Analytical coupling losses modelling with COLISEUM: generalized approach upgraded to all stages

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***Abstract*— Predicting analytically the coupling losses generated in a cable for fusion magnets is still a significant challenge. Difficulties are related to the complex geometry of the system: several multi-strand stages embedded in one another with different twist pitches length, difficulty to model multiplets of strands, including compaction to the final shape. A two-stage analytical geometry based model (COLISEUM) has previously been developed at CEA. We try to extend it to any n-stage cables We detail here an iterative enhancement method to an n-stage model . We validated it against experimental data and shown that it is robust enough to fit our measured coupling losses. Finally, this upgraded model can be used to assess coupling losses in fusion n-stage cables in a particularly precise way from only geometrical information and analytical tools .**

***Index Terms*— AC losses, superconducting, CICCs, fusion magnets**

I. Introduction

COUPLING losses modelling of CICC for fusion magnets remains a domain of interest as seen in [1],[2], [3], [4], [5] and are often obtained by using numerical codes as in [2] or [6]. We propose here an analytical general method applicable to any n-stage cable to reach this objective. In order to establish and develop this n-stage model from the two-stage COLISEUM [7], several input parameters are taken into account at each stage, such as: number of bundles N, twist pitches length l_p, interstage conductances σ, as well as filamentary zone radius of the basic strand R_f. We show that the initial two-stage COLISEUM [7] can be derived to obtain a time constant and a shielding coefficient ($n\kappa$,τ) for each simulated stage. The model enhancement is realized in two steps: Firstly, the reduction of the two-stage COLISEUM's matrix equation from dimension four to two without loss of information and secondly, we rewrite the system of matrix equations as a unique matrix equation in order to describe any cable with an indefinite number of stages.

Starting from a two-stage interaction in the initial model, we implement first neighbors coupling through the rewriting of systems equations. In the end, we obtain a set of n time constants and n shielding coefficients (n-stage), i.e. one couple of magnetic parameter per stage as in the MPAS model [8].

This newly developed n-stage COLISEUM is confronted to MPAS and assessed against the data measured at CEA Cadarache in the JOSEFA facility from a sample representative of JT-60SA TF [9].

II. System Reduction

The initial development of COLISEUM is fully detailed in [7] along with the complete expressions of the time constants τ_{ij}, and of the amplitudes of current I. It was then applied to a two-stage system which is described by a 4x4-matrix equation (1):

$$(1)\quad I_0 + [\tau]\dot{I}_0 = I_{0_{ext}} \text{ where } [\tau] = \begin{pmatrix} \tau_{00} & \tau_{01} & 0 & 0 \\ \tau_{10} & \tau_{11} & \tau_{12} & 0 \\ 0 & \tau_{21} & \tau_{22} & \tau_{23} \\ 0 & 0 & \tau_{32} & \tau_{33} \end{pmatrix} \quad (2)$$

After diagonalization of the matrix $[\tau]$, we obtain the four coupled time constants τ_i of the related system (two-stage cable) and evaluate the four corresponding shielding coefficients $n\kappa_i$ by using the procedure explained in [7].

We previously showed [6] that among the four magnetic parameters, two $n\kappa_0\tau_0$ and $n\kappa_3\tau_3$ are always close to zero and negligible compared to the others. Therefore, the relevant set of magnetic parameters is the pair $\left((n\kappa_1,\tau_1),(n\kappa_2,\tau_2)\right)$ where the first set can be related to the first stage contribution and the second set to the second stage one. We also showed that diagonalizing $[\tau]$ in (1) or only its central part by using (3) will give nearly identical pairs of parameters $((n\kappa_1\tau_1),(n\kappa_2\tau_2))$. This is due to the small norm of the terms ($\tau_{00},\tau_{01},\tau_{10},\tau_{32},\tau_{23}$ and τ_{33}) involved in the diagonalization of the initial matrix $[\tau]$.

The practical most interesting result from dimension reduction is that, we are now able to analytically diagonalize the reduced matrix $[\tau]$:

$$[\tau] = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{21} & \tau_{22} \end{pmatrix} \quad (3)$$

where $\tau_1$and τ_2 are the eigenvalues of this 2x2 matrix. Their expressions are:

$$\tau_1 = \frac{1}{2}\left(\tau_{11} + \tau_{22} + \sqrt{(\tau_{11}-\tau_{22})^2 + 4\tau_{12}\tau_{21}}\right) \quad (4.1)$$

$$\tau_2 = \frac{1}{2}\left(\tau_{11} + \tau_{22} - \sqrt{(\tau_{11}-\tau_{22})^2 + 4\tau_{12}\tau_{21}}\right) \quad (4.2)$$

where τ_2 is always greater than τ_1 as all matrix terms are positive and $\tau_{11} < \tau_{22}$. With this first step, we simplified a four

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Maxime Chiletti is with Commissariat à l'Energie Atomique et aux Energies Alternatives, CEA/DRF/IRFM, CEA Cadarache 13115 St Paul-Lez-Durance, France (e-mail: *maxime.chiletti@cea.fr*)

Louis Zani, Bernard Turck, Alexandre Louzguiti and Jean-Luc Duchateau are with Commissariat à l'Energie Atomique et aux Energies Alternatives, CEA/DRF/IRFM, CEA Cadarache 13115 St Paul-Lez-Durance, France.

Frédéric Topin is with Aix Marseille Université, CNRS, IUSTI UMR 7343, 13453, Marseille, France (e-mail: Frederic.topin@univ-amu.fr).

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TABLE I
COLISEUM OUTPUTS

4x4 simulation		2x2 simulation	
$n\kappa$ (adim)	τ (ms)	$n\kappa$ (adim)	τ (ms)
$5.00.10^{-5}$	0.890		
$9.03.10^{-2}$	1.30	$0.903.10^{-2}$	1.30
0.923	5.16	0.923	5.16
$4.30.10^{-6}$	20.4		

Comparison of magnetic parameters given by the 4x4 simulation and by the 2x2 analytic calculation.

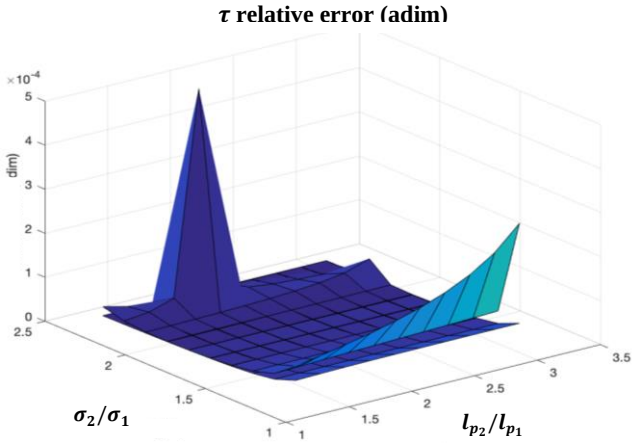

Figure 2: Map of discrepancy between the magnetic parameters (τ_1,τ_2) given by the four dimensions and the two dimensions system. Shielding coefficients discrepancy exhibits the same behavior.

dimensions matrix equation that must be solved numerically to compute the magnetic parameters of a two-stage cable, to a fully analytical matrix equation of dimension two. After the reduction, we are left with only one couple of magnetic parameters ($n\kappa$,τ) per stage as in the MPAS model (see [8]). This reduction has been initiated in [6] with the broad parametric exploration of the two-stage COLISEUM.
Table I show the validation of our simplification in an application case using the geometric parameters of the two-first stage of JT-60SA TF cable that can be found in [9]:

This comparison can be carried out on a large domain of ratio of consecutive twist pitch length ratios $\frac{l_{p_{i+1}}}{l_{p_i}}$ and conductances ratios $\frac{\sigma_{i+1}}{\sigma_i}$ as shown in Figure 1. We check if the relative error between the four dimensions and two dimensions approach is negligible (as in Table I).

As illustrated on Figure 1 for time constants, we check that the relative difference between the two approaches is negligible on all the explored domain (<5.10^{-2} %). These studies on time constants and shielding coefficients are complementary with the study led on the contribution of $n\kappa\tau$ product led in [10].
This show clearly that the dimension reduction does not affect the values of the two remaining time constants and shielding coefficients that are indeed representative of the system. We are now in line with the MPAS formulation of coupling losses: one couple ($n\kappa$,τ) per stage of cable (see [8]).

III. Coupling and Iteration

Using the reduced two-stage COLISEUM we now extend the model to the description of complex cable with indefinite

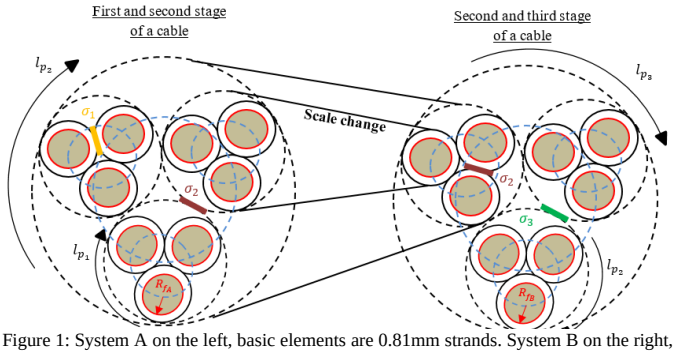

Figure 1: System A on the left, basic elements are 0.81mm strands. System B on the right, basic elements are homogenized triplet of strands.

number of stages. We initialize the iteration by considering three consecutive stages that we model by using twice the reduced two-stage COLISEUM: first on system A, a triplet of triplet, i.e. first and second stage of a cable; then, on system B, , also a triplet of triplet, i.e. second and third stage of a cable. We thus try to model three consecutive stages of a cable as depicted in Figure 2.
It should be noted that the second stage of the cable is included in both system: it is the second stage of system A and also the first stage of system B. The two associated model describe respectively the coupling of the first and the second stage in the system A and the coupling between the second and the third stage in the system B.
System A (cable stage 1 and 2) is described by using:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} + \begin{pmatrix} \tau_{11} & \tau_{12}/N_1 \\ N_1\tau_{21} & \tau_{22} \end{pmatrix}_A \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \end{bmatrix} = \begin{bmatrix} 4\sigma_1 R_{c_1} \sin^2\left(\frac{\pi}{N_1}\right)\left(\frac{l_{p_1}}{2\pi}\right)^2 \\ 4\sigma_2 R_{c_2} \sin^2\left(\frac{\pi}{N_2}\right)\left(\frac{l_{p_2}}{2\pi}\right)^2 \end{bmatrix} \dot{B}_a \quad (5)$$

and system B (cable stage 2 and 3) is described by using:

$$\begin{bmatrix} I'_2 \\ I_3 \end{bmatrix} + \begin{pmatrix} \tau_{22} & \tau_{23}/N_2 \\ N_2\tau_{32} & \tau_{33} \end{pmatrix}_B \begin{bmatrix} \dot{I}'_2 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} 4\sigma_2 R_{c_2} \sin^2\left(\frac{\pi}{N_2}\right)\left(\frac{l_{p_2}}{2\pi}\right)^2 \\ 4\sigma_3 R_{c_3} \sin^2\left(\frac{\pi}{N_3}\right)\left(\frac{l_{p_3}}{2\pi}\right)^2 \end{bmatrix} \dot{B}_a \quad (6)$$

It is stressed that τ_{22} of system A is strictly equal to τ_{22} of system B by construction.
Equation (3.2) is describing the second stage as the super-stage of system A and the equation (4.1) is also describing the second stage, but seen as the sub-stage of system B. In order to get a "full" first neighbor coupling, we couple the two differential equations ((3.2) plus (4.1)) by redefining the coupling between consecutive stages. The new driving equation is:

$$N_1\tau_{21}\dot{I}_1 + I_2 + \tau_{22}\,\dot{I}_2 + \frac{\tau_{23}}{N_2}\,\dot{I}_3 = 4\sigma_2 R_{c_2} \sin^2\left(\frac{\pi}{N_2}\right)\dot{B}_a/\alpha_2^2 \quad (7)$$

Instead having two systems of dimension 2x2 we can gather both systems into a bigger one of dimension 3x3 where the second stage will be coupled to first and third stages:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + \begin{pmatrix} \tau_{11} & \tau_{12}/N_1 & 0 \\ \tau_{21}N_1 & \tau_{22} & \tau_{23}/N_2 \\ 0 & N_2\tau_{32} & \tau_{33} \end{pmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} 4\sigma_1 R_{c_1} \sin^2\left(\frac{\pi}{N_1}\right)\left(\frac{l_{p_1}}{2\pi}\right)^2 \\ 4\sigma_2 R_{c_2} \sin^2\left(\frac{\pi}{N_2}\right)\left(\frac{l_{p_2}}{2\pi}\right)^2 \\ 4\sigma_3 R_{c_3} \sin^2\left(\frac{\pi}{N_3}\right)\left(\frac{l_{p_3}}{2\pi}\right)^2 \end{bmatrix} \dot{B}_a \quad (8)$$

This new matrix equation of dimension three describes the coupling of three consecutive stages using the first neighbor interaction assumption (mutual inductance). Consistently with MPAS approach, this new system provides one time constant and shielding coefficient per stage (here three stages = three set of magnetic parameters). Iterating this method, we are able to construct and describe any n-stage system as presented in [11]. Expression of the matrix equation and magnetic parameters are given in dimension n as well as the dissipated power per unit volume of circumscribed cable. This newly developed model is named n-stage COLISEUM.

$$\begin{bmatrix} \boldsymbol{I_1} \\ \boldsymbol{I_2} \\ \boldsymbol{I_3} \\ \boldsymbol{I_4} \\ \vdots \\ \boldsymbol{I_n} \end{bmatrix} + [\boldsymbol{\tau}] \begin{bmatrix} \dot{\boldsymbol{I}}_1 \\ \dot{\boldsymbol{I}}_2 \\ \dot{\boldsymbol{I}}_3 \\ \dot{\boldsymbol{I}}_4 \\ \vdots \\ \dot{\boldsymbol{I}}_n \end{bmatrix} = [\boldsymbol{Y}] \dot{\boldsymbol{B}}_{\boldsymbol{a}} \text{ with } [Y] = \begin{bmatrix} 4\sigma_1 R_{c_1} \sin^2\left(\frac{\pi}{N_1}\right)/\alpha_1^2 \\ 4\sigma_2 R_{c_2} \sin^2\left(\frac{\pi}{N_2}\right)/\alpha_2^2 \\ 4\sigma_3 R_{c_3} \sin^2\left(\frac{\pi}{N_3}\right)/\alpha_3^2 \\ 4\sigma_4 R_{c_4} \sin^2\left(\frac{\pi}{N_4}\right)/\alpha_4^2 \\ \vdots \\ 4\sigma_n R_{c_n} \sin^2\left(\frac{\pi}{N_n}\right)/\alpha_n^2 \end{bmatrix} \quad (9)$$

where

$$[\tau] = \begin{pmatrix} \tau_{11} & \tau_{12}/N_1 & 0 & 0 & 0 & 0 \\ N_1\tau_{21} & \tau_{22} & \tau_{23}/N_2 & 0 & 0 & 0 \\ 0 & N_2\tau_{32} & \tau_{33} & \tau_{34}/N_3 & 0 & 0 \\ 0 & 0 & N_3\tau_{43} & \tau_{44} & \ddots & 0 \\ 0 & 0 & 0 & \ddots & \ddots & \tau_{n-1\,n}/N_{n-1} \\ 0 & 0 & 0 & 0 & N_{n-1}\,\tau_{n\,n-1} & \tau_{nn} \end{pmatrix} \quad (10)$$

The coupled time constants τ_i of the system are the diagonal elements of $[\tau]_{coupled}$ which is obtained by diagonalizing the above time matrix $[\tau]$ by using the passage matrix $[V]$.
The dissipated power per unit volume of circumscribed cable is expressed by using the same methodology developed in [7]:

$$P_{vol} = \lambda_1 I_1^2 + \lambda_2 I_2^2 + \cdots + \lambda_n I_n^2 \quad (11)$$

with the λ coefficients : $\lambda_k = \frac{\left(\frac{l_{p_k}}{2\pi}\right)^2 \prod_{l=k}^{n}(N_l)}{8\sigma_k \sin^2\left(\frac{\pi}{N_k}\right)\pi R_{circ}^2}$

The shielding coefficients expressions are extended to the description of n-stage cable from those given in [7] as follows:

$$\boldsymbol{n\kappa_i} = \boldsymbol{2\mu_0} \sum_{\boldsymbol{k=1}}^{\boldsymbol{n}} \sum_{\boldsymbol{l=1}}^{\boldsymbol{n}} \boldsymbol{\lambda_k} \frac{\boldsymbol{V_{ki} Y_{b_i} V_{kl} Y_{b_l}}}{\boldsymbol{\tau_i + \tau_l}} \quad (12)$$

Where V_{ij} are elements of the passage matrix $[V]$ issued from the diagonilzation of the system and Y_{b_i} are elements of the vector $[Y_b] = [V]^{-1}\,[Y]$.

Coupling losses per cycle of external magnetic field excitation $B_a = B_m \sin(\omega t) + B_{off}$ per unit circumscribed volume for such a system writes:

$$Q_{coupling}(f) = \sum_{k=1}^{n} n\kappa_k \frac{B_m^2}{\mu_0} \frac{\pi\omega\tau_k}{1 + (\omega\tau_k)^2} \quad (13)$$

IV. Crosscheck with MPAS and validation against JOSEFA data

A. Application of the n-stage COLISEUM to MAG42-3 data

We confront the experimental data measured on MAG42-3 samples under transverse sinusoidal field excitation using JOSEFA (see [9]) to the modelling given by the n-stage COLISEUM. Giving all geometrical parameters of the cable (R_{strand}, l_p sequences, and the cable pattern ex: 3x3x3x3x6) as inputs, it is then possible to construct the 5x5-matrix equation corresponding to the desired five-stage cable. The only adjustable parameters of the system are the transverse conductances (at each cable stages). We first chose to model the MAG42-3 cable with only five stages without considering the strand interaction with the surrounding stages in order to confront our model to the advanced MPAS (see [9]) which is a five-stage model. Adjusting the conductances set as follows gives us a fairly good agreement with the data we measured in [9] (see Table II and Table III). The conductance set have been restrained and defined by using σ_1 the interstage conductance of the first cabling stage, p the ratio between consecutives σ and q a multiplicative factor:

$$q[\sigma_1 \quad p\sigma_1 \quad p^2\sigma_1 \quad p^3\sigma_1 \quad p^4\sigma_1]$$

TABLE II
SET OF CONDUCTANCES

Stage i	1	2	3	4	5
σ_i ($10^8\ S.m^{-1}$)	0.768	0.983	1.26	1.61	2.06

Conductances set chosen for the best fit by using $p = 1.28$ and $q = 1$.

TABLE III
n-STAGE COLISEUM OUTPUTS

Stage #	$\boldsymbol{n\kappa}$ (adim)	$\boldsymbol{\tau}$ (ms)
1	0.144	1.58
2	0.177	6.67
3	0.425	24.5
4	0.193	69.3
5	2.65	223
$\boldsymbol{\Sigma n\kappa\tau}$ (ms)	617	

Magnetic parameters of n-stage COLISEUM to fit data from JOSEFA. All shielding coefficients are referred to the area of superconducting strand.

The corresponding $Q(f)$ issued from the magnetic parameters of Table III is depicted in Figure 3 along with the experimental coupling losses [9]. We stress that the description of coupling losses given by the n-stage COLISEUM in Figure 3 is obtained by hand as a first try of fit for this model (onto JOSEFA's data [9]) and can be improved by the use of a least square method. We also note that the last stage seems to be the major contributor to the predicted coupling losses.

B. Crosscheck with MPAS

The magnetic parameters from the advanced MPAS gathered in Table IV are slightly different from the one already presented in [9] because this time we use a least square method in order to be sure that the fit found is the best fit.

We can see as already shown before in [9] that the description of coupling losses given by MPAS also point out the fact that the last stage plays a predominant role in coupling losses generated in JT-60SA TF cable. The shielding coefficients given by MPAS are decreasing from the last stage to the first one whereas in n-stage COLISEUM the last stage dominates and there is no clear rules for the other sub-stages. Both coupling losses given by the advanced MPAS and the n-stage COLISEUM are depicted in Figure 3.

TABLE IV
MPAS OUTPUTS

Stage #	$n\kappa$ (adim)	τ (ms)
1	0.220	6.02
2	0.254	14.6
3	0.293	42.8
4	0.340	85.9
5	2.23	250
$\Sigma n\kappa\tau$ (ms)	604	

Magnetic parameters of MPAS to fit data from JOSEFA. All shielding coefficients are referred to the area of superconducting strand.

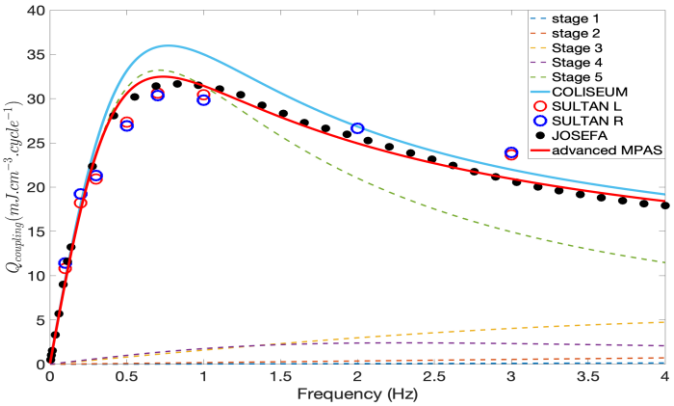

Figure 3: n-stage COLISEUM fit (sky blue) over coupling losses measured in SULTAN and JOSEFA. Only five stages are considered in MPAS (red line) and COLISEUM (blue line). Black dots represent JOSEFA data; Blue and red circles represent SULTAN data. Dashed lines are stages contribution from COLISEUM.

Both descriptions are in good agreement with each other and with the experimental data.

C. *Comments on the n-stage COLISEUM*

We can notice that the behavior shown in [9], i.e. the shift of the coupling losses curves with respect to the void fraction, is perfectly reproducible with the n-stage COLISEUM by acting only on conductances set as shown in Figure 4.

We also demonstrate analytically that multiplying globally the whole set of conductances shifts our coupling losses curves toward low or high frequency depending on the multiplying coefficient q. The greater conductances are, the lower in frequency the maximum amplitude will be and reversely. If we take $\overline{\tau_i} = q\tau_i$ as homothetic transformation of all σ, it will be seen as the change of variable into $qf = F$, giving:

$$Q(f) = \sum_{i=1}^{j} n\kappa_i \frac{B_m^2}{\mu_0} \frac{2\pi^2 (fq)\tau_i}{1 + (2\pi(fq)\tau_i)^2} = \sum_{i=1}^{j} n\kappa_i \frac{B_m^2}{\mu_0} \frac{2\pi^2 F\tau_i}{1 + (2\pi F\tau_i)^2}.$$

As in the n-stage COLISEUM, time constant are linearly conductance dependent, the effect of a homothetic transformation of the conductance set will be a shift in frequency for the related $Q(f)$curves (with conserved amplitudes) as seen in Figure 4.

It is established that the n-stage COLISEUM can be used to assess the coupling losses of a cable but also to model different void fraction by acting through its conductance set. We note that the behavior obtained after mechanical cycling on CICCs in [12] can be also reproduced as seen in detail in [11].

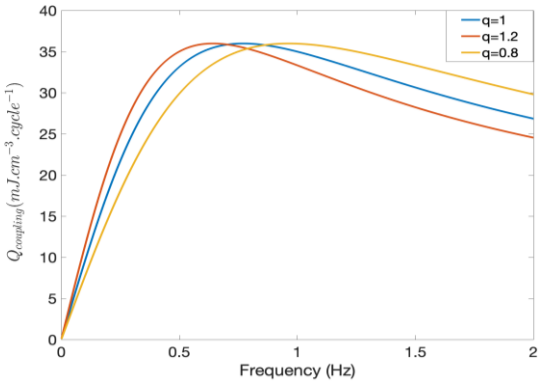

Figure 4: Homothetic transformation of coupling losses by using the n-stage COLISEUM. Adjusting the multiplicative parameter q in the conductance set.

V. Conclusion

In a first step, we succeeded at finalizing the reduction of the two-stage COLISEUM initiated in [7] in order to be in line with the description of coupling losses given by MPAS: one couple of magnetic parameters $(\tau, n\kappa)$ per stage at the two-stage level. This was the first step of the iteration of this model to the description of n-stage cables.

Then we have established the methodology to iterate the modelling of consecutive cabling stages (see [11] for detailed development). We have presented here the first step of the iteration, i.e. redefining the system equation of consecutive stages in order to introduce the first neighbor interaction.

This redefinition allows to define a matrix equation with dimension equal to the number of simulated stage, allowing COLISEUM to be in line with MPAS description of losses: one couple of magnetic parameter $(\tau, n\kappa)$ per stage for any n-stage system. Moreover, the contribution of each stages are compared between MPAS and COLISEUM on one case and we showed that they share a common outcome on coupling losses about the last stage playing a major role in the total of losses.

The newly developed n-stage COLISEUM could be used to predict the coupling losses in a CICC but in order to consolidate its predictability, several checks are still to conduct: applying the model on an existing large database of coupling losses tests in order to validate its analytical development and explore its application limits. Crosschecking its prediction ability with existing codes (e.g. JackPot, see [6] [13]) is also an important point.

Further on, the exploration of geometrical compaction cases (deviating the stages from tangency condition) should be explored to apply the n-stage COLISEUM in a more realistic cable configuration.

AKNOWLEGMENT

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