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Analytical modeling of coupling losses in CICCs, extensive study of the COLISEUM model

R. Babouche, L. Zani, A. Louzguiti, B. Turck, J.L. Duchateau, F. Topin

Abstract— Cable-in-Conduit Conductors (CICC) are made of several hundreds of superconducting and copper strands twisted together and gathered into multiple stages. To ensure safe and reliable operation of tokamaks, it is essential to take into account AC losses occurring in such conductors. Recently developed at CEA, the fully analytical model named COLISEUM (COupling Losses analytIcal Stages cablEs Unified Model) aims at predicting the coupling losses at various cable scales using only geometrical and electrical parameters. The most recent version of the COLISEUM model addresses the coupling losses for a full CICC, accounting contributions from the strand to the last stage of the cable. In this paper, we investigate the COLISEUM model in non-tangential conditions. On the other hand, we present a methodology to derive geometrical model inputs from tomographic images.

Index Terms— AC losses, CICC, superconducting magnets, tomography.

I. INTRODUCTION

The COLISEUM (Coupling Losses analytIcal Stages Cables Unified Model) model [1]- [2] is a fully analytical model addressing the coupling losses for a complete CICC. The hysteretic losses are not considered in this model. In addition, it assumes not saturated composites. In the baseline of the model, a stage is composed of several elements. They can either be a strand, a multiplet of strands or multiplet of multiplets. A basic element is represented by a superconducting tube. The model inputs refer to intrinsic geometrical parameters of each stage (twist pitch, l_p [m], and cabling radius, R_c [m]) and the inter-stage conductance per unit length, noted σ [S/m]. The COLISEUM model can either be used in tangential conditions, i.e. all the elements are tangent to each other, or, in nontangential conditions. In [2], the tangent COLISEUM model was used to predict AC coupling losses occurring in CICC samples close to the JT60-SA TF one. Geometrical inputs were taken from specifications and inter-stage transverse conductances were used as fitting parameters. This study showed a good agreement between the model and the experimental data. Nevertheless, inter-stage transverse conductances were not crosschecked with experimental data. In that case, the COLISEUM model is used but not fully validated. On the other hand, the non-tangential condition has not been studied yet. The objective of this paper is to determine the potential limits of the model in such condition. The tangential configuration leads to cable dimensions larger than real ones.

The second configuration allows cable dimensions in the model closer to the reality.

The second part of this paper describes the extension of the work started in [3] to determine realistic effective parameters to be used as COLISEUM inputs.

II. STUDY OF THE COLISEUM MODEL

A. AC Coupling losses

When the CICC is subject to time-varying magnetic fields, the instant power density in the j^{th} stage of the model can be expressed as

$$P_j = n\kappa_j \tau_j \frac{B_{int j}^2}{\mu_0} \tag{1}$$

The term n κ corresponds to the shielding coefficient; it describes the ability of the CICC to shield an inner volume from the external field variation. The second term, τ , is a time constant of the induced current loops responsible for the coupling losses. As in the MPAS model [4], [5], recent developments on the COLISEUM model lead to consider a number of (n κ , τ) couples equal to the number of cabling stages [2].

B. Study in non-tangential conditions

In this section we present the method to study the COLISEUM model in non-tangential conditions. This paper presents the investigations on the two-stage COLISEUM model configuration. The study is in fact an approach of the effect of a cable compaction.

To set the model in non-tangential conditions, elements containing the tubes of current penetrate each other. On Fig 1, the tubes of current are displayed as green circles, the elements as black circles and the circumscribed area of the cable in blue. For each stage of the cable, a penetration coefficient called $\gamma \in$ [0; 1] is defined. On the one hand, $\gamma = 1$ refers to the tangent condition (Fig 1 left). Strands and stages are all tangent to their direct neighbours. On the other hand, $\gamma = 0$ refers to the fully penetrated condition. It is a theoretical configuration impossible to build, thus, not shown. The formula of the penetration coefficient of the jth stage is defined in figure 1 on the right. During penetration steps, only the cabling radius decreases. The elements and the tubes of current are fixed in size. Fig 1 presents an example of a two stages cable, a triplet of triplets

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(3x3 multiplicity). We check the values of the magnetic coefficients ($n\kappa$ and τ) through the penetration steps to assess the results of the study. The limit of the COLISEUM model is reached when the value of $n\kappa$ and/or τ are equal to zero.



Fig 1: Case of a two stages cable (3x3). Peculiar case $\gamma_1 = \gamma_2$. γ_j and R_{cj} are respectively the penetration coefficient and the cabling radius of the jth stage. R_{c1} and R_{c2} are displayed in the left schematic in dashed magenta circles. Left: $\gamma_1 = \gamma_2 = 1$: tangent condition. Right: $\gamma_1 = \gamma_2 = 0.7$: intermediary condition.

As well as the penetration coefficient, a void rate indicator (noted VR) is defined. It corresponds to the ratio of the circumscribed area of the cable minus the area occupied by the elements to the circumscribed area of the cable.

$$VR = \frac{\pi \left(R_{elem} + \sum_{j} R_{cj}\right)^2 - (\pi R_{elem}^2 \times \prod_{j} N_j)}{\pi \left(R_{elem} + \sum_{j} R_{cj}\right)^2}$$
(2)

Where, j is the jth stage of the cable, with N_j its multiplicity and R_{elem} the radius of the elements. It is chosen to compute the void rate considering all the elements in the cable. Therefore, it can be seen as the global void rate of the cable. It is also possible to compute the void rate of each stage. It is chosen not to subtract the overlapped element areas when computing the void rate indicator. The

Fig 2 (a) presents a schematic of a cable and the considered elements and area. This indicator, is used to compare our study with real cables data.



Fig 2: Schematic of a two stages cable (3x3). The grey colour corresponds to the considered area to compute the void rate. Elements are coloured in black. (a) Tangential condition configuration showing a global void rate of 58.25%. (b) Non-tangential condition configuration with the penetration coefficients $\gamma_1 = \gamma_2 = 0.79$ and a global void rate equal to 32.69%.

III. RESULTS ON THE MODEL IN NON-TANGENTIAL CONDITIONS

Using the COLISEUM model, we have computed the coupling losses of the cable presented in Fig 2. The Fig 3 displays the coupling losses expressed per unit volume of cable and per cycle as a function of the frequency of the external magnetic field. Note that this volume refers to the circumscribed volume of the cable. For a sinusoidal field excitation, the coupling losses are calculated with the following formula

$$Q_{coupling \ cable} = \sum_{j=1}^{j=2} n\kappa_j \tau_j \frac{B_m^2}{\mu_0} \frac{\pi\omega}{1 + (\omega\tau_j)^2} \qquad (3)$$

Using Fourier transform principles, this formula can be applied to every type of signal. The cable coupling losses are the sum of the losses of all the stages. Table 1 shows the calculated coupled and uncoupled magnetic coefficients. Note that the term "uncoupled" refers to the case where only one stage can develop coupling currents (i.e. the conductance of the other stage is set to zero). In this example, both inter-stage conductances, σ_1 (relative to the first stage) and σ_2 (relative to the second stage), are kept constant and set equal to $6x10^7$ S/m. Only the geometrical distances are modified by the compaction in this calculation. The maximum amplitude of the magnetic field is equal to 0.2 T for both configurations. For the tangential condition, the maximum coupling losses are equal to 116 mJ/cm⁻³.cycle⁻¹ and are reached at a frequency of 0.03 Hz. This value decreases to 69 mJ/cm⁻³.cycle⁻¹ at a frequency of 0.04 Hz for the non-tangential one. In fusion reactors, CICC conductors undergo external transient magnetic fields. Due to its larger cable dimensions, the tangential condition configuration implies a larger magnetic flux than the non-tangential condition one. All things being equal, it leads to higher calculated losses.

Table 1: Coupled and uncoupled magnetic coefficients calculated with the COLISEUM model

	Tangential condition		Non-tangential condition	
	nκ	τ [ms]	nκ	τ [ms]
uncoupled	1.46	1.68	1.23	1.25
	1.93	4.77	1.16	3.90
coupled	0.22	1.30	0.16	0.72
	2.21	5.16	1.34	4.43



Fig 3: Coupling losses as a function of the frequency of the external

sinusoidal magnetic field ($B_m = 0.2 T$). Results per unit volume of cable. The case of the two stages (3x3) cable is presented in tangential (blue curve) and non-tangential condition (black curve).

The void rate presented in Fig 2 (b) is obtained for one peculiar combination of γ_1 and γ_2 ($\gamma_1 = \gamma_2$). Several combinations of those coefficients could lead to the same void rate. Therefore, we have studied the respective influence of γ_1 and γ_2 and their combination on the cable behaviour. The results are illustrated using maps of magnetic coefficients in Fig 4.

The typical void rate values of CICC conductors are within the 30-40 % range. Fig 4 shows in black dashed lines the contours of all the (γ_1, γ_2) combinations leading to specific void rates values between 25 and 50 %. This range is chosen to enclose a broad variety of cases and to be more representative of real cables even though we consider only a two stages cable. Furthermore, Fig 4 shows the maps of the coupled magnetic coefficients ($n\kappa$, τ) as a function of the penetration coefficients combinations. We show the magnetic coefficients relative to the second stage only since the behaviour of the first stage magnetic coefficients is similar. The red areas correspond to values being null or negatives. Therefore, they act as forbidden areas and limits of the model. One can notice that, for considered void rates, the COLISEUM model outputs stay out of these forbidden areas. The shielding coefficients, $n\kappa_2$, Fig 4 (left), cross the critical area for the 25% void rate contour at $\gamma_2 = 1$ and $\gamma_1 \approx 0.55$. It corresponds to an extreme case where the super stage is in tangential condition and only the sub stages are penetrated. However, we assume that consecutive stages should see similar compaction, thus, similar penetration coefficients. In Fig 4, white dotted lines are bounding a 20% interval around the first bisector for γ_1 and γ_2 . We consider it to be the probable zone for real cables.



Fig 4: Map of the magnetic coefficients as a function of the $\gamma 1$ and $\gamma 2$ coefficients. (left) shielding coefficients, (right) time constants [ms]. The red area refers to nonphysical values (negative or null). The white dotted lines delimit the most probable zone for real cable void rate and compaction coefficients.

In this section we have developed a method to study the COLISEUM model in non-tangential conditions. It aims at bringing it closer to realistic cable geometries. We have shown that, in the most likely realistic area, both magnetic coefficients $(n\kappa and \tau)$ stay far from the nonphysical areas. Therefore, the COLISEUM model stays consistent in non-tangential conditions for realistic void rate values.

IV. TOMOGRAPHIC DATA AS MODEL INPUT

In the framework of a collaboration between the CEA (France) and INFLPR (Romania), CICC samples were tomographied using a 320 kV high penetration power microtomograph allowing sufficient image resolution and contrast to identify each strand in the cable. Details about the experimental setup are available in [6] and [3]. The images were used to identify and reconstruct the strand trajectories which will be used in the future to measure the associated geometrical parameters (cabling radii and the twist pitches). The objective is to use those realistic effective parameters as input for the COLISEUM model.

A. Sample characteristics

In this paper the study is focused on the sample "MAG42-2". It is made of 324 Nb-Ti strands and 162 copper strands (see Fig 7) of 0.81 mm diameter. The void rate is equal to 33.2% [7] and the sample length is about 300 mm (slightly more than the last stage twist pitch). Characteristics parameters of the sample are gathered in Table 2.

Table 2: Characteristics parameters of the MAG42-2 sample.			
Void fraction [%]	33.2		
Sample cross-section	18 x 22 mm		
Cable pattern	(2 Sc + 1 Cu)x3x3x3x6		
Number of strands	486 (324 Sc + 162 Cu)		
Twist pitches specifications [mm]	45-70-120-190-290		

We extracted from the 3D tomographic images, a set of 1058 slices (perpendicular to cable axis) with an inter-slices distance of about 283 μ m. A database of the positions of each of the 486 strands is constructed. Note that at this stage only the strands trajectories are reconstructed along the cable.

B. Tomographic data post-treatment

This section presents the ongoing study on post-treatment and interpretation of the tomographic data. The determination of realistic effective parameters is expected to be improved thanks to the identification of the different stages of the cable which was not possible at the time of the effective geometrical parameters determination conducted in [1].

We developed an algorithm based on the mean squared distance between strands and group of strands along the cable. The association of strands into stages is based on their mean distance to each other along the cable. The Fig 5 presents the squared distance between the strand labelled 1 and its fifteen closest neighbours. From this statistics, strands 1, 30 and 31 are associated to form a triplet. This operation is repeated for each strand. For super stages identification, the same algorithm is applied. In this case, the distance is no longer computed between strands centers but between sub-stage barycenters which are calculated as the mean position of the considered stage.



Fig 5: Squared distance from the reference strand labelled $n^{\circ}1$ to its fifteen closest neighbours. Strands labels are displayed above the bars.

The output of the algorithm is a list of strand combinations that form the different stages. We developed three check steps to verify them. The first one checks if the obtained multiplets of strands are consistent (e.g. strand 1 should appear in the two closest neighbours of strands 30 and 31, etc.). From this point, the correct association list is created and the inconsistent associations are placed in a remaining pool. The second step deletes each strand of the remaining pool already appearing the correct list. Finally, the last check step selects the most frequent associations among the remaining strands still present in the pool. This algorithm can also be enhanced by defining a distance threshold. Thus, it is possible to determine several contact statistics (length, width, frequency).

In the case of the MAG42-2 sample, 162 first stages (composed of 3 strands each) have been found as well as 54 second stages (composed of 9 strands each), 18 third stages (composed of 27 strands each), 6 fourth stages (composed of 81 strands each) and one fifth stage composed of the 6 fourth stages and the 486 strands. Regarding the first stage, the first check step leads to 111 triplets recognized, the second step to 39 more and the third step to 12 more, leading to the 162 triplets. Each super stage is found after the first check step only. Results are shown in Fig 6. Each colour identify a stage family. For super stages (every colour except the blue one) triangles and hexagon summits are located at the barycenters of the direct sub-stage.



Fig 6: Stages identification. Blue triangles: 162 first stages composed of 3 strands each; green triangles: 54 second stages with 9 strands each; red triangles: 18 third stages with 27 strands each; black triangles: 6 fourth stages with 81 strands each; white hexagon: fifth stage composed of the 6 fourth stage and the 486 strands.

In addition to tomographic data, pictures of the sample extremities are available as shown in Fig 7. Thus, it is possible to identify the strand type as "superconducting" or "copper". We have manually recognized the strand type in the start extremity, see Fig 7. Then, we have displayed the tomographic image of the end extremity with a corresponding colour code for "superconducting" (yellow) or "copper" (green) strands. The resulting image is compared with the real picture of the end extremity as shown in Fig 7. The results show that the tomographic picture and the real end extremity picture match at 100%. Moreover, it has been shown in [3] that the identified strand stays the same from slice to slice. Therefore, no strand substitution is responsible for that result.



Fig 7: (Start extremity) manually identified strands. (End extremity) plotted considering start slice identification. Yellow strands stands for superconducting ones and green for copper ones.

The MAG42-2 sample is composed of 324 superconducting strands and 162 copper strands. In order to validate the identified stages we have verified that each of the 162 first stages triplet are composed of two superconducting strands and one copper strand. Results show that 100% of them verify that condition.

The two previous verifications (strand type and first stage composition) ensure the trustworthiness of the developed algorithm in identifying each stage of the cable.

V. CONCLUSION AND PERSPECTIVES

We have conducted an extensive study of the COLISEUM model in a two-stage configuration. For a specific cable layout, this study has shown that COLISEUM can be used in nontangential conditions. It allows the model to consider cable topology closer to the reality. This study allowed to assess the consistency of COLISEUM in non-tangential conditions for the two-stage configuration and will be followed for other cable layouts and higher number of stages in the cable.

On the other hand, a post-treatment method is currently developed to use tomographic data to determine realistic effective cable parameters. We have shown that the identified stages match the cable specifications. Those encouraging results will allow to determine realistic effective geometrical and electrical parameters. Those parameters will then be used as input for the COLISEUM model. It is planned to apply this algorithm on several CICC samples. In addition, thanks to the stages identification, it will be possible to select the relevant strands and/or stages to conduct inter-stage conductance measurements.

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REFERENCES

- A. Louzguiti, «Magnetic screening currents and coupling losses induced in superconducting magnets for thermonuclear fusion,» *PhD Thesis*, 2017.
- [2] M. Chiletti, «Coupling losses in large superconducting Cable In Conduit Conductors for fusion reactors: analytical modelling and experimental investigations.,» *PhD Thesis*, 2020.
- [3] L. Zani, M. Chiletti, D. Dumitru, M. Lungu, I. Tiseanu et F. Topin, «Extensive analyses of superconducting cables 3D geometry with advanced tomographic examinations,» *IEEE Transactions on Applied Superconductivity*, vol. 31, n° %15, pp. 1-5, 2021.
- [4] B. Turck et L. Zani, «A macroscopic model for coupling current losses in cables made of multi-stages of superconducting strands and its experimental validation,» *IEEE Transactions on Applied superconductivity*, vol. 18, n° %11, pp. 18-28, 2008.
- [5] J. Duchateau, B. Turck, A. Torre et L. Zani, «An analytical model for coupling losses in large conductors for magnetic fusion,» *Cryogenics*, vol. 120, 2021.
- [6] I. Tiseanu, «Multi-scale 3D modelling of a DEMO prototype cable from strand to full-size conductor based on X-ray tomography and image analysis,» *Fusion Engineering and Design*, vol. 146, pp. 568-573, 2019.
- M. Chiletti, L. Zani, B. Turck, J. Duchateau et F. Topin, «Void Fraction Influence on CICCs Coupling losses: Analysis of Experimental Results With MPAS Model,» *IEEE Transactions on Applied Superconductivity*, vol. 30, n° %14, pp. 1-5, 2020.
- [8] A. Louzguiti, L. Zani, D. Ciazynski, B. Turck, J. Duchateau, A. Torre, F. Topin, M. Bianchi, A. Ricchiuto, T. Bagni, V. Anvar, A. Nijhuis et I. Tiseanu, «Development of a New Generic Analytical Modeling of AC Coupling Losses in Cable-in-Conduit Conductors,» *IEEE Transactions on applied Superconductivity*, vol. 28, n° %13, pp. 1-5, 2018.