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Tuned Windings*:* the window of opportunity for the implementation of solid conductors in high frequency cryogenic electric machines

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Abstract. Optimization techniques can significantly improve the performance of electrical machines. The analysis and the optimization algorithms focus on computational efficiency. In this paper, the optimization of a high frequency electrical machine in cryogenic conditions is proposed. The losses introduced by AC current in a conductor are directly proportional with the applied frequency in terms of skin effect and proximity effect. The stator coil, made from two aluminium (Al) turns, in the presence of cryogenic coolants has been analysed at frequencies up to 1000 Hz. In order to reduce the AC losses introduced by the magnetic fields, Nonlinear Conjugate Gradient (NCG) method has been applied for the stator coil thickness optimization. Frequency dependence is observed in most simulations. In the presence of Liquid Hydrogen (LH2) coolant, Al 1100 conductor presents the minimum power loss.

1. Introduction

High frequency electric machines are providing consistent advantages versus classic machines with condition that the cooling is done properly. In a high frequency machine, a coil placed inside the stator slot is subjected to skin effect and proximity effect [1]. The addition of these two effects results in a higher resistance of the coil. Skin effect is the predisposition of the alternating current to flow near the surface of a conductor, thus reducing the effective cross-section of the conductor and increasing its resistance. Proximity effect takes place when multiple layers of current carrying electrical conductors are in a close region and is caused by the time-varying magnetic field of the nearby conductors, resulting in a "current crowding" effect on certain regions of a conductor. Therefore, in the slot of an electrical motor with several turns both effects take place. For the reduction of AC losses, a numerical optimization of the layers (thickness) is recommended. The optimization of the coil turns has the role to reduce the AC losses induced by skin effect and proximity effect. The formula of AC resistance is a nonlinear function of the thickness of the coil [2]. The minimum of the objective function is found by searching in the direction of the negative of the gradient [3]. Conjugate gradient is an algorithm with strong local and global convergence properties [4], [5]. NCG method has been successfully applied for electrical machines optimization problems in [6],[7]. When discussing of high frequency electric machines, cooling systems are considered a crucial factor. Cryogenic cooling refers to the use of extremely low temperatures to cool down materials in a very fast and efficient way [8]. This is done mostly by liquified gasses that can reach temperatures of -153°C or below [9].

In this study, the tuned winding of a 1 MW Ring motor has been subjected to coil optimization in the presence of cryogenic coolants. Tuned coil theory is based on the "Dowell Approach" and pursues the minimization of the AC losses in the windings of the rotating machines [1]. Inside the slot, the coil has a unique shape and dimension. Figure 1 shows a cross-section of the motor with two rectangular bars per each stator slot and oval bars for the rotor. The current distribution is shown with conventional colour scale Blue Red Yellow – we note also that in this particular implementation the rotor is external and the stator is internal (out-runner construction) due several reasons, including a better power density as a result of the motor weight decrease [1].

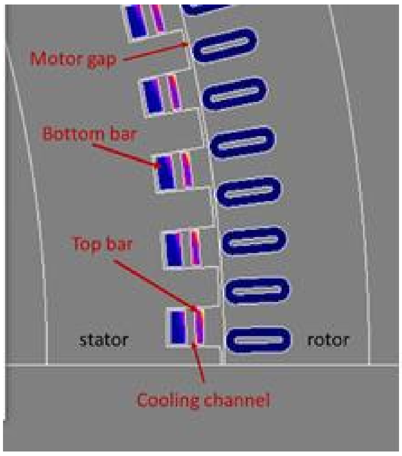

Figure 1. Motor cross-section

Gradient based optimization methods are robust and with little memory requirements. Nonlinear Conjugate gradient method has been used to minimize the AC losses in the coil, considering a frequency range of 500-1000 Hz. For the electric circuit, aluminium conductors have been considered and all the magnetic circuits are from regular electric steel. The Al bar dimensions are presented in figure 2.

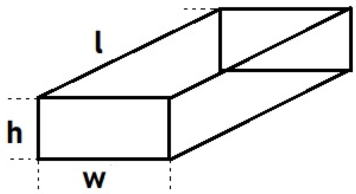

Figure 2. Al conductor dimensions

The coils of the stator have no insulation, the coolant being regarded as an endless life insulator. In this work, the power loss of an Al 1100 conductor cooled by Liquefied Natural Gas (LNG at 112 K), Liquid Nitrogen (LN2 at 77 K) and Liquid Hydrogen (LH2 at 20.28 K) has been studied. The last coolant has a very low temperature and was also used with pure Al. The coils' behaviour has been observed at three frequencies: 500 Hz, 750 Hz and 1 kHz.

2. Materials and methods

The magnetic fields inside the slot of the stator are produced only by the current in the coils. As the frequency increases, the eddy currents produced by the magnetic fields induce significant AC losses in the coil. The coil material and its dimensions can be chosen in a way that the AC losses are reduced.

2.1. Aluminium alloys

One of the most commercial pure aluminium alloys is the 1100 series with minimum 99% Al. The rest of the elements that improve the electrical and mechanical properties of Al alloy are: copper, iron, magnesium, manganese, silicon, titanium, vanadium, and zinc [10]. Due to its low strength, softness, and high conductivity, Aluminium 1100 series has been used as a conductor in our motor simulations. The electrical characteristics of pure Al (99.999%) and Al 1100 series are presented in table.1.

Table 1. Electrical resistivity of pure Al and Al 1100

	Al Pure @ 20°C	Al Pure @ 20.28K	Al 1100 @ 20°C	Al 1100 @ 20.28K	Al 1100 @ 77K	Al 1100 @ 112K
Resistivity [Ω*m]	$2.655 \cdot 10^{-8}$	$3.33 \cdot 10^{-11}$	$2.8 \cdot 10^{-8}$	$9.333 \cdot 10^{-11}$	$3.111 \cdot 10^{-9}$	$6.222 \cdot 10^{-9}$

2.2. Nonlinear Conjugate Gradient (NCG) method

Numerical optimization is widely used in science, industry or engineering in order to avoid excessive risks while achieving the optimum results [3]. The optimization, in general refers to finding an extremum (maximum or minimum) of an objective function over a set of variables. Knowing the limitations of these algorithms in terms of constraints, maximum efficiency in minimum steps can be obtained. An optimization problem becomes nonlinear when the objective function or part of the constraints are nonlinear. NCG is one of the most useful iterative methods when dealing with nonlinear problems and can be used on any continuous function for which the gradient can be computed. That is mostly because of the vector property known as conjugacy. While in the case of linear conjugate gradient method, each direction is set to be a linear combination of the steepest descent direction for the non-linear gradient the search direction is included into the line search procedure. Fletcher-Reeves and Polak-Ribiere are a best fit for search direction methods [11],[12]. Global convergence of NCG is strongly dependent on the type of objective function (convex or non-convex) and the line search algorithm [13]. In some cases, if the initial values are chosen too far from the optimum the method might not converge.

In this study, NCG method has been applied to find the optimum thickness of the coil in the slot, where coil turns are seen as different layers. Two layers have been considered and the function to be minimized is given by the total AC resistance of the layers:

$$R_{ac_t}(h1, h2) = R_{dc1}(h1) \cdot F_{R1}(h1) + R_{dc2}(h2) \cdot F_{R2}(h2) \tag{1}$$

where R_{dc1}, R_{dc2} are the DC resistances of the coils and F_{R1}, F_{R2} are the AC resistance factors of the first and second turn, respectively [2].

The minimum of the objective function, is found when its gradient is zero:

$$\frac{\partial R_{ac_t}}{\partial h1 \cdot \partial h2} = 0 \tag{2}$$

Using a sequence of conjugate directions, the vector of optimum solution is determined by successive approximations:

$$h_{k+1} = h_k + \alpha_k \cdot d_k \tag{3}$$

where d_k is the vector of conjugate directions and α scalars are chosen to minimize the expression:

$$min(f(h_k) + \alpha_k \cdot d_k) \tag{4}$$

The search of the conjugate directions, d, is achieved by using Polak-Ribiere formula, as it has a faster convergence [10]:

$$d_{k+1} = r_{k+1} + \frac{\boldsymbol{r_{k+1}^T \cdot r_{k+1}}}{\boldsymbol{r_k^T \cdot r_k}} \cdot d_k \tag{5}$$

where r are the residuals, calculated as the negative of the gradient. The convergence of Polak-Ribiere method (β^{P-R}) can be improved by setting β:

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$$\beta = max\{\beta^{P-R}, 0\}$$

This ensures the restart of NCG that drops the past search directions and starts the NCG in a new direction.

3. Results and discussions

All calculations were implemented in Mathcad software. The length of coil in the slot was set to 30 mm and the coil width was 11 mm, the dimensions are drawn in figure 2. The optimized values of the two layers of Al 1100 at 20°C and at LH2 temperature have been used as a starting point and are presented in table 2. As expected, the total power loss in the Al 1000 at 20°C will increase with frequency. This effect is mainly due to the dc resistance that increases as the thickness of the coils decreases. When the Al bar operates at LH2 temperature, the thickness of the conductor should be reduced further due to a sensible smaller resistivity. As a result, the AC resistance increases also, but the total power loss is no longer as dependent on the frequency. This effect suggests that high-frequency motors may benefit even further, especially the air-core topologies which are not frequency limited by the magnetic materials.

Table 2. Thickness values for Al 1100 @ 20°C and at LH2 temperature

	Al 1100 @ 20°C, $\rho=2.8\cdot10^{-8}$			Al 1100 @ LH2, $\rho=9.333\cdot10^{-11}$		
	500 Hz	750 Hz	1000 Hz	500 Hz	750 Hz	1000 Hz
h1 [mm]	5.94	4.84	4.18	1.02	0.83	0.48
h2 [mm]	3.63	2.97	2.56	0.68	0.17	0.14
Power Loss [W]	11.802	14.45	16.7	1.225	0.861	0.996

Using the same optimization settings, the values *h1* and *h2* for the Al 1100 conductor have been determined when coolants were used at all three frequencies.

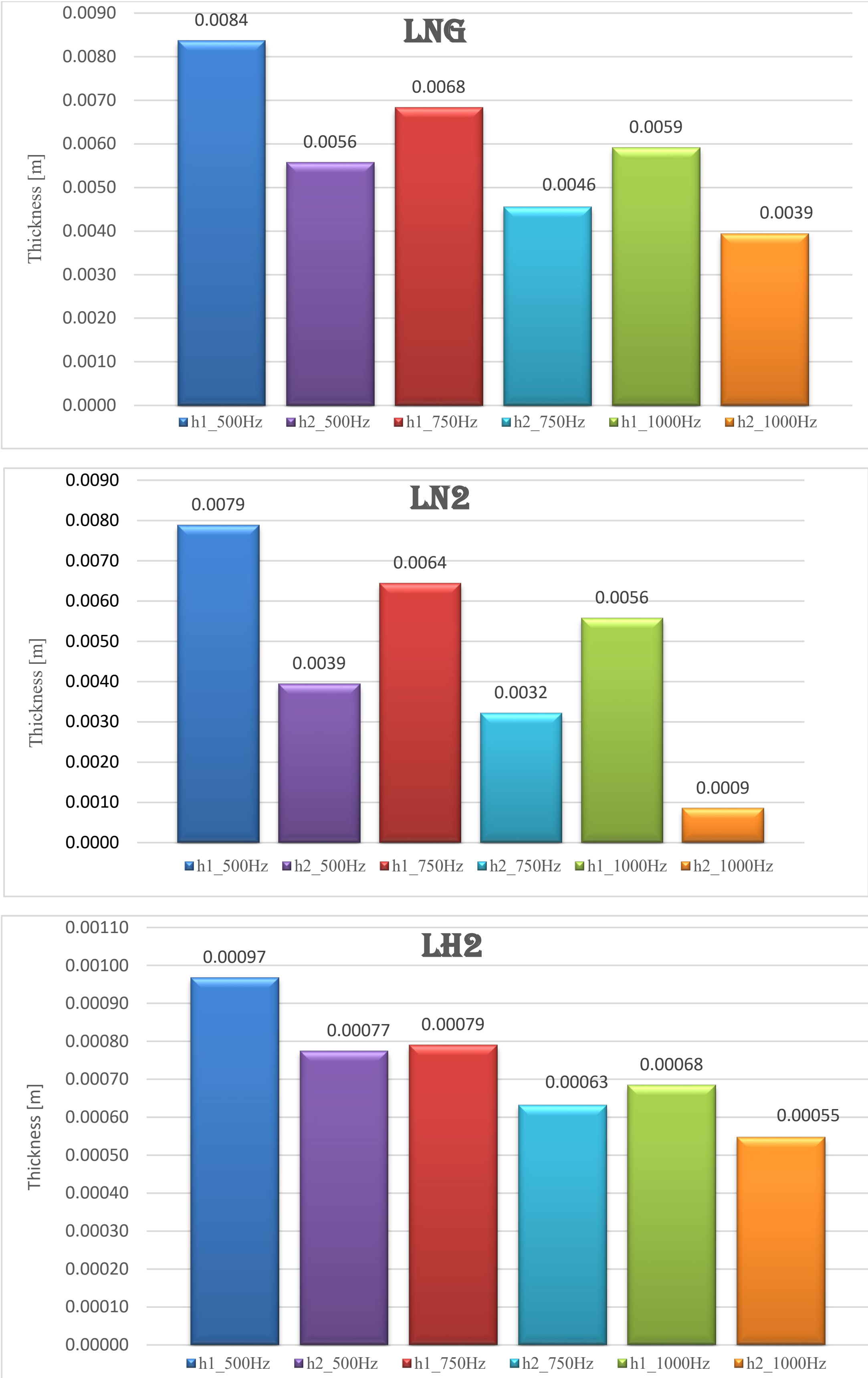
3.1. Al coil thickness for LNG, LN2 and LH2

In cryogenic conditions the resistivity of Al is decreasing depending on the coolant used. LNG and LN2 has been simulated for Al 1100, while LH2 has been used with pure Al. The optimized values of the Al coils thickness, in the presence of coolants are summarized in table 3. The resistivity of Al changes with the type of coolant used. The total power loss in the coil is thickness and frequency dependent. For each set of data, the solver finds the values of *h1* and *h2* that minimize the electrical resistance and thus the power loss.

Table 3. Optimized *h1* and *h2* values and the total power loss

	Al 1100 with LNG $\rho=6.222\cdot10^{-9}$			Al 1100 with LN2 $\rho=3.111\cdot10^{-9}$			Pure Al with LH2 $\rho=3.33\cdot10^{-11}$		
	500 [Hz]	750 [Hz]	1000 [Hz]	500 [Hz]	750 [Hz]	1000 [Hz]	500 [Hz]	750 [Hz]	1000 [Hz]
h1 [mm]	8.36	6.83	5.91	7.88	6.44	5.57	0.97	0.79	0.68
h2 [mm]	5.57	4.55	3.9	3.94	3.22	0.85	0.77	0.63	0.55
Power loss [W]	9.99	12.24	14.14	7.07	8.66	5.755	0.662	0.811	0.937

As it can be seen both layers thicknesses decrease as the frequency increases, for all coolants. The thickness of the first turn is always higher as it is only exposed to its own field. For a better visualization, in figure 3, a 2D bar chart has been developed for each gas. For LH2, due to its very low temperature boiling point, the thickness of the layers is with one order of magnitude less than the other two gasses.



a)

b)

c)

Figure 3. Comparison among *h1* and *h2* values of the coolants: a) LNG; b) LN2; c) LH2

Despite this fact, the frequency dependency is still maintained. The power loss for LNG and LH2 is dependent of frequency, meanwhile for LN2 coolant, the dependency on the frequency is less obvious. That is mainly due to the *h1* and *h2* values found by the solver which in a given set of electromagnetic circumstances might become a window of opportunity.

3.2. Convergence analysis of NCG

Several line search strategies have been proposed in order to attain global convergence of Polak-Ribiere method, but further compromises must be adopted [3]. If the objective function is far from a quadratic function, the search directions can easily loose conjugacy. Convergence of NCG method can be seen in figure 4.

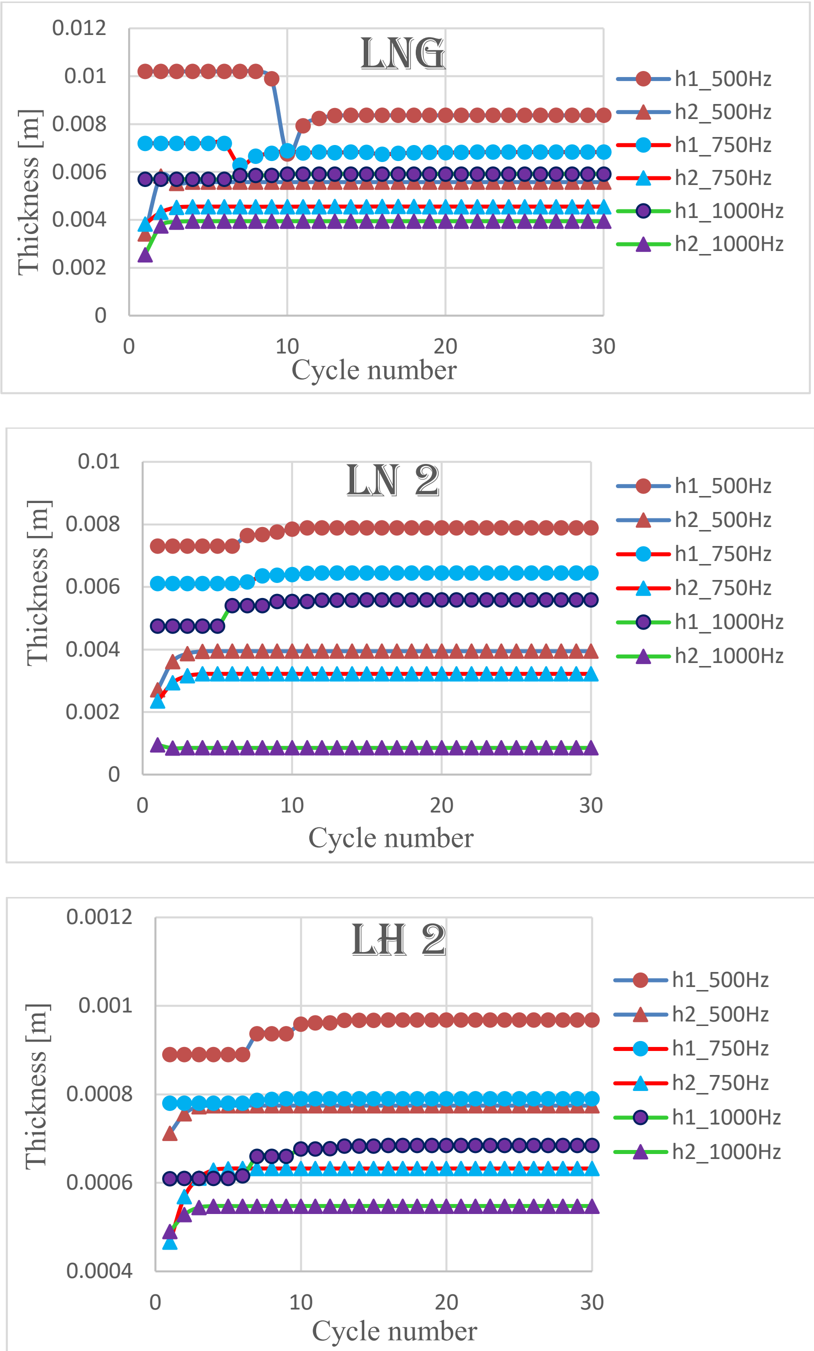


Figure 4. Convergence of NCG method for all coolants

It can be noticed that convergence is reached in less than 15 iterations, that is the initial guess values are chosen in the close vicinity of the solution. Several local minimum values can be found and the best fit is the chosen solution.

4. Conclusion

In this paper, the optimization of an Al bar thickness used as a coil in the stator slot of a cryogenic high frequency electrical machine has been performed. NCG method has been applied to the AC resistance formula for three frequencies: 500 Hz, 750 Hz and 1 kHz in the presence of LNG, LN2 and LH2 coolants. It has been found that the optimum thickness of the top conductor is inferior to the bottom conductor thickness for all cases. The influence of frequency, coolant, and Al conductor thickness on the total power loss in the coil proved to be significant. The minimum power loss of the Al 1100 bar was found in the presence of LH2 coolant and the highest loss was determined for Al 1100 @ 20°C.

5. References

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