Simulation of Hybrid Switching Technique for driving High-Speed BLDC Motor

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Abstract – High Speed Brushless DC Motors (BLDC) with power ratings of a few tens of watts to a few kilowatts and rotational speeds in the range of 1000 to 35000 revolutions per minute are employed in blowers and compressors. The trend toward higher rotational speeds is mainly driven by the need of a higher power density in emerging applications. The main challenges in these drives are to ensure low losses and high efficiencies while operating in wide speed ranges. In this paper, a new BLDC motor drive with a hybrid switching mechanism employing pulse-width modulation (PWM) control at low-speed region and pulse-amplitude modulation (PAM) control at high-speed region is introduced with an improved voltage gain technique at the front-end side for high speed applications. The simulation results are also discussed and analyzed in order to verify the effectiveness of the proposed design.

INTRODUCTION

Recently, there has been an increasing trend in requests for Brushless DC motors for high speed applications of BLDC motors especially in compressors and blowers. But these applications demands low losses, low cost and maintenance, and compactness. The trend toward higher rotational speeds is mainly driven by the need of a higher power density in emerging applications. Thus to assure the above mentioned characteristics, an appropriate driving method need to be designed while operating for wide speed control ranges. For BLDC motor drives, the inverter can be controlled through either PWM with a fixed DC-link voltage or PAM with controlled DC-link voltage amplitude. The pulse width modulation PWM-controlled BLDC motor drive system is the most commonly applied technique for driving a motor inverter bridge. Unfortunately, the PWM techniques can induce serious current and torque ripples for the ironless stator motor. In addition, the high-frequency and large-range current ripple will inevitably increase the copper and iron losses at high speed. The comparative results using conventional PWM techniques have been fully explored here to highlight the advantages of PAM techniques at high speed operations [1].

At low speed regions, say upto 700 rpm, BLDC motors are driven with pulse-width modulation (PWM) inverters and by ideally applying sinusoidal three-phase currents. Due to the high fundamental frequency of the currents, the PWM frequency has to be increased, or an ac filter is employed in between the inverter and the motor. At speeds above 700 rpm, pulse-amplitude modulation (PAM) inverters are suggested. In those converters, the DC-DC buck-boost converter can be used to vary the dc link voltage (voltage at the inverter input) and to control the dc link current, whereas the inverter switches at the fundamental frequency of the machine, limiting the switching losses and limiting the need for a high-bandwidth current control. This paper organized as follows. The current section presents an introduction and gives the objective of the work. Section II explains the literature review on the performance comparison between PWM & PAM techniques and the need of a hybrid switching technique. Section III is focused on the circuit description and block diagram explanation of the existing and the proposed motor drive system. Section IV is based on the control theory of the PAM and PWM control modes and proposes a hysteresis comparator to switch between the two modes. The final section deals with the simulation model and results of the proposed design.

II. OPERATIONAL COMPARISON BETWEEN PWM AND PAM TECHNIQUES

In most of the BLDC drive systems, the three phase inverter is controlled by the PWM techniques by keeping the DC-link voltage constant. Furthermore, the PWM control is extensively employed in low and high power BLDC motor drives. The motor performance is these drives are decided by the commutation control techniques. Commutation control of inverter provides smooth rotation of the stator magnetic field. The interaction between stator magnetic field and the permanent magnet gives the torque.

The typical PWM control contains six different PWM techniques namely, H-PWM_L_ON, H_ON_L_PWM, PWM_ON, H_PWM_L_PWM, and PWM_ON_PWM respectively [2]. For instance, when H_PWM_L_ON is employed, the high-side power device is controlled by the PWM chopper signal every consecutive 120° in a fundamental period. Meanwhile, the low side of the same leg control signal is shifted by 180° without the PWM chopper signal, as compared to its high-side one, to clamp the related inverter output to the negative dc-link rail. The control signals for the other two legs are shifted by 120°and 240°, respectively.

But ineffectively, these PWM techniques have many drawbacks while operating at high-speed regions. It includes:

a) High frequency harmonic waves with the frequency of $(k\omega_s \pm n\omega_s)$ are introduced because of the PWM control; these harmonics will increase both the copper loss.
b) PWM control decreases the motor power factor (large lag angle (δ); when the active power is constant, the small power factor will increase the reactive power, apparent power, and motor loss.
c) The large lag angle (δ) will result in a large commutation delay it has a significant influence on the phase current and drive performance at high speed.

In order to counteract these effects, another popular control method for the BLDC motor is the PAM control. For PAM control, 120°commutation control, i.e., the so-called six-step mode is generally used and the dc-link voltage can be adjusted according to the error between the speed and its reference. The variable dc voltage can be adjusted by a DC-DC converter, and the inverter legs participate only in commutation instead of involved in modulation.

The PAM control is superior to the PWM control for providing good performance at high speed. Under PAM control, following are the merits:

a) Power factor is far higher.
b) Less harmonic content.
c) Less torque ripples.
d) Higher efficiency.
e) Low motor losses.

Although the PAM control for the BLDC motor is predominant to the PWM control as discussed above, still the PAM control is not employed in the whole speed range for the following two reasons:

a) Wide-ranging dc-link voltage fluctuation can limit its application at low and medium speed.
b) At low speed, it is unable to produce a small enough dc voltage to achieve the PAM control due to the small phase-winding resistance and phase-winding inductance.

Combining the merits and demerits of both PAM and PWM control, it is being inferred that both the methods are imperative for driving a high-speed BLDC motor [3]. PAM control is the main drive method, since the high speed region is the most common working range. Thus the aim of the PWM control is merely to guarantee that the high-speed motor can be accelerated to a high speed. It is just an auxiliary drive method. The operation time of the PWM control is far shorter than that of the PAM control, thus mitigating the disadvantage of the PWM control. The transition process between PWM and PAM can be achieved by a hysteresis comparator [4].

III. PROPOSED MOTOR DRIVE SYSTEM

The conventional BLDC drive circuit structure - block diagram and topology are shown in Fig.1 and Fig.2. It consists of a single phase AC supply source, a single-phase uncontrolled rectifier along with an output filter, a DC link and a three-phase inverter on the motor supply side. Existing motor drive system works in PWM control mode for both low and high speeds. Thus the actual speed is sensed and it is compared with the reference speed. The error in speed is processed through a PI (Proportional Integral) controller. PI controller along with the saturation block limits the error within the prescribed limits. It is then compared with a carrier wave of suitable high switching frequency to generate PWM gate pulses for the inverter switches. Thus, by varying the inverter switches duty cycle, the PWM controlled BLDC motor drive can be implemented.

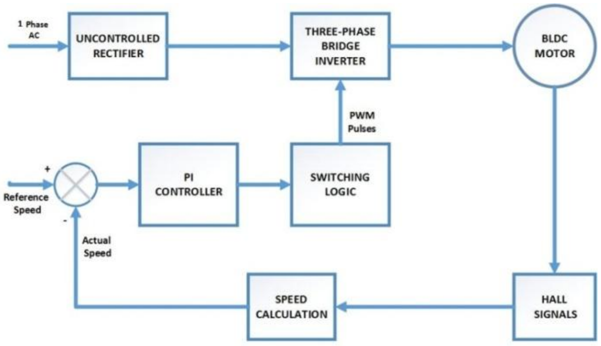

Fig.1: Conventional BLDC drive structure

But the problem with such a drive circuit structure is that, the output voltage obtained from the single-phase uncontrolled rectifier, is more than 30 V. Though the three-phase inverter is controlled by the PWM scheme for reducing the voltage, the start-up current is still far larger than the rated current. Moreover, the inverter cannot work anymore, as the protection circuit blocks the inverter due to the large current. So this common circuit structure is not employed.

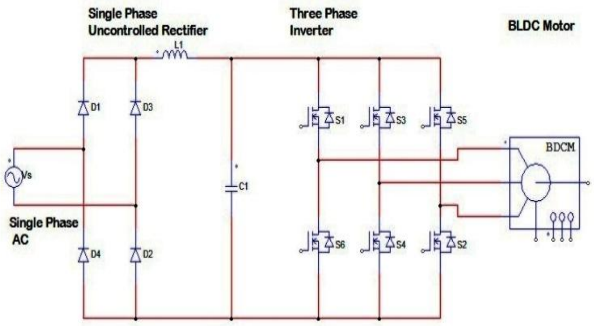

Fig.2: Topology of existing motor drive system

Also PWM controlled BLDC motor drives suffers from various drawbacks as discussed earlier. Due to the PWM period interruption caused by the commutation and limitation of the resolution of PWM generator, more torque ripple can be produced in the performance of PWM-controlled BLDC motor drives. This phenomenon will become more serious when the motors work at high speed. Moreover, it will lead to high motor loss. In order to satisfy the commutation control of high-speed BLDC motor in a widespread range and improve the motor efficiency, a hybrid drive method combining PWM and PAM is proposed. When the motor runs at low speed, the PWM control is adopted with a fixed dc-link voltage. When the motor speed reaches a threshold value (the enough back-EMF can counteract the dc-link voltage); the PAM control works with an adjustable dc-link voltage. Fig.3 shows block diagram of proposed motor drive system. When the motor starts, the initial DC voltage of the three-phase inverter should be smaller enough to limit the startup current, as the back-EMF is too small to counteract a large dc voltage at the very low speed. Therefore, a suitable drive circuit should be first selected to reduce the initial dc voltage and guarantee the safe motor starting process. In the proposed motor drive system, actual speed, N is sensed and it is compared with a reference value given by Nref. The actual speed is also given as input to the hysteresis comparator; which selects the switching control mode (PAM or PAM). The error in speed is processed through a PI (Proportional Integral) controller. The PI controller is used to get good steady-state accuracy and to attenuate noise. The selected switching control mode is given to the corresponding switching logic. For PWM control mode (if speed is below 700 rpm), the switching logic is selected for varying the duty cycle of PWM gate pulses for inverter switches. For PAM control mode (if speed is above 700 rpm), the switching logic is selected for varying the duty cycle of PWM gate pulses for DC-DC converter switch. Thus, by controlling the converter's duty cycle, the inverter's dc input voltage can be varied, allowing more flexible inverter operation at different power levels.

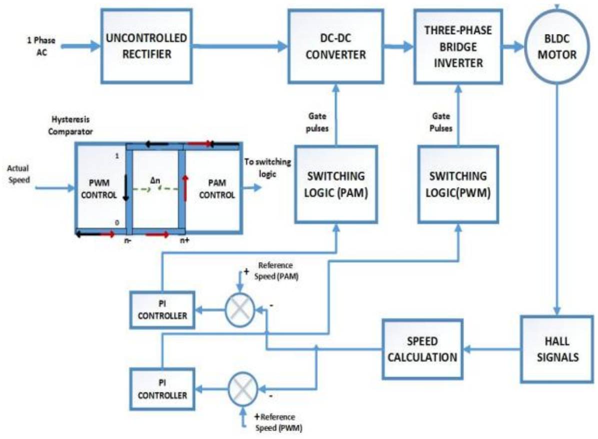

Fig.3: Proposed BLDC drive structure

From a single-phase uncontrolled rectifier and an output filter, the single phase AC is converted to an appropriate level of DC voltage. The stepped up or down adjustable DC voltage from the two switch buck-boost (TSBB) DC-DC Converter is fed to the three-phase two-level IGBT Inverter and BLDC motor (24V/4000 rpm) combination. Thus the whole system contains

AC-DC, DC-DC and DC-AC portions, with an overall topology, as shown in Fig.4.

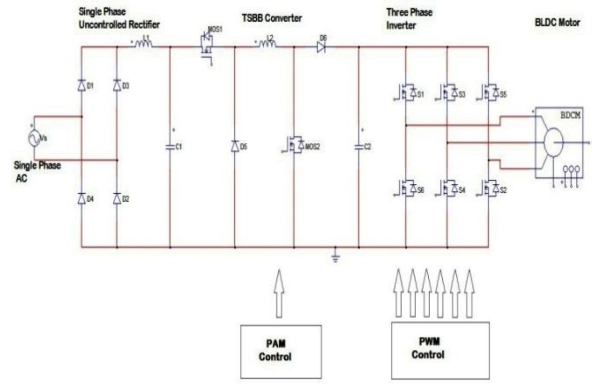

Fig.4: Topology of proposed motor drive system

The voltage conversion equation of a TSBB Converter is given by:

$$V_O = \frac{D_1}{1-D_2} \qquad (1)$$

where D1 and D2 are duty cycles of switches MOS1 and MOS2 , D1 and D2 are controlled independently in two mode control scheme. When the input voltage is higher than the output voltage, the TSBB converter operates in buck mode, where D2 = 0 and D1 is controlled to regulate the output voltage. When the input voltage is lower than the output voltage, the TSBB converter operates in boost mode, where D1=1 and D2 is controlled to regulate the output voltage.

The voltage equation of a BLDC motor is given as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (2)$$

where ea, eb, ec represent the back-EMFs, and ia, ib, ic are phase currents, and Laa, Lbb, Lcc are the self inductance of phase A, B, and C, respectively, and Lab, Lbc, Lca are mutual inductances.

IV. CONTROL THEORY

The purpose of the control strategy implemented is to adjust the input voltage of the inverter whenever necessary, while providing 120° square wave conduction on the inverter side. A hysteresis comparator is used to select the PAM or PWM control modes.

1) PWM Control

The PWM technique used here is ON_PWM technique. Fig.5 depicts the switching control pattern of the BLDC machine drive systems [5]. Each switch is operating for one third of the fundamental cycle, completely turned on for 60° and operating in the PWM mode for another 60°. At any time, only two phases are conducting simultaneously

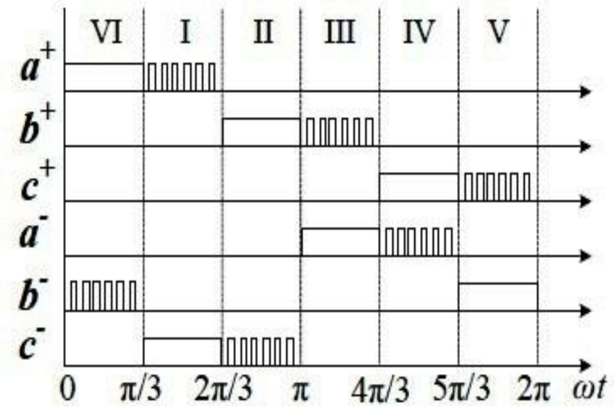

Fig.5: ON_PWM Control Pattern

If “1” and “0” are used to represent the on and off statuses of each switch, the power converter operation modes can be described by six active statuses: (100010), (100001), (010001), (010100), (001100) and (001010). Each vector shows the on-off statuses of a+, b+, c+, a-, b- and c-. In the three-phase stationary reference frame, six space voltage vectors V1 to V6 can be used to represent the six active statuses as shown in Fig.6 [6].

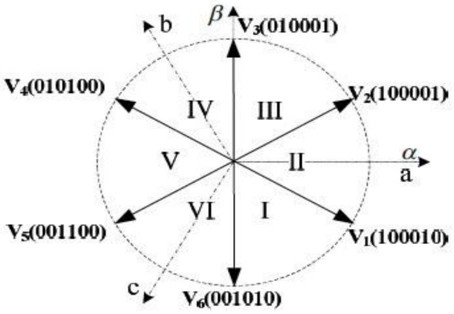

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Fig.6: Space vectors in BLDC machine drive

2) PAM Control

The voltage adjustment in PAM control is realized by modifying the duty cycle of the TSBB converter through a speed control loop as shown in Fig.7.

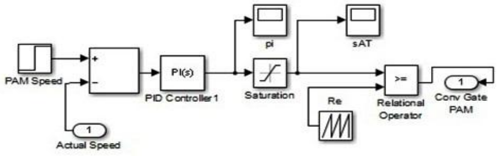

Fig.7: Speed control loop

First, the speed information is obtained from the motor. In practice is not desirable to have an encoder or, for that matter, any kind of position sensor, to save space and money. However, in some applications, where position information is very important for drive dynamics, Hall sensors are still used.

Speed error, between measured and prescribed speed, is fed to a PI speed controller to obtain the prescribed value of the duty cycle. The output of this block is then compared with a triangular carrier voltage to impose the switching frequency of the MOSFET. In this case, the switching frequency was chosen to be 20 kHz.

3) Hysteresis Comparator

The transition process between PWM and PAM is achieved by a hysteresis comparator expressed as:

$$\tau\big(n(k+1)\big) = 1, n(k+1) > n_+ \qquad (3)$$

$$\tau\big(n(k+1)\big) = \tau(n(k)), n_- \le n(k+1) \le n_+ \qquad (4)$$

$$\tau\big(n(k+1)\big) = 0, n(k+1) < n_- \qquad (5)$$

where τ (n(k+1)) is the (k+1)th hysteresis comparator output value, τ (n(k)) is the (k)th hysteresis comparator output value, n- and n+ are the two endpoint speeds of the hysteresis comparator, n(k+1) is the (k+1)th calculated speed value, and n(k) is the (k)th calculated speed value.

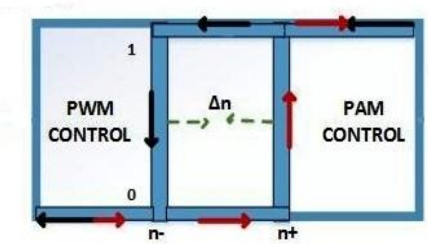

Fig.8: Hysteresis loop schematic diagram

The hysteresis loop schematic diagram is shown in Fig.8. The region between n- and n+ is defined as the transition region. If τ (n(k+1))=1, the PAM control mode will start to work, while if τ (n(k+1))=0, the PWM control mode will start to work.

When the speed reaches n+, if the speed is decelerating, the drive method may switch between the PAM control and the PWM control repetitiously which aggravates the current ripple. Therefore, a proper hysteresis width (Δn) is critical to eliminate the unexpected repetitious switching. The proper hysteresis width is selected from many initial experiments, of which accelerate and decelerate the motor to pass the transition region with different hysteresis widths automatically, when the motor first runs. Once Δn is selected, it will be saved and does not need to be calculated in the subsequent experiments.

RESULTS AND DISCUSSIONS

The proposed design is verified by computer simulation using MATLAB/SIMULINK software package. The overall simulation diagram is shown in Fig.9. The TSBB DC-DC converter is supplied by a single phase uncontrolled rectifier which successfully steps-up or down 12-V DC to the required DC voltage. The system parameters of TSBB DC-DC converter and the BLDC motor parameters are listed in Table I and II respectively.

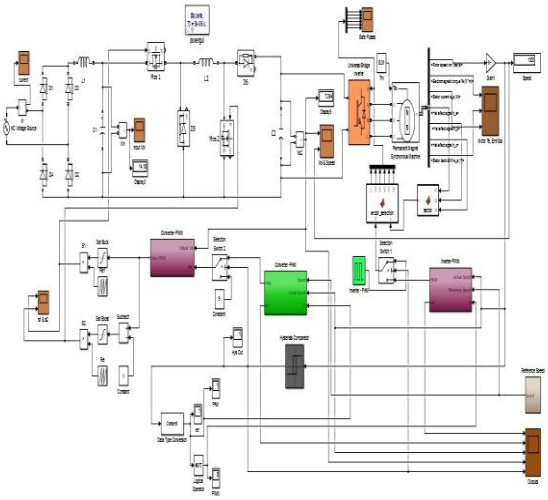

Fig.9 MATLAB/SIMULINK Model for proposed system

I: Parameters of TSBB DC-DC Converter

Parameter	Value
Switching Frequency (fs)	20 kHz
Inductor (L)	0.5 mH
Output Filter Capacitance (C)	40 mF

II: BLDC Motor Parameters

Parameter	Value
Motor Line-Line RMS back-EMF	1.885 V/krpm
Rated DC Voltage	24 V
Rated Power	50 W
Rated Speed, n	4000 rpm

The Fig.10 shows the Speed and DC link voltage waveforms for PWM Technique at Low Speed (N=300 rpm). It can be observed that the speed settles to 300 rpm after 1.1 secs with a fixed DC link voltage of about 9 V. For implementing the PWM technique the inverter's carrier switching frequency is fixed at 1 kHz. A closed loop control of buck-boost converter is also employed to obtain a fixed DC output voltage of 9 V. The converter switches at a frequency of 20 kHz.

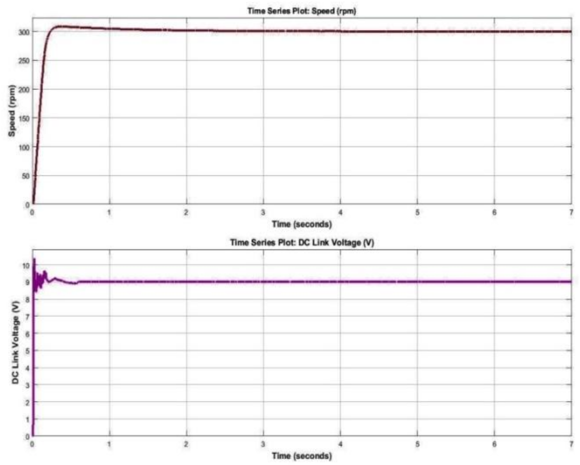

Fig.10 Speed and DC link voltage (Vo=9V) at N=300rpm

The Fig.11 shows the Speed and DC link voltage waveforms for PAM Technique at High Speed (N=1300 rpm). It can be observed that the speed settles to 1300 rpm after 1.5 secs with an adjustable DC link voltage of about 5.6 V. For implementing the PAM technique the inverter switches pulse width is fixed at 90 percent at 1 kHz switching frequency. The converter switches at a frequency of 20 kHz.

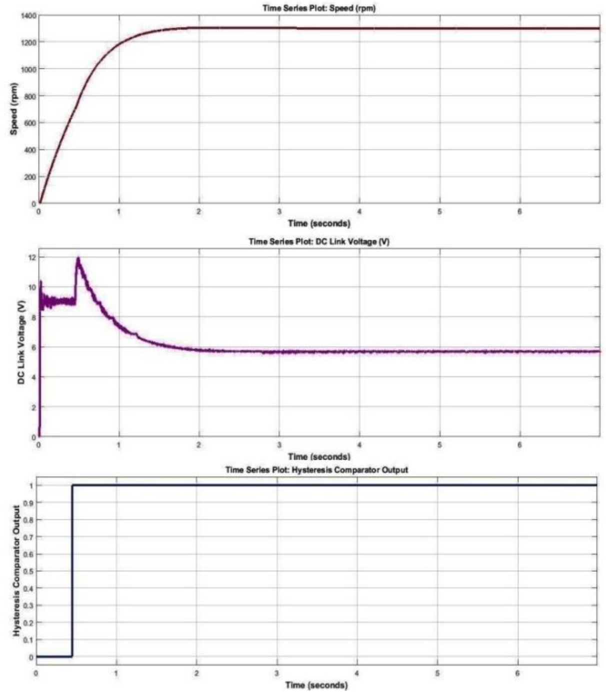

Fig.11 Speed, DC link voltage & Hysteresis Comparator Output (Vo=5.6 V) at N=1300 rpm

The Fig.12 and Fig.13 shows waveforms for stator current and torque for PWM and hybrid PWM-PAM techniques at high speed (N=1300 rpm). On comparing both, it can be inferred that stator current and torque ripples reduces significantly; i.e., THD in torque has decreased from 28% to 5.45% at a speed of 1300 rpm when hybrid PWM-PAM technique is employed.

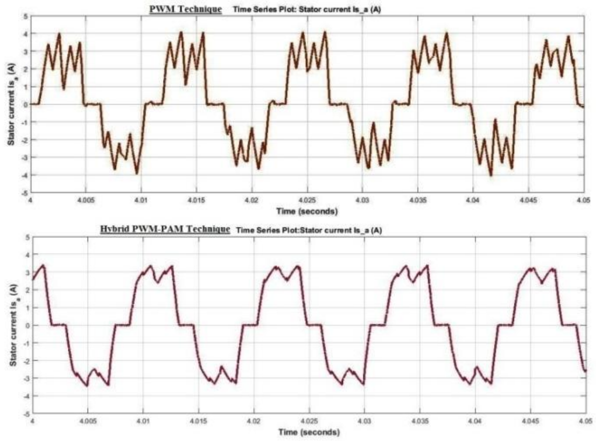

Fig.12 Stator Current Waveforms at High Speed (N=1300 rpm) for PWM and Hybrid PWM-PAM Techniques

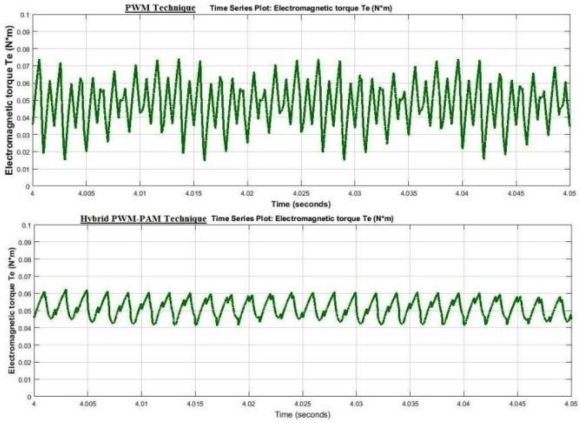

Fig.13 Torque Waveforms at High Speed (N=1300 rpm) for PWM and Hybrid PWM-PAM Techniques

CONCLUSION

After simulation of the proposed design in MATLAB/SIMULINK, it is proven that a high speed BLDC motor can be driven using a hybrid switching employing PAM-PWM technique. The system was observed to be feasible and efficient in the simulation. Performance comparison was done on PAM and PWM techniques at a high speed. After simulation, it was proven that PAM control remains superior to the PWM control at high speeds. The current ripples were reduced significantly by employing PAM control at high speed. The proposed design first uses a two switch buck-boost converter topology to adjust the DC voltage to an appropriate value and then applies this voltage to an IGBT-based VSI. The IGBT inverter provides the high-side phase currents to drive the high speed brushless DC motor.

The objective was to separate the speed control from inverter commutation, introducing a buck-boost converter in the DC link. By doing so, the inverter switches will work at a lower frequency and can be downsized, which is economically efficient. Also, inverter switching losses are reduced, only the DC-DC converter is chopping at a high frequency. Therefore such a type of motor drive system using a hybrid switching mechanism can be employed for aeration blowers for the sewage treatment. It secures high efficiency with low motor losses.

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