

Article

Comparative Study of Short Circuits and Demagnetization in Delta, Star, and Hybrid Winding Connections for Surface-Mounted Permanent Magnet Machines

Junyi Chen ¹, Yidong Du ^{1,*}, Haolan Zhan ², Kai Zhou ¹ and Yuan Sun ¹

¹ School of Mechanical and Electrical Engineering, Soochow University, Suzhou 215006, China; jychen10@stu.suda.edu.cn (J.C.); kzhou@suda.edu.cn (K.Z.); yuansun@suda.edu.cn (Y.S.)

² College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China; zhanhaolan@zju.edu.cn

* Correspondence: yddu@suda.edu.cn

Abstract: This article comprehensively compares the short circuits and irreversible demagnetization in star, delta, and hybrid winding connections for surface-mounted permanent magnet (SPM) machines, including the three-phase short circuit (3PSC) and two-phase short circuit (2PSC). The analytical and finite element (FE) methods are adopted. It is found that when 3PSC or 2PSC happens, the peak current is the largest in the hybrid connection, which further results in the severest demagnetization. In addition, the delta connection always results in a larger 2PSC peak current than the star connection. Under relatively low permanent magnet (PM) temperature, the delta connection leads to more severe demagnetization than the star connection. However, when PM temperature increases, the opposite condition can occur. As for 3PSC, whether the peak current of the delta connection exceeds that of the star connection is determined by the phase of the third back-EMF harmonic. The delta connection shows higher 3PSC peak current when the third harmonic is in phase with the fundamental back EMF, and conversely, the star connection shows higher peak current. The comparison of demagnetization also heavily depends on PM temperature. Finally, the experiments are conducted to verify the theoretical analysis.



Citation: Chen, J.; Du, Y.; Zhan, H.; Zhou, K.; Sun, Y. Comparative Study of Short Circuits and Demagnetization in Delta, Star, and Hybrid Winding Connections for Surface-Mounted Permanent Magnet Machines.

Machines **2024**, *12*, 401.

<https://doi.org/10.3390/machines12060401>

Academic Editor: Parviz Famouri

Received: 11 May 2024

Revised: 31 May 2024

Accepted: 8 June 2024

Published: 12 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: demagnetization; SPM; 3PSC; 2PSC; winding connection

1. Introduction

Surface-mounted permanent magnet (SPM) machines play a significant role in industrial applications due to their high torque/power density, efficiency, and simple structure [1–3]. The choice of winding connection is crucial for SPM machines, which typically include two methods: star and delta, as shown in Figure 1a,b. A hybrid connection combining the star and delta connection was also proposed in [4–7], as shown in Figure 1c. Among them, the star connection is more commonly used. The delta connection, characterized by higher line currents yet lower line voltages, is preferred in high-voltage settings [8]. However, it has been experimentally verified that the third back-EMF harmonics lead to zero-sequence currents in the delta connection [9]. It was reported in [10] that the delta connection can result in about 5.8% larger copper loss than the star connection due to the zero-sequence currents. However, when a PWM inverter is adopted, the iron loss of the delta connection can be smaller than that of the star connection [11]. Nevertheless, experiments still show that 15% higher efficiency can be achieved at light load when the delta connection is changed into a star connection [12]. As for the hybrid connection, despite its increased complexity, it achieves higher winding factor, reduces winding losses, and minimizes torque pulsations [13–16]. Furthermore, it exhibits superior performance in open-circuit faults [16,17], thereby ensuring safety in practical applications [18]. In addition, the star connection exhibits better withstanding capabilities against voltage unbalance than the other winding connections [19].

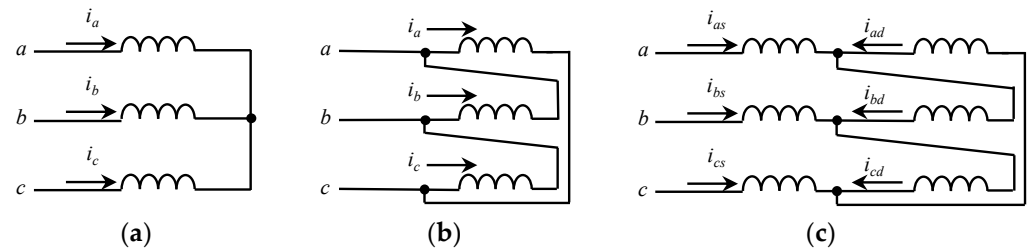


Figure 1. Star, delta, and hybrid winding connections. (a) Star. (b) Delta. (c) Hybrid.

However, for SPM machines, the risk of irreversible demagnetization in permanent magnets (PMs) is a major drawback that cannot be ignored. Demagnetization can reduce the average torque and exacerbate torque ripple [20–22], which has great influence on machine reliabilities. It usually results from short-circuit faults under high PM temperature [21,23,24]. Short circuits are one of the most critical faults in SPM machines. Although there are usually circuit breakers in the machine system, they only cut off short-circuit currents at the zero-crossing point, before which the largest transient peak current has already occurred [25]. Among the short-circuit faults, three-phase short circuits (3PSCs) and two-phase short circuits (2PSCs) are two typical types, which are usually caused by inverter failure or control faults [26–28]. The large short-circuit currents produce large reverse magnetic fields, making PMs easily demagnetized. Consequently, it is first necessary to investigate how the largest peak short-circuit current can be obtained for each winding connection to guide the demagnetization check for a specific design of SPM machines. On this basis, which winding connection type can provide the greatest resistance to short-circuit current and demagnetization should be given focused attention to guide the choice of winding connection during the design of SPM machines, especially those used in safety-critical applications, such as wind power generators or servo motors in aero-space applications.

In [29], the demagnetization was compared between the star and delta connection for a brushless DC motor (BLDCM). It was revealed that the star connection resulted in a larger maximum magnetomotive force than the delta connection under input PWM currents with the same switching frequency, which further led to more severe demagnetization. However, the above conclusions were based on the normal operating state instead of the short-circuit fault. In [17], the short-circuit fault of a hybrid connection was investigated by finite element (FE) simulation and experiments. It was found that the peak current increased with rotor speed. However, further investigation and comparison with other winding connections were not conducted. In [18], a triple three-phase PM-assisted synchronous reluctance machine with a hybrid winding connection was proposed and compared with the star connection. It was found that, when a 3PSC happened in one set of windings, the hybrid connection led to a smaller peak current. However, since the PM volume was limited, the short-circuit current was even lower than the rated current. Therefore, the above conclusions cannot be applicable to SPM machines, especially in large-scale ones using high volumes of PM materials, where short-circuit peak currents can be several times larger than the rated currents.

This article comprehensively compares short circuits and the resulting irreversible demagnetization in delta, star, and hybrid connections for SPM machines, including the 3PSC and 2PSC. This paper aims to provide clear insight into the winding selection principles for the practical design of SPM machines, especially those requiring high torque density and high reliability. Section 2 shows the different winding connections and compares the basic performances. Section 3 makes comparisons of 3PSCs and demagnetization in different connections. Section 4 focuses on the comparison of 2PSCs and the resulting demagnetization. Section 5 performs experimental validation. The main contributions are summarized as follows.

- (1) The short-circuit analytical models of different winding connections are developed and the relationship of short-circuit peak currents is revealed. It is found that the largest 3PSC or 2PSC peak current happens in the star-side of a hybrid connection.

- In addition, the delta connection leads to a larger 2PSC peak current than the star connection. As for the 3PSC, the delta connection shows slightly higher peak current when the third harmonic is in phase with the fundamental back EMF. In contrast, the star connection shows a higher peak current. Additionally, the conditions resulting in the largest peak short-circuit current for each winding connection are also provided.
- (2) The demagnetization in different winding connections is compared by FE analysis. It is found that the hybrid connection can lead to the severest demagnetization due to the largest peak current, which is not suggested for safety-critical applications. The comparison between delta and star connections depends on PM temperature. When the 2PSC happens under relatively low PM temperature, the delta connection can lead to more severe demagnetization than the star connection, whereas the opposite condition can occur when PM temperature increases. Since the demagnetization level under high PM temperature is much more severe, which is not acceptable in most scenarios, and the difference between star and delta connections can be neglected, the star connection can be a better selection for safety-critical applications. For a similar reason, the comparison of demagnetization due to 3PSC depends on the phase of the third back-EMF harmonic.
 - (3) It is also found that, compared to the 3PSC peak current, the 2PSC peak current is smaller in the star and hybrid connection. In the delta connection, the 3PSC and 2PSC peak currents are comparable. In addition, the 3PSC usually leads to more severe demagnetization than the 2PSC in different winding connections.

2. Winding Connections and Basic Performances

2.1. Prototype Machine

A 10-pole/12-slot SPM machine was selected for investigation, which is shown in Figure 2a. The parameters are shown in Table 1, which are the same for different winding connections. Under the rated condition and ambient temperature of 20 °C, the temperature distribution via natural cooling is shown in Figure 3, which is analyzed by Motor-CAD. It can be found that the PM temperature distribution was almost even and reached about 100 °C. Therefore, the PM temperature of 100 °C was selected as the basic condition. Nevertheless, PM temperature has great influence on the machine performances, particularly the demagnetization characteristics. Considering the possible change in ambient temperature, the close lower and higher PM temperatures were also selected for investigation. The demagnetization curves under different PM temperatures are shown in Figure 4. The influence of PM temperature can be analyzed by changing the demagnetization curves according to the PM temperature in an FE simulation, which is conducted by JMAG Designer in this article.

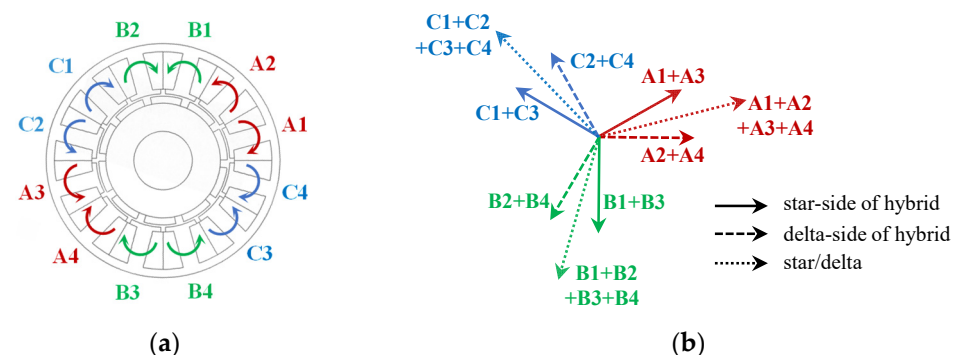
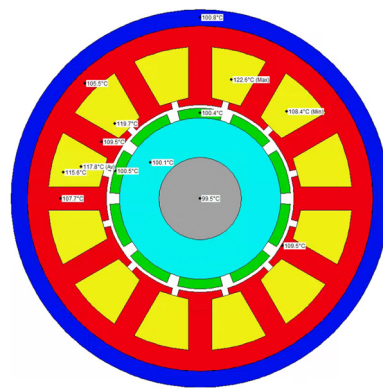
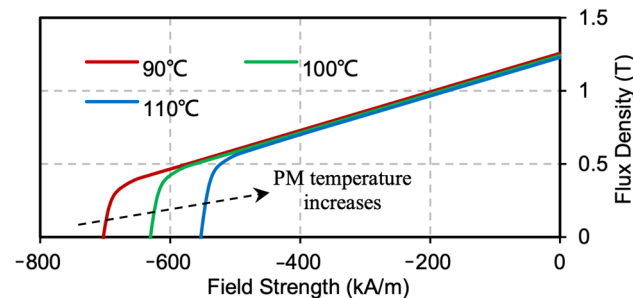


Figure 2. The investigated 10-pole/12-slot SPM machine. (a) Model. (b) Phasor diagram of different winding connections.

Table 1. Parameters of investigated SPM machine.

Parameters	Value	Parameters	Value
Stator outer radius	50 mm	Stack length	50 mm
Number of turns/coil	45	Airgap length	1 mm
Magnet thickness	3 mm	Coil resistance	0.19 Ω
Sheet material	35WW250	PM material	N45H
Volume	$9.8 \times 10^{-5} \text{ m}^3$	Rated phase current (star)	5.85 A
Rated speed	500 rpm	Rated power	265 W

**Figure 3.** Temperature distribution of the investigated SPM machine.**Figure 4.** Demagnetization curves under different PM temperatures.

For the star and delta connections, the coils within one phase were connected in series. Taking phase A as an example, A1, A2, A3, and A4 were connected in series. For the hybrid connection, since there is a current phase shift between the star- and delta-side windings [30], which is $\pi/6$, A1, A3, and A2, A4 should be divided into star- and delta-side windings, respectively, to maximize the average torque. The phasor diagrams for star, delta, and hybrid connections are shown in Figure 2b, where “+” represents that the coils are connected in series.

2.2. Back EMF

The back-EMF waveforms of different winding connections in phase A are shown in Figure 5, which were obtained by the FE method under the rotor speed of 500 rpm and an open-circuit condition, and the spectra are shown in Figure 6. It should be noted that, for the delta and hybrid connection, the back EMF was obtained after disconnecting each phase winding with other phases, i.e., there was no circulating current. The PM temperature was 100 °C. It should also be noted that the rotors of different connections were in the same mechanical position. The back EMF of star and delta connections were the same. The amplitude of the hybrid connection was slightly larger than half the value of the star/delta

connection due to a higher wind factor. In addition, compared to the star/delta connection, the star-side back EMF of the hybrid connection leads for $\pi/12$ whilst the delta-side one lags for $\pi/12$.

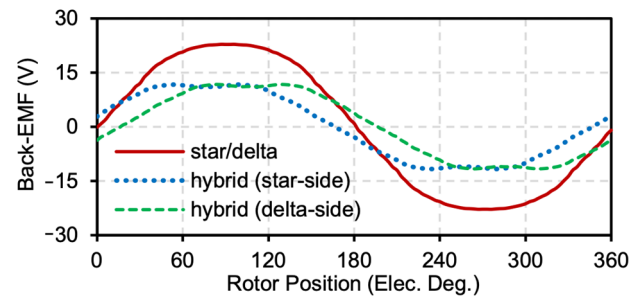


Figure 5. Phase back-EMF waveforms of different winding connections under rotor speed of 500 rpm.

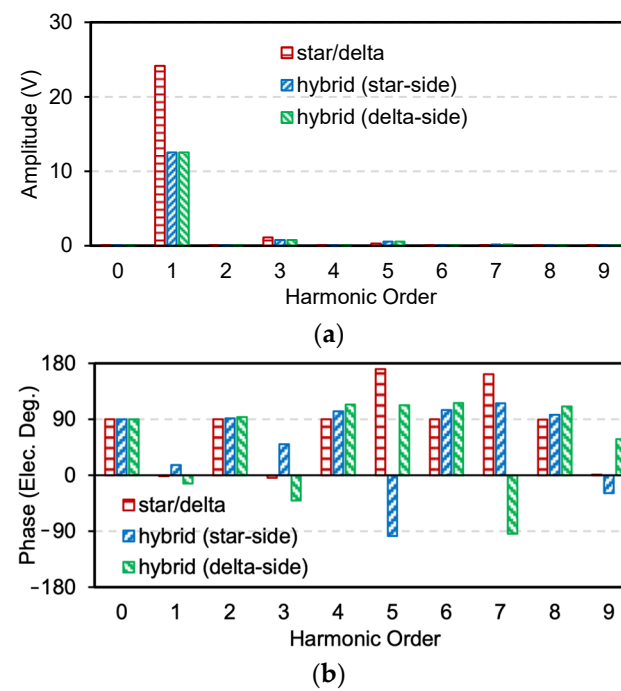


Figure 6. Phase back-EMF spectra of different winding connections. (a) Amplitude. (b) Phase.

2.3. Current and Torque

For the star and delta connections, the average torque can be expressed as

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \quad (1)$$

where Ω is the mechanical angular speed, e_a , e_b , and e_c are the back EMF of the star/delta connection, and i_a , i_b , and i_c are the currents of the star/delta connection. Taking e_a as examples, according to Figure 6, the fundamental back EMF can be expressed as

$$e_a = E_{m1} \sin(\omega t + \alpha) \quad (2)$$

where E_{m1} is the fundamental back-EMF amplitude, ω is the electrical angular speed, and α is the initial rotor position. To maximize the average torque, the corresponding current should be

$$i_a = I_{m1} \sin(\omega t + \alpha) \quad (3)$$

where I_{m1} is the current amplitude. Therefore, the average torque can be obtained as

$$T_e = \frac{3E_{m1}I_{m1}}{2\Omega} \quad (4)$$

For the hybrid connection, the average torque can be expressed as

$$T_e = \frac{e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs} + e_{ad}i_{ad} + e_{bd}i_{bd} + e_{cd}i_{cd}}{\Omega} \quad (5)$$

where e_{as} , e_{bs} , and e_{cs} are the star-side back EMF of the hybrid connection, respectively. e_{ad} , e_{bd} , and e_{cd} are the delta-side back EMF, and i_{as} , i_{bs} , i_{cs} , i_{ad} , i_{bd} , and i_{cd} are the corresponding currents. Taking e_{as} and e_{ad} as examples, the fundamental back EMF can be expressed as

$$\begin{cases} e_{as} = \frac{E_{m1}}{2\cos(\pi/12)} \sin(\omega t + \alpha + \frac{\pi}{12}) \\ e_{ad} = \frac{E_{m1}}{2\cos(\pi/12)} \sin(\omega t + \alpha - \frac{\pi}{12}) \end{cases} \quad (6)$$

The corresponding current can be expressed as

$$\begin{cases} i_{as} = \sqrt{3}I_{m1h} \sin(\omega t + \alpha + \frac{\pi}{12}) \\ i_{ad} = I_{m1h} \sin(\omega t + \alpha - \frac{\pi}{12}) \end{cases} \quad (7)$$

where I_{m1h} is the amplitude of the delta-side current. It is assumed that the influence of circulating current is neglected and the copper loss is the same as that in the star and delta connections, which is

$$\frac{3}{4}RI_{m1h}^2 + \frac{1}{4}RI_{m1h}^2 = \frac{1}{2}RI_{m1}^2 \quad (8)$$

Therefore, the relationship between I_{m1} and I_{m1h} can be expressed as

$$I_{m1h} = \frac{I_{m1}}{\sqrt{2}} \quad (9)$$

Hence, according to (5), the average torque of the hybrid connection can be obtained as

$$T_e = \frac{3E_{m1}I_{m1}}{2\Omega} \quad (10)$$

It can be found that, under fixed copper loss and neglecting the circulating current, the three winding connections show the same average torque. However, in the FE simulation, the circulating currents cannot be neglected. The phase A currents of different winding connections by FE analysis are shown in Figure 7. It can be found that the circulating currents exist in the delta connection and the delta-side of the hybrid connection, which hardly contribute to the average torque. The torque waveforms are shown in Figure 8. It can be found that under fixed copper loss, the star connection leads to the largest average torque, which is about 5.339 Nm. The circulating currents in the delta connection are the largest, and thus the average torque is the smallest, which is about 5.302 Nm. The average torque of the hybrid connection is 5.337 Nm. Nevertheless, the difference of average torque is slight and negligible.

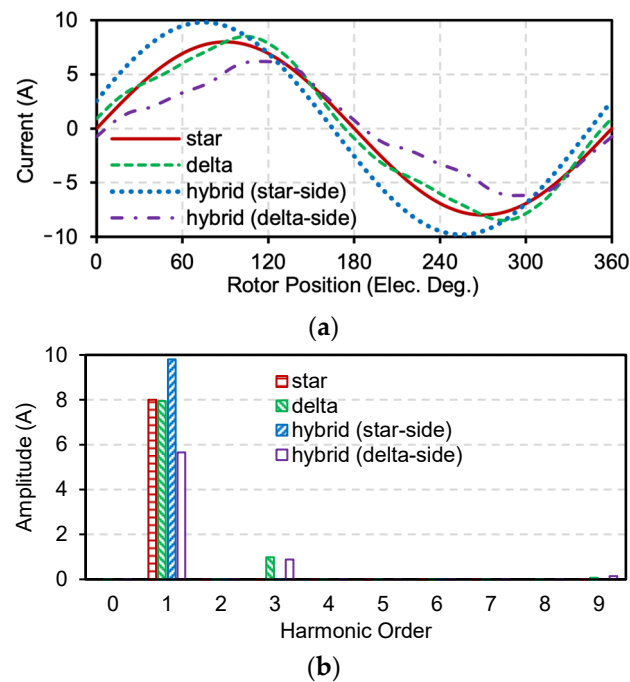


Figure 7. Input phase A currents of different winding connections. (a) Waveforms. (b) Spectra.

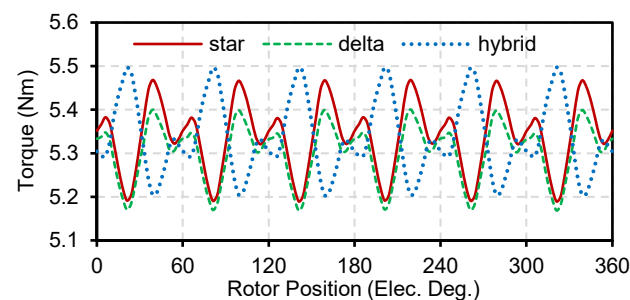


Figure 8. Torque waveforms of different winding connections.

3. Comparison of the 3PSC and Demagnetization

3.1. Equivalent Circuits of the 3PSC

Practically, short-circuit faults are more likely to happen in the converters than the SPM machine itself because the power electronic devices are usually easier to fail than the well-insulated windings. It is assumed that the 3PSC happens when all upper switches in the inverter are closed whilst all lower ones are open to prevent shoot-through, which is equivalent to the terminals *a*, *b*, and *c* in Figure 1 being short-circuited in each winding connection. The equivalent circuits are shown in Figure 9. The back-EMF has been analyzed in the previous section. *R* represents the phase resistance of the star/delta connection. In the hybrid connection, the phase resistance is half the value. In addition, *L* represents the inductance of the star/delta connection, which consists of both self-inductance and mutual inductance. In the hybrid connection, the self-inductance is smaller than half that of the star/delta connection. However, the mutual inductances between phases are almost the same for different winding connections. Therefore, the inductance in the hybrid connection is only slightly smaller than $L/2$. In this article, the difference is neglected. In addition, it is assumed that the temperature rise of PMs during a 3PSC is neglected.

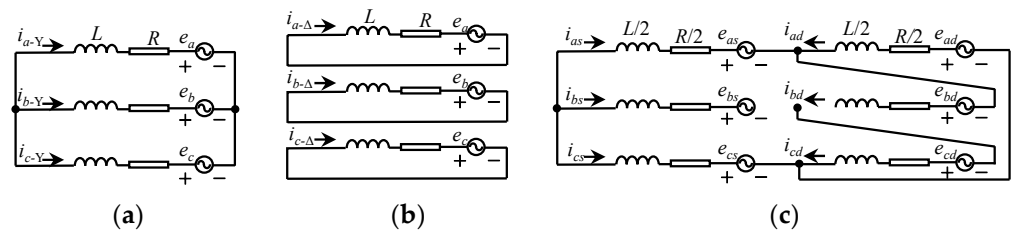


Figure 9. Equivalent circuits of 3PSC for different winding connections. (a) Star. (b) Delta. (c) Hybrid.

3.2. Analytical Model of the 3PSC

According to [31], 3PSC currents result from the back EMF and initial current whilst the back EMF leads to the dominant component. Therefore, the influence of the initial current is neglected in the article. For the star and delta connections, since the short-circuit current usually produces a voltage against the back EMF, the terminal voltage of each phase is approximately 0 V during a 3PSC. Therefore, when only the fundamental back-EMF is considered, the 3PSC currents for star and delta connections are almost the same.

However, when the phase third back-EMF harmonic is considered, it is compensated in each loop for the star connection and does not contribute to the 3PSC currents. For the delta connection, the third back-EMF harmonics cannot be compensated and lead to an additional 3PSC current component. Therefore, the third back-EMF harmonic is particularly considered when developing the 3PSC analytical model for the delta connection. To simplify the analysis, the core saturation is neglected. The 3PSC current in phase A is analyzed as an example. According to Figure 9b, when the 3PSC starts from α , the voltage equation of phase A can be expressed as

$$L \frac{di_{a-\Delta}}{dt} + Ri_{a-\Delta} = -e_a - e_{a3} = -E_{m1} \sin(\omega t + \alpha) - kE_{m3} \sin 3(\omega t + \alpha) \quad (11)$$

where E_{m3} is the third back-EMF harmonic amplitude. The coefficient k indicates the phase difference between the fundamental back EMF and the third harmonic, which equals 1 or -1 . By solving (11), the 3PSC current in phase A of the delta connection can be obtained as

$$i_{a-\Delta} = -\frac{E_{m1}}{\sqrt{\omega^2 L^2 + R^2}} \left[\sin(\omega t + \alpha - \varphi) + e^{-\frac{t}{\tau}} \sin(\varphi - \alpha) \right] - \frac{kE_{m3}}{\sqrt{(3\omega L)^2 + R^2}} \left[\sin(3\omega t + 3\alpha - \eta) + e^{-\frac{t}{\tau}} \sin(\eta - 3\alpha) \right] \quad (12)$$

where $\tau = L/R$, $\varphi = \arctan(\omega L/R)$, and $\eta = \arctan(3\omega L/R)$. It should be noted that the first term with only E_{m1} is exactly the phase A current of the star connection.

As for the hybrid connection, according to Figure 9c, the voltage equations during the 3PSC can be expressed as

$$\begin{cases} \frac{L}{2} \left(\frac{di_{as}}{dt} + \frac{di_{bd}}{dt} - \frac{di_{bs}}{dt} \right) + \frac{R}{2} (i_{as} + i_{bd} - i_{bs}) = -e_{as} + e_{bd} + e_{bs} \\ \frac{L}{2} \left(\frac{di_{bs}}{dt} + \frac{di_{cd}}{dt} - \frac{di_{cs}}{dt} \right) + \frac{R}{2} (i_{bs} + i_{cd} - i_{cs}) = -e_{bs} + e_{cd} + e_{cs} \\ \frac{L}{2} \left(\frac{di_{ad}}{dt} + \frac{di_{bd}}{dt} + \frac{di_{cd}}{dt} \right) + \frac{R}{2} (i_{ad} + i_{bd} + i_{cd}) = e_{ad} + e_{bd} + e_{cd} \end{cases} \quad (13)$$

It should be noted that the third back-EMF harmonic is not considered since it does not lead to the main difference between star/delta and hybrid connections. Taking the star-side phase A and delta-side phase B as examples, 3PSC current can be solved as

$$i_{as} = \frac{\sqrt{12 + 6\sqrt{3}}}{4 \cos(\pi/12)} \frac{E_{m1}}{\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \varphi + \frac{\pi}{12}\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \varphi - \frac{\pi}{12}\right) \right) \quad (14)$$

and

$$i_{bd} = \frac{\sqrt{4+2\sqrt{3}}}{4\cos(\pi/12)} \frac{E_{m1}}{\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \varphi + \frac{\pi}{4}\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \varphi - \frac{\pi}{4}\right) \right) \quad (15)$$

Based on the above analytical models, the largest peak currents for different connections can be obtained. Taking (14) as an example, the star-side current of hybrid connection consists of the steady and transient components. Since the short-circuit peak current increases with angular speed, it is assumed that ω is large enough to get the largest value. Under such condition, the transient component almost does not decay and φ is approximately $\pi/2$. To get the largest peak current, it is necessary to maximize both the steady and transient components at the same time, which requires

$$\begin{cases} -\alpha + \varphi - \frac{\pi}{12} = \frac{\pi}{2} + k\pi \\ \omega t + \alpha - \varphi + \frac{\pi}{12} = \frac{\pi}{2} + k\pi \end{cases} \quad (16)$$

Therefore, α and ωt should be $-\pi/12 + k\pi$ and π , respectively. This means that, when the 3PSC starts at the rotor position $-\pi/12 + k\pi$ and the rotor rotates π after a 3PSC, the peak current occurs, which is larger than the peak current starts at other rotor positions. The largest peak currents of other winding connections and the corresponding conditions, including the star rotor position and rotor position after a 3PSC, are summarized in Table 2. For the star and delta connection, it shows that the effect of the third back-EMF harmonic heavily depends on the coefficient k . The additional 3PSC current component caused by the third back-EMF harmonic increases the peak current from the fundamental back-EMF when k equals 1. When k equals -1 , the phase peak currents are reduced. In addition, the star-side peak current of the hybrid connection is the largest, which is about 1.23 times that of the star connection. Moreover, the delta-side peak current is the smallest, which is about 0.71 times that of the star connection.

Table 2. The largest 3PSC peak currents and corresponding conditions.

The Largest 3PSC Peak Currents		Conditions	
		Start Rotor Position	Rotor Position after 3PSC
Star	$i_{a-Y-peak} = \frac{2E_{m1}}{\omega L}$	$\alpha = k\pi$ (k is integer)	$\omega t = \pi$
Delta	$i_{a-\Delta-peak} = \frac{2E_{m1}}{\omega L} + \frac{2kE_{m3}}{3\omega L}$	$\alpha = k\pi$	$\omega t = \pi$
Hybrid, star-side	$i_{as-peak} = \frac{\sqrt{12+6\sqrt{3}}E_{m1}}{2\cos(\pi/12)\omega L} \approx 2.45 \frac{E_{m1}}{\omega L}$	$\alpha = -\pi/12 + k\pi$	$\omega t = \pi$
Hybrid, delta-side	$i_{bd-peak} = \frac{\sqrt{4+2\sqrt{3}}E_{m1}}{2\cos(\pi/12)\omega L} \approx 1.41 \frac{E_{m1}}{\omega L}$	$\alpha = -\pi/4 + k\pi$	$\omega t = \pi$

3.3. FE Analysis Considering Demagnetization

To verify the above analysis, an FE simulation was conducted on the SPM machine in Figure 2a. The variations in 3PSC peak current with start rotor position are shown in Figure 10. The PM temperature was 100 °C and its influence will be investigated later. It can be found that the 3PSC start rotor positions leading to the largest peak current correspond to the analytical results. The largest peak current of the delta connection was 46.3 A, which was slightly larger than that of the star connection, at 44.3 A. This is because $k = 1$, which can be obtained in Figure 6b, and the third back-EMF harmonic increases the peak current from the fundamental back-EMF. In the hybrid connection, the star-side largest peak current of 53.6 A was about 1.21 times the value of the star connection, which is close to the analytical results.

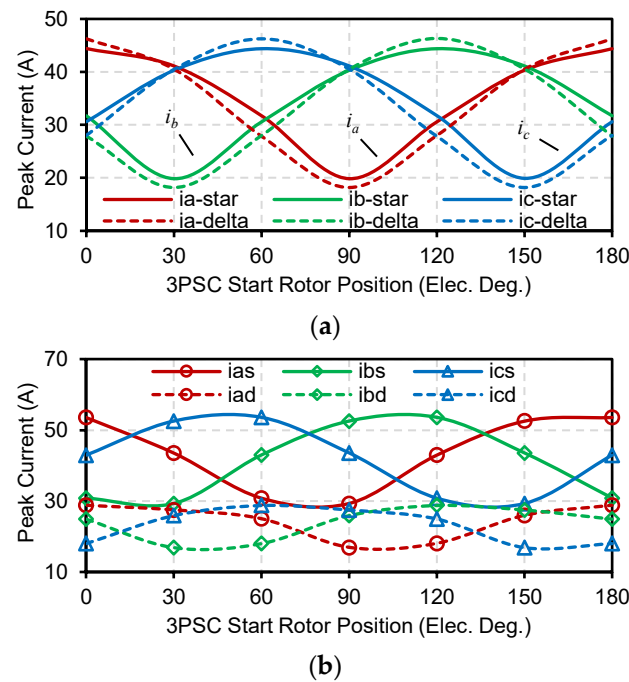


Figure 10. Variations in the 3PSC peak current with start rotor position for different connections. (a) Star and delta. (b) Hybrid.

As for demagnetization, the overall demagnetization level is evaluated by torque loss, which is defined as

$$\text{Torque Loss} = \frac{T_{\text{before}} - T_{\text{after}}}{T_{\text{before}}} \times 100\% \quad (17)$$

where T_{before} and T_{after} are the average torque before and after demagnetization. In addition, before the demagnetization caused by the 3PSC was investigated, the phase current threshold, under which the demagnetization does not occur or is negligible, was first analyzed. It was obtained as follows. DC currents of different values are first input into a single phase to demagnetize PMs when the SPM machine rotates an electrical period. Then, the torque loss is also calculated by (8). The variation in torque loss with DC current value is shown in Figure 11. It can be found that the phase current thresholds are about 20 A, 30 A, and 40 A for the PM temperatures of 90 °C, 100 °C, and 110 °C, respectively. It should be noted that when the DC current exceeds the threshold, the resulting torque loss can be overestimated, compared to the 3PSC with the same peak currents. Nevertheless, it can still be concluded the demagnetization level almost increases linearly with peak current when it is larger than the threshold.

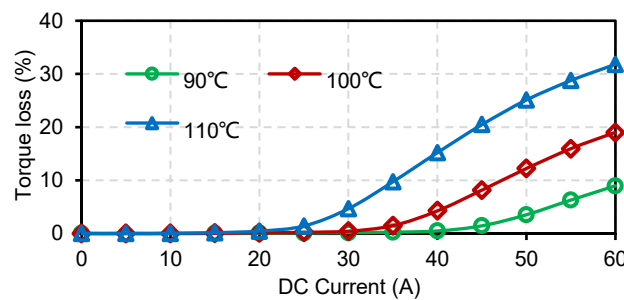


Figure 11. The variation in torque loss with DC current value under different PM temperatures.

The variations in torque loss with 3PSC start rotor position for different winding connections are shown in Figure 12, which repeat every $\pi/3$ in an electrical period. This is because the variation in peak currents in each phase with 3PSC start rotor position

repeats every π in an electrical period, as shown in Figure 10. However, since the three phases are balanced, the variation in peak currents with 3PSC start rotor position repeats every $\pi/3$ from the view of three phases, which makes the variation in torque loss also repeat every $\pi/3$. For the star and delta connections, the peak torque losses are 6.14% and 6.20%, respectively, which occur when $\alpha = \pi/6$. From Figure 10a, the phase B current is smaller than 30 A, which hardly contributes to torque loss. The phase A and C peak currents lead to the main demagnetization. Consequently, the difference between the star and delta connections is negligible, which can also be seen from the demagnetization ratio distribution of PMs shown in Figure 13a,b. The demagnetization ratio is defined as

$$\text{Demagnetization Ratio} = \frac{B_{r_before} - B_{r_after}}{B_{r_before}} \times 100\% \quad (18)$$

where B_{r_before} and B_{r_after} are the PM remanence before and after demagnetization, respectively. As for the hybrid connection, the torque loss is larger than that of the delta/star connection since the peak current is much larger, and the corresponding demagnetization ratio distribution is shown in Figure 13c.

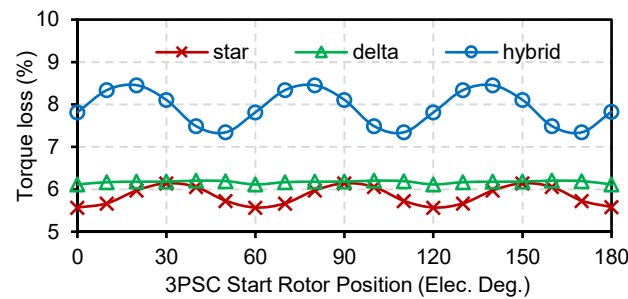


Figure 12. Torque loss under different 3PSC start rotor positions for different winding connections under PM temperature 100 °C.

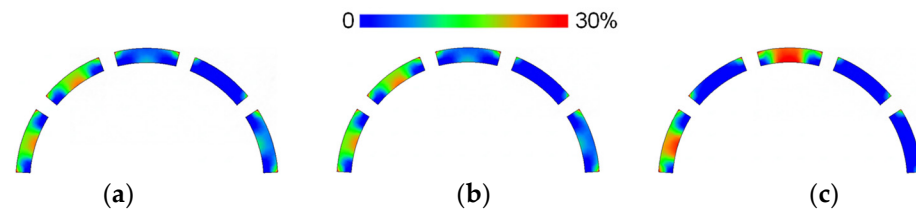


Figure 13. Demagnetization ratio of PMs under 3PSC when $\alpha = \pi/6$. (a) Star. (b) Delta. (c) Hybrid.

3.4. Influence of PM Temperature

PM temperature has a significant effect on both remanence and coercivity. However, the coercivity is more sensitive to PM temperature. Therefore, when PM temperature increases, the short-circuit current decreases, whereas the demagnetization deteriorates.

As shown in Figure 14a, when the PM temperature decreases to 90 °C, although the start rotor positions leading to the largest torque loss can shift, the relationships of torque loss in star, delta, and hybrid connections are similar to that under a PM temperature of 100 °C. This is mainly because the current threshold increases, which means the demagnetization level further depends on the largest peak current. When the PM temperature increases to 110 °C, as shown in Figure 14b, the hybrid connection still leads to the severest torque loss. However, the torque loss of the star connection exceeds that of the delta connection. Taking the peak torque loss at $\alpha = \pi/6$ as examples, the phase A and C currents are close for the star and delta connections whilst the phase B current is larger in the star connection, as shown in Figure 10a. Under a PM temperature of 110 °C, the current threshold leading to demagnetization decreases. Therefore, the phase B current also leads to demagnetization, and thus the torque loss is larger in the star connection.

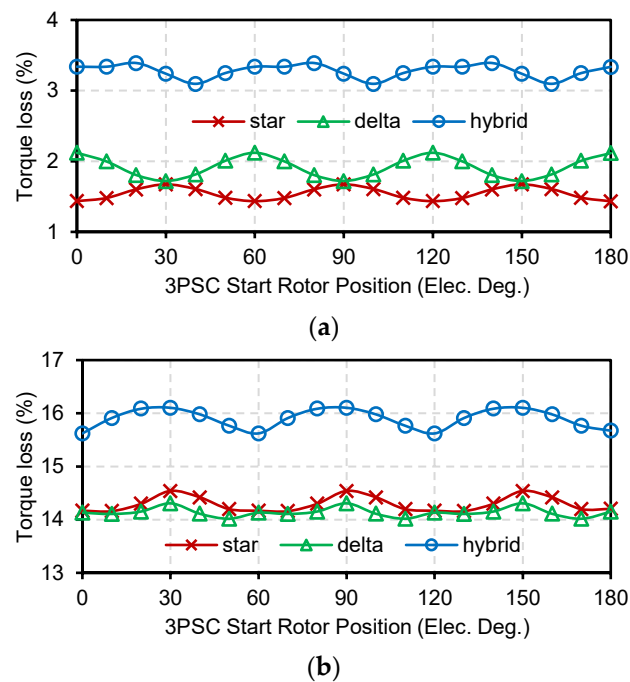


Figure 14. Variation in torque loss with 3PSC start rotor positions under different PM temperatures. (a) 90 °C. (b) 110 °C.

Considering the demagnetization under high PM temperatures is much more severe, which is usually not allowed when designing practical SPM machines, and the difference between the star and delta winding connections is negligible, the star connection should be adopted in the investigated SPM machine to mitigate demagnetization risk. In SPM machines with the fundamental back EMF and the third harmonic in the opposite phase, the delta connection can be the better selection for applications requiring high reliabilities.

As aforementioned, the 3PSC peak current increases with rotor speed. However, according to (12) and (14), the comparison result of peak currents in different winding connections does not change. In addition, the demagnetization deteriorates when the rotor speed increases, which is similar to increasing the PM temperature. Therefore, their effects on the comparison result of torque loss are also similar.

4. Comparison of the 2PSC and Demagnetization

4.1. Equivalent Circuits of the 2PSC

The 2PSC happens when the terminals *a* and *b* in Figure 1 are short-circuited and the equivalent circuits for different winding connections are shown in Figure 15.

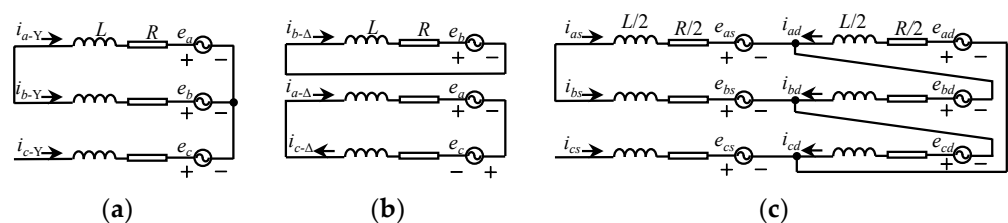


Figure 15. Equivalent circuits of the 2PSC for different winding connections. (a) Star. (b) Delta. (c) Hybrid.

4.2. Analytical Model of the 2PSC

The 2PSC current is analytically modelled with the same assumptions as those in the previous section. The third back-EMF harmonic is neglected since it is not the main reason for the difference of 2PSC current in the three winding connections. According

to the equivalent circuits in Figure 15a and Kirchhoff's voltage law, the voltage equation during 2PSC for the star connection is

$$L \frac{di_{a-Y}}{dt} + Ri_{a-Y} + e_a = L \frac{di_{b-Y}}{dt} + Ri_{b-Y} + e_b \quad (19)$$

In addition, the relationship between the phase A and B currents can be expressed as

$$i_{a-Y} = -i_{b-Y} \quad (20)$$

Therefore, the voltage equation of (19) can be rewritten as

$$2L \frac{di_{a-Y}}{dt} + 2Ri_{a-Y} = -e_a + e_b \quad (21)$$

By solving this first order non-homogeneous linear differential equation, the 2PSC currents can be obtained, which are

$$i_{a-Y} = -i_{b-Y} = -\frac{\sqrt{3}E_{m1}}{2\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha + \frac{\pi}{6} - \varphi\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha - \frac{\pi}{6} + \varphi\right) \right) \quad (22)$$

Similarly, according to the equivalent circuits in Figure 15b, the voltage equations during the 2PSC for the delta connection can be expressed as

$$\begin{cases} L \frac{di_{b-\Delta}}{dt} + Ri_{b-\Delta} = -e_b \\ 2L \frac{di_{a-\Delta}}{dt} + 2Ri_{a-\Delta} = -e_a - e_c \end{cases} \quad (23)$$

By solving (23), the 2PSC currents for the delta connection can be obtained as

$$\begin{cases} i_{b-\Delta} = -\frac{E_{m1}}{\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \frac{2\pi}{3} - \varphi\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \frac{2\pi}{3} + \varphi\right) \right) \\ i_{a-\Delta} = i_{c-\Delta} = \frac{E_{m1}}{2\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \frac{2\pi}{3} - \varphi\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \frac{2\pi}{3} + \varphi\right) \right) \end{cases} \quad (24)$$

This shows that the phase B current of the delta connection is twice the phase A or C current yet in the opposite phase.

As for the hybrid connection, according to Figure 15c, the voltage equations are

$$\begin{cases} \frac{L}{2} \left(\frac{di_{as}}{dt} + \frac{di_{bd}}{dt} - \frac{di_{bs}}{dt} \right) + \frac{R}{2} (i_{as} + i_{bd} - i_{bs}) = -e_{as} + e_{bd} + e_{bs} \\ \frac{L}{2} \left(\frac{di_{bd}}{dt} + 2 \frac{di_{cd}}{dt} \right) + \frac{R}{2} (i_{bd} + 2i_{cd}) = e_{ad} + e_{bd} + e_{cd} \end{cases} \quad (25)$$

By solving (25), the star-side currents can be solved as

$$i_{as} = -i_{bs} = \frac{3\sqrt{4+2\sqrt{3}}E_{m1}}{8\cos(\pi/12)\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \varphi + \frac{\pi}{4}\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \varphi - \frac{\pi}{4}\right) \right) \quad (26)$$

The delta-side currents are

$$\begin{cases} i_{bd} = \frac{\sqrt{4+2\sqrt{3}}E_{m1}}{4\cos(\pi/12)\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \varphi + \frac{\pi}{4}\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \varphi - \frac{\pi}{4}\right) \right) \\ i_{ad} = i_{cd} = -\frac{\sqrt{4+2\sqrt{3}}E_{m1}}{8\cos(\pi/12)\sqrt{\omega^2 L^2 + R^2}} \left(\sin\left(\omega t + \alpha - \varphi + \frac{\pi}{4}\right) + e^{-\frac{t}{\tau}} \sin\left(-\alpha + \varphi - \frac{\pi}{4}\right) \right) \end{cases} \quad (27)$$

It can be found that the star-side current is 1.5 times the larger one of the delta-side current and three times the smaller one. In addition, the star-side phase A current is in the same phase as the delta-side phase B current, which is opposite to other phases.

Based on the above analytical models and using a similar method to that analyzing the 3PSC peak currents, the peak currents for each winding connection and the corresponding conditions are summarized in Table 3. It can be found that the hybrid connection leads to the largest peak current, which is about 1.06 times that of the delta connection and 1.22 times that of the star connection. In addition, compared to the 3PSC, the 2PSC peak currents of star and hybrid connections are smaller, whilst the 2PSC current of the delta connection is comparable.

Table 3. The largest 2PSC peak currents and corresponding conditions.

The Largest 2PSC Peak Currents		Conditions	
		Start Rotor Position	Rotor Position after 3PSC
Star	$i_{a-Y-peak} = \frac{\sqrt{3}E_{m1}}{\omega L}$	$\alpha = -\pi/6 + k\pi$ (k is integer)	$\omega t = \pi$
Delta	$i_{b-\Delta-peak} = \frac{2E_{m1}}{\omega L}$	$\alpha = 2\pi/3 + k\pi$	$\omega t = \pi$
Hybrid, star-side	$i_{as-peak} = \frac{3\sqrt{4+\sqrt{3}E_{m1}}}{4\cos(\pi/12)\omega L} \approx \frac{2.12E_{m1}}{\omega L}$	$\alpha = -\pi/4 + k\pi$	$\omega t = \pi$
Hybrid, delta-side	$i_{as-peak} = \frac{\sqrt{4+2\sqrt{3}E_{m1}}}{2\cos(\pi/12)\omega L} \approx \frac{1.41E_{m1}}{\omega L}$	$\alpha = -\pi/4 + k\pi$	$\omega t = \pi$

4.3. FE Analysis Considering Demagnetization

Based on the SPM machines in Figure 2a, the variations in 2PSC peak currents with start rotor position for different winding connections are shown in Figure 16. It can be found that the start rotor positions leading to the largest peak current correspond to the analytical results. The peak currents for the star, delta, and hybrid connections are 38.5 A, 46.4 A, and 47.4 A, respectively. The peak current of the hybrid connection is about 1.02 times the value of the delta connection and 1.23 times the peak current of the star connection, which is close to the analytical results. The slight difference can be attributed to the neglected core saturation effect.

The variations in torque loss with start rotor position are shown in Figure 17. The demagnetization ratio distribution corresponding to the peak torque loss for each winding connection is shown in Figure 18. Different from the torque loss caused by the 3PSC, the variation in torque loss with the 2PSC start rotor position repeats every π . In addition, the 2PSC start rotor positions leading to the peak torque loss are almost the same as those resulting in the largest peak currents for each winding connection. At such start rotor positions, the largest peak torque loss of 6.1% happens in the hybrid connection due to the maximum peak current, which is shown in Figure 16c. Moreover, the peak torque loss of the star connection is the least severe due to the smallest peak current. Compared to the torque loss in the 3PSC, as shown in Figure 12, the 2PSC generally results in less severe demagnetization. This is not only because the 2PSC peak currents are smaller than the 3PSC peak currents, but also because there are fewer faulty coils.

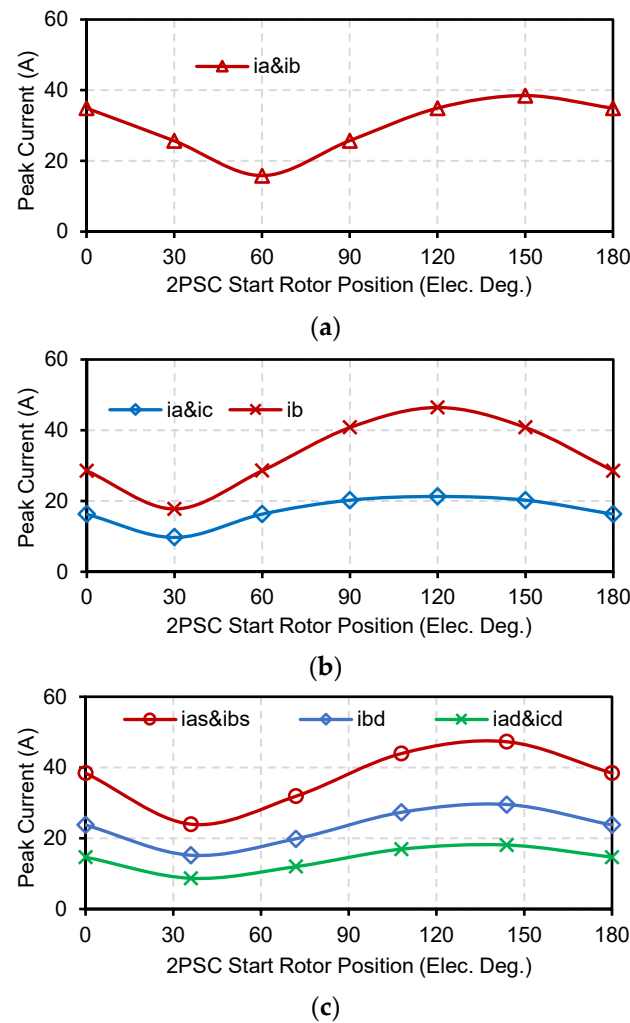


Figure 16. Variations in 2PSC peak currents with start rotor position for different winding connections. (a) Star. (b) Delta. (c) Hybrid.

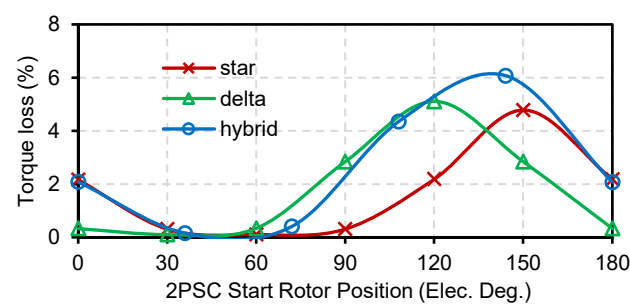


Figure 17. Variation in torque loss with the 2PSC start rotor position under PM temperature 100 °C for different winding connections.

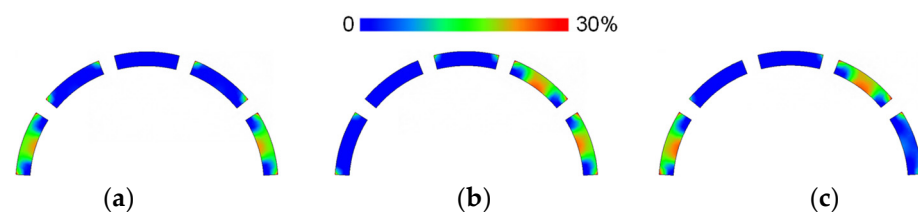


Figure 18. Demagnetization ratio distribution for PMs under the 2PSC. (a) Star. (b) Delta. (c) Hybrid.

4.4. Influence of PM Temperature

The variations in torque loss with the 2PSC start rotor position under different PM temperatures are shown in Figure 19. It can be found that the hybrid connection still leads to the largest peak torque loss. As for the star and delta connections, when the current threshold leading to demagnetization increases with lower PM temperature, the torque loss is further determined by the largest peak currents. Therefore, the star connection still leads to smaller peak torque loss when PM temperature decreases to 90 °C. On the contrary, when PM temperature increases to 110 °C, although the delta connection still leads to larger peak current, it only exists in phase B and the peak current of other phases is smaller than the phase A peak current in the star connection, as shown in Figure 16. Hence, the delta connection leads to smaller peak torque loss. Considering the demagnetization under a high demagnetization level is not acceptable in practice and the difference is slight, the star connection can be a better selection against demagnetization.

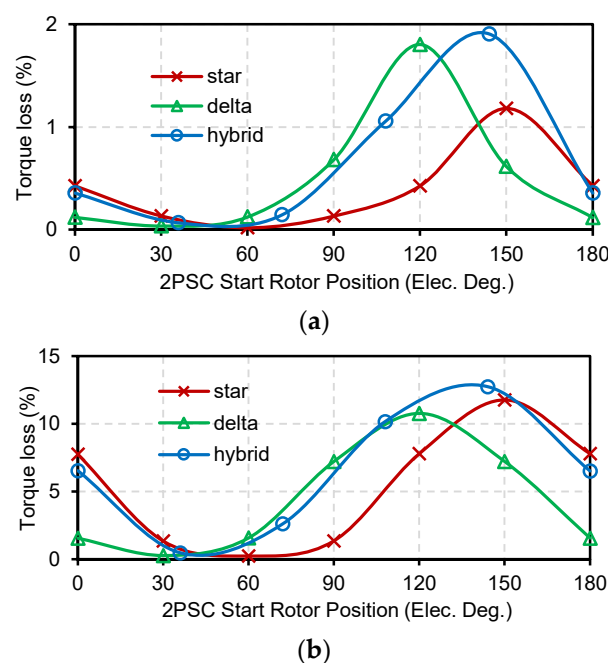


Figure 19. Variation in torque loss with the 2PSC start rotor positions under different PM temperatures. (a) 90 °C. (b) 110 °C.

5. Experimental Validation

Since short-circuit and demagnetization tests are dangerous and even destructive, only the 3PSC at low rotor speed was experimentally validated on a star-connected SPM machine. Nevertheless, the accuracy of the analytical model and FE analysis can still be verified, as well as the above theoretical analysis.

5.1. Prototype Machine and Experimental Setup

The prototype 10-pole/12-slot SPM machine is shown in Figure 20. The parameters are shown in Table 4. The back EMF of the prototype SPM machine is shown in Figure 21. It can be found that the amplitude of measured back EMF is slightly smaller than the predicted results due to the end effect.

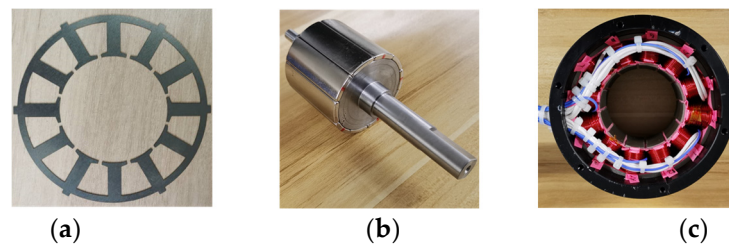


Figure 20. Prototype SPM machine. (a) Steel sheet. (b) Rotor. (c) Stator.

Table 4. Parameters of prototype SPM machine.

Parameters	Value	Parameters	Value
Stator outer radius	50 mm	Rotor outer radius	28 mm
Airgap length	1 mm	Magnet thickness	3 mm
Stack length	50 mm	Pole-arc to pole-pitch ratio	1
Number of turns/coil	70	Coil resistance	0.45 Ω
Sheet material	35WW400	PM material	N52

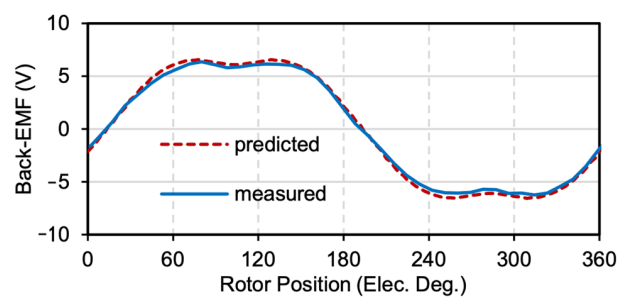


Figure 21. FE predicted and measured back EMF waveforms under rotor speed of 400 rpm.

The test setup for the 3PSC experiment is shown in Figure 22. The windings are connected to a three-phase inverter and controlled by the dSPACE controller. The experiments are conducted under an ambient temperature of about 20 °C. Before each time of the 3PSC experiment, the prototype SPM machine was naturally cooled down to the ambient temperature. Therefore, the winding and PM temperature can be approximately regarded as being unchanged for each time of the experiment to make a fair comparison. In the experiments, the prototype SPM machine was first dragged to 400 rpm by a servo motor. The 3PSC was started by forcing the duty cycle to be 1 for all upper switches. In addition, the 3PSC started at different rotor positions from the open-circuit state.

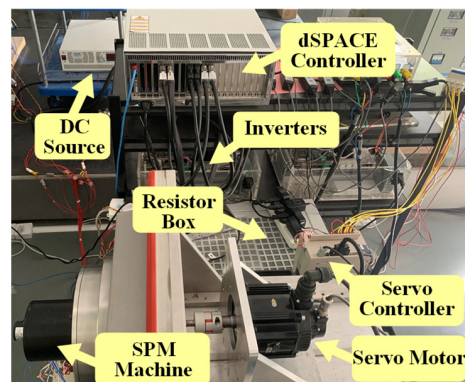


Figure 22. Test setup of the 3PSC.

5.2. Experimental Results and Discussion

The 3PSC current waveforms by analytical, FE, and experimental methods are shown in Figure 23. In the analytical model, the open-circuit inductance and the fundamental back EMF from the FE simulation are adopted. Considering the short-circuit current can lead to core saturation, the 3PSC current calculated by the analytical model is smaller than the FE results. For the measured results, since the 3PSC leads to braking torque, which reduces the rotor speed, the transient current is smaller than the FE predicted results. In the steady state, since the back EMF is slightly smaller than the FE predicted results, the steady current is also smaller. Nevertheless, the 3PSC current waveforms match well with each other.

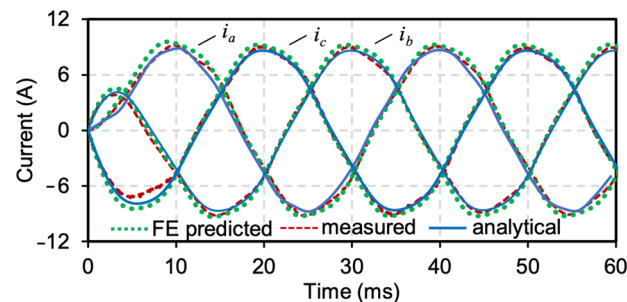


Figure 23. Current waveforms at the 3PSC start rotor position 0.

The 3PSC experiments from different rotor positions were also conducted. As shown in Figure 24, the start rotor positions lead to the largest peak current shift because the rotor speed is not large enough to neglect the resistance. However, the results from the analytical model, FE simulation, and experiments are close to each other. Therefore, the analytical and FE methods have decent accuracy and the above theoretical analysis is verified.

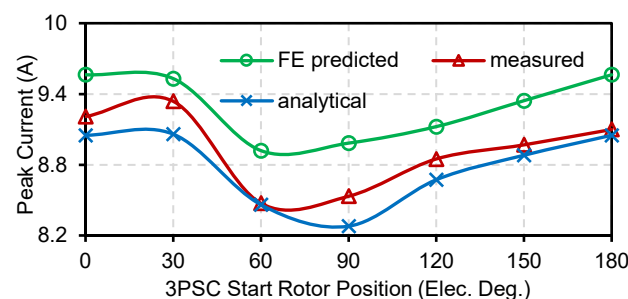


Figure 24. Variation in phase A peak currents with the 3PSC start rotor position.

6. Conclusions

This article comprehensively compares the 2PSC/3PSC and irreversible demagnetization in different winding connections for SPM machines, including the star, delta, and hybrid connections.

It was found that when a 3PSC or 2PSC happens, the peak current is the largest in the hybrid connection, which further results in the severest demagnetization. Therefore, the hybrid connection is not suitable for safety-critical applications.

In addition, a delta connection always leads to a larger 2PSC peak current than the star connection. Under relatively low PM temperature, the delta connection leads to more severe demagnetization than the star connection. However, when PM temperature increases, the opposite condition can occur. Nevertheless, since the overall demagnetization level is high, the demagnetization difference at high PM temperature can be neglected. Hence, the star connection has better withstanding capability against the 2PSC and demagnetization.

As for the 3PSC, whether the peak current of the delta connection exceeds that of the star connection is determined by the phase of the third back-EMF harmonic. The

delta connection shows a higher 3PSC peak current when the third harmonic is in phase with the fundamental back EMF, and conversely, the star connection shows higher peak current. Similar to the 2PSC, the difference in demagnetization is more obvious when the PM temperature is relatively low, where demagnetization is mainly influenced by the largest peak current. Therefore, which winding connection should be selected to mitigate demagnetization also depends on the phase of the third back-EMF harmonic.

Finally, experiments were conducted to verify the theoretical analysis.

It should be noted that, although the above conclusions are developed based on the investigated small-size SPM machine, they are also applicable to SPM machines with larger size and higher PM volume.

Author Contributions: Conceptualization, J.C., Y.D. and H.Z.; methodology, J.C.; software, Y.D.; validation, J.C., Y.D. and H.Z.; formal analysis, J.C.; investigation, J.C.; resources, Y.D. and H.Z.; data curation, J.C. and Y.D.; writing—original draft preparation, J.C. and Y.D.; writing—review and editing, J.C., Y.D., K.Z. and Y.S.; visualization, Y.D.; supervision, H.Z., K.Z. and Y.S.; project administration, J.C., Y.D. and H.Z.; funding acquisition, Y.D., H.Z., K.Z. and Y.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Jiangsu Funding Program for Excellent Postdoctoral Talent, and the funding number is 2023ZB259.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no potential conflicts of interest of this article.

References

1. Wu, L.; Du, Y.; Chen, Z.; Guo, Y.; Wen, H.; Fang, Y. Influence of Load Characteristics on Three-Phase Short Circuit and Demagnetization of Surface-Mounted PM Synchronous Motor. *IEEE Trans. Ind. Appl.* **2020**, *56*, 2427–2440. [\[CrossRef\]](#)
2. Darmani, M.A.; Poskovic, E.; Bramerdorfer, G.; Vaschetto, S.; Cavagnino, A.; Tenconi, A. Surface-mounted and flux-switching pm structures trade-off for automotive smart actuators. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 6555–6561. [\[CrossRef\]](#)
3. Chen, H.; El-Refaie, A.M.; Demerdash, N.A.O. Flux-Switching Permanent Magnet Machines: A Review of Opportunities and Challenges—Part I: Fundamentals and Topologies. *IEEE Trans. Energy Convers.* **2019**, *35*, 684–698. [\[CrossRef\]](#)
4. Ibrahim, M.N.; Silwal, B.; Sergeant, P. Permanent magnet-assisted-assisted synchronous reluctance motor employing a hybrid star-delta winding for high-speed applications. In Proceedings of the 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, Greece, 3–6 September 2018; pp. 379–385. [\[CrossRef\]](#)
5. Ibrahim, M.N.; Abdel-Khalik, A.S.; Rashad, E.M.; Sergeant, P. Comparison between two combined star-delta configurations on synchronous reluctance motors performance. In Proceedings of the 2017 20th International Conference on Electrical Machines and Systems (ICEMS), Sydney, NSW, Australia, 11–14 August 2017; pp. 1–5. [\[CrossRef\]](#)
6. Silwal, B.; Ibrahim, M.N.; Sergeant, P. Synchronous reluctance machine: Combined star-delta winding and rotor eccentricity. In Proceedings of the 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, Greece, 3–6 September 2018; pp. 427–432. [\[CrossRef\]](#)
7. Yu, J.; Yang, J.; Li, Q.; Zhao, X.; Huang, S.; Huang, S. An improved two-terminal hybrid connection method to reduce the armature winding MMF space harmonics of asymmetric six-phase machine. In Proceedings of the 2023 26th International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 5–8 November 2023; pp. 2594–2599. [\[CrossRef\]](#)
8. Yang, S.; Tong, C.; Sui, Y.; Zhou, Z.; Zheng, P. Three-phase current-source inverter-based PMSM control scheme considering star and delta winding connections. In Proceedings of the 2022 25th International Conference on Electrical Machines and Systems (ICEMS), Chiang Mai, Thailand, 29 November–2 December 2022; pp. 1–5. [\[CrossRef\]](#)
9. Decker, S.; Rollbuhler, C.; Brodatzki, M.; Rehm, F.; Liske, A.; Hiller, M. Comparison of losses in small star and delta-connected permanent magnet synchronous machines. In Proceedings of the 2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe), Ghent, Belgium, 6–10 September 2021; pp. 1–10. [\[CrossRef\]](#)
10. Rehm, F.; Breining, P.; Decker, S.; Kolb, J.; Hiller, M. Loss comparison of small delta- and star-connected permanent magnet synchronous machines. In Proceedings of the IECON 2019—45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 14–17 October 2019; pp. 1171–1176. [\[CrossRef\]](#)
11. Odawara, S.; Fujisaki, K.; Fukuhara, S. Investigation on iron loss characteristics in star-connection and delta-connection under three phase PWM inverter excitation. In Proceedings of the 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 ECCE-ASIA), Hiroshima, Japan, 18–21 May 2014; pp. 289–293. [\[CrossRef\]](#)
12. Ferreira, F.; de Almeida, A. Method for In-Field Evaluation of the Stator Winding Connection of Three-Phase Induction Motors to Maximize Efficiency and Power Factor. *IEEE Trans. Energy Convers.* **2006**, *21*, 370–379. [\[CrossRef\]](#)

13. Ibrahim, M.N.F.; Abdel-Khalik, A.S.; Rashad, E.E.M.; Sergeant, P. An Improved Torque Density Synchronous Reluctance Machine with a Combined Star-Delta Winding Layout. *IEEE Trans. Energy Convers.* **2017**, *33*, 1015–1024. [\[CrossRef\]](#)
14. Kasten, H.; Hofmann, W. Electrical machines with higher efficiency through combined star-delta windings. In Proceedings of the 2011 IEEE International Electric Machines & Drives Conference (IEMDC), Niagara Falls, ON, Canada, 15–18 May 2011; pp. 1374–1379. [\[CrossRef\]](#)
15. Ibrahim, M.N.; Sergeant, P.; Rashad, E.E.M. Performance comparison of conventional synchronous reluctance machines and PM-assisted types with combined star-delta winding. *Energies* **2017**, *10*, 1500. [\[CrossRef\]](#)
16. Ibrahim, M.N.; Sergeant, P.; Rashad, E.E.M. Combined Star-Delta Windings to Improve Synchronous Reluctance Motor Performance. *IEEE Trans. Energy Convers.* **2016**, *31*, 1479–1487. [\[CrossRef\]](#)
17. Bianchi, N.; Cinti, L.; Contó, C.; Ortombina, L. Experimental tests of fractional-slot SPM motor with star-delta windings. In Proceedings of the 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 29 October–2 November 2023; pp. 4414–4420. [\[CrossRef\]](#)
18. Wang, B.; Luo, L.; Hua, W.; Cheng, M.; Niu, S. High Performance and Strong Fault Tolerant Triple 3-phase PMA-SynRM with Star-delta Windings. *IEEE Trans. Energy Convers.* **2022**, *37*, 1977–1986. [\[CrossRef\]](#)
19. Ferreira, F.J.T.E. On the star, delta and star-delta stator winding connections tolerance to voltage unbalance. In Proceedings of the IEEE International Electric Machines & Drives Conference (IEMDC), Coeur d’Alene, ID, USA, 10–13 May 2015; pp. 1888–1894. [\[CrossRef\]](#)
20. Mahmouditabar, F.; Vahedi, A.; Marignetti, F. The Demagnetization Phenomenon in PM Machines: Principles, Modeling, and Design Considerations. *IEEE Access* **2023**, *11*, 47750–47773. [\[CrossRef\]](#)
21. Choi, G.; Jahns, T.M. Post-demagnetization characteristics of permanent magnet synchronous machines. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition, Montreal, QC, Canada, 20–24 September 2015; pp. 1781–1788. [\[CrossRef\]](#)
22. Chen, Z.; Fan, C.; Wan, X.; Ling, Z.; Wang, F. Demagnetization fault analysis of FSCW-PMM with four-layer star-delta winding. In Proceedings of the 2023 26th International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 5–8 November 2023; pp. 4977–4980. [\[CrossRef\]](#)
23. Xiao, L.; Yu, G.; Zou, J.; Xu, Y.; Zheng, B.; Liu, C. Experimental investigation of the relationship between magnetic properties of permanent magnet against temperature and pressure coupling environment. In Proceedings of the 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), Harbin, China, 11–14 August 2019; pp. 1–5. [\[CrossRef\]](#)
24. Valle, R.L.; de Almeida, P.M.; Fogli, G.A.; Ferreira, A.A.; Barbosa, P.G. Simple and Effective Digital Control of a Variable-Speed Low Inductance BLDC Motor Drive. *IEEE Access* **2020**, *8*, 13240–13250. [\[CrossRef\]](#)
25. Du, Y.; Dong, Z.; Zhan, H.; Wu, L.; Zhou, K.; Yu, L.; Fang, Y.; Sun, L. Investigation of Post-Demagnetization Torque Ripple in Fractional-Slot Surface-Mounted PM Wind Power Generators after Short Circuit Faults. *IEEE Trans. Ind. Appl.* **2024**, *60*, 1. [\[CrossRef\]](#)
26. Peng, W.; Kun, W.; Meng, F. Demagnetization study of permanent magnet machine under three phase short circuit. In Proceedings of the 2023 IEEE 6th International Electrical and Energy Conference (CIEEC), Hefei, China, 12–14 May 2023; pp. 2705–2710. [\[CrossRef\]](#)
27. Welchko, B.; Jahns, T.; Soong, W.; Nagashima, J. IPM synchronous machine drive response to symmetrical and asymmetrical short circuit faults. *IEEE Trans. Energy Convers.* **2003**, *18*, 291–298. [\[CrossRef\]](#)
28. Choi, G.; Jahns, T.M. Investigation of key factors influencing the response of permanent magnet synchronous machines to three-phase symmetrical short-circuit faults. *IEEE Trans. Energy Convers.* **2016**, *31*, 1488–1497. [\[CrossRef\]](#)
29. Seo, M.-K.; Lee, T.-Y.; Ko, Y.-Y.; Kim, Y.-J.; Jung, S.-Y. Irreversible Demagnetization Analysis with Respect to Winding Connection and Current Ripple in Brushless DC Motor. *IEEE Trans. Appl. Supercond.* **2018**, *28*, 5203604. [\[CrossRef\]](#)
30. Lei, Y.; Zhao, Z.; Wang, S.; Dorrell, D.G.; Xu, W. Design and Analysis of Star-Delta Hybrid Windings for High-Voltage Induction Motors. *IEEE Trans. Ind. Electron.* **2010**, *58*, 3758–3767. [\[CrossRef\]](#)
31. Chu, W.Q.; Zhu, Z.Q. Analytical modeling and investigation of transient response of PM machines with 3-phase short-circuit fault. In Proceedings of the 2011 IEEE International Electric Machines & Drives Conference (IEMDC), Niagara Falls, ON, Canada, 15–18 May 2011; pp. 125–130. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.