Optimization Procedure to Design a Low-Losses MgB_2 Wire

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***Abstract*—The EU-funded MARES project aims to develop a novel design of superconducting generator integrated into a wave energy converter (WEC). The superconducting generator consists of two parts, one assembled using REBCO tapes and the other using magnesium diboride (MgB_2) wires, with the latter offering a more cost-effective alternative. Assessing the optimal design of MgB_2 wires for this application is not straightforward, since AC losses represent a major technical issue of this device. In this work, a genetic algorithm is applied to determine the optimal design of the MgB_2 wires. The algorithm is coupled with a finite element method (FEM) electrodynamic model that computes the AC losses in the MgB_2 wires. The goal of the algorithm is to identify the key parameters of the wire configuration (filaments number and diameter, fill-factor, wire diameter, twist pitch) minimizing the AC losses in the device operating conditions.**

***Index Terms*—Wave energy converter, MgB_2, AC losses, genetic algorithm, optimized design.**

I. Introduction

THE mission of the EU-funded MARES project (Marine Reciprocating Superconducting Generator) is to develop a superconducting direct-drive Power Take-Off (PTO) for marine renewable energy systems [1], [2], [3], [4]. This superconducting technology is able to considerably increase the specific force and, consequently, the overall efficiency of the system. The superconducting generator will be assembled using either cuprate tapes or magnesium diboride (MgB_2) wires [5], [6], with the latter offering a more cost-effective alternative to cuprate tapes, at least an order of magnitude cheaper.

However, assessing the optimal design of MgB_2 wires for this application is not straightforward. AC losses under time-varying working conditions represent a major source of losses of this device, 10 Hz, 125 A, 05 T [4]. Minimizing these losses is therefore an important step forward in the application of MgB_2 wires to this device.

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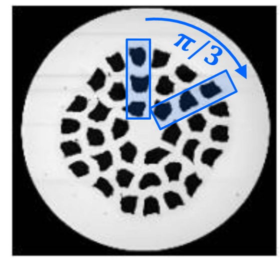

Fig. 1. 36-filaments MgB_2 wire under analysis produced by ASG Superconductors, Italy. Sketch of the periodicity [6].

In this work, a preliminary estimate of the electrodynamic losses in the MgB_2 wire during the operating conditions of the wave energy converter is presented. The losses are computed with the CATI (Coupled Axial and Transverse Currents Method) model based on finite element method (FEM), that computes the AC losses in the MgB_2 wires under different working conditions [7], [8]. The FEM model is able to distinguish between various sources of losses, such as eddy-current losses in the wire matrix and hysteresis losses in both the superconductor and the ferromagnetic portion of the wire (as Nickel). The commercial multifilamentary MgB_2 wire manufactured by ASG Superconductors S.p.A is used as baseline. This wire is composed of 36 MgB_2 filaments arranged in 3 layers, see Fig. 1, in a Nickel matrix, surrounded by a Monel sheath (30%Cu 70%Ni).

A genetic algorithm [9], [10], capable of solving a constrained minimization problem for a multivariable function, is then applied to design the optimal configuration of MgB_2 wires. The algorithm is coupled with the CATI model. The ultimate goal of the algorithm is to identify the key wire parameters, such as filament number and diameter, fill-factor, wire diameter, twist pitch etc., that minimize the AC losses.

II. Model Description and Losses Calculation

In this section a short description of the CATI model is presented, more details can be found in [7], [8]. The preliminary electrodynamic losses computed in a wire during the duty-cycle of the wave energy converter are presented.

A. CATI Model

The CATI method (Coupled Axial and Transverse Currents Method) [8], [9] is a 3D finite element method (FEM) based on two 2D FE models coupled together:

1) a model describing the "out-of-plane" currents (y-z plane) induced by the transverse magnetic field, referred to as Axial Current (AI)
2) a model describing the "in-plane" currents (x-y plane, perpendicular to z-axis), representing the coupling effect between filaments, referred to as Transversal Current (TI).

The Axial Current (AI) model solves the Maxwell equations in quasi-static electrodynamic regime in the *transverse* plane (z-y plane), see (1)-(3).

$$\nabla \cdot \boldsymbol{B} = 0 \tag{1}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J_{op}} \tag{2}$$

$$\nabla \times \boldsymbol{E_{op}} = -\partial \boldsymbol{B}/\partial t \tag{3}$$

where $\boldsymbol{B}$ is the magnetic flux density (T), $\boldsymbol{H}$ the magnetic field (A/m), $\boldsymbol{J_{op}}$ the operating current density (A/m^2), $\boldsymbol{E_{op}}$ the electric field (V/m) generated by the operating current.

The Transversal Current (TI) model is governed by Maxwell's equations in stationary electrodynamics, see (4-6).

$$\nabla \cdot \boldsymbol{J_{ip}} = 0 \tag{4}$$

$$\nabla \times \boldsymbol{E_{ip}} = 0 \tag{5}$$

$$\boldsymbol{J_{ip}} = -\sigma \nabla V \tag{6}$$

where $\boldsymbol{J_{ip}}$ represents the "in plane" (x-y plane) coupling current density (A m^{-2}), $\boldsymbol{E_{ip}}$ the "in plane" electric field (V/m.), $\boldsymbol{\sigma}$ is the electrical conductivity (S/m) and $\boldsymbol{V}$ the electrical scalar potential (V).

This decomposition of the problem into a quasi-static and a stationary electrodynamic problem allows a substantial reduction of the computation effort compared with a fully quasi-static formulation.

The 3D model is decomposed into two coupled 2D models, since the filaments exhibit periodicity within the wire. In fact, each filament takes the position of another filament after a fraction of the twist length. In the wire under investigation, which contains of 36 filaments arranged as shown in Fig. 1, the filaments exhibit a periodicity (symmetry) equal to $s = \pi/3$. Two filaments return to an identical position after a fraction of the twist pitch equal (p) to $l = p/(2\pi/s)$.

The AI and TI models are coupled by circuit equations. In fact, due to the periodicity of the filaments, the difference between the current in two periodic filaments (I_k and I_i, in general) will generate a current I_j over the periodicity length l, see (7).

$$I_j = I_k - I_i \tag{7}$$

Similarly, the difference between voltages in two periodic strands (V_k and V_i) will result in a voltage V_i over the periodicity length l, see (8)

$$V_j = V_k - V_i \tag{8}$$

The CATI model is also able to include loss contributions due to ferromagnetic materials, namely into the Ni matrix and Monel sheath.

In summary, the loss contributions that can be computed with the CATI model are the following:

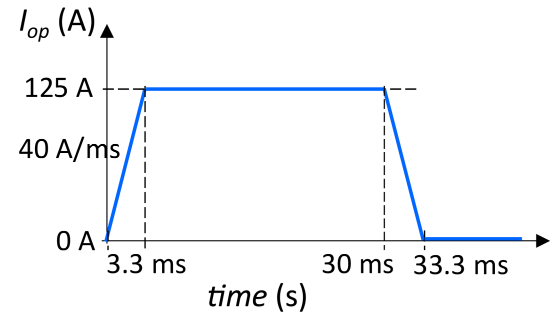

Fig. 2. Duty-cycle of the MgB_2 wire in the wave-energy converter.

1) eddy current losses due to currents induced in the resistive matrix and sheath
2) hysteresis losses in the MgB_2 due to the magnetization currents flowing in the superconducting material
3) coupling current losses due to currents flowing between MgB_2 filaments
4) ferromagnetic Losses due to the hysteresis of the ferromagnetic materials

B. Preliminary Loss Estimation in the Wave Energy Converter

The losses in the MgB_2 wire are computed at the operating conditions of the wave energy converter, accounting for transport current and applied transverse external field. The operating current during the duty-cycle of the wave energy converter is shown in Fig. 2. It consists of a linear current ramp up to $I_{op} =$ 125 A reached at $t = 3.3$ ms with a ramp-rate of 40 A/ms. A current flat-top up to $t = 30$ ms. A ramp-down with the same ramp-rate. The background field has the same profile in time with a maximum value of 0.5 T (first test condition) or 1.5 T respectively (second test condition). The first test condition is the reference for the project instead the second one is an upper bound limit.

The losses during these two test conditions are shown in Fig. 3. During the current-ramp-down, the losses exhibit a lower peak value than during current-ramp-up. In fact, during this latter phase, an additional source of losses is generated to reach penetration [11]. An average value of 0.2 W/m is computed during the cycle. In case of a background field of 1.5 T, a factor ten higher losses are computed, with an average value of 2 W/m. In Fig. 3(a), the current density distribution in the MgB_2 wire at different time instants is shown. Due to the combined effect of external and self-field, that are summing on the left-side and subtracting on the right side, see Fig. 3(a), the current distribution in the wire is not symmetrical.

During an electrodynamic transient in a multi-filamentary wire, a pattern of screening current (onion layers) is expected in each filament. However, in this specific operating condition, these screening currents in the filaments are not observed but are instead observed at the wire level (see Fig. 3). The wire behaves like a monolithic material (monofilament). This behavior is due to the combined effect of the transport current in the wire and the "low" frequency regime (10 Hz) of the transient. At

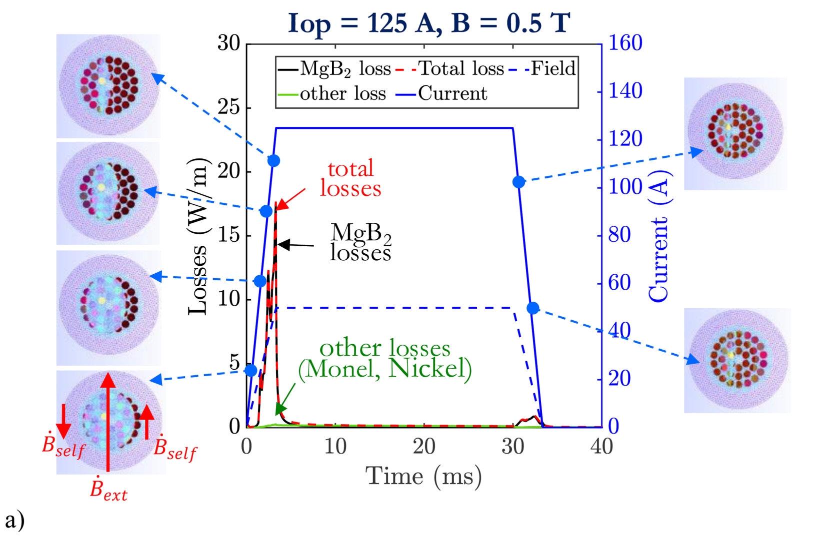

Fig. 3. Electrodynamic losses during duty cycle of the wave energy converter consisting of current ramp up to 125 A with a ramp-rate of 40 A/ms and a linear ramp of the magnetic flux density with the same ramp-rate up to a) 0.5 T and b) 1.0 T. In Fig. 3(a), the current density distribution in the wire during the linear ramp is shown.

higher frequencies, such as 50 Hz, the screening currents in each filament are observed.

In both test-conditions here analyzed, the hysteresis losses in the superconductors are the major contributor. Eddy current losses, coupling-current losses and hysteresis losses in the ferromagnetic material are negligible. These results already show that a possible way to minimize AC losses is to reduce the amount of superconducting material.

III. Optimization Tool and Optimized Wire Design

A. Optimization Tool

A constrained minimization problem for a multivariable function, corresponding to the AC losses (Q_{AC}), see (9), is solved using a genetic algorithm implemented in MATLAB.

$$fmin\,(Q_{AC}) \tag{9}$$

The genetic algorithm solver is selected as it easily allows one to impose some optimizable variables to be integers. Such as the number of layers in this case. The solver returns the values of the set of variables corresponding to the lowest AC losses of the wire under a sinusoidal current profile with a frequency f = 10 Hz and a peak current value of I_{op} = 125 A with a constant background field of B = 0.5 T. The operating temperature is set to T = 24 K. These conditions are close to those one of the duty cycle of the wave energy converter discussed in the previous paragraph.

The genetic algorithm is coupled with the CATI model. A schematic representation of the coupling between the CATI model and the MATLAB genetic algorithm is shown in Fig. 4. Each induvial of the genetic algorithm requires the calculation of the AC losses with the CATI model. The computational time of the optimization tool is not straightforward.

The variables optimized by the tool within upper and lower bounds are the following:

1) twist pitch [60 mm ÷ 1000 mm];

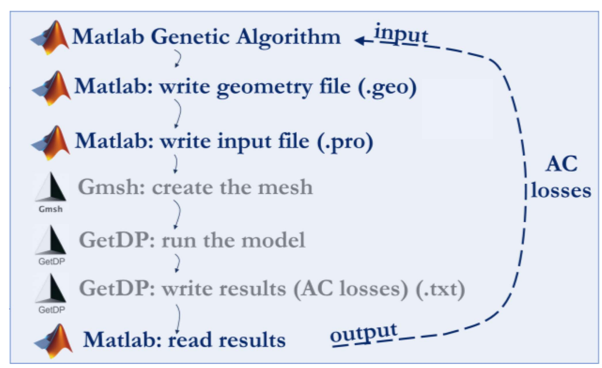

Fig. 4. Sketch of the optimization model: coupling between CATI model and genetic algorithm.

2) number of layers [2 ÷ 6];
3) wire radius [0.35 mm ÷ 0.50 mm];
4) fill factor [15% ÷ 25%], computed as the ratio between the superconducting cross-section and the total wire cross-section.

The upper and lower bounds of the optimized variables are set to respect the requirements of the manufacturing process. To avoid unreasonable results, a set of constraints are imposed:

1) the outer radius of the monel sheat is between 60 % and 90 % of the total radius;
2) the I/I_c ratio between 50 % and 75 %.

B. Optimized Wire Design

The results of the optimization tool are shown in Fig. 5. In particular, in Fig. 5(a) the AC losses for each genetic algorithm are shown while from Fig. 5(b) to (e) the number of layers, twist pitch, wire radius, fill factor and the I/I_c ratio are reported. The moving average was added to show the trend of the genetic algorithm. The results indicate that the number of layers has major impact on the losses. Since the wire is behaving like a

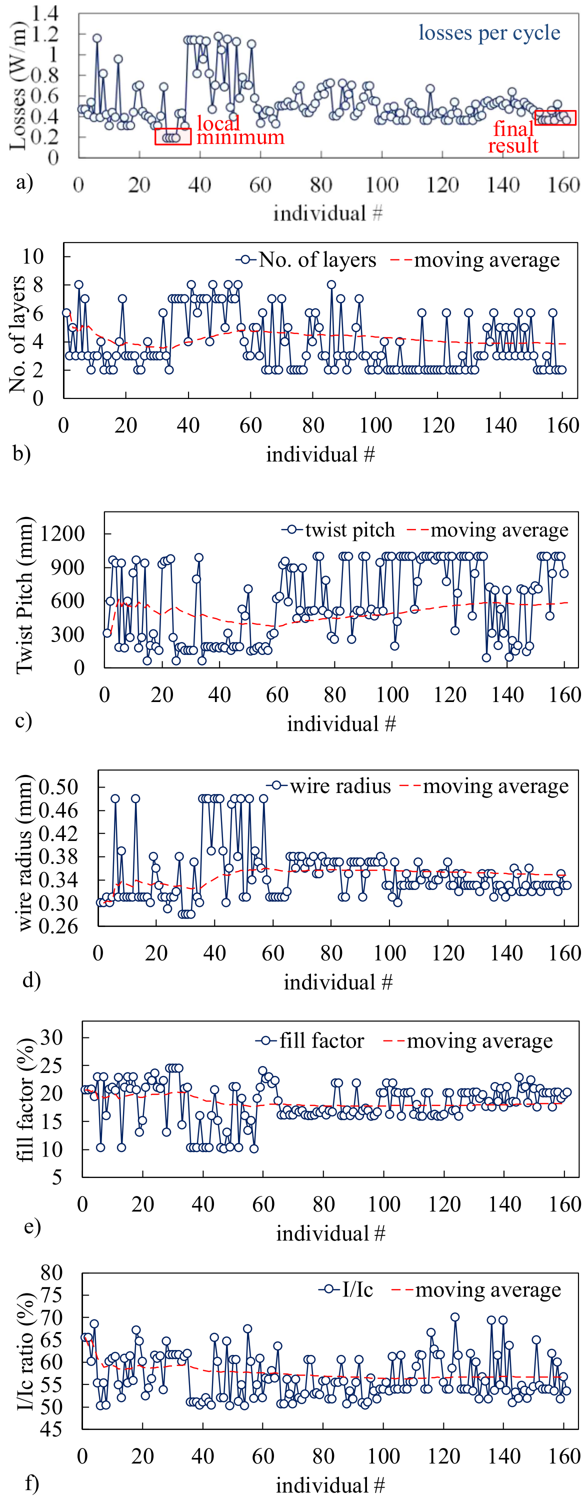

Fig. 5. Result of the optimization tool a) AC losses, b) number of layers, c) wire radius d) fill factor e) I/I_c ratio.

monolithic material, the screening effect of the external layers on the inner ones is limited and, generally, the higher the number of layers, the higher are the losses (in W/m). The results show that after the individual #60, the algorithm converges to a number of layers between 2 and 3. A number of layers between 4 and 6 is not convenient. In this configuration, the twist pitch has a minor impact on the losses since the wire is behaving like a monolithic material. Low-loss configurations can be achieved with both "short twist pitch" around 300 mm and "long twist pitch" of 900 mm.

TABLE I
OPTIMIZED WIRE DESIGN

	Reference Design	Optimized Design (local min)	final result)
No. of layers	3	3	2
Twist Pitch	90 mm	160 mm-	850 mm
Wire Radius	0.5 mm	0.3 mm	0.3 mm
Filament Radius	36 µm	23 µm	33 µm
No. of filaments	36	36	18
fill factor	20 %	25 %	20 %
I/I_{cc} ratio	30 %	60 %	55 %
Losses per cycle	0.8 W/m	0.2 W/m	0.4 W/m

The algorithm is able to find two minimum-loss configurations. The first one, named as "local minimum" in Fig. 5(a), is characterized by 3 layers, 36 filaments with a radius of 23 µm, see Table I. This result is very similar to the wire configuration already produced by ASG superconductor (see Fig. 1). This "local minimum" can be considered as a rescale of the wire produced by ASG, with smaller filaments and consequently with a lower amount of superconductors. The I/I_c ratio (transport current of 125 A), in fact, increases from 30 % to 60 %. The wire is in a more "stressed" working condition during the duty cycle of the wave energy converter. The second optimized layout, that is the result at which the algorithm reach convergence, named as "final result", is characterized by 2 layers, a larger filament radius, 33 µm, but a lower number of filaments, 18. Also this wire configuration is characterized by a lower amount of superconductor and by an I/I_c ratio of about 60 %. Both wire designs, the so called "local minimum" and the "final results" allow a reduction of the losses by a factor of 4 and 2 respectively.

IV. Conclusion

In the framework of the EU-funded MARES project, the electrodynamic losses in a MgB_2-base superconducting wave energy converter are estimated. The wire actually produced by ASG Superconductor with 36 filaments arranged in 3 layers is assumed as the reference for the project. The preliminary losses estimate, computed with the CATI FEM model, is about 0.2 W/m during the wave energy converter duty cycle.

A genetic algorithm coupled with the electrodynamic CATI model was developed to design the low-loss configuration of a MgB_2 wire for the wave energy converter. Each individual performed by the genetic algorithm require a simulation with CATI model. The computation time is not straightforward.

A optimized wire design with 2 or 3 layers, and with a wire radius of 0.3 mm (instead of 0.5 mm of the reference design) allows to reduce the AC losses of factor 2 or 4. Both proposed configurations are characterized by a lower amount of superconducting material, with a I/I_c ratio between 55 % and 60 %, this resulting in a more "stressed" configuration. This higher I/I_c ratio however will reduce the margin and the stability of the wire. The optimization indicates that the crucial parameter to reduce losses is the number of layers and, as discussed above, the overall amount of superconducting material.

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