A Review Paper on Torque Ripple Reduction and Power Quality Improvement in Brushless DC Motor Drives

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Abstract — In recent years brushless DC motors (BLDC) are the research hotspot in speed precision and household applications due to its high reliability, simple frame, high efficiency, fast dynamic response, compact size, low maintenance, etc., It is an electronically commutated motor. The operation of these motors is based on the rotor position sensing using sensors or sensor less scheme. Because of this commutation, the ripples are generated in the electromagnetic torque and the power factor of the AC mains gets affected due to its operation. So, in order to improve the performance of these motors the ripple in the electromagnetic torque could be reduced and the power factor of the AC mains should be increased. This paper presents the review of different torque ripple reduction techniques used for reducing the ripple in the electromagnetic torque and different converter topologies used for improving the power factor of the AC mains near to the unity.

Index Terms — Brushless direct current motor (BLDC), multilevel inverter (MLI), back EMF, power factor corrected (PFC), power quality, discontinuous inductor current mode (DICM), bridge less (BL).

I. INTRODUCTION

Household appliances like washing machines, room air conditioners, refrigerators, fans, water pumps, vacuum cleaner and freezer are to be expected one of the fastest growing end products in the market over the next few years [1-4]. Conventionally DC motors are widely used in these appliances and due to some drawbacks like frequent maintenance and sparking in brushes, consumers are switching over to single phase induction motors including split phase, capacitor-start, capacitor-run type motors and universal motors. These motors operate at constant speed directly from AC mains with low efficiency. Now-a-days acoustic consumer demand for high efficiency, low cost, low noise and better performance motors for these appliances. The conventional technologies doesn’t meet these demands. The use of special electrical machines like brushless DC motors (BLDC), permanent magnet synchronous motors (PMSM) in these appliances are a better choice due to the features of high reliability, high efficiency, low maintenance, high flux density per unit volume, high power density due to absence of field winding and low electromagnetic interference problem [5-6]. By comparing with PMSM, the speed adjusting performance of BLDC motor is high and also power density. So BLDC motor is preferable in many appliances. The other applications of BLDC motors are robotics, medical equipment, precise motion control systems, industrial tools, heating and ventilation systems.

A BLDC motor has three phase distributed winding on the stator, which is made up of stacked steel lamination. Based on the construction of stator, the generated back EMF is in trapezoidal waveform. For PMSM the generated back EMF is in sinusoidal waveform. The rotor of the BLDC motor is made up of permanent magnets. Based on the application requirement, the configuration of permanent magnet placed in the rotor is varied. The magnets are placed either in surface mounted magnet type or buried magnet type. The BLDC motor is powered by VSI or CSI, which is controlled by rotor position. The rotor position can be sensed by using sensors like hall sensors, resolvers, optical encoders or sensor less scheme. As the name indicates, there are no brushes in the BLDC motor. It is an electronically commutated motor, based on rotor position, three square wave signal with 1200 phase shift has been generated to provide firing signals to commutate the power electronic switches in the inverter [7].
II. Torque Ripple Reduction Techniques

Owing to different applications of BLDC motors in industries as well as household applications, the performance of these motors is considered to be quite important. Due to manufacturing limitation and design consideration of magnetic materials, the generated back-electromotive force (EMF) waveform departed from its original shape. Also due to commutation of power electronic switches and PWM switching that causes generated electromagnetic torque containing ripple in its waveform [8]. These torque ripple produces noise which degrades the performance of the motor and affect the speed-control characteristics especially at low speed. So commutation torque ripple, torque ripple produced by diode freewheeling in an inactive phase are the research hotspot in recent years [9].

Conventional control techniques injecting the similar rectangular phase current command to the stator without the knowledge of non-linearity in the back EMF waveform which causes more amount of ripple in the generated electromagnetic torque. Calson et al. analyze the torque ripple in the BLDC motor due to phase commutation and proposed that the ripple in the electromagnetic torque is related to the relative current and varies with speed. Two levels of the current control scheme is proposed to minimize the torque ripple in BLDC motor. The first method utilizes the position sensor to determine the phase sequence and the moment of current commutation from one phase to another phase and the other method controls the current amplitude by PWM switching [10].

Chuang et al. analyze the different PWM techniques used for commutation torque ripple reduction in BLDC motor drive with ideal back EMF waveform and proposed that PWM_ON method is the best choice for BLDC motors. But the non-linearity in the back EMF was not considered in this method [11].

Zhang et al. adding the buck converter in front of the VSI and regulating the DC link voltage by step down the supply voltage to reduce the commutation torque ripple. PWM_ON switching pattern is used for commutation of VSI. The proposed method effectively reduced the torque spikes and dips, but it doesn’t considered the bandwidth of the buck converter, so it is suitable at the low speed range only [12].

Chen et al. proposed Superlift luo converter topology for DC link voltage regulation, but this topology is more complex compared to buck converter and give better performance under high-speed operation only. The buck converter is replaced with SEPIC converter which needs three additional switches and their corresponding inductance, capacitance and diodes [13].

The torque ripple due to diode freewheeling current in inactive phase was analyzed with different modulation techniques and while considering the power dissipation PWM_ON_PWM is the better modulation method [14-15].

To reduce the torque ripple with non-linearity in the back EMF there are mainly two kinds of resolvers. One is to employ the direct torque control to regulate the armature current [16-19] and the other one is to apply the motor’s back EMF as a function to regulate the current. In direct torque control, the measurement of back EMF and phase current increase the complexity of the circuit [20-23].

Fang et al. analyze the torque ripple in gyro/BLDC motor with novel automatic current control method. The non-linearity in the back EMF was considered and PWM_ON_PWM modulation method is used which reduces the torque ripple due to the diode freewheeling current in inactive phase [24].

In recent years, several control algorithms are proposed to minimize the torque ripple with non-ideal back EMF method. Some of them are harmonic injection method which reduce the torque ripple due to back EMF harmonics. But this method ignores the higher order fouries series terms because of complexity and time-consuming calculations also it is more complicated for practical implementation due to real time harmonics calculation [25-26].

Torque control of the multiphase BLDC motor was analyzed with inequality constraints via Kuhn-Tucker theorem which leads to copper loss and torque ripple reductions. But it requires feedback sensors like high resolution encoders and torque transducer which increase the overall cost of the system [27].

In direct torque and indirect flux control method, Clarke and Park transformations are used for flux and torque estimation. But the accuracy of the parameter estimation was affected in these transformations which leads to more time consuming [28-29].

Shakouhi et al. proposed phase to phase back EMF estimation method for commutation torque ripple. But in these method commutation torque ripple was achieved by energizing all phases at a specific time before the end of each conduction interval. Energizing all phases for particular instant is quite complicated [30]. Modifying the inverter topology is the one way to reduce the commutation torque ripple. The voltage source inverter (VSI) is replaced with current source inverter (CSI) and the circuit was analyzed with different speed conditions. Conventionally controlled rectifier with large value of inductor act as a current source which increase the overall cost of the system. Then controlled rectifier with large inductor is replaced with a buck converter switching at high frequencies. The additional converters increase the complexity of the circuit.

III. Multilevel Inverter Topology

The practical BLDC motor setup and trapezoidal back EMF waveforms are shown in Fig. 1 and Fig. 2. The square wave output of the VSI is fed to the stator winding of the motor. Based upon the rotor position the power electronic switches in the inverter are commutated. Normally the harmonic content is high in the square wave output of the power electronic switches in the inverter are commutated.
VSI, which increase the THD of the output. Due to these effects the ripples are created in the output electromagnetic torque and distortion in the trapezoidal back EMF waveform.

When the level of the output waveform is increased the harmonic content is automatically gets reduced. So the ripples created in the output torque are reduced. Also two level inverter doesn’t suitable for high power rating applications. Multilevel inverter is the alternative best choice for these applications because the output waveform of these inverters is staircase form which looks like a sinusoidal waveform. When the level gets increased the THD value gets reduced. It is obvious that an output with voltage with low THD is desirable.

A comparative analysis between the two level inverter and multilevel inverter with different modulation index condition were tabulated in table 1. From the graphical representation it was clearly depicted that multilevel inverter is the best choice for motors as compared to two level inverter. When the output voltage level gets increased, harmonics content will automatically get reduced. Although increasing the number of levels needs more hardware and the control will be more complicated, which is often a limitation for the use of the multi-level inverter, better quality of load torque is considered to be the outcome of the MLI fed BLDC motor. Compared to two level inverter fed motor drives, the multilevel inverter fed motor drives offers less noise and current distortions.
A. Diode Clamped Multilevel Inverter

The voltage stress in the power devices is limited by using diodes is the major concept of this inverter[41]. The voltage over each capacitor and each switch are \( V_{dc} \). The components required for \( n \)-level inverter is \( (n-1) \) voltage sources, \( 2(n-1) \) switching devices and \( (n-1)*(n-2) \) diodes. It is also known as neutral clamped inverted. DC link voltage unbalancing problems occur in this inverter. The circuit configuration for 5-level inverter is shown in Fig 5. It is a single leg. For three phase output, three legs are serially connected.

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**Table 1**

Comparative Analysis of Two Level Inverter and Multilevel Inverter Fed Induction Motor under Different Modulation Index Condition

<table>
<thead>
<tr>
<th>S.No</th>
<th>M.I</th>
<th>( P_{mech} ) (W)</th>
<th>PF</th>
<th>Efficiency (%)</th>
<th>Speed (rpm)</th>
<th>Torque (Nm)</th>
<th>( P_{mech} ) (W)</th>
<th>PF</th>
<th>Efficiency (%)</th>
<th>Speed (rpm)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.2</td>
<td>263.7</td>
<td>0.6</td>
<td>59.7</td>
<td>145.7</td>
<td>1.827</td>
<td>743.7</td>
<td>0.835</td>
<td>72.23</td>
<td>146.7</td>
<td>5.13</td>
</tr>
<tr>
<td>2.</td>
<td>0.4</td>
<td>256.6</td>
<td>0.59</td>
<td>54.4</td>
<td>151.3</td>
<td>1.724</td>
<td>784</td>
<td>0.83</td>
<td>69.67</td>
<td>149.9</td>
<td>5.253</td>
</tr>
<tr>
<td>3.</td>
<td>0.5</td>
<td>112.7</td>
<td>0.165</td>
<td>17</td>
<td>156.7</td>
<td>0.723</td>
<td>835.9</td>
<td>0.697</td>
<td>58.17</td>
<td>153.3</td>
<td>5.476</td>
</tr>
<tr>
<td>4.</td>
<td>0.7</td>
<td>190.2</td>
<td>0.159</td>
<td>16.14</td>
<td>159.2</td>
<td>1.3</td>
<td>798.2</td>
<td>0.684</td>
<td>47.78</td>
<td>152.5</td>
<td>5.237</td>
</tr>
<tr>
<td>5.</td>
<td>0.8</td>
<td>240.9</td>
<td>0.146</td>
<td>15.92</td>
<td>156.5</td>
<td>1.445</td>
<td>774.4</td>
<td>0.667</td>
<td>52.33</td>
<td>153</td>
<td>5.02</td>
</tr>
<tr>
<td>6.</td>
<td>0.9</td>
<td>310.7</td>
<td>0.137</td>
<td>15.2</td>
<td>157</td>
<td>1.9</td>
<td>866.3</td>
<td>0.63</td>
<td>55.3</td>
<td>154.6</td>
<td>4.96</td>
</tr>
</tbody>
</table>

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B. 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. For n-level inverter it requires (n-1) main capacitors and (n-1)*(n-2)/2 auxiliary capacitor. The main advantages of this converter is it doesn’t require filters for high level and active and reactive power flow is possible. But the control of the system is complicated when the output level is increased. The circuit diagram for single leg is shown in Fig 6.

C. Cascaded Multilevel Inverter

The series connection of H-bridge inverter with separate DC sources is termed as cascaded H-bridge multilevel inverter. It doesn’t requires any clamping diodes and flying capacitors. For three phase configuration, the cascaded converters can be connected either in star connection or delta connection. Compare to other topologies, it uses fewer components. The control is also simple. But it needs separate 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. The circuit configuration of single phase five level inverter and its output voltage waveform is shown in Fig. 7 and Fig. 8 respectively. Each cell contains isolated DC source.
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.

IV. POWER QUALITY ISSUES

The power quality has become the most important factor to be considered at the point of BLDC motors. The international standards such as International Electrotechnical Commission (IEC) 61000-3-2, recommended such that the harmonics in the supply current should be within the limit. For class-A equipment (< 600 W, 16 A per phase) which includes household appliances, the IEC 61000-3-2 restricts that the THD of the supply current should be below 19% [31]. Conventionally diode bridge rectifier (DBR) is used as a front-end rectifier in VSI fed BLDC motors with high value of DC link capacitors. This circuit result in highly distorted supply current with THD of 65% and a poor power factor of 0.8 which is not accepted by International Power Quality (PQ) standards such as IEC-61000-3-2 [32]. Hence a power factor corrected (PFC) frontend rectifiers are required to improve the power factor in order to improve the power quality (PQ) at the AC mains.

Two stage PFC converters are in normal practice in which one PFC converter improves the power quality (PQ) at AC mains which is typically a boost converter and another one is for voltage control, which depends upon the choice of application. Due to more number of components in the above circuit losses gets increased. A single stage PFC converters has gained much more attention because the PFC operation and the DC-link voltage control can be achieved in a single stage. Also it is more efficient compared to two stage converters [32-33].

The another critical issue in the BLDC motor is the choice of mode of operation of a PFC converters, because it directly affects the cost of the components used in the PFC converters as well as ratings. The PFC converters are designed to operate in two basic mode of operation either in continuous conduction mode (CCM) or discontinuous conduction mode (DCM) [34-35]. As the name indicates, the voltage across the intermediate capacitor and current in the inductor remains constant. But it requires two voltage sensors (dc link voltage and supply voltage) and one current sensor (Supply current) for PFC operation. But in DCM operation single voltage sensor is enough for dc link voltage control to achieve better PFC is achieved at AC mains [35]. But in DCM operation the stresses across the switch of PFC converters are high compared to CCM operation. So it is not preferable for higher power rating applications. Hence the choice of the mode of operation trade-off between the stresses and allowable power rating.

V. PFC CONVERTERS

In the conventional PFC scheme the speed control can be achieved by pulselength-modulated voltage source inverter (PWM-VSI) with constant dc link voltage. This results higher switching losses in the VSI which is the square function of switching frequency. The speed of the BLDC motor is directly proportional to the DC link voltage. So the speed control can be achieved by a variable DC link voltage of VSI with fundamental frequency switching (electronic commutation). This offers minimum switching losses.

Singh and Singh [36] have proposed the concept of buck-boost converter fed BLDC motor with constant DC link voltage and PWM-VSI for speed control, which offers high switching losses. The buck-boost converter is replaced with single-ended primary-inductance converter (SEPIC)
based VSI fed BLDC motor drive has been proposed by Gopalarathnam and Taliyat. Due to higher number of current and voltage sensors restricts its applicability to low power applications [37].

The switching losses across the switches due to fundamental frequency switching of VSI for electronic commutation of BLDC motor can be minimized by Cuk converter fed BLDC motor drive with a variable DC link voltage has been proposed by Singh and Singh [32]. But it needs three voltage control sensors for PFC operation which is not cost effective and suitable for high power applications only.

For further improvement in the efficiency and performance of the BLDC motor the front-end DBR is replaced with bridgeless (BL) topologies. The BL topology offers less conduction losses across the switches. Jang and Jovanovic [38] and Huber et al. [39] have proposed the BL buck and boost converter for PFC operation. But it limits the operating range of the dc link voltage control due to separate buck and boost operation of the converter. Also high starting inrush current is major drawback of these converters.

Abbas A. Fordoun et al. analyze the Cuk derived converters from PFC operation in BLDC motors. The Cuk converter has inherent advantages like natural protection against inrush current and overload current, lower ripple content in the current and low electromagnetic interference (EMI). The equivalent circuit of Cuk derived converters is shown in Fig.9 (a)-(c).

Thus the Cuk derived converters do not suffer from common-mode EMI noise emission problem compared to conventional Cuk converter topology. Also “near-zero-current-ripple” condition at the input and output port of the converter can be achieved without compromising the performance. But the component count gets increased in the Cuk derived converters which increase the switching losses in the converter [40].

Among the different BL converter topologies, the bridgeless buck-boost rectifier has less component count. To achieve inherent power factor correction at AC mains, the rectifier is operated in a discontinuous inductor current mode (DICM). This rectifier offers low switching losses in VSI, because the VSI operates in low frequency for electronic commutation in BLDC motor [41]. The equivalent circuit for the BL buck-boost converter is shown in Fig. 10. The comparative analysis between the different PFC converter topologies is tabulated in table 2.

Hence the BL buck-boost PFC converter is a best choice for improving the power factor at the AC mains in order to obtain the best power quality. Compared to other BL topologies the buck-boost converter have a minimum number of components. So the losses associated with the switches and stress on switches gets reduced.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>No. of Devices</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL-BUCK</td>
<td>2 4 2 2 10</td>
<td>NO</td>
</tr>
<tr>
<td>BL-BOOST</td>
<td>2 2 1 1 6</td>
<td>NO</td>
</tr>
<tr>
<td>BL-CUK T-1</td>
<td>2 3 3 3 11</td>
<td>YES</td>
</tr>
<tr>
<td>BL-CUK T-2</td>
<td>2 2 3 4 11</td>
<td>YES</td>
</tr>
<tr>
<td>BL-CUK T-3</td>
<td>2 4 3 4 13</td>
<td>YES</td>
</tr>
<tr>
<td>BL-BUCK-BOOST</td>
<td>2 4 2 1 9</td>
<td>YES</td>
</tr>
</tbody>
</table>
An exhaustive overview of torque ripple minimization 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. Also different PFC converters are analyzed for power quality improvement at AC mains. From this analysis the BL buck-boost converter provides reduced switching losses and stresses across the switches. The BLDC motor has inherent household applications and the performance of these motors have been improved by BL buck boost converter as front-end rectifier and cascaded H-bridge multilevel inverter fed BLDC motor drive.

VI. CONCLUSION

REFERENCES


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[31] Limits for Harmonic Current Emissions (Equipment Input Current ≤16 A Per Phase), Int. Std. IEC 61000-3-2, 2000.


