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NUMERICAL EVALUATION OF THE USE OF TURBULENCE GENERATORS ON THE AMPACITY OF OVERHEAD LINES

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Abstract. *An important object of study is how to increase the ampacity or the electrical current transport capacity of overhead transmission lines. However, the raise of electric current generates thermal energy by Joule effect and ferromagnetic ionization in the conductor. This results in higher wire temperatures considering constant climate conditions as ambient temperature, wind speed, intensity of solar radiation among other factors. The objective of this work is to build a computational model and use the finite volume technique to numerically evaluate the thermal effects from the use of unconventional geometries in energy cables with or without turbulence generators. Six wind speed conditions were simulated to the cross flow over geometry in each case. Comparing the numerical and the analytical results, the use of turbulence generators led to steady state with smaller wire temperatures in all cases and reduced the mean temperature from 6 % up to 12 %. By simply changing geometry, it was possible to enhance the maximum electrical current capacity and the ampacity, optimizing the process of supplying energy by reducing installation costs, maintenance and energy loss in overhead transmission lines. Thus, the benefits of using turbulence generators were noticeable from a thermal point of view.*

Keywords*: Ampacity, CFD, Electrical power cable, Heat Transfer, Turbulence.*

1) INTRODUCTION

High temperatures could cause mechanical effects in conductors such as traction loss and permanent elongation. Thus, some corrective measures are usually taken in order to reduce superheating on conductors of overhead lines, including ampacity, current and temperature assessment on the transmission line. Increasing ampacity or current transport capacity on overhead lines is a world demand. However, the raise of electric current generates thermal energy by Joule effect and ferromagnetic ionization in the conductor. This results in higher wire temperatures considering constant climate conditions such as ambient temperature, wind speed, intensity of solar radiation among other factors.

According to a study by Isozak and Iwama (1890), it is possible to reduce the temperature of a conventional conductor surrounding it with two spiral wires of aluminium alloy to generate turbulence. Since aluminium is a good thermal conductor, the spiral shaft accelerates heat dissipation due to the increased surface area (fin). This causes a diffusion effect accompanied by increased wind turbulence. As a result, thermal capacity is increased and restricts the temperature rise. Thus, these devices may be used to dissipate heat.

The objective of this work is to build a computational model and use the finite volume technique to numerically evaluate the thermal effects from the use of unconventional geometries in plain energy cables and cables with turbulence generators (TG). The abbreviation TG will be used throughout the text.

Building new transmission lines disturbs the environment in many ways. It interferes with animals' migration routes, creates visual pollution; obstructs departing and landing of airplanes, occupies spaces that could hold other constructions. Thus, enhancing the performance of the already existent transmission overhead lines is an essential area to develop research. By simply changing cable geometry, it was possible to enhance the maximum electrical current capacity and the ampacity, optimizing the process of supplying energy by reducing installation costs, maintenance and energy loss in overhead transmission lines.

2) METHODOLOGY

2.1) Generating a computational model

The chosen cable for this simulation was the Aluminium Conductor Steel Reinforced (ACSR) cable whose core is made of steel and its function is only to support the cable. Thus, since the objective of this study is to evaluate thermal effects of using a metal wire surrounding ASCR cable, the cable was approximated by a full aluminium cylinder with smooth surface. This leads to a computational effort reduction and, consequently, reduces simulation time. Drawings are shown on Fig. 1.

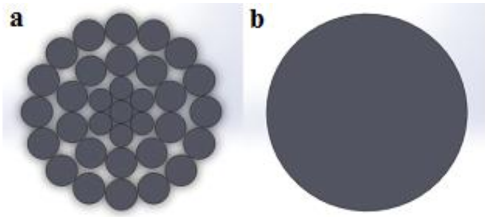

Figure 1 - (a) ACSR cable (b) Aluminium cylinder

It was chosen a small value (5 mm) on axial dimension in order to approximate the original 3D model by a simpler 2D model. To create a model that generates turbulence, two wires of 4 mm diameter each were included to the system. This diameter was tested on an experimental work of Isozak and Iwama (1890).

Since cable and TG are cylindrical, their contact will be at a single point, which makes it difficult to mesh on ANSYS software and increases computational effort. During the confection process of the wires, they are tensioned together with the cable and suffer a small deformation, enhancing the contact with the conductor. The interface cable-TG was made with an area of 14 mm^2. This resulted on a linear dislocation of 0.1 mm of TG towards the centre of the conductor.

Whereas both TG are corded with the cable forming a spiral along the main body at each point, they will be at a different axial angle along the conductor. Therefore, for analysis of this device's efficiency, hypothetical angles of 90 ° and 270 ° were chosen. The TG were made of aluminium, as other authors have made experimental tests with this material. Figure 2 shows the isometric view from both models and also details of interface cable-TG.

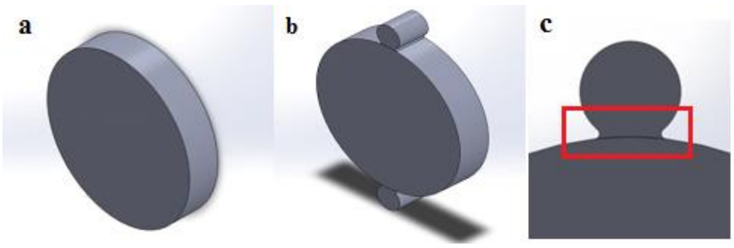

Figure 2 - Isometric view (a) plain cable (b) with TG and (c) details from interface cable-TG

2.2) Boundary conditions

Setting the domain discretization, the next step was to model the physical parameters in CFX-Pre. For numerical simulation in the plain cable, the problem is divided into two regions (fluid and aluminium) and a third region (aluminium wire) was included when simulating the cable with TG. The fluid used was air at 25 °C.

As shown in Fig.3, on the west border (O) of the flow field area, a flow was set up in the X direction, crossing the cable section. The other three boundaries of the fluid region, east (E), north (N) and south (S) were set to open and the inward and outward boundaries were defined as symmetric. Wind speeds vary from 0.1 m/s up to 4.0 m/s.

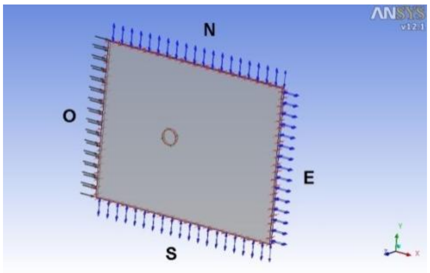

Figure 3 - Boundary conditions

The reference pressure was set to 1 atm. Buoyancy effect was considered as a result of fluid's density variation and the acceleration of gravity -9.8 m/s^2 is relative to the axis Y. The negative sign of the acceleration of gravity is due to the orientation of the Y axis upward. The interface region between aluminium-air, air-TG and TG-aluminium cable were activated to heat transfer with conservative interface flow. Equation (1) was used for the calculation of Joule heating effect,

—— (1)

where q denotes the power generation in W/m^3, R denotes the resistance in mΩ, I denotes the current in A and V is the volume in m^3. Ampacity was set to 887 A (Nexans, 2013).

Resistance decreases with decreasing temperature and,consequently, with increasing wind speed. Therefore, each tested wind speed presented a specific generation. Table 1 shows the different generations depending on temperature, electric resistance and desired wind speeds. These temperature values were calculated according to the IEEE (2008), through an iterative process, using the software EES®.

Table 1 - Power generation as function of temperature

Power Generation [W/m³]	T_{Mean} Conductor IEEE - [°C]	Resistance [mΩ/m]	Wind Speed [m/s]
222970	168	0.141	0.1
182013	96	0.115	0.6
170600	76	0.108	1.0
159900	57	0.101	2.0
155900	50	0.099	3.0
153100	45	0.097	4.0

The equations used in this simulation were the mass conservation and Navier-Stokes in X, Y and Z directions. The turbulence model used was the Shear Stress Transport (SST). Flow was considered laminar just for 0.1 m/s. For all other speeds, the flow was considered turbulent.

To prove independence of the results, mesh tests were done considering an overall maximum residue or Root Mean Square (RMS) with a value of 10^{-5} as a criterion of convergence for plain cable and cable with TG. Tests with different RMS values were held in order to ensure the results' independence in relation to the chosen criterion. At each iteration, the maximum residue for each variable is compared to the target residue to verify convergence. When the residue becomes less than or equal to the convergence criterion used, the calculation is terminated. Heat loss by radiation and solar heating were not considered.

Software's reference temperature was defined in Tab.2.

Table 2 – Software's reference temperature as function of wind speed

Wind Speed [m/s]	0.1	0.6	1.0	2.0	3.0	4.0
T_{bulk} [K]	435	365	345	325	320	310

3) RESULTS AND DISCUSSION

3.1) Mesh and elements

After modelling the cable with and without TG, mesh test was made from results of multiple simulations with different sizes, starting from a coarse mesh and refining the mesh until the results were not dependent on it.

3.1.1) Model: Plain cable

Four different types of mesh were tested for 3 m/s using the Shear Stress Transport (SST) turbulence model.

Table 3 - Mesh tests: Plain Cable

Mesh	Nodal Points	Conductor - T_{Mean} [K]
1	276310	318.8
2	290643	319.6
3	389542	319.1
4	499597	318.6

Considering the small temperature differences (about 1 %) on meshes 2, 3 and 4, mesh 2 (290643 nodal points) was chosen in order to reduce computational effort.

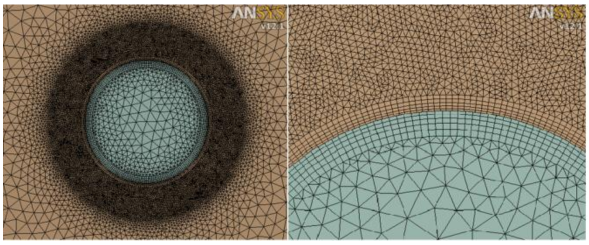

Figure 4 - Mesh - Cylinder (left), Interface cylinder-air (right)

3.1.2) Model: Cable with TG

Three different types of mesh were tested for 2 m/s using the Shear Stress Transport (SST) turbulence model.

Table 4 - Mesh tests:Cable with TG

Mesh	Nodal Points	Conductor - T_{Mean} [K]
1	338907	321.5
2	951344	321.5
3	1417414	321.9

The temperature differences between meshes 1, 2 and 3 were below 1 %. However, the convergence of mesh 1 was bad, with RMS residue above the amount considered ideal for this model, which is 10^{-5}. Since mesh 2 (951344 nodal points) reached RMS below 10^{-5} it was chosen for the simulation.

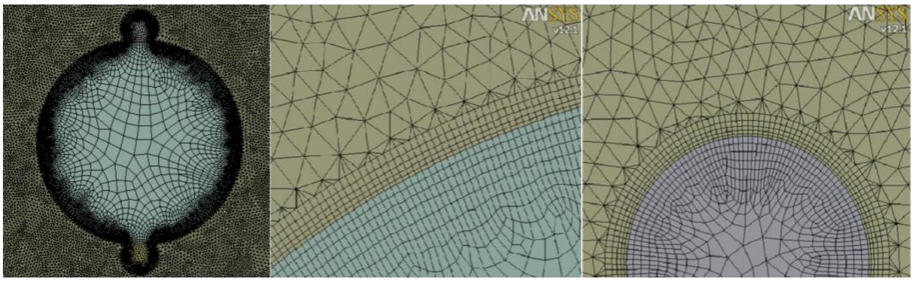

Figure 5 - Mesh - Cylinder with TG (left), Interface cylinder-air (centre), Interface TG-air (right)

3.2) Validating results by analytical methods

As seen in Tab.5, simulations were validated by comparing the values obtained with those calculated numerically from literature correlations, such as IEEE (2008), CIGRÉ (1998), Morgan (1981) and Incropera (1992). However, the references are for common geometries such as cylinders. Thus, these analytical methods can only be used to verify the simulations without TG. For unconventional geometry, the reliability of the simulation was guaranteed from the mesh test and the observation of the physical behaviour, which was expected to be similar to the cylinder case, but with smaller average temperatures of the cable and higher convective coefficients in each wind speed tested.

Table 5 – Mean temperature of the conductor
IEEE (2008), CIGRÉ (1988), MORGAN (1981) and numerical simulation

Wind Speed [m/s]	Conductor - T_{Mean} [°C]			
	IEEE	CIGRÉ	Morgan	Numerical Simulation
0.1	168	163	138	152
0.6	96	92	93	86
1.0	76	75	76	69
2.0	57	58	58	53
3.0	50	48	48	47
4.0	45	43	43	43

Thus, one can calculate the convective coefficient (h), Nusselt number (Nu_D) and Rayleigh number (Ra_D) and compare these parameters from existing analytical relationships in literature and also from the values obtained by numerical method without TG.

To 0.1 m/s speed, convection is almost free, so the correlation used to Nu calculation was that of Rohsenow et al. (1998) for Rayleigh number smaller than 10^7 ($Ra<10^7$), since in this case Ra = 82,220. Rayleigh number was calculated according to Eq. (2) and Nusselt number, according to Eq. (3) with c_1 = 0.47 for a horizontal cylinder. The surface temperature T_s was considered that equal to the average conductor temperature and T_∞ was fixed in 25 °C.

(2)

(3)

A dimensionless representation of the existing convective heat transfer measurements is the ratio of Nusselt number (Nu_D) with Reynolds number (Re_D). Table 6 presents Reynolds number for every speed tested, the correspondent Nu_D values calculated from analytical correlations and numerical values, and also the percentage difference between them.

Table 6 – Comparison of numerical and analytical Nusselt number

Wind Speed [m/s]	T_{Mean} [°C]	Re_D	Nu_D		Percentage Difference [%]
			Numerical Method	Analytical Method	
0.1	152.2	115.2	9.2	7.5	18
0.6	86.4	815.1	16.9	14.5	14
1.0	69.1	1423.0	22.6	19.3	15
2.0	53.0	2976.0	34.1	28.3	17
3.0	46.6	4545.0	43.4	35.3	19
4.0	42.9	6124.0	51.7	41.4	20

The difference between analytical and simulated convective coefficients varies up to 20 %.According to Incropera (1992), these differences of the order of 20 % are expected in engineering calculations for convective coefficients.

3.2) Comparing results between plain cable and cable with TG

Table 7 compares the simulated conductor's mean temperatures of the plain cable and with TG. There was a reduction of 12 % in the avarege temperature when the turbulence generators were used. The most effective reductions were for lower wind speeds, a behaviour similar to that found by Isozak and Iwama (1890) in their experimental tests in wind tunnel.

Table 7 – Mean conductor temperatureof plain cable and cable with TG

Wind Speed [m/s]	Conductor -T_{Mean} [°C]		Percentage Difference [%]
	Plain Cable	Cable with TG	
0.1	152	135	11
0.6	86	77	11
1.0	69	61	12
2.0	53	48	9
3.0	47	44	6
4.0	43	40	6

An important parameter to evaluate turbulence generator's efficiency is the convective heat transfer coefficient (h). Table 8 shows convective coefficient values. The best results were reached when the wind speed was 1.0 m/s. The increase of the convective heat transfer coefficient and the increase of the superficial area to exchange heat due to the TG turn possible to increase the ampacity on the overhead transmission lines.

Table 8 – Convective heat transfer coefficient

Wind Speed [m/s]	Convective coefficient h [W/m²K]		Percentage Difference [%]
	Plain Cable	Cable with TG	
0.1	11.025	12.735	16
0.6	18.634	21.987	18
1.0	24.333	29.957	23
2.0	35.920	42.835	19
3.0	45.399	52.216	15
4.0	53.799	62.201	16

Figure 6 shows the flow field to the speed of 0.1 m/s applied to west, in (a) the plain cable and (b) cable with TG. For both cases, there is an upward movement of fluid due to the heating and the fluid tends to remain adhered to the surface of the cable due to the non-slip condition. In this speed, the flow was laminar.

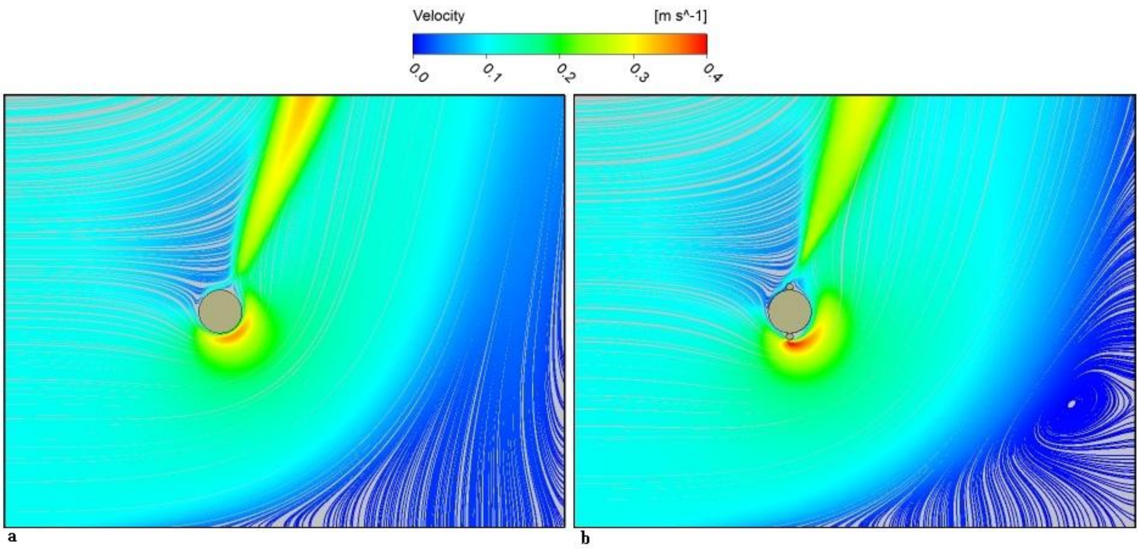

Figure 6 - Velocity field v=0.1 m/s (a) Plain cable (b) Cable with TG

For speed of 0.6 m/s, there is a significant increase in the fluid recirculation region downstream to the cable, as presented in Fig.7 . Consequently, there is increased stagnation region where part of the flow is directed upward while the other part flows downward. The increased turbulence due to TG contributes to cooling the conductor. At other tested speeds, the flow is turbulent and behaves similarly to 0.6 m/s.

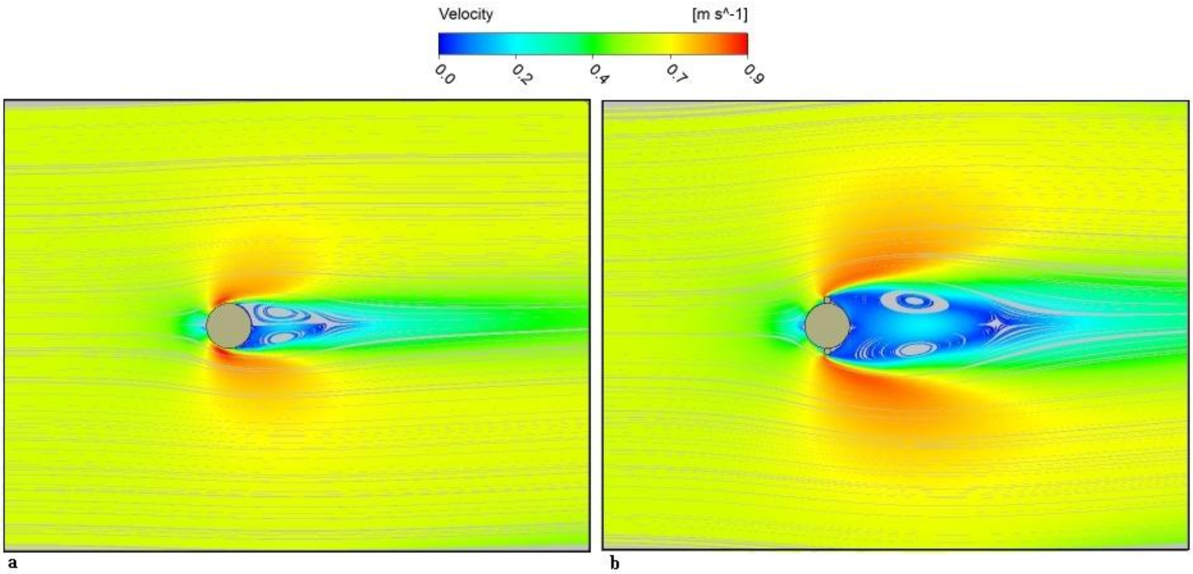

Figure 7 - Velocity field v=0.6 m/s (a) Plain Cable (b) Cable with TG

4) CONCLUSION

The present study examined numerically heat transfer process and flow in a conventional model for power cables. The simulation results were compared with published correlations as IEEE (2008), CIGRÉ (1998) and Morgan (1981), and also with analytical models. The numerical method adopted was found to provide a reliable and comprehensive analysis, allowing visualization of the heat transfer processes and phenomena occurring in the flow around the conductor. In sequence, the thermal effects from the use of a wire as TG in order to increase the external cooling of the conductor by thermal convection were evaluated.

The use of TG provided a reduction from 6 % to 12 % on the average conductor temperature when compared to the plain cable. Since this effect is more effective for lower speeds such as 0.1 m/s; 0.6 m/s; 1 m/s or 2 m/s, it was noticed a similar behaviour to that found by Isozak and Iwama (1890) in experimental tests in wind tunnel. The wire accelerates heat dissipation due to the increased surface area (fin) and causes diffusion effect accompanied by increased wind turbulence. As a result, thermal capacity is increased and restricts the temperature rise. It was also observed that convective coefficient h increased from 15 % to 23 %, evidencing the increased convective air mass transfer from the cable surface to the environment.

The reduction in average temperature of the conductor and increase of the convective coefficient show that the use of TG is an effective solution for increasing the maximum flow capacity when compared to conventional cables of electric power by optimizing the process of providing electricity due to reduced installation and maintenance costs of new overhead lines.

5) ACKNOWLEDGEMENTS

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