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Comparative Study on Single Pulse and Dual Pulses Variable Width Control Strategies for High-Speed PM BLDC Motor Drive

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Pulse width modulation (PWM) of voltage source inverter (VSI) is common for speed regulation of permanent magnet (PM) brushless direct-current (BLDC) motor drives. However, when the motor runs at high speed, the conventional PWM technique may become unfeasible due to the low carrier ratio of inverter, which makes the motor current distorted and the motor core loss increased significantly. In this paper, two control strategies, namely single pulse variable width (SPVW) and dual pulses variable width (DPVW), are introduced for the high-speed PM BLDC motor drives, and are comprehensively investigated. Finite element method (FEM) is employed to evaluate and compare the drive system performance when using the conventional PWM, and the proposed SPVW and DPVW, respectively. Influence of the control techniques, especially on the loss distribution, is revealed.

Keywords : High-speed motor drive, PM BLDC motor, rotor eddy current loss, iron loss, inverter switching loss

1. Introduction

Permanent magnet (PM) brushless direct-current (BLDC) motor driven with voltage source inverter (VSI) using pulse width modulation (PWM) technique can achieve virtually a linear speed regulation performance [1]. In general, a high carrier ratio (i.e., ratio of the inverter switching frequency to the motor fundamental frequency) is of essence to guarantee sufficient switching cycles during each electrical period for good control performance [2]. However, the resultant high switching frequency during high-speed operation leads to excessive switching loss and hence thermal issue in the switching power devices. As a result, superior power devices such as SiC or GaN devices are usually required to compensate this problem. Nevertheless, such devices are expensive and will also cause some other problems, e.g., high dv/dt, EMI and motor insulation issues.

In most PM BLDC motor applications, conventional power devices rather than the SiC or GaN devices are used. Thus, high carrier ratio can hardly be realized in high-speed PM BLDC drives due to the particularly high fundamental frequency of motors and the limited switching frequency of the power devices. As a result, the conventional PWM technique cannot achieve sufficient control performance, as the motor currents will be distorted. To prove this, a 2-pole PM BLDC drive with speed of 70 krpm (i.e., the fundamental frequency being 1,167 Hz), load torque of 1.2 N·m and DC link voltage of 400 V is taken as an example, whilst different switching frequencies of the inverter, e.g., 50 kHz (corresponding to the SiC devices) and 10 kHz (corresponding to the IGBT devices), are investigated. The respective phase current waveforms of the machine are derived from simulations and illustrated in Fig. 1. The 50 kHz switching frequency which is impractical for the conventional power devices does result in quite regular current waveforms, while the common 10 kHz switching frequency incurs evident current distortion. As will be stated hereafter in this paper, current distortion will cause further problems, such as extra core iron loss and rotor eddy current loss. Therefore, it is essential to study new control techniques to solve the problems of the PWM technique for the high-speed BLDC motor drives.

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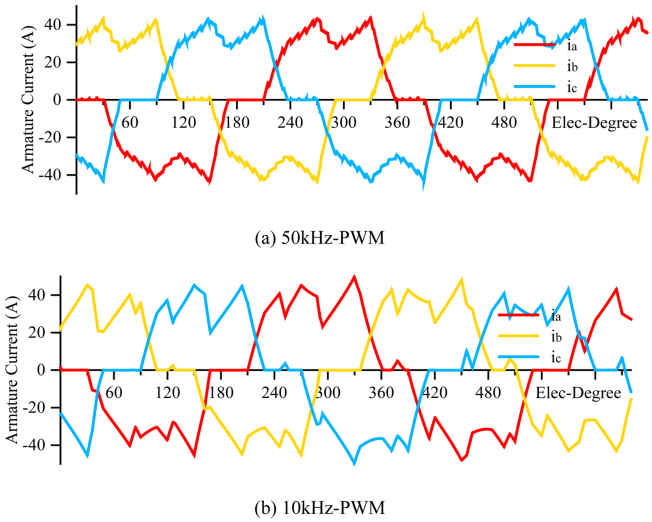


Fig. 1. (Color online) Armature current waveforms of BLDC motor driven with 50 kHz and 10 kHz conventional PWM control strategy at 70 krpm, 1.2 N·m, and 400 Vdc.

2. Strategy Definition

2.1. Basic BLDC control strategy

The basic control strategy of the three-phase PM BLDC motor drive with no PWM applied is the 6-state and 120-degree-conducting mode. The gate control signals are depicted in Fig. 2, in which the positive and negative signals turn on the upper and lower power devices of the corresponding leg, respectively, while the zero signal turns off both devices of the leg.

Adjusting the DC link voltage is a direct way to regulate the speed of the BLDC motor, which is called pulse amplitude modulation (PAM) control. The PAM strategy advantages in motor loss suppression, but an additional DC/DC converter is added before the inverter, leading to higher cost, larger volume and weight, as well as additional DC/DC converter loss. Therefore, PAM is hardly used in practical applications. However, the PAM performance will be presented in this paper, as a benchmark to comparatively study the PWM techniques as well as the proposed new control techniques.

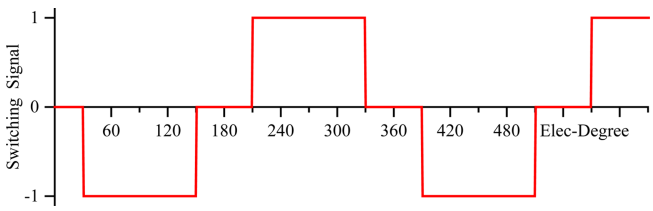


Fig. 2. (Color online) Switching signal of the basic BLDC control strategy (showing one phase only).

2.2. Single pulse variable width (SPVW) control strategy

It is well known that in the traditional 6-state and 120-degree-conducting mode of BLDC drive, there are one positive power pulse and one negative power pulse applied on the BLDC motor during each electrical period, and the width of each power pulse is 120 electric degrees. The PWM technique is to apply switchings during the interval of 120 degrees, therefore, actually there are many pulses during the interval.

In order to solve the above-mentioned problems of the PWM technique during high-speed operation, the most direct way is to remove the PWM switchings. Then, to realize speed regulation, it is hereby proposed to keep a single positive pulse and a single negative pulse within each electrical period, but to vary the pulse to narrower width from 120 degrees. This technique is hence called single pulse variable width (SPVW) control, and it can equivalently change the applied voltage on the motor and consequently regulate the motor speed.

Generally, the SPVW technique can be classified into two categories. In the first category, denoted as SPVW-1, the central point of each pulse is kept the same as that of the basic BLDC strategy, but the pulse width is shrunk symmetrically. The resultant gate control signals are shown in Fig. 3(a), the Phase-a is highlighted, and the other two phases are symmetrical to Phase-a. It should be noted that this SPVW technique is applied on both upper and lower devices. However, considering that the conducting upper devices and lower devices are always connected in series, it is also workable to apply the SPVW on either the upper or the lower devices, whilst the other devices conducting continuously for 120 electric degrees. The resultant gate

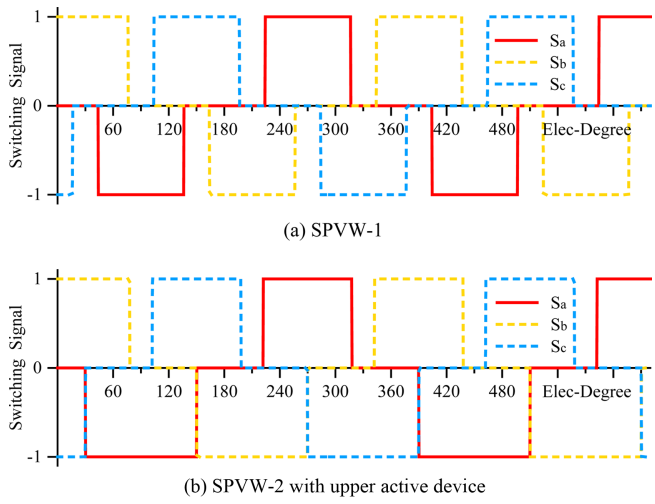
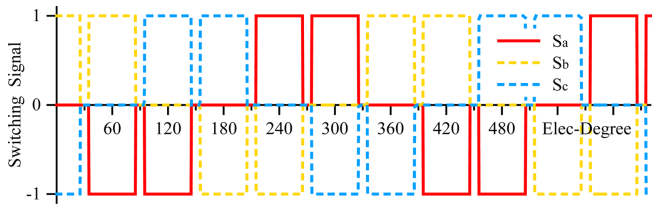
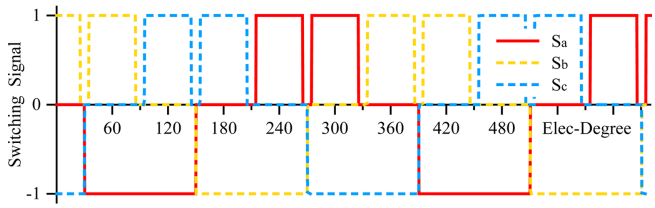


Fig. 3. (Color online) Switching signal of SPVW control strategies.



(a) DPVW-1



(b) DPVW-2 with upper active device

Fig. 4. (Color online) Switching signal of DPVW control strategies.

control signals of this strategy, i.e., the second category (SPVW-2), are demonstrated in Fig. 3(b). Note, hereafter the devices with shrunk pulse width is called active device.

2.3. Dual pulses variable width (DPVW) control strategy

As mentioned in 2.1, in the basic PM BLDC drive, for each phase, there are one positive power pulse and one negative power pulse within one electric period, and each pulse width is 120 electric degrees. However, it can also be said that there are two continuous positive power pulses (i.e., the positive set) and two continuous negative power pulses (i.e., the negative set), with the width of 60 electric degrees for each pulse. Then, to reduce the equivalent voltage of VSI, each set of two pulses can vary symmetrically from 60 degrees to narrower. This technique is thus called dual pulses variable width (DPVW) control.

Similar to the SPVW, the DPVW can be applied on both upper and lower devices, denoted as DPVW-1 and shown in Fig. 4(a), or, can be applied on either the upper or the lower devices only, denoted as DPVW-2 and shown in Fig. 4(b).

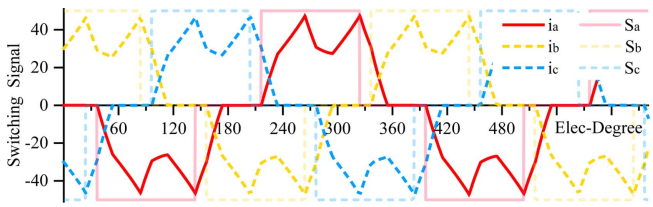
Clearly, with the SPVW strategies, the active power devices switch on and off only once within each electric period, but with the DPVW strategies the active devices switch twice.

3. Current Waveform Analysis

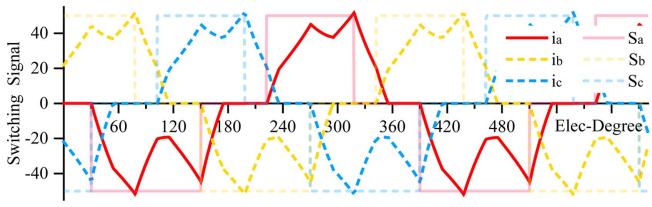
The pulse width of the SPVW and DPVW control strategies represents the duty cycle of the conventional PWM strategy, hence it is usually determined by the speed controller according to the motor operation point (e.g. speed and load) and the DC link voltage. For the given PM BLDC motor shown in the Introduction, to make it run at 70 krpm and 1.2 N·m with the DC link voltage of 400 V, it can be obtained through simulation that the pulse width of the active devices should be 108 electric degrees for the SPVW-1 strategy, 96 degrees for the SPVW-2, 54 degrees for the DPVW-1, and 52 degrees for the DPVW-2. On the other hand, if the traditional PWM strategy is applied, the duty cycle should be 84.5 % when the inverter carrier ratio is high enough (e.g., the switching frequency being 50 kHz), and the resultant current waveform has been illustrated in Fig. 1(a). However, when the inverter carrier ratio is low, for examples, if the switching frequency is 10 kHz, the PWM duty cycle should be slightly adjusted to 84.1 %, and the current waveform is distorted (Fig. 1(b)), containing rich time harmonics of both odd and even-number orders, and, if the switching frequency is 5 kHz, the current is further distorted. Furthermore, if the basic BLDC control strategy is applied, at the operation point of 70 krpm and 1.2 N·m, the DC link voltage should be adjusted to 340 V with the PAM strategy, and the resultant current waveform is similar to that in Fig. 1(a), but with no high-frequency ripples.

3.1. Current waveforms of SPVW

With the basic PM BLDC control strategy, there are only six basic states, in each state there are one upper device and one lower device of different phase legs conducting. However, the SPVW-1 and SPVW-2 techniques add extra six and three states in between these six basic states, respectively, the extra six states induced by the SPVW-1 are of only one upper or one lower switch conducting, while the extra three states induced by the



(a) SPVW-1



(b) SPVW-2 with upper active device

Fig. 5. (Color online) Switching signal and corresponding current waveform for SPVW strategies.

SPVW-2 with the upper active devices have only one lower device conducting. Those extra operational states result in the difference of the stator current waveforms of the SPVW-1 and SPVW-2 form the basic BLDC operation, which are clearly manifested in Fig. 5.

It can also be noticed that the positive and negative halves of the phase current waveform are no longer identical for the SPVW-2 strategy, due to the asymmetricity between the positive and negative power pulses. This will cause even-order time harmonics in the phase current. It is also noticed that the peak of phase current increases if compared with that in Fig. 1(a), this is because the power pulses with the SPVW strategies have become narrower.

3.2. Current waveforms of DPVW

The respective phase current waveforms with the DPVW-1 and DPVW-2 (upper active devices) are also obtained with FEM simulations, Fig. 6. In addition to the six basic states, the DPVW-1 strategy introduces extra six identical in-between states with no device conducting, while the DPVW-2 has extra six in-between states with only one upper device or one lower device conducting. The differences of the extra states and their relative position make the current waveforms with the DPVW strategies deviated noticeably from the SPVW ones, as can be seen from Fig. 5 and 6.

The centers of the extra states align with the positive and negative peaks of the phase back EMF, and the extra states make the phase current decline. Therefore, to ensure sufficient electromagnetic torque, the current must have higher peaks before and after the extra states, as can be seen from Fig. 6 and Fig. 1 & Fig. 5. Moreover, the positive and negative halves of the current waveform are no longer symmetric for the DPVW-2 operation due to the different conducting patterns of the upper and lower devices in each phase leg.

4. Loss Analysis

4.1. Stator iron loss

The stator iron loss of the PM BLDC machine is mainly induced by the rotating magnetic field excited by PMs and armature currents. For a given BLDC motor, the PM-excited field is more or less constant, whilst the armature current characteristics (namely the time harmonics of armature current) due to various control strategies will largely influence the stator iron loss.

Comprehensive FEM simulations are employed to evaluate the performance of the given high-speed PM BLDC motor drive with different control strategies at various operational speeds and the constant torque of 1.2 N·m. The corresponding stator iron loss results are compared in Fig. 7. The stator iron loss grows gradually along with the motor speed. Clearly the PAM strategy presents the lowest iron loss, however it needs more complicated and expensive hardware. For the commonly used power converter topology, it can be seen from Fig. 7 that the proposed SPVW strategies exhibits the lowest stator iron loss. As the stator phase flux linkage is the the temporal integration of the subtraction of phase voltage and resistive voltage drop, the stator phase voltage can be used to investigate the stator iron loss especially for the high-speed cases. The phase voltage waveforms of the PM BLDC machine driven with the proposed four control strategies at the speed of 70 krpm and torque of 1.2 N·m

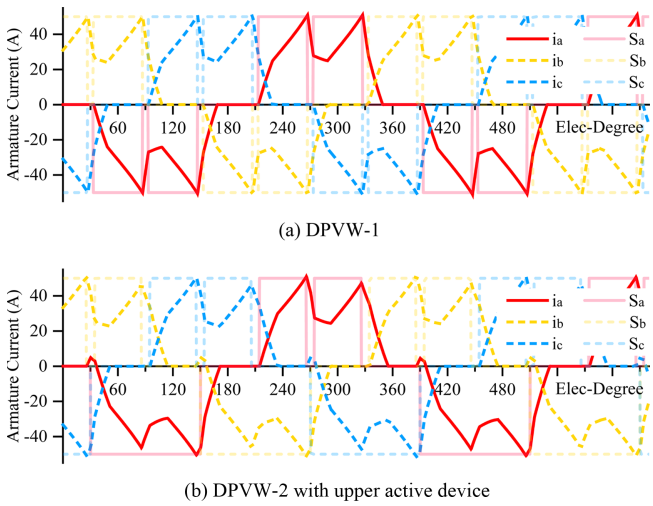


Fig. 6. (Color online) Switching signal and corresponding current waveform for DPVW strategies.

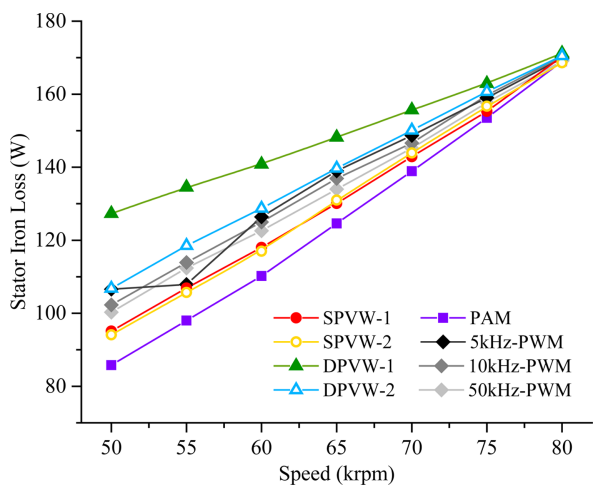


Fig. 7. (Color online) Stator iron loss with different control strategies at various speeds.

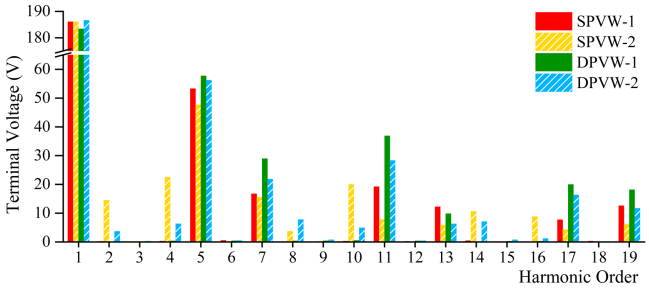


Fig. 8. (Color online) Phase voltage harmonic spectra with SPVW and DPVW strategies.

are obtained, and their spectra are compiled as Fig. 8. Generally, the DPVW techniques produce higher belt voltage harmonic components so that they cause higher stator iron loss, as shown in Fig. 7. Although the SPVW-2 and DPVW-2 techniques do introduce extra even-number-order voltage harmonic components, they incur much lower than the odd-number-order harmonic components. On the whole, the SPVW-2 and DPVW-2 techniques generate lower stator iron loss than their SPVW-1 and DPVW-1 counterparts.

4.2. Rotor eddy current loss

Rotor eddy current loss becomes the prominent contributor of the overall loss in the high-speed PM BLDC motors. Basically, the rotor eddy current loss is caused by: 1) the unevenness of the stator permeability; 2) spatial harmonics of the armature reaction field; 3) time harmonics of the armature reaction field [3, 4]. Since the PM BLDC machine exhibits different phase current profiles with various control strategies even under the same operational condition, the time harmonic components in the phase current with different amplitudes or even different frequencies can result in very deviated eddy current loss in the rotor [5].

As conductive retaining sleeve is employed in the studied PM BLDC machine to protect the PMs, there will be significant eddy current loss occurring in the sleeve due to its direct exposure to the air gap. Moreover, additional eddy currents and hence loss will be induced in the PMs and the conductive shaft. These loss components in the machine with different control strategies at various speed and the constant torque of 1.2 N·m are evaluated in FEM simulations, and the total rotor eddy current loss is shown in Fig. 9. It can be observed that the control strategies have great impact on the rotor eddy current loss [6].

As the motor speed increases, the rotor eddy current loss results from the proposed four control strategies all converge to the value of the basic PM BLDC operation

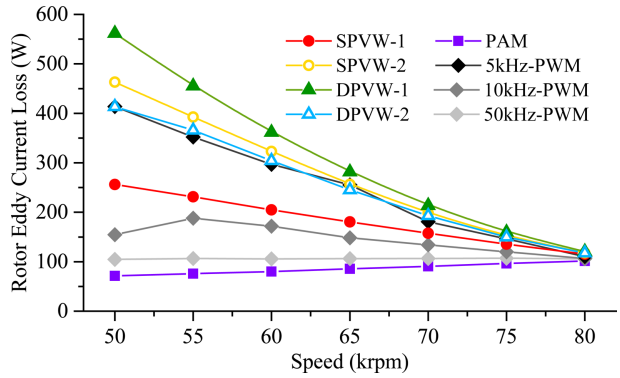


Fig. 9. (Color online) Rotor eddy current loss with different control strategies at various speeds.

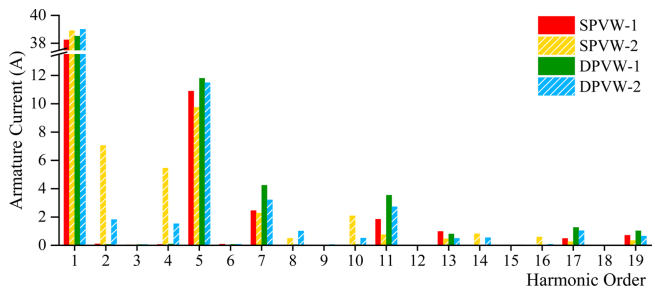


Fig. 10. (Color online) Phase current harmonic spectra with SPVW and DPVW strategies.

with PAM. It can be easily found that all the four control strategies approach to exactly the same at the high-speed limit. The results in Fig. 9 have implied that the stator current harmonic contents impose huge influences on the rotor eddy current loss in the studied PM BLDC machine. The phase current spectra of the machine with the proposed four control strategies at 70 krpm and 1.2 N·m are calculated and illustrated in Fig. 10. Similarly, the SPVW techniques generate lower current harmonic components than their DPVW counterparts. On the other side, the SPVW-2 and DPVW-2 techniques inevitably introduce even-number-order current harmonic components as previously discussed. Overall, the SPVW-1 technique delivers the smallest rotor eddy current loss among the four, while the DPVW-1 one induces the largest. Although the SPVW-2 technique has lowest odd-number-order current harmonic components, it adds excessive even-number-order harmonic components especially the second and fourth ones. As a result, the rotor eddy current loss from the SPVW-2 technique exceeds the DPVW-2 one.

4.3. Winding copper loss

As the machine delivers the same torque output, the phase currents with different control strategies have similar rms values. For the proposed SPVW and DPVW techni-

ques, as aforementioned, extra non-conducting states become longer, making the equivalent torque constant decrease when the motor speed declines. Therefore, the phase current increases as the speed reduces, so as to maintain the torque. Generally, SPVW-1 technique results in the smallest phase current rms value and hence the lowest copper loss of windings, while the rest three techniques possess very similar copper loss. Nevertheless, the stator winding copper loss is rather small in the studied PM BLDC machine under high-speed operation [7].

4.4. Inverter loss

Generally, the inverter loss comprises the conduction loss and switching loss. In literature, the conduction loss of an IGBT module can be calculated with the formula [8]:

$$P_{CT} = V_{CE0} \cdot I_{C,avg} + R_C \cdot I_{C,rms}^2$$

where P_{CT} is the average conduction loss of an IGBT module, V_{CE0} represents the IGBT on-state zero-current collector-emitter voltage drop, R_C is the collector-emitter on-state resistance, and $I_{C,avg}$ is the average and $I_{C,rms}$ is the rms current of IGBT.

In the same way, the antiparallel diode average conduction loss can be calculated with the formula [8]:

$$P_{CD} = V_{F0} \cdot I_{D,avg} + R_F \cdot I_{D,rms}^2$$

where P_{CD} is the average conduction loss of the diode, V_{F0} represents the on-state zero-current forward voltage drop, R_F is the on-state resistance, $I_{D,avg}$ is the average and $I_{D,rms}$ is the rms current of the diode.

Considering the characteristic of IGBT module BSM75GB60DLC, which is used for the studied motor drive, $V_{CE0} = V_{F0} = 0.5$ V, and $R_C = R_F = 30$ mΩ, so the value of P_{CT} and P_{DT} can be calculated, with the total value of about 110 W under all control methods aforementioned. It can be regarded that the conduction loss

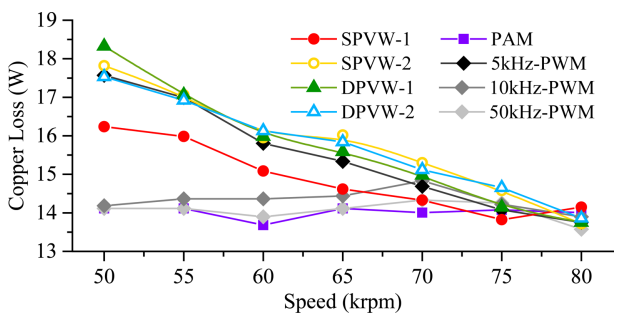


Fig. 11. (Color online) Copper loss with different control strategies at various speeds.

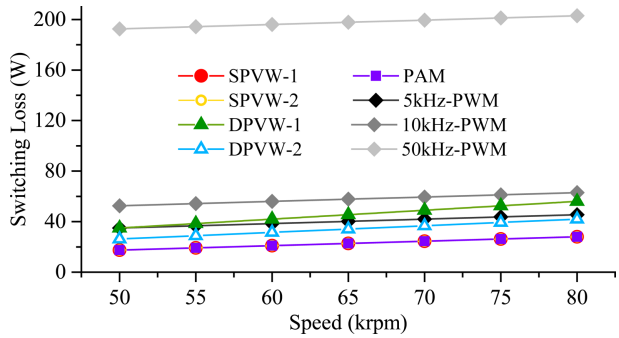


Fig. 12. (Color online) Switching loss in the VSI with different control strategies at various speeds.

maintains nearly the same at the same output torque of 1.2 N·m for different motor speeds and control strategies.

On the other hand, the inverter switching loss is approximately proportional to the switching times per cycle. For the conventional PWM strategies with the PWM applied to the upper (or lower) switches only, the number of switching per second (f_S) can be calculated as $f_S = 6*(n/60) + f_{PWM}$, where n is the motor speed in rpm and f_{PWM} is the PWM switching frequency. Hence, the switching power loss can be calculated by multiplying f_S by the coefficient of loss per single switch of the power device. It is found from the data sheet of the related power devices that such coefficient is 3.5 mW. The inverter switching losses under different control strategies at different motor speeds and the constant torque of 1.2 N·m are calculated and shown in Fig. 12, which confirms that the proposed SPVW and DPVW techniques can effectively mitigate the inverter switching loss.

4.5. Total loss comparison

The total electromagnetic loss of the studied high-speed

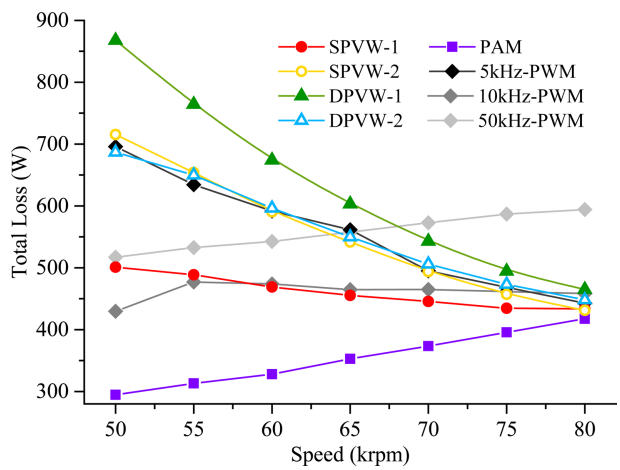


Fig. 13. (Color online) Total electromagnetic loss with different control strategies at various speeds.

PM BLDC motor drive system under various drive conditions can be compiled and shown in Fig. 13. Although the PAM seems to be the most efficient when taking into account the motor and inverter losses, it should be noted that the conduction loss and switching loss of the DC/DC converter, as well as the losses in the inductor and capacitor which are used in the DC bus after the DC/DC converter, are not included in the PAM-associated total loss in Fig. 13. therefore, the actual total loss with the PAM strategy is much higher. with further consideration of the cost, volume, weight and reliability of the DC/DC conversion subsystem, the PAM strategy is hardly used. It can be observed that the proposed techniques show quite big promise. Especially, the SPVW-1 technique maintains the lowest overall loss when the drive operational speed exceeds 60 krpm. It confirms the superiority of this technique over the conventional PWM technique for the high-speed PM BLDC motor drive.

5. Conclusions

If traditional power switching devices such as IGBT are used, the excessive switching loss makes the conventional PWM technique with high switching frequency unpractical for the high-speed PM BLDC motor drive system. On the other hand, the PWM technique with moderate switching frequency can result in severe current distortion and hence considerably deteriorate the overall performance of the high-speed BLDC motor. Therefore, new SPVW and DPVW techniques, which actually concentrate the off states of the PWM switches, are proposed in this paper to overcome the aforementioned problems. Comprehensive FEM results have revealed the validity of the proposed techniques. The results have underpinned that the proposed SPVW and DPVW techniques, especially the SPVW-1 one, have higher efficiency over the conventional PWM technique. It can be envisaged that application of the SPVW-1 technique to the high-speed PM BLDC motor drive can deliver significant advantages over the existing techniques, whilst such advantages will be further verified with experiments in our future work.

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