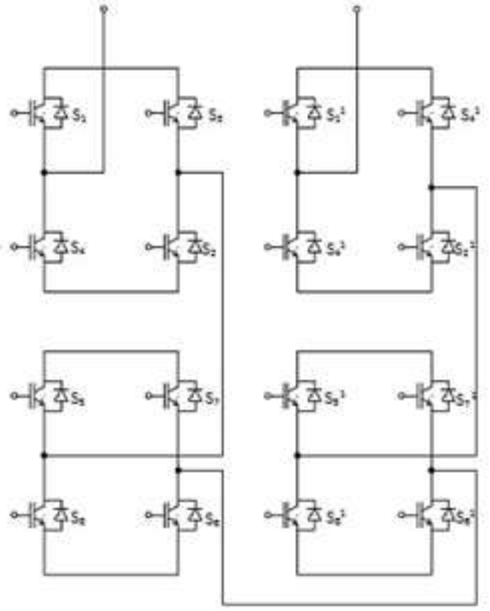

Figure 6. Cascaded H-bridge Multilevel Inverter

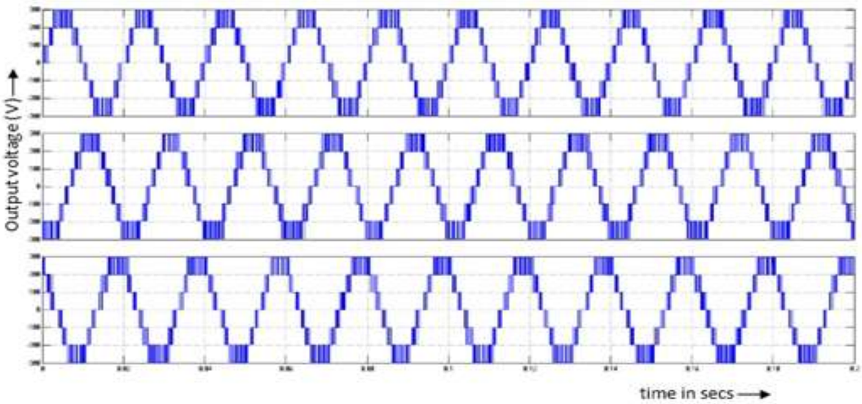

Figure 7. Five level output voltage waveform

In the look up table, diode freewheeling occurs at the zero voltage level. At Vdc only two switches are in conducting mode. When the level gets increased, the number of switches conducted is also increased. Two switches from upper cell and the two switches from lower cell are conducted. When the BLDC motor is powered with two level inverter, the generated torque contains significant amount of ripple which is shown in Figure 8.

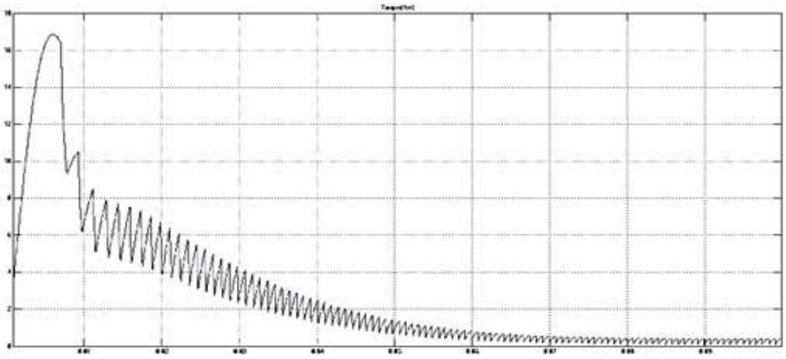

Figure 8 Electromagnetic Torque Waveform (Two level Inverter)

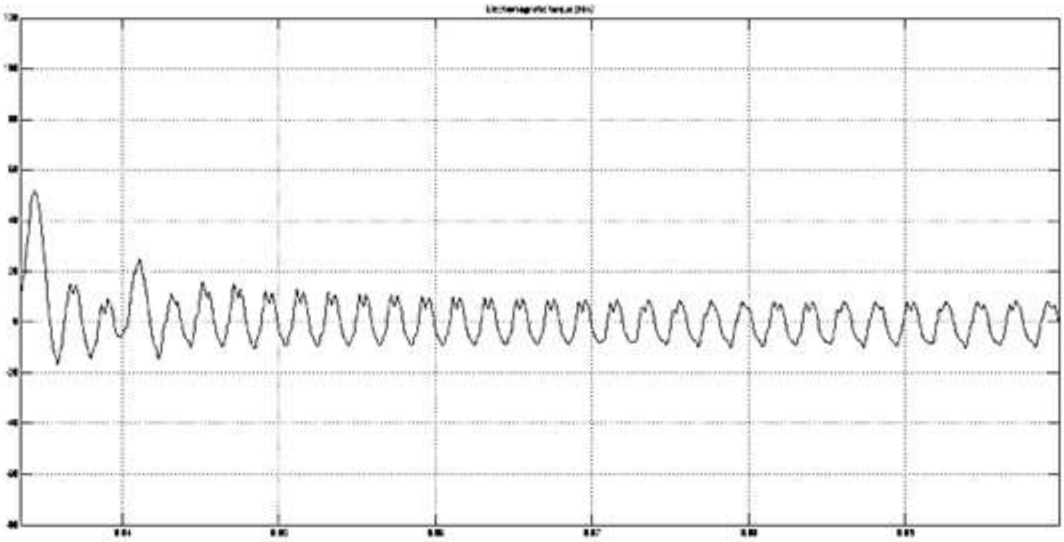

Figure.9 Electromagnetic Torque Waveform (Multilevel Inverter)

When the BLDC motor is powered with multilevel inverter, the generated electromagnetic torque contains minimum amount of ripple in its waveform.

Among these three topologies single source, multi DC link cascaded H-bridge multilevel inverter is the best choice for torque ripple minimization in the BLDC motor drive.

III. Conclusion

An exhaustive overview of torque ripple minimization techniques with different multilevel inverter topologies and power quality improvement in the brushless dc motors (BLDC) has been presented in this paper. Among different torque minimization techniques, the cascaded H-bridge multilevel inverter gives better performance in the efficiency as well as smoother distortion less stator current. The harmonics in the stator current are effectively reduced which minimize the THD.

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