AC Loss Analysis in Superconducting Cables Carrying Characteristic and Non-Characteristic Harmonic Currents

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***Abstract*- Harmonic distortions - especially in current waveform - are the inherent nature of any power system such as urban grids, wind farms, electric aircraft, and other electrified transportation units that could change the AC loss value in High Temperature Superconducting (HTS) cables. The aim is to investigate the impact of non-sinusoidal currents with different integer-harmonics, inter-harmonics, and sub-harmonics on the AC loss characteristics of a 22.9 kV, 50 MVA HTS cable. This was accomplished by using an Equivalent Circuit Model (ECM). To do so, current waveforms containing different harmonic components were passed to the ECM of HTS cable. For evaluating the impact of distorted current waveforms on the AC loss of the HTS cable, the ECM was validated by means of Finite Element Method (FEM) in tape level. The results of validation phase have shown a good agreement between the AC loss value derived by ECM and those calculated by FEM published in literature. The results showed that when current waveform was distorted by harmonics, the value of AC loss was changed significantly with respect to variations of harmonic phase angle, order, and amplitude. Results also indicated that 5th harmonic order has the highest impact on the AC loss value and could increase 6% to 80% of AC loss in comparison to pure sinusoidal current. Sub-harmonics and inter-harmonics could also increase the AC loss value to maximum 88% and 64% higher than that of sinusoidal condition.**

***Index Terms*- HTS cable, Harmonic phase angle, Integer-harmonics, Inter-harmonics, Sub-harmonics.**

I. Introduction

High-Temperature Superconducting (HTS) cables were proposed as one of the most promising solutions to increase power density and efficiency. Moreover, HTS cables can also help to address many other problems of conventional transmission and distribution lines including their large size and footprint [1]. Prior to installation of HTS cables in any electrical system, their behavior must be characterized using models and simulations during design stages and R&D studies. The most important characteristics of HTS power devices for power applications are AC loss [2], fault/transient behavior [3]–[5], thermal characteristic [6], [7], and harmonics analysis. In most of electric power systems, the nonlinear loads such as home appliances, power converters, semiconductor switches, etc. result in the harmonic distortions of current waveform.

Harmonics reduce the life of electrical devices, increase the energy consumption in power system, increase the operational temperature of power apparatuses, and many other consequences. Thus, if HTS cables are implemented in any power system, harmonics would increase their AC loss, generate extra heat load in their cryostat, increase the inefficiency of their cooling system, and many other undesirable and sometimes destructive consequences [8]. To avoid this, models and simulations are required to study the behavior of the HTS cables under harmonic currents and improve their performance, before fabrication and installation of HTS cables. AC loss characteristics of HTS tapes under non-sinusoidal currents with the variation of harmonic phase angle was studied in [9]. Also as reported in [10,11], the impact of harmonic waveforms on the performance of superconducting machines and transformers was analyzed. Although many investigations were conducted on the harmonic characteristic of superconducting power devices and HTS tapes, there is a gap in analyzing the AC loss characteristic of AC HTS cables under distorted current waveforms by considering the impact of phase angle. However, multiple studies have been conducted to evaluate the performance of DC HTS cables under harmonic distortions [12]–[18]. Any AC loss increase caused by harmonics results in more heat load in HTS cable and therefore, superconducting tapes may suffer premature quenches, weak points, hotspots, and even burnouts [19]. There are three main types of harmonics in electric systems, i.e. integer-harmonic or simply called harmonic, sub-harmonic, and inter-harmonic. It should be noted that characteristic harmonic currents are referred to harmonics with integer orders while non-characteristic harmonics are those with non-integer orders. Current waveforms, with harmonic orders between 0 and 1, are called sub-harmonic [20]. Also due to some changes in electrical loads and some types of electrical nonlinear loads, the harmonics could also have non-integer orders such as 5.3, 7.9, etc. known as inter-harmonics [21].

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Usually, to calculate the basic heat load of a cable, a rated sinusoidal current is considered, however, as explained above, the current in real electric systems can be distorted by harmonics, sub-harmonics, and inter-harmonics, which need to be considered in AC loss calculation and heat load estimation of HTS cables in design stage.

In this paper, the AC loss characteristic of a 22.9 kV tri-axial HTS cable is evaluated under harmonic current waveforms with different harmonic orders, amplitudes, phase angles, and also under different integer-harmonics, sub-harmonics and inter-harmonics. Harmonic orders of 5, 7, 11, 13, 17, and 19 were considered in this study while the impact of harmonic phase angle and harmonic amplitude were evaluated. To characterize the harmonic AC loss of HTS cable, an Equivalent Circuit Model (ECM) is developed. To validate the presented model, the computed AC loss by the proposed ECM is compared with the results computed by Finite Element Method (FEM) in tape level, based on a previously published paper in [9].

II. Modelling Methodology

A. AC Loss Calculation in HTS Cable

The rated current passes through HTS cable that induces a magnetic field consisting of two parallel and longitudinal components. The magnetic field of the HTS cable is function of twisting specifications and radius (or essentially diameter) of each phase/layer. To calculate the parallel and longitudinal magnetic field components in each phase of an n layer HTS cable, equations (1) and (2) can be used [22]:

$$B_{par_i} = B_{z_i} \sin\left(\frac{2rp_i}{\ell_{p_i}}\right) - B_{\theta_i} \cos\left(\frac{2rp_i}{\ell_{p_i}}\right) \quad (1)$$

$$B_{long_i} = B_{z_i} \cos\left(\frac{2rp_i}{\ell_{p_i}}\right) + B_{\theta_i} \sin\left(\frac{2rp_i}{\ell_{p_i}}\right) \quad (2)$$

where, B_{z_i} and B_{θ_i} are axial and azimuthal components of the magnetic field calculated based on [23], ℓ_{p_i} is twist pitch in each layer, and rp_i is distance from axis at a point of ith layer. By knowing the values of magnetic field, the total AC loss of the HTS cable can be calculated using equation (3) [3]:

$$Q_{AC} = Q_{mag} + Q_{trans} \quad (3)$$

where, Q_{mag} is magnetization loss, Q_{trans} is transport current loss, magnetization and transport current losses are two components of AC loss that their calculation method is reported in [24]–[26] and shown in equations (4) to (8):

$$Q_{mag} = \begin{cases} \dfrac{2fB_i^{\,2}}{\mu_0}\dfrac{\beta_i}{3}S_i & \beta_i < 1 \\ \dfrac{2fB_i^{\,2}}{\mu_0}\left(\dfrac{1}{\beta_i} - \dfrac{2}{3\beta_i^{\,3}}\right)S_i & \beta_i > 1 \end{cases} \quad (4)$$

$$B_i = \sqrt{B_{zi}^{\,2} + B_{\theta i}^{\,2}} \quad (5)$$

$$\beta_i = \frac{B_i}{\mu_0 J_C b} \quad (6)$$

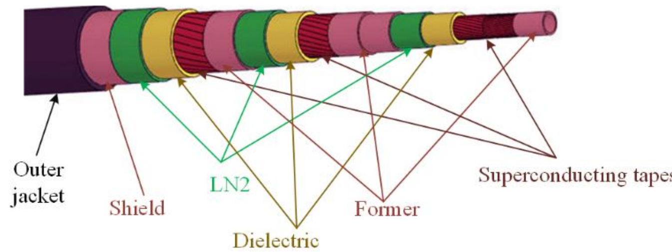

Figure 1. The structure of the under-investigation HTS cable consisting of two superconducting layers in phase A and two copper formers in phase B with liquid nitrogen as coolant

Table 1. The geometrical specifications of the superconducting cable

Parameter	Ph-A	Ph-B	Ph-C
Number of copper formers	1	2	1
Number of superconducting layers	2	1	1
Pitch length (mm)	326 & 284	221	164
Pitch angle (degree)	18.1 & -16.3	30.7	45.8
Former radius (mm)	17	20 & 21	28
Number of tapes	22 & 22	24	28

$$Q_{trans} = \frac{\mu_0 f I_{Ci}^{\,2}}{2\pi}\{(2 - F_i)F_i + 2(1 - F_i)\ln(1 - F_i)\} \quad (7)$$

$$F_i = \frac{I_{Pi}}{I_{Ci}} \quad (8)$$

where, Q_{mag} is magnetization loss, Q_{trans} is transport current loss, f is frequency, S_i is cross-section of ith layer, $J_C$is critical current density, b is half of HTS tapes width and I_{Pi} is the peak value of current.

B. ECM of HTS cable

The HTS cable considered in this paper for harmonic analysis is shown in Figure 1. The under-investigation cable consists of four copper formers, one copper former in phases A and C and two copper formers in phase B. In phase A, there are two layers of HTS tapes while in other phases, there is only one superconducting layer. At last, there is the shield layer consisting of copper wires to mitigate any excessive magnetic field. The geometrical specifications of the HTS cable are reported in Table 1.

Figure 2 shows the ECM of under-investigation HTS cable, where the variable resistances are representing the resistivity of superconducting layer in steady state which are considered to be 10^{-14} Ω.cm [27]. The constant resistances are the resistance of copper formers and shield layer which can be calculated using equations (9) to (10) [28].

$$R_{cu-dc} = \frac{\rho_{cu}\mathcal{L}}{\pi(r_{cu}^2 - (r_{cu} - \sigma_{cu})^2)} \quad (9)$$

$$R_{cu-ac} = R_{cu-dc} \times \left[1 + \left(k_s + k_p\right)\right] \quad (10)$$

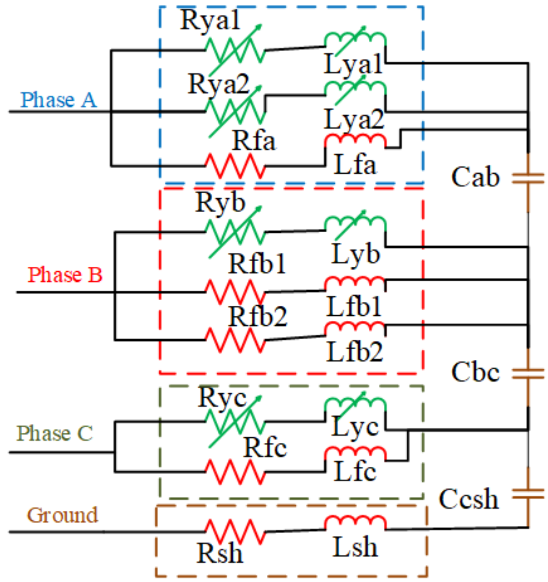

Figure 2. The equivalent circuit model of the HTS cable

where ρ_{cu} is specific resistivity of copper equal to 1.68*10^{-8} Ω.m, $\mathcal{L}$ is length of cable, r_{cu} is radius of former/shield, σ_{cu} is thickness of former/shield equal to 1 mm, k_s is skin effect factor equal to 0.435, and k_p is proximity effect factor equal to 0.370 [29].

At last, to calculate the self-and-mutual-inductances and capacitances, equations (11) to (13) could be applied [28]:

$$L_i = \frac{\pi\mu_0 r_i^2}{\ell_i} + \frac{\mu_0}{2\pi}\ln\frac{D}{r_i} \tag{11}$$

$$M_{ij} = \frac{a_i a_j \pi\mu_0 r_i^2}{\ell_i \ell_j} + \frac{\mu_0}{2\pi}\ln\frac{D}{r_j} \tag{12}$$

$$C_{ij} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\frac{r_i}{r_j}} \tag{13}$$

where, r_i is radius of ith layer, D is geometrical mean distance, ε_0 is relative permittivity of free air, and ε_r is relative permittivity of dielectric material.

C. Harmonic Modelling

Prior to analyze a harmonic waveform, Total Harmonic Distortion (THD) level must be defined. In this papers, THD is the distortion level of transport current by each harmonic current component which is calculated as equation (14) [9]:

$$THD = \frac{I_{h^k}}{I_{h^f}} \tag{14}$$

where, I_{h^k} is amplitude of each current harmonic, and I_{h^f} represents the amplitude of fundamental current harmonic. Here, we have considered the maximum $I_{h^f} = 0.46\, I_c$, where I_c is the total critical current of the cable. To conceive the impact of harmonic parameters, equation (15) is presented that models the harmonic current based on order, amplitude, and phase angle [9].

$$I_{h^k}(t_i) = I_p \sin(2\pi f t_i) + THD \times I_p \times \sin(2H\pi f t_i + \varphi_k) \tag{15}$$

where, I_{h^k} is harmonic current, I_p is amplitude of fundamental current, t_i is ith time step, H is order of harmonic, and φ_k is the phase angle of harmonic.

In this paper, harmonic orders of current waveform are considered to be 5, 7, 11, 13, 17, and 19 as they are main harmonics in any electric system [9] while the harmonic amplitudes vary from 10% to 50% of the fundamental current, and phase angle is between 0^o to 180^o, also sub-harmonics and inter-harmonics are considered and evaluated. There are three important standards that concern about the allowable harmonics:

- IEEE Std 519-1992, Harmonic Control in Electric Power Systems
- IEC61000-3-2, the limitation of harmonic currents injected into the public supply system
- IEC61000-3-12, harmonic currents produced by equipment

These standards have dedicated a 1% to 5% allowable amplitude for "voltage harmonics". However, the "current harmonics" have a bit different story. Also, based on "Technical guide No. 6 Guide to harmonics with AC drives" a 6-pulse rectifier without choke could inject a distorted current with 63% amplitude for 5th harmonic, 54% for 7th harmonic, etc. while these harmonic currents will distort the voltage with an amplitude less than 5%. Thus, it can be concluded that the new power-electronic-based devices could even inject a distorted current waveform with amplitude higher than 50% without surpassing the voltage distortion limits. On the other hand, these numbers could be even further reduced when using HTS cables in power system. According to "IEEE 519 Guidelines" the maximum allowable current harmonic could be even further increased by enhancement the ratio I_{sc}/I_L where I_{sc} is the short circuit current and I_L is load current. Therefore, considering amplitudes less than 50% is completely realistic which is due to the fact that last recently power systems tend to use more and more power electronic devices such as 12 pluses converters, 6 pulses converters, etc. This is obligated by increasing the penetration level of using renewable energy resources such as wind farms and photovoltaic farms, increasing the number of charging stations of electric cars, and also digitalization of data centers, computer centers, etc. So, it is very necessary to study and characterize the performance of HTS cable in future urban grids with a high level of current distortion that imposes a high level of AC loss, and temperature rise, etc. to the cable and cooling systems. This is also necessary for long term planning of power systems in distribution, Subtransmission, and transmission levels to consider further level of harmonic distortion in cable studies.

Third harmonic order and its multiplies are not considered in this study due to the fact that in any real electrical systems, they are usually mitigated. These harmonics have destructive impacts on the apparatus in the electrical system and are usually mitigated by means of filters or choosing proper winding connections in transformers. The impact of harmonics on distortion of the current waveform is shown in Figure 3(a)

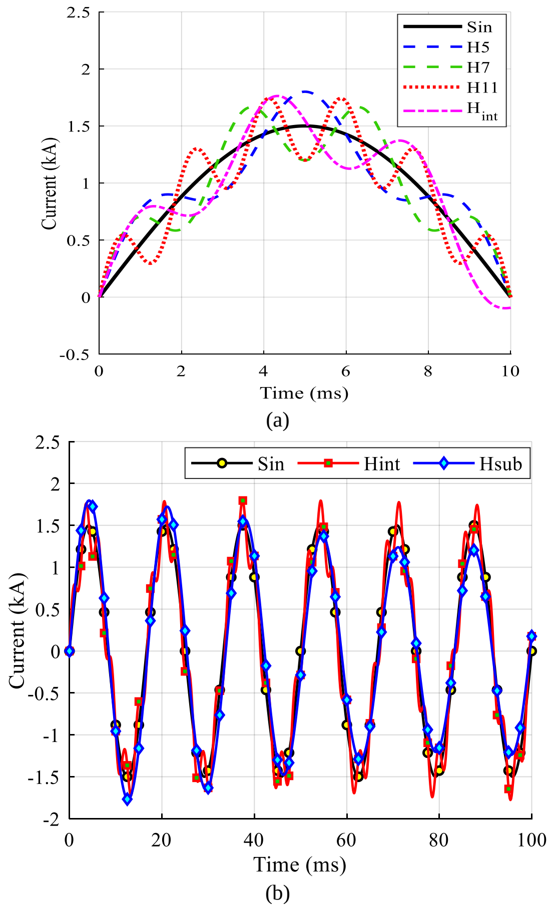

Figure 3. The impact of harmonic order on the current waveform of the HTS cable: a) Comparison of current harmonics according to different integer and non-integer orders with pure sinusoidal current b) Comparison of inter-harmonic, sub-harmonic, and pure sinusoidal current. In this figure subscript "int" stands for inter-harmonic and "sub" stands for sub-harmonic, harmonic amplitude is considered to be 0.5 for all cases

for different integer-harmonic orders and in Figure 3(b) for inter-harmonics and sub-harmonics. It should be mentioned that to clearly illustrate the impact of harmonic current, only a half cycle is shown. Also, the shown distorted current waveforms are injected to model to characterize the performance of under-investigation HTS cable against harmonics.

D. An Overview on Model of AC Loss, ECM, and Harmonics

The HTS cable is installed in a South Korean power grid, as shown in Figure 4, known as Shingal project [30]. The 22.9 kV HTS cable is utilized to feed the Heugdeok substation through Shinagal substation where the HTS cable has replaced one of the 154 kV conventional overhead lines. Here, 154 kV feeders are used to connect the parallel overhead lines while 22.9 kV feeder is used for HTS cable.

In general, the procedure of the harmonic characteristic analyzing for HTS cable could be summarized as shown in flowchart of Figure 5. Firstly, the time step (Δt) and initial simulation time (t_i) is set through the Simulink model in MATLAB. Then, the design parameters of HTS cable such as operating voltage, rated current, pitch specifications, etc. are adjusted into the model. The next step is to initially calculate the resistance, self-inductance, mutual inductance, and

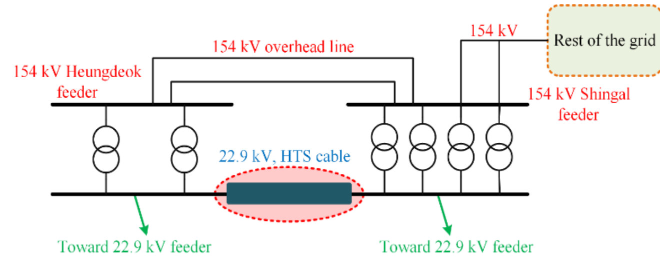

Figure 4. The power grid where the 22.9 kV HTS cable is installed

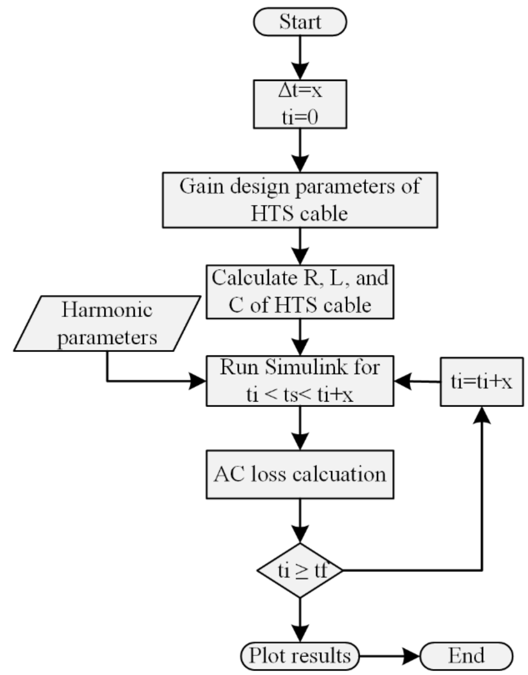

Figure 5. Modelling diagram of harmonics and AC loss through ECM for the HTS cable

capacitance of HTS cable to prepare the ECM for the next level. After computing aforementioned values, harmonic features such as amplitude, phase angle, etc. are fed into the Simulink model, basically ECM. Next, AC loss under harmonic situation is computed, based on the equation (1) to (6).

The next step is to set the ECM for the subsequent iteration or time step. At the end, if (t_i) be higher than final allowable time (t_f), the calculations are done. Else, the simulation timeframe must be updated and the AC loss must be calculated for next iteration.

III. Results and Discussions

In this section, the AC loss characteristic of the HTS cable is validated and evaluated, based on characteristic and non-characteristic harmonic currents. To do this, firstly, the impact of a single harmonics order superimposed on sinusoidal current was investigated for different harmonics orders to show that which harmonic orders can increase the AC loss more effectively. This might not be the case in power system analysis where a non-sinusoidal current consists of different many harmonic orders together, however, it will be a good measure to find and study the significance of each harmonic

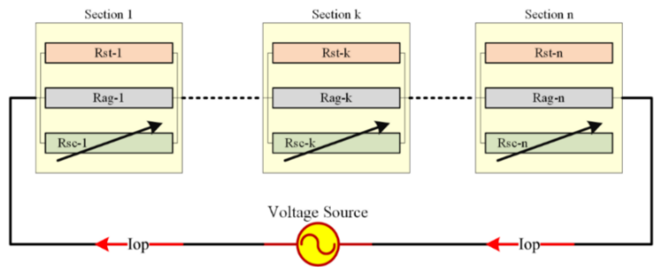

Figure 6. Equivalent circuit model of HTS tape consisting of n sections

separately to find the most important order. Later on, we also studied the effect of harmonic spectrum while many orders (up to 19th order) together superimposed on the fundamental order. This is what we usually see in harmonic studies in power system.

A. Validation of Proposed ECM

In this subsection, the results of calculated AC loss in superconducting layer of HTS tape by ECM is compared and validated by those of FEM which are conducted for an HTS tape with 4 mm width, 100 µm thickness, and 86 A critical current at 77 K and self-field. The FEM-based simulation is also conducted based on H-formulation in COMSOL software package and published in [9].

A ladder type ECM is built for the HTS tape analyzed in [9] that is shown in Figure 6. In this figure, the Rsc-i stands for resistivity of superconducting layer in ith section, Rst-i stands for resistivity of stabilizer layer in ith section, and Rag-i stands for resistivity of silver shield layer in ith section. More discussions and details about the ECM of HTS tapes and the impact of sections on the results are presented in [3] which could be summarized as follow: the more sections results in an ECM with higher accuracy and higher computational time. In [9], transport AC loss is taken into account and thus, in ECM, Norris model [31] is used to calculate the distorted harmonic AC loss.

Figure 7 shows the results of AC loss calculation by ECM and FEM for the HTS tape studied in [9]. The results of AC loss calculated by ECM are in a good coordination with the result of AC loss computed by FEM. The agreement of ECM and FEM results is not only in AC loss values but also in the trend of AC loss variations with respect to the harmonic phase angle.

B. Integer-harmonics

It is worth mentioning that in each case study, the harmonic current was superimposed on the fundamental current as shown in equation (15). The AC losses in different phases caused by applying distorted current with integer-harmonics to the HTS cable are tabulated in Table 2.

Due to value of pitch angle and direction of twisting, the value of AC loss in phase B is higher than two other phases. The AC loss value of a pure sinusoidal current is about 0.931, 0.0663, 0.1222, and 0.985 J/cycle/m for A1, A2, B, and C layers of cable, respectively. By comparing these values with

Table 2. AC loss in each phase of the HTS cable under different integer-harmonic currents

Current	**AC loss (J/cycle/m)**			
	A1	**A2**	**B**	**C**
Sin	0.0931	0.0663	0.1222	0.0985
H1+H5	0.1402	0.0812	0.2114	0.1562
H1+H7	0.1277	0.0773	0.1955	0. 1463
H1+H11	0.1290	0.0777	0.1899	0.1427
H1+H13	0.1307	0.0782	0.1855	0.1396
H1+H17	0.1259	0.0767	0.1777	0.1345
H1+H19	0.1226	0.0757	0.1769	0.1341

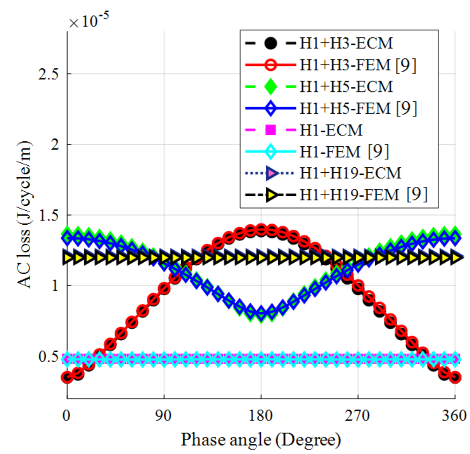

Figure 7. Comparison of transport AC loss value resulted by FEM and ECM [9]

the AC loss of different harmonic currents, it can be seen that the value of AC loss under different harmonic orders are drastically increased. Among different integer-harmonic orders, 5th order has the highest AC loss in different layers of cable. AC loss of 5th harmonic order has 50.6%, 22.47%, 73%, and 58.6% higher than that of purely sinusoidal current, in A1, A2, B, and C layers of HTS cable, respectively.

The amplitude of distorted current waveform consisting of 5th harmonic component is 50%, in other words 2.55 kA, (70% higher than peak of nominal current) while this value for 7th and 11th harmonic current is about 66% and 65%, respectively. In this case, harmonic phase angle is considered to be 0º. The resulted AC loss values would change the cable heat load and could significantly increase the required cooling power from cryogenic cooling system. It should be noted that different values of AC loss in different layers are caused by different number of tapes, twisting angles, and twisting directions in those layers. Larger radius of layer results in lower AC loss [3]. However, in the investigated cable this is not the case which is due to the fact that AC loss in A1 layer is affected by reverse twisting direction in A2 layer of the cable that reduces the AC loss in phase A. In other words, the bigger radius equals to higher pitch angle and higher pitch angle results in lower magnetic field and thus lower AC loss. So, phase A should have highest AC loss. However, in this phase, there are

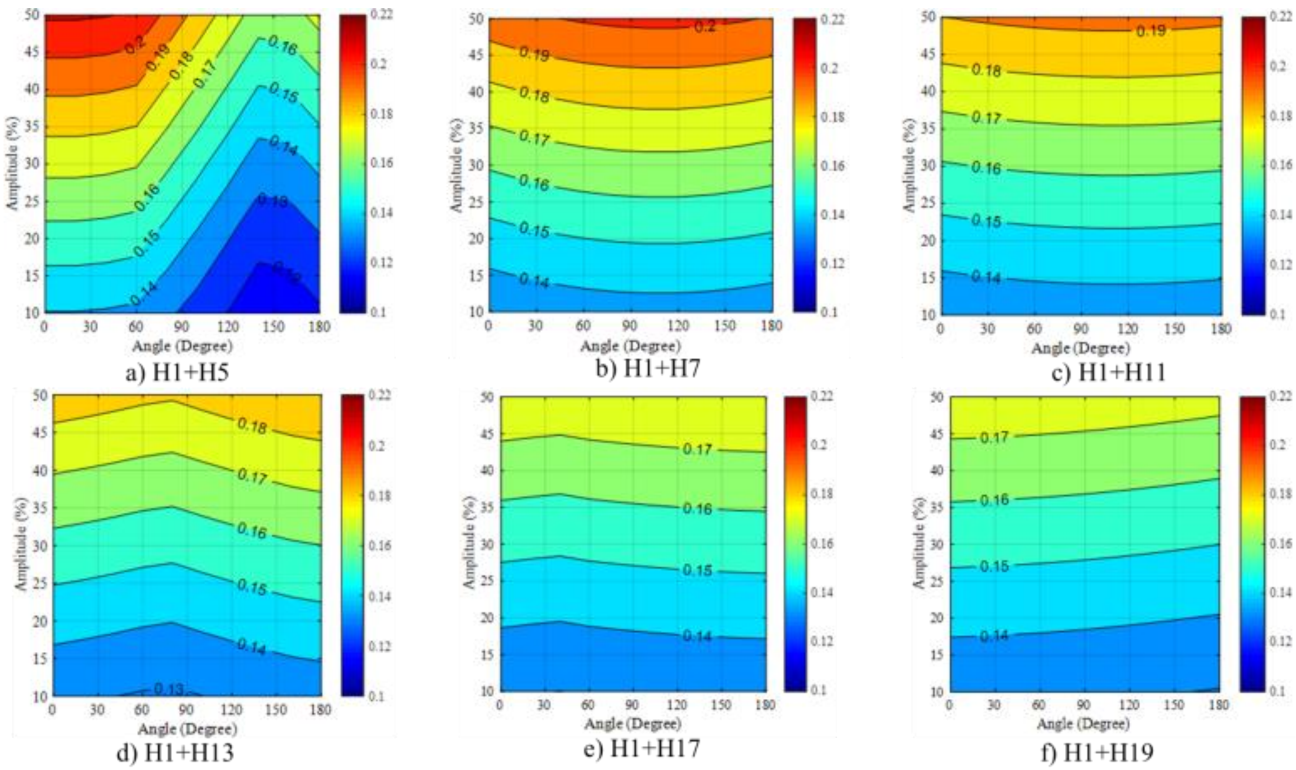

Figure 8. The impacts of integer-harmonic order, amplitude and phase angle on the AC loss of HTS cable in phase B

two HTS layers that are twisted in opposite direction and as a consequence magnetic field is a reduced. To get a complete view on how integer-harmonic can change AC loss of the HTS cable, the impact of harmonic amplitude and phase angle on the AC loss value was analyzed. Figure 8(a) shows the AC loss value under distorted current waveforms with 5th harmonic order for phase B (as worst-case scenario) at different amplitudes and phase angles. Under such circumstances, it can be seen that maximum AC loss value is when phase angle of harmonic is between 0^{o} to 35^{o} and its amplitude is in 45% to 50% range. However, as shown in Figure 8(b) for 7th harmonic order, the maximum value of AC loss is occurred when phase angle is between 60^{o} and 150^{o}. The trend of AC loss for 11th and 19th orders under different phase angles and amplitudes is the same as 7th order harmonic while 13th and 17th harmonics follow the trend of 5th harmonic order, as shown in Figure 8(c) to Figure 8(f). One of the important results of Figure 8 is that phase angle has the highest impact on the 5th harmonic order among all other integer-harmonic. By having these figures for any HTS cable, the maximum possible heat load could be estimated so that the cooling system could be designed in such a way to compensate the excessive heat load.

C. Sub-harmonics

The impact of sub-harmonics is studied in this section by presenting the AC loss variations under different amplitude, phase angle, and sub-harmonic orders including 0.1, 0.3, 0.5, 0.7, and 0.9. Figure 9(a) shows the AC loss value in phase B for sub-harmonic order of 0.1. By comparing this figure with sinusoidal AC loss, calculated in Table 2 based on ECM approach, it can be seen the AC loss in phase B is 15% to 64% increased, also results show that that harmonic phase angle has the least impact on the AC loss value. Figure 9(b) shows the AC loss value for harmonic order of 0.3. The range of changes in comparison to sinusoidal AC loss is same as harmonic order of 0.1 while the phase angels have a more significant impact on AC loss, comparing to 0.1 harmonic order. Figure 9(c) illustrate the harshest impact of sub-harmonic on AC loss value with a harmonic order of 0.5. Under such conditions, AC loss increases to be 88% higher than sinusoidal AC loss. In this case also the highest impact of phase angle on AC loss could be seen. In this case, phase angles between 15^{o} and 45^{o} has the highest AC loss value when amplitude is about 0.45 to 0.5. At last, Figure 9(d) and Figure 9(e) depict the AC loss for harmonic order of 0.7 and 0.9, respectively. By analyzing Figure 9, one can conceive the importance of analyzing the AC loss characteristic resulted by sub-harmonic components of rated current. AC loss of sub-harmonic currents can be sometimes higher than integer-harmonics and thus could results in weak-points and quenches.

D. Inter-harmonics

This section is dedicated to analyze the impact of non-integer harmonic with an order around 5th harmonic i.e. inter-harmonics currents, on the AC loss of HTS cable. For this purpose, 5.1, 5.3, 5.5, 5.7, and 5.9 inter-harmonic orders was selected and applied to the model. The consideration of harmonic orders between 5th and 6th order is because of that in previous section it was concluded that 5th order harmonic had the severest impact on AC loss. As illustrated in Figure 10, the maximum AC loss value of inter-harmonic current belongs

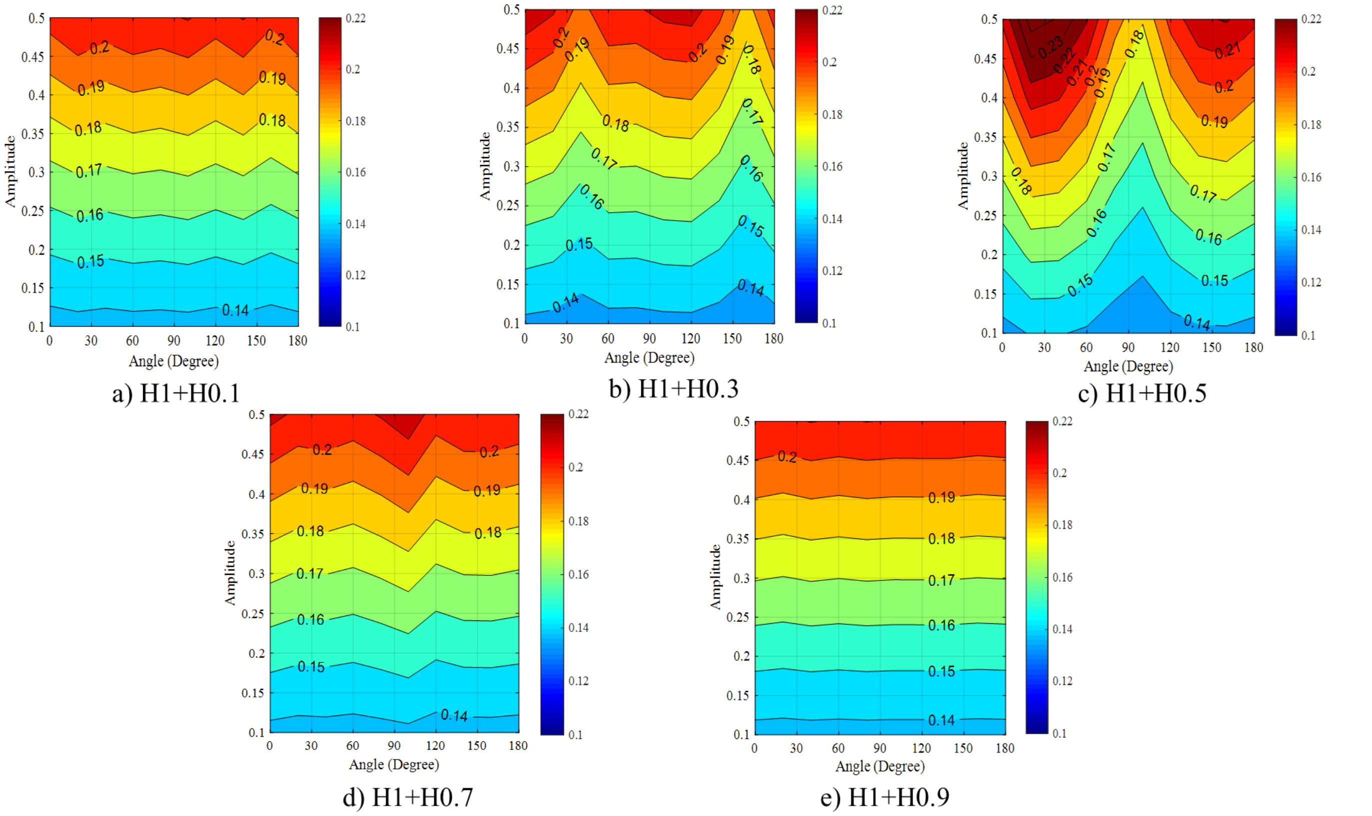

Figure 9. The Impact of sub-harmonics on the maximum value of AC loss in Phase B, as the worst-case scenario, with respect to phase angle and amplitude of sub-harmonic

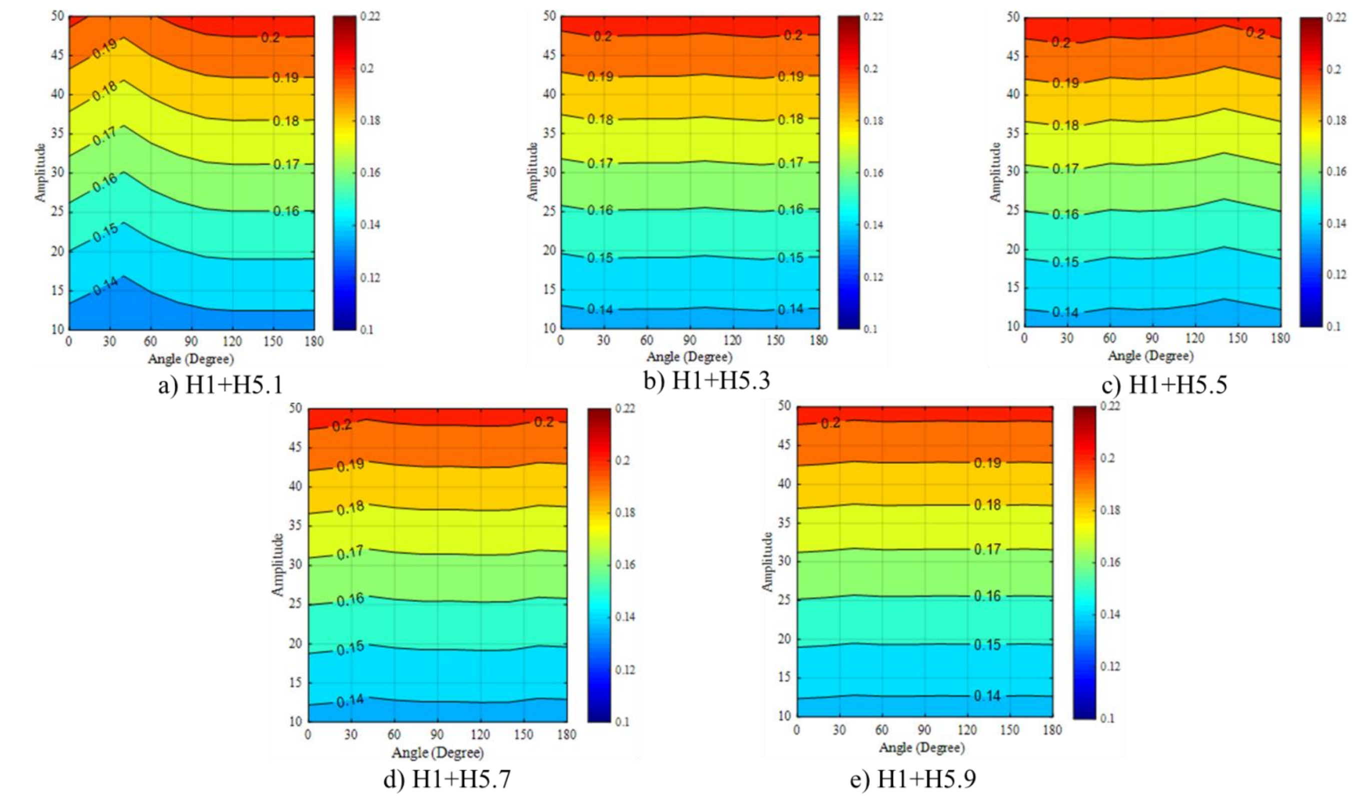

Figure 10. The Impact of inter-harmonics on the maximum value of AC loss in Phase B, as the worst-case scenario, with respect to phase angle and amplitude of sub-harmonic

Table 3. Harmonic current spectrum profile [32]

Order	Frequency (Hz)	Magnitude (%)	Phase (degree)
1	50	100	-26
5	250	19.2	-94
7	350	13.2	-67
11	550	7.3	-67
13	650	5.7	-46
17	850	3.5	-36
19	950	2.7	-60

Table 4. AC loss value of three different case studies based on the harmonic profile reported in [32]

Parameter	Q (J/cycle/m)			
Scenario	A1	A2	B	C
#1	0.0930	0.0663	0.1222	0.0984
#2	0.1719	0.0908	0.3764	0.1754
#3	0.1924	0.0970	0.4373	0.1989

to harmonic amplitude of 45% to 50%. Under such circumstances, AC loss becomes 0.2 J/cycle/m that means 63.7% higher than that of sinusoidal current and 10% lower than worst-case scenario of 5th harmonic current. The results indicate that the AC loss value caused by inter-harmonics has a value near integer-harmonics and 25% lower than worst-case of sub-harmonics. Inter-harmonic current waveform has a very close peak value to integer-harmonics. As observed in Figure 10, phase angle has the least impact on AC loss value of inter-harmonics.

E. Harmonic spectrum analysis

So far, the discussion of this paper concentrated on the impact of single order of harmonics on the AC loss value of HTS cable. In this section, a real non-sinusoidal current waveform which is injected into a power cable in [32] is considered for harmonic AC loss calculations. The Fourier transform details of the harmonic contents of this non-sinusoidal current is shown in Table 3. Its total harmonic distortion is 26% [32]. We used this spectrum since it is a real distorted current passing through a power cable, however, the proposed model in this paper is capable of modelling harmonic currents with even higher harmonic orders.

To analyze the AC loss results, three scenarios are considered, the first scenario (#1) is pure sinusoidal current, the second one (#2) is when all harmonic orders are in-phase (with fundamental current), and the third scenario (#3) is similar to the second one while the phase angles for each harmonic order are considered separately as tabulated in Table 3. The calculated AC loss results under these three scenarios are tabulated in Table 4. As can be seen, the worst-case scenario is the “not-in-phase harmonic waveform” or third scenario that increases AC loss value by 46% to 257% higher than that of sinusoidal current. Also, by comparing case study #2 and #3 for phase B, it can be seen that under non-in-phase condition, AC loss is 16% increased while this number for A1, A2, and C layers is about 15%, 7%, and 13%, respectively. According to the discussions made in this sub-section,

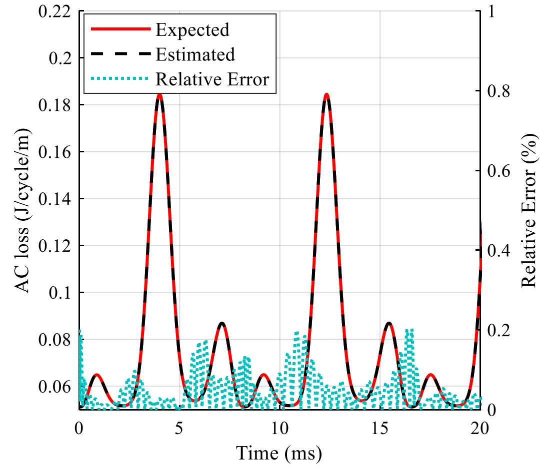

Figure 11. Estimation of distorted instantaneous AC loss by means of ANN-based model

harmonic spectrum analysis plays an important role to evaluate the performance of HTS cables under harmonic currents in electrical systems. Also, it should be noted that, considering phase angles during harmonic analysis of HTS cables highly impact the AC loss value of HTS cables.

F. Artificial neural networks for distorted AC loss estimation

During the design stage of HTS cables, methods like FEM and ECM could be used to characterize the AC loss of cable facing harmonic currents. While, faster methods are needed during condition monitoring of HTS cables for accurately estimating the AC loss, in a real-time manner. As a matter of fact, the real-time AC loss monitoring of HTS cables could improve the reliability, safety, and stability of power system where HTS cables are installed. Thus, AC loss estimation methods are required to be as accurate as ECM and FEM while their computation time should much lower than these methods, that is why artificial intelligence based models are required for such a purpose [33]. Techniques based on artificial intelligent are among the fast and reliable solutions to estimate any non-linear characteristic such as AC loss. These techniques, especially Artificial Neural Network (ANN)-based models, were used recently for the designing, condition monitoring [33], and characterizing the electromagnetic behavior of superconducting devices [34]. In fact, ANN-based models are practical tools that could predict/estimate any nonlinear and highly complex characteristics [33]. AC loss computation accounted also as a complex problem with a high level of nonlinearity, especially under harmonic conditions, that could be conducted by means of ANN-based models. By doing this, not only the computation time would be reduced but also a system would be trained that is capable of being adapted after adding new input data [8]. Thus, in this section, an ANN-based model with four inputs is used to estimate the distorted instantaneous AC loss. These inputs are harmonic order, harmonic phase angle, and harmonic amplitude. By having these and applying an ANN-based model with 5 hidden layers and 15 neurons in each layer, an estimation is conducted. More information and details about the design and construction of these ANN-based models are discussed and presented in [34]. Figure 11 shows the estimated AC loss by the proposed ANN model (black dashed line) versus expected values (red solid line). As can be seen, the expected values and estimated values are in an excellent coordination with each other that shows the accuracy of the ANN-based model. It should be noted that the estimated instantaneous AC loss waveform is related to a distorted current with 5th harmonic order, 50% harmonic amplitude, and 40^{o} phase angle. In addition, the dotted cyan lines in Figure 11 shows the value of relative error in each time step. As can be seen, the maximum relative error is about 0.2% that means the estimated value is just 0.2% higher/lower than expected value. In other words, accuracy of model is 99.8% at worst-case scenario.

IV. Conclusion

High Temperature Superconducting (HTS) cables are promising elements of modern electrical systems. In these electrical systems, current harmonics caused by nonlinear loads results in distorted current waveform composed of many harmonics, sub-harmonics, and inter-harmonics. Harmonic distortions increase the AC loss in HTS cables and reduce the efficiency of their cooling systems. Harmonic types, orders, amplitudes, and phase angles are four main characteristics of non-sinusoidal current waveforms. This paper has analyzed and discussed the impact of harmonics on electromagnetic characteristic of a 22.9 kV HTS cable. To do this, an equivalent circuit model was developed to analyze the AC loss.

The most important findings of this paper are as follows:

- The 5th harmonic current with 50% amplitude and 0o to10o phase angle has the maximum impact on the AC loss value that could increase the AC loss of the HTS cable to be 50.6%, 22.47%, 73%, and 58.6% higher than that of sinusoidal current in A1, A2, B, and C layers of the cable, respectively.
- AC loss could be increased significantly under sub-harmonics and inter-harmonics so that sub-harmonics and inter-harmonics could increase the AC loss 104.5% and 63.7% in comparison to pure sinusoidal current.
- Artificial Neural Networks model was used to estimate the maximum AC loss of HTS cable under harmonic conditions, with an accuracy higher than 99%.
- Harmonic spectrum analysis showed that a current waveform consisting of multiple harmonics could increase the AC loss so that it is about 46% to 257% higher than pure sinusoidal current for non-in-phase harmonics.

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