AC Transport Loss in Superconductors Carrying Harmonic Current with Different Phase Angles for Large Scale Power Components

Mohammad Yazdani-Asrami, *Member, IEEE*, Wenjuan Song, *Member, IEEE*, Min Zhang, *Member, IEEE*, Weijia Yuan, *Senior Member, IEEE*, and Xiaoze Pei

Abstract— **It is of great industrial interest and academic importance to investigate current harmonics impacts on AC losses of superconductors, especially in large scale power devices. However, only effect of amplitude of in-phase current harmonics on AC loss has been studied in literatures. We numerically characterized nonsinusoidal AC loss of superconducting tape carrying harmonic currents with orders below 20th versus phase angles. A drastic AC loss variation was found when phase angle was considered for harmonic components. We observed that different harmonic orders show different AC loss profile versus phase angle.**

Index Terms— **AC loss, Harmonic phase angle, HTS tapes, Nonsinusoidal current.**

I. INTRODUCTION

SUPERCONDUCTIVITY is a key technology for modernizing large scale power components, since high temperature superconducting (HTS) devices will bring many advantages over their conventional counterparts, such as higher efficiency, less energy consumption, compactness, lighter weight, and lower loss. HTS technology helps manufacture transformers, cables, motors, and generators with higher current density, and higher power to weight ratio and torque to weight ratio [1-4].

AC loss in HTS windings is one of the most critical aspects to consider during R&D stage for any large scale HTS electric application. AC loss, as a source of heat load, is closely linked with the thermal load and efficiency of cryogenic cooling system, which adjusts and maintains the operating temperature of HTS components [5-6]. It is vital to accurately estimate AC losses in HTS devices under real operating conditions for designing efficient and reliable cooling system.

Nowadays, AC/DC converters and nonlinear loads are widely used in power grids, industries, and also in different transportation systems, including aerospace, railway, and naval applications [7-10]. Current harmonics, therefore, are inevitably produced inside power system, with different harmonic orders, amplitudes, and phase angles as compared to the sinusoidal current waveform at fundamental frequency. Thus, it is important to precisely calculate AC losses in superconducting devices under nonsinusoidal condition. A number of previous literatures reported the nonsinusoidal AC loss analysis of HTS tapes under current harmonics at different harmonic orders, different amplitudes and total harmonic distortions (*THD*s) [11-17]. However, researchers merely considered the in-phase harmonic current with fundamental current, and effect of phase angle of harmonic current on AC loss behavior needs to be addressed.

In this paper, AC transport loss in a typical HTS tape carrying distorted current was modeled by *H*-formulation in COMSOL Multiphysics. The nonsinusoidal AC loss was calculated at different carrying current levels, current harmonic amplitudes, *THD*s, and different harmonic phase angles. All odd harmonic orders below 20th were considered in this work.

II. NUMERICAL CALCULATION METHOD

All calculations were realized using a 2D model in COMSOL Multiphysics based on *H*-formulation [18-20]. Maxwell equations, Ohms law, and constitutive law were combined to solve the electromagnetic problem in an HTS tape carrying harmonic currents, as follows:

$$\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t \tag{1}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{2}$$

$$\boldsymbol{E} = \rho \boldsymbol{J} \tag{3}$$

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H} \tag{4}$$

$$\boldsymbol{E} = E_0 (\boldsymbol{J}/J_c)^n \tag{5}$$

where, $\boldsymbol{E}$ is electric field, $\boldsymbol{B}$ is magnetic flux density, $\boldsymbol{H}$ is magnetic field, $\boldsymbol{J}$ is current density, ρ is resistivity, μ_0 is permeability of free space, μ_r is relative permeability, $E_0 = 1$ μV/cm, J_c is critical current density, and n is power law index.

The governing equation for solving this electromagnetic problem is expressed as follows [18-20]:

M. Yazdani-Asrami, M. Zhang, and W. Yuan are with Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, G1 1XW, U.K. (e-mail: m.yazdaniasrami@gmail.com, mohammad.yazdani-asrami@strath.ac.uk, min.zhang@strath.ac.uk, weijia.yuan@strath.ac.uk).

W. Song, and X. Pei are with the Department of Electronic & Electrical Engineering, The University of Bath, Bath, BA2 7AY, U.K. (e-mails: ws603@bath.ac.uk, x.pei@bath.ac.uk).

$$\partial(\mu_0 \mu_r \boldsymbol{H})/\partial t + \nabla \times (\rho \nabla \times \boldsymbol{H}) = 0 \qquad (6)$$

The AC loss Q in the domain Ω is derived as [18-20]:

$$\boldsymbol{Q} = 2 \int_{T/2}^{T} \int_{S} \boldsymbol{E} \cdot \boldsymbol{J} \, d\Omega \, dt \qquad (7)$$

where S and T are the cross section of tape and period of one cycle of applied current, respectively. The AC loss is calculated by the integral of power density in the second half cycle, knowing that it is from the second half cycle that the magnetization process reaches a steady state.

Table I lists the specifications of the HTS tape used in this paper [21-22]. The nonsinusoidal current considered here is composed of fundamental current component, and a superimposed current harmonic with order $k = \{3, 5, 7, 9, 11, 13, 15, 17, 19\}$. *THD* is defined as the distortion level of transport current by each harmonic current component:

$$THD_k = I_{hk}/I_{h1} \qquad (8)$$

where $THD_k = \{0.1, 0.2, 0.3, 0.4, \text{ and } 0.5\}$. I_{hk} is amplitude of each current harmonic, and I_{h1} represents the amplitude of fundamental current harmonic; here, I_{h1} was expressed as:

$$I_{h1} = i_m \cdot I_c \qquad (9)$$

where I_c is the critical current of tape and $i_m = \{0.1, 0.2, 0.3, 0.4, \text{and } 0.5\}$, indicating 10% to 50% of tape I_c.

To study the effect of phase angle of current harmonics on AC loss, the initial phase angle of fundamental current was kept as 0° in the calculation, whilst phase angle of each current harmonic, φ_k was varied from 0° to 360° (i.e., 0 to 2π) and simulated by every 10°. The instantaneous applied nonsinusoidal current, $i_{nonsin}(t)$ is formulated as follows:

$$i_{nonsin}(t) = I_{h1}\sin(\omega t) + THD_k \cdot I_{h1} \cdot \sin(k\omega t + \varphi_k) \quad (10)$$

where $\omega = 2\pi f$ and $f = 50$ Hz.

III. HARMONIC AC LOSS IN HTS TAPE CARRYING CURRENT WITH LOW ORDER HARMONICS

A. Effect of harmonic phase angle on AC losses

Figs. 1(a)-(c) report AC losses in HTS tape carrying nonsinusoidal current which is distorted by the 3rd, 5th, and 7th harmonics, respectively, illustrated against the phase angle φ of current harmonic ranging from 0° to 360°, at identical *THD* = 0.2, with i_m varies from 0.2 to 0.5. As it is shown in Figs. 1(a)-(c), nonsinusoidal AC loss curves is symmetrical at $\varphi = 180°$, when the current is distorted by the 3rd, the 5th, and the 7th harmonic orders with different phase angles.

At a given phase angle and harmonic order, nonsinusoidal AC loss increases with the increase of i_m, when the current is distorted by the 3rd, the 5th or the 7th harmonic. This is due to stronger perpendicular magnetic field caused by higher i_m, as explained in [16].

Nonsinusoidal AC loss reaches the minimum at $\varphi = 0°$ and the maximum at $\varphi = 180°$, in Fig. 1(a) and (c), when tape carries current with the 3rd and the 7th harmonic, at a given i_m and *THD* = 0.2. When $0° < \varphi < 180°$, AC loss increases with the increase of φ. The AC loss curve for the 5th harmonic order in Fig. 1(b)

TABLE I
SPECIFICATIONS OF HTS TAPE

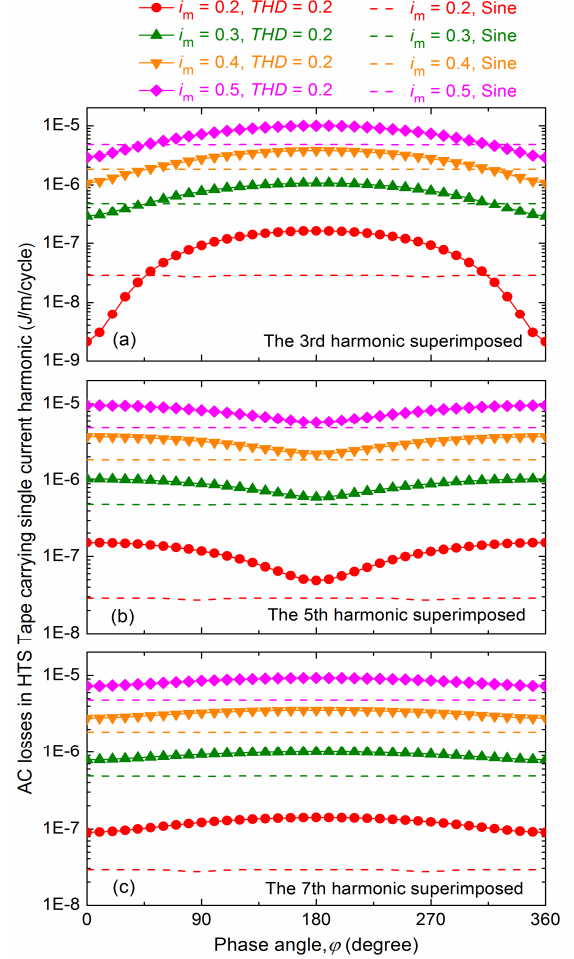| Parameter	Value	Unit
Thickness of superconducting layer (t_{sc})	1	μm
Width of tape (w_{tape})	3	mm
Critical current density (J_{c0}) @ 77 K	1	MA/cm²
E-J power law factor (n)	25	---

Fig. 1. AC losses in HTS tape carrying distorted current with different i_m, plotted against phase angle φ of current harmonics: the 3rd, the 5th, and the 7th harmonics at $THD_k = 0.2$.

is opposite to the trend for the 3rd, and 7th orders, i.e. nonsinusoidal AC losses reach the minimum and maximum at $\varphi = 180°$ and 0°, respectively.

In Figs. 1(b) and (c), nonsinusoidal AC loss is always higher than sinusoidal AC loss, when current is distorted with the 5th and the 7th harmonic at any phase angle and at fixed *THD* = 0.2. Nonsinusoidal AC loss in Fig. 1(a), however, is higher than sinusoidal AC loss, when $50° < \varphi_3 < 310°$ while it is smaller than sinusoidal AC loss, when $\varphi_3 < 50°$ or $\varphi_3 > 310°$. This is due to the fact that superimposing a current harmonic to the sinusoidal current alters the current waveform, and thus, either strengthens or weakens the peak value of total resultant nonsinusoidal current.

Fig. 2 shows four nonsinusoidal current waveforms distorted by the 3rd harmonic when $THD_3 = 0.2$, at $\varphi_3 = 0°$, 30°, 90°, and 180°. The sinusoidal current waveform was plotted as well in per-unit, as a guideline. The maximum peak of waveforms
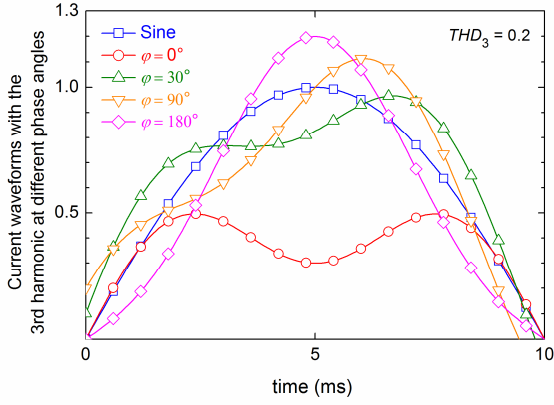
Fig. 2. Nonsinusoidal current waveforms with the 3rd harmonic at $THD_3 = 0.2$, and different phase angles, $\varphi = 0°$, $30°$, $90°$, and $180°$, plotted together with sinusoidal current waveform in per-unit scale

follows a relation, $I_{max, \varphi3 = 0} < I_{max, \varphi3 = 30} < I_{max, sine} < I_{max, \varphi3 = 90} < I_{max, \varphi3 = 180}$. It is noticed that higher nonsinusoidal AC loss occurs at phase angle which leads to higher current peak.

B. Effect of THD on harmonic AC losses

Fig. 3(a)-(c) show the nonsinusoidal AC losses in HTS tape carrying distorted current with the 3rd, the 5th, and the 7th harmonics, at $i_m = 0.3$ and φ ranges from $0°$ to $180°$, plotted versus THD values. Here, only $0° < \varphi < 180°$ was considered, due to the aforementioned symmetry in results.

An interesting phenomenon was observed in Fig. 3(a), that when $0° \leq \varphi_3 \leq 60°$, there exists a minimum AC loss value at a specific THD. This minimum occurs at $THD_3 = 0.2$ for $\varphi_3 = 0°$, which agrees with the finding in our previous paper [16]; at $\varphi_3 = 30°$, the minimum loss occurs at $THD = 0.1$. This shows that with the increase of φ_3, this minimum loss displaces towards lower THDs. Actually, it is inferred that when φ_3 is low, there will be always such a minimum AC loss value at a certain THD level. When $60° < \varphi_3 < 300°$, AC loss monotonically increases with the increase of THD.

At $\varphi_5 = 180°$ in Fig. 3(b), nonsinusoidal AC loss reduces first as THD_5 increases from 0; then there appears a minimum AC loss when THD_5 is around 0.1; after a certain THD_5, AC loss monotonically increases with the increase of THD_5. When $\varphi_5 < 150°$, AC loss monotonically increases versus THD. In Fig. 3(c), however, nonsinusoidal AC loss value monotonically increases with increase of THD_7, at any phase angle.

An overview of Figs. 3(a)-(c) was drawn that, the AC loss curves versus THD at different phase angles are much more scattered for the 3rd harmonics while it is less scattered in case of the 7th harmonics. This indicates at a given THD level, nonsinusoidal AC loss result in HTS tape get less affected by the phase angle of the 7th harmonic order than the 3rd.

IV. HARMONIC AC LOSS IN HTS TAPE WITH CURRENT HARMONIC ORDER BELOW 20TH

In many large scale power applications, higher order harmonics appear in current waveform. For most of these cases, especially for grid connected devices, current harmonics below 1 kHz (below the 20th order), must be considered. It should be
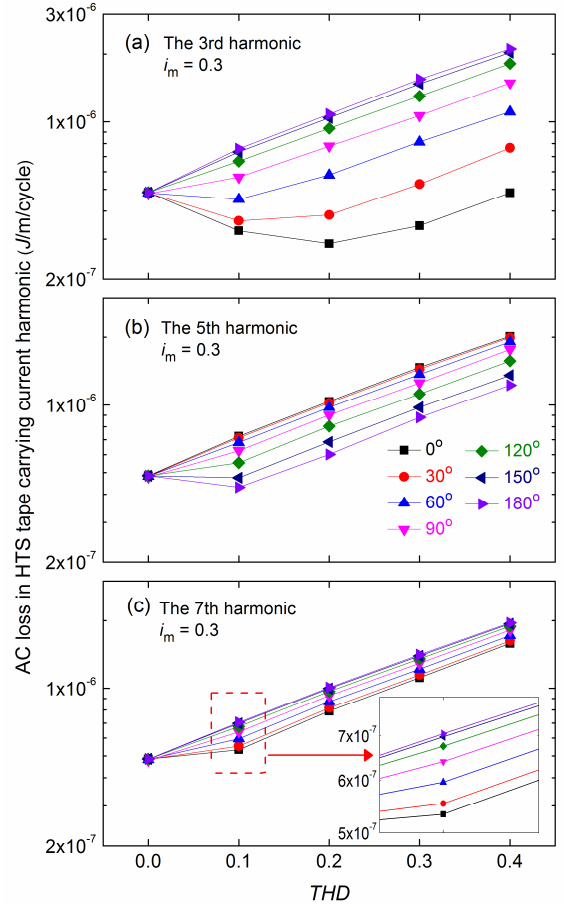

Fig. 3. AC losses in HTS tape carrying distorted current with the 3rd, the 5th, and the 7th harmonics plotted against different THDs, at $i_m = 0.3$ and different φ

mentioned that the phase angle of the harmonics is practically found by applying Fourier Transform to the time domain current waveforms, and is not an independent parameter.

Fig. 4 shows the nonsinusoidal AC losses in HTS tape carrying current harmonics with orders below the 20th, plotted versus phase angle at $i_m = 0.5$ and $THD_i = 0.3$, and compared with sinusoidal AC loss results. It was observed that AC losses in tape carrying harmonic current with harmonic order of {5, 7, 9, 11, 13, 15, 17, 19}, are much higher than the sinusoidal AC loss at any phase angle. However, AC loss in tape carrying the 3rd harmonic is lower than sinusoidal AC loss, when $0° < \varphi_3 < 25°$ and $335° < \varphi_3 < 360°$; whilst AC loss is higher than sinusoidal loss when $25° < \varphi_3 < 335°$.

It is found that the maximum nonsinusoidal AC loss in HTS tape appears at $\varphi = 180°$ for harmonic order $k = \{3, 7, 11, 15, 19\}$, and at $\varphi = 0°$ for harmonic order $k = \{5, 9, 13, 17\}$. On the contrary, the minimum nonsinusoidal AC loss in HTS tape appears at $\varphi = 0°$ for $k = \{3, 7, 11, 15, 19\}$, and at $\varphi = 180°$ for harmonic order $k = \{5, 9, 13, 17\}$. Assuming $k = (2m-1)$, where $m = \{2, 3, 4,...\}$, the maximum AC loss occurs at $\varphi = 0°$ if m is an odd number, and at $\varphi = 180°$ if m is an even number.

It was also observed in Fig. 4, as the harmonic order increases, nonsinusoidal AC losses in HTS tape converge towards a constant value, although the phase angle varies. It indicates AC loss gets insusceptible to phase angle at higher harmonic orders. This phenomenon is further illustrated in Fig. 5, which shows
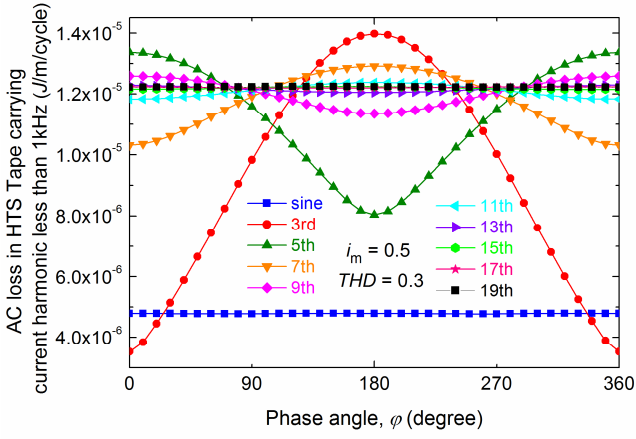
Fig. 4. Calculated harmonic AC losses in HTS tape carrying current harmonics below 20th, plotted against phase angle, at $i_m = 0.5$ and $THD_i = 0.2$.
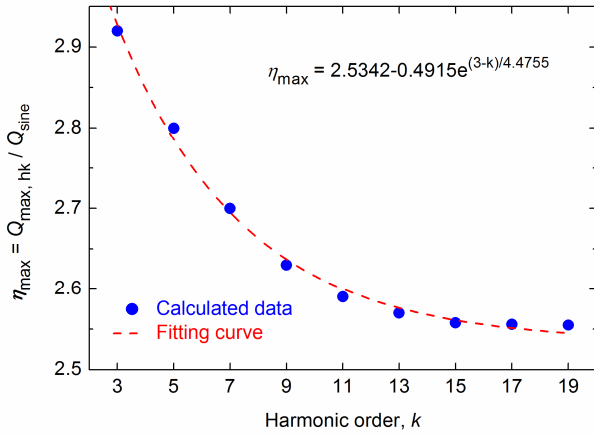

Fig. 5. The variation of ratio of nonsinusoidal AC loss in respect to sinusoidal one for harmonic orders below 1 kHz at $i_m = 0.5$ and $THD_i = 0.3$.

Fig. 6. Applied nonsinusoidal current containing harmonic orders below 20th at $i_m = 0.5$, $THD_i = 0.3$, and phase angle correspondent to the maximum AC loss.

TABLE II
HARMONIC SPECTRUM OF DISTORTED CURRENT WAVEFORM

Harmonic order	Amplitude (%)	Phase angle (°)
1st	100	- 26
5th	25	- 94
7th	17	- 67
11th	9	- 67
13th	5	- 46
THD %	32	

TABLE III
THE RESULTS OF AC LOSS CALCULATION FOR DISTORTED CURRENT SPECTRUM

Scenario no.	AC loss (J/m/cycle)
#1 Scenario	4.78 E-6
#2 Scenario	7.69 E-6
#3 Scenario	1.55 E-5
Loss ratio (#2 to #1 Scenario)	1.61
Loss ratio (#3 to #2 Scenario)	2.02
Loss ratio (#3 to #1 Scenario)	3.24

the $\eta_{max} = Q_{max,hk} / Q_{sine}$, ratio of the maximum nonsinusoidal AC loss under each harmonic order, $Q_{max,hk}$, to sinusoidal AC loss value, Q_{sine}, at $i_m = 0.5$ and $THD = 0.3$, where $k = \{3, 5, 7, 9, 11, 13, 15, 17, 19\}$. As shown in Fig. 5, η_{max} decreases from around 3 to 2.55, when harmonic order increases from 3 to 19. Fig. 4 and the exponential fit in Fig. 5, clearly show that when the harmonic order exceeds 15, $Q_{max,hk}$ and η_{max} tends to get constant. This is to say, at higher harmonic orders, the maximum nonsinusoidal AC loss is less dependent on harmonic order. The loss ratio for higher order harmonics tends to be about 2.537 based on curve fitting data in Fig. 5, indicating the dependency of AC loss of HTS tape to phase angle as well as the harmonic order itself reduces at higher order harmonics.

This is a very important finding for thermal load estimation in cooling system design (especially considering existing technology of cryocoolers with penalty factors of about 15 at 77 K, and 100 at 20 K respectively) [5-6], since it reduces the design complexity when it comes to AC loss calculation for final heat load estimation. In addition, it simplifies the nonsinusoidal AC loss calculation task, when one considers a wide range of harmonics in superconducting windings. Nonsinusoidal AC loss could be predicted by a constant value for higher order harmonics above 1 kHz, even as a pessimistic design. The argument is at higher order harmonics, though the
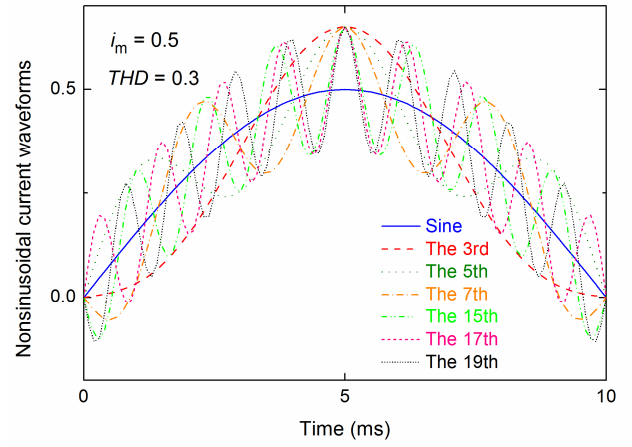
number of peaks in each cycle of applied current increases, the waveform of currents gets more similarly distorted as depicted in Fig. 6. At higher order harmonics, the distorted waveforms are modulated very rapidly and converging towards same peak. In other words, the harmonic current becomes a ripple on the fundamental waveform rather than a huge change in waveform itself.

V. EFFECT OF PHASE ANGLE OF HARMONICS IN A DISTORTED CURRENT SPECTRUM ON AC LOSS

This section demonstrates how AC loss results could be affected, if the phase angle of current harmonics is not well considered. Three scenarios were chosen and compared to achieve this goal: #1) pure sinusoidal current. #2) a current harmonic spectrum, but all harmonic orders are in-phase with fundamental order. #3) a current harmonic spectrum considering phase angle of each individual harmonic order.

For this purpose, a real current spectrum was considered. Table II shows the harmonic spectrum of a transformer current waveform which supplies plug-in electric vehicle chargers [23]. This current harmonic spectrum was applied to the HTS tape under the three aforementioned scenarios, and the sinusoidal and nonsinusoidal AC losses were calculated and reported in

Table III. As it can be seen from Table III, nonsinusoidal AC loss of both #2 and #3 scenarios when current is distorted is much higher than sinusoidal AC loss. In addition, with/without considering the harmonic phase angle, AC loss increases by 3.24 and 2.02 times of that of sinusoidal value. It is found that conventional harmonic analysis modeling approach without considering phase angle of each harmonic order leads to a tremendous underestimation of AC loss value, and as a consequence, underestimation of heat load for cooling system.

VI. CONCLUSION

In this work, we numerically investigated the AC loss characterization in HTS tape carrying harmonic currents with orders below 20th, considering the phase angles φ varies from 0 to 2π, based on H-formulation in COMSOL Multiphysics. Effect of harmonic amplitude and THD on AC loss behavior were also considered. The conclusions are summarized as follows:

1) Different phase angles change the maximum amplitude of the resultant nonsinusoidal current. When the maximum amplitude of the resultant current is bigger, nonsinusoidal AC loss in HTS tape is higher in that corresponding phase angle.

2) The nonsinusoidal AC loss might be lower than that of sinusoidal, when the phase angle falls in a certain range.

3) In case of nonsinusoidal current with 3rd harmonics, with the increase of φ_3, the minimum loss displaces towards lower THDs. But meeting this minimum is also phase angle dependent.

4) Assuming the harmonic order $k = (2m\text{-}1)$, where $k < 20$ and $m = \{2, 3, 4, 5, 6, 7, 8, 9, 10\}$, at a given harmonic amplitude and i_m, the maximum nonsinusoidal AC loss appears at $\varphi = 180°$ if m is an even number, and at $\varphi = 0°$ if m is an odd number, when HTS tape carrying a single current harmonic component.

5) At higher current harmonic orders, nonsinusoidal AC loss is less phase angle dependent, compared to lower orders. It indicates AC loss gets unsusceptible to phase angle at higher harmonic order.

This study investigates the effect of harmonic phase angle, harmonic orders up to the 19th, and harmonic amplitude on AC losses of HTS coated conductor, when the current contains one harmonic component, and also builds a fundamental understanding on the influencing aspects of nonsinusoidal AC loss. In the future, we will carry out the AC loss investigation of current spectrum which consists of multiple harmonic components.

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