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

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Abstract— **It is of great industrial interest and academic importance to investigate the effect of phase angle of current harmonics on AC losses in superconductors especially for large scale power applications. Whilst, only effect of amplitude of in-phase current harmonics on AC loss has been studied in literature. We have numerically characterized nonsinusoidal AC loss of superconducting tapes carrying harmonic currents with phase angles φ varying from 0 to 2π, and orders below 20th. A drastic AC loss variation was observed when phase angle was considered for harmonic components. Eventually, we found 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 electric components in large scale power applications, since high temperature superconducting (HTS) devices will bring many advantages compared to conventional counterparts, such as higher efficiency, less energy consumption, compactness, lighter weight, and lower loss. HTS technology helps to manufacture transformers, cables, motors, and generators with higher current density, as well as higher power and/or torque to weight density [1-4].

AC loss in HTS windings is one of the most critical aspects that need to be considered during R&D stage for any large scale HTS electric component. AC loss, as a heat load, is closely linked with the power/efficiency of any cryogenic cooling system, which further adjusts and maintains the operating temperature of HTS components [5-6]. It is vital to accurately estimate AC loss in HTS devices under real operating circumstances for designing safe and reliable cooling system.

Recently, AC/DC converters and nonlinear loads have been widely used in power grids, industries, and also in variety of transportation systems, including aerospace, railway, and naval applications [7-8]. Current harmonics, therefore, are inevitably produced inside power system, with different harmonic orders, amplitudes, and phase angles with respect to the sinusoidal current waveform at the fundamental frequency. So, it is important to accurately estimate the loss in superconducting devices under nonsinusoidal condition.

In literature, the nonsinusoidal AC loss analysis of HTS tapes is reported under current harmonics at different harmonic orders, different amplitudes and total harmonic distortions (*THD*s) [9-15]. However, researchers only considered the in-phase harmonic current with the fundamental current, and there is a lack of understanding in addressing the effect of phase angle of harmonic current on AC loss behavior.

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, and *THD*s, as well as different harmonic phase angles. All odd harmonic orders below 20th were considered in this paper.

II. NUMERICAL CALCULATION METHOD

In this paper, all calculations were realized using a 2D model in COMSOL Multiphysics based on *H*-formulation [16-18]. Maxwell equations, Ohms law, and constitutive law were combined to solve the electromagnetic problem in an HTS tape carrying harmonic currents, as follow:

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

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

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

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

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

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, $\boldsymbol{E}_0 = 1$ µV/cm, J_c is critical current density, and n is power law index.

The governing equation for solving the electromagnetic problem is expressed as follows [16-18]:

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

The AC loss Q in the domain Ω is derived as [16-18]:

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

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 1 lists the specifications of the HTS tape used in this paper [19-20]. The considered nonsinusoidal current is composed of fundamental current component at 50 Hz, and a superimposed current harmonic with harmonic 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 $i_m = \{0.1, 0.2, 0.3, 0.4, \text{and } 0.5\}$, which means 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) by 10° steps. 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 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 $THD = 0.2$, while i_m varies from 0.2 to 0.5. As it is shown in Figs. 1(a)-(c), nonsinusoidal AC loss curves have a line of symmetry 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 [14].

It was observed from Fig. 1(a) and 1(c) that nonsinusoidal AC loss reaches the minimum and maximum at $\varphi = 0°$ and $\varphi = 180°$, respectively, 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.

TABLE I
SPECIFICATIONS OF HTS TAPE

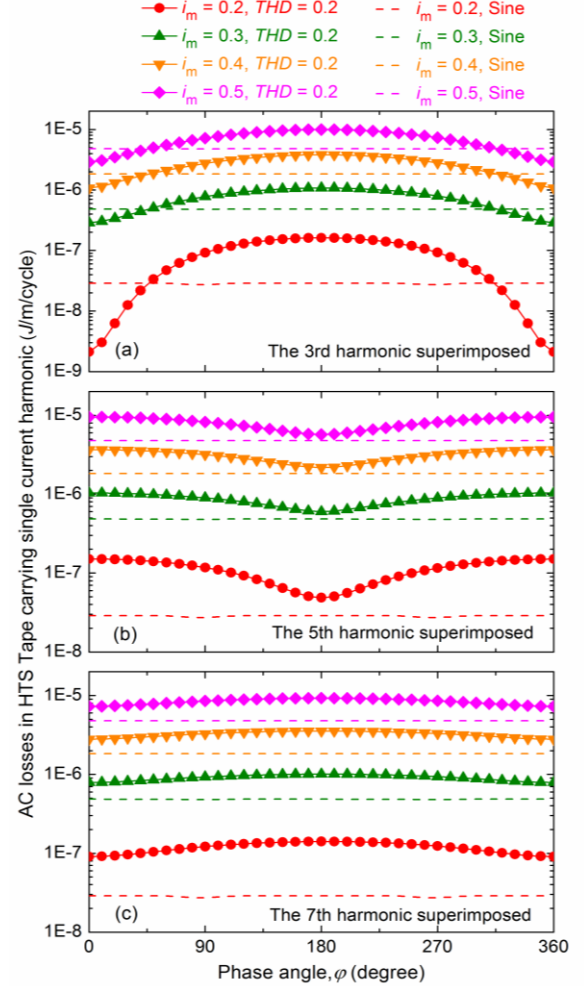| Parameter	Value	Unit
Thickness of superconducting layer (t_{sc})	1	µm
Width of tape (w_{tape})	3	mm
Critical current density (J_{c0}) @ 77 K	1	MA/cm²
E-J power law factor (n)	25	---

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 $THD_k = 0.2$.

As seen in Fig. 1(b), this tendency for the 5th harmonic order is opposite of the 3rd, and 7th orders, i.e. nonsinusoidal AC losses reach the minimum and maximum at $\varphi = 180°$ and 0°.

As shown in Fig.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 $THD = 0.2$. 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 mainly due to the fact that the addition of a harmonic current to the sinusoidal current changes the current waveform, and at the same time, either strengthens or weakens the peak value of total resultant nonsinusoidal current. Fig. 2 shows four nonsinusoidal current waveforms with 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 comparison. As seen from

Fig. 2, the following relation is valid between the maximum values of the waveform, $I_{max, \varphi3 = 0} < I_{max, \varphi3 = 30} < I_{max, sine} < I_{max, \varphi3 = 90} < I_{max, \varphi3 = 180}$. Thus, the order of maximum value of nonsinusoidal current with different phase angle basically agrees with the AC loss behavior and order.

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 ranging from 0° to 180°, plotted versus *THD* values. Here, only φ from 0° to 180° were 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 [14]; and 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 *THD*s. 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*.

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

In a whole view it is clear from Figs. 3(a)-(c) 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 ORDERS BELOW 20TH

In many large scale power applications, higher order harmonics appear in current waveform. For most of these cases, especially for grid devices, current harmonics below 1 kHz, below the 20th, must be considered. It should be 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 $THD_i = 0.3$, 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}, is 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, when $25° < \varphi_3 < 335°$, AC loss is higher than sinusoidal loss.
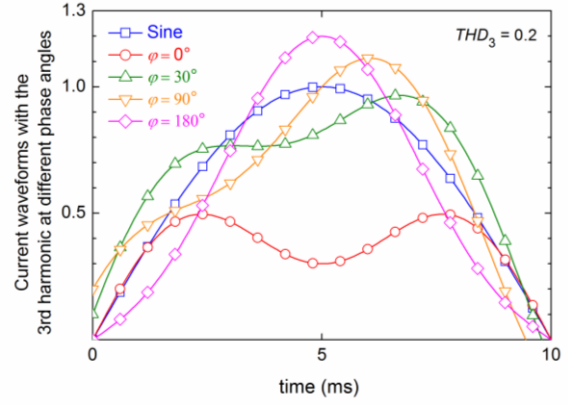

Fig. 2. Nonsinusoidal current waveforms with the 3rd harmonic at $THD_3 = 0.2$, and different phase angles, $\varphi = 0°$, 30°, 90°, and 180°, plotted together with sinusoidal current waveform in per-unit scale
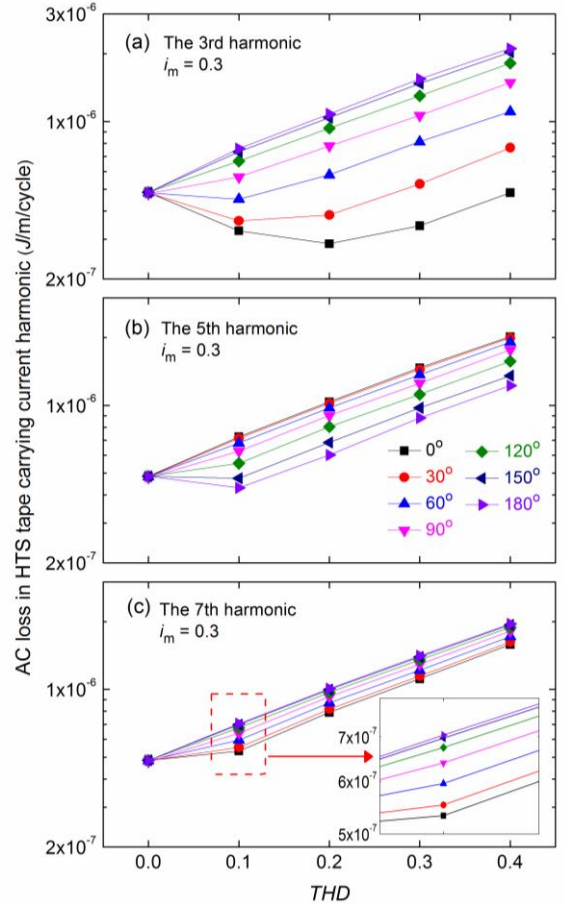

Fig. 3. AC losses in HTS tape carrying distorted current with the 3rd, the 5th, and the 7th harmonics plotted against different *THD*s, at $i_m = 0.3$ and different φ

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 $\varphi = 0°$ and 180° if m is an odd and even number; respectively.
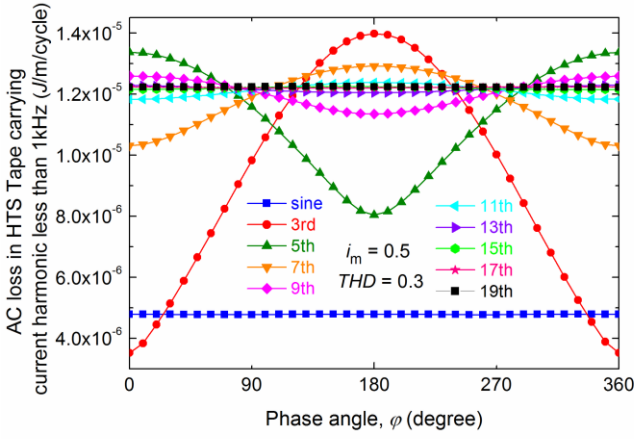
Fig. 4. Calculated harmonic AC losses in HTS tape carrying current harmonics below 20th, plotted against phase angle, at $i_m = 0.5$ and $THD_i = 0.2$.

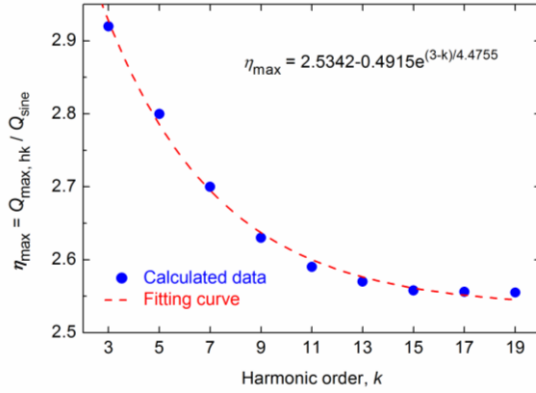$$\eta_{max} = 2.5342 - 0.4915 e^{(3-k)/4.4755}$$

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 $THD_i = 0.3$.

It was also observed in Fig. 4, as the harmonic order increases, nonsinusoidal AC loss in HTS tape converge toward 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 the $\eta_{max} = Q_{max,hk} / Q_{sine}$, ratio of the maximum nonsinusoidal AC loss under each harmonic order, $Q_{max,hk}$, with respect 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. The Fig. 4, and 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, and 100 at 77 K, and 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, which
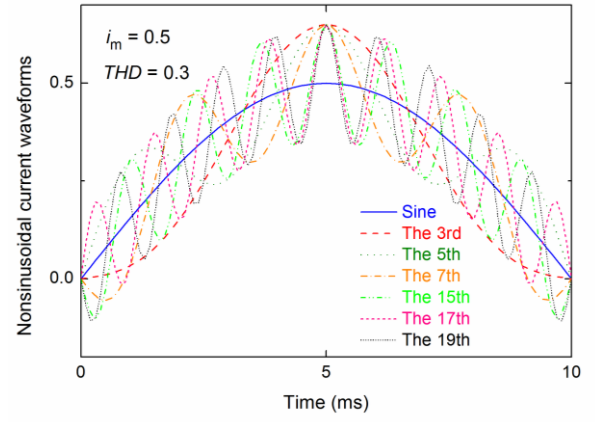

Fig. 6. Applied nonsinusoidal current containing harmonic orders below 20th at $i_m = 0.5$, $THD_i = 0.3$, and phase angle correspondent to the maximum AC loss.

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	

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 pessimistic design. The argument is that at higher order harmonics, while the number of peaks in each cycle of applied current increases, the waveform of currents get more similarly distorted, i.e. as it is 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 CURRENT HARMONICS IN A SPECTRUM ON AC LOSS

In this section, we tired to demonstrate that if the phase angle of current harmonics is not considered how it can drastically affect the results of AC loss calculation. For this purpose, three scenarios were considered as follows: 1) pure sinusoidal current. 2) a current harmonic spectrum, but all orders in-phase with fundamental order. 3) a current harmonic spectrum considering phase angle of each individual harmonic order.

For this purpose, a real case of current spectrum was considered. Table II shows the harmonic spectrum of a transformer current waveform which supplies plug-in electric vehicle chargers [21]. This current harmonic spectrum was applied to the HTS tape under the three scenarios, and the sinusoidal and nonsinusoidal AC losses were calculated and results were reported in Table III. As it can be seen from the content of Table III, nonsinusoidal AC loss of both 2nd and 3rd 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

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

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

of sinusoidal value. It is quite obvious that using conventional harmonic analysis modeling without considering phase angle of each harmonic order leads to a tremendous error in AC loss evaluation, and as a consequence heat load estimation for cooling system.

VI. CONCLUSION

In this paper, 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 phase angle.

2) The nonsinusoidal AC loss is lower than that of sinusoidal, when the phase angle of the 3rd harmonic ranges between 0° to 30°, as well as between 270° to 360°, due to the symmetry.

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 $k = (2m-1)$, 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 harmonic orders of current, 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.

The presented study builds up a fundamental understanding on the effect of harmonic order, phase angle, and amplitude on AC loss, when the HTS tape carries only one harmonic component. In the future, we will carry out the AC loss investigation of current spectrum which consist of multiple harmonic components.

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