Weight Estimation of the Wiring in a Distributed Propulsion System for Aircraft

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Abstract—**The full electric/hybrid electric propulsion is nowadays a promising technology for the aircraft. The problems related to the electric flight are inherent the storage system sizing, the design of lightweight motors and the power electronics converters. In this paper is proposed a preliminary study about the on-board wiring system. In particular, the maximum power transferrable with the common aeronautic wires in a distributed propulsion system has been investigated.**

Keywords—Distributed Propulsion, Full Electric Propulsion, Hybrid Aircraft, Wiring,

I. INTRODUCTION

The large interest in the electrification of aircraft propulsion introduces new problems in the development of high-power density electrical architecture. Recent technical papers investigate the optimization of battery storage systems [1-3], the electrical machines [4] and the power electronics architecture [5-7] which can be used in the aircraft propulsion systems. The main characteristics of an electrical drives used in aerospace are the reliability and the low weight. In an electric drive an important role is played by the wiring systems adopted for the supply of the components. Usually in industrial applications, the wiring systems must guarantee only the correct performance and continuous supply of the drives. While in electric vehicle and in the propulsion applications the wiring systems must be optimized also to reduce the weight and the length for the installation in a reduced volume. These goals could be very difficult to reach because the power request can be very high (also some hundreds kW) and the external condition can be very critical (e.g. high and frequent temperature variations). Therefore, in the design of an electrical drives for the aircraft propulsion it is necessary to optimize the wiring systems adopted, reducing the total weight of the wires and guaranteeing the high reliability required. As indicated in the aerospace standard AS 50881, MIL-W-5088L [8,9], the sizing of a wire for aerospace application depends by many factors: altitude of the flights, number of wires in a bundle, difference of temperature between the ambient and the cable temperature. In the all electric/hybrid propulsion architecture, the distributed propulsion [10] could introduces some advantages in terms of aerodynamic behavior and reliability. From an electric point of view, this determines the necessity to install some cables of a certain length and the respect of thermal and voltage drops constraints. This paper analyzes the total weight necessary for the wiring system used in an electrical propulsion distributed architecture, in order to determine the maximum power transferrable for a distributed propulsion configuration.

II. VOLTAGE SYSTEM ADOPTED

The voltage systems adopted in the aircraft is regimented by the MIL-STD 704F [11]. The standard describes the different level of voltage which can be used on-board:

- AC Voltage system 115 V, 400 Hz;
- DC Voltage system: 28 Vdc and 270 Vdc;

Recently, due to the increase of electrical power required by the "more electric aircraft" applications, some companies [12] proposes the use of a high voltage system bases on 540 Vdc (more precisely the system used a ±270 Vdc voltage level) and a 230/400 V levels at variable frequency 360-800 Hz. Both the standard and the "new" voltage levels are lower than the values of voltage used for example in the traction vehicles, where the value of 1 kV is often exceeded. The benefits in the increase of voltage levels are well-know, but in the aircraft applications the low value of pressure and the rapid variation of temperature due to the altitude could determine an increase of the probability to determine the discharge around the wire and in the void present in the insulation [13]. In the paper the feasible analysis of the distribution system for the electric propulsion is carried out using the 270 Vdc and the steading state upper and lower limits indicate in MIL-STD-704F.

III. DERATING FACTOR OF AIRCRAFT WIRE

As previous mentioned, the standards [8,9] indicate the value of derating factors which must be considered for the wire. The derating factors are related to the difference between the ambient temperature and the working temperature of the wire, the number of wires in a bundle and the altitude. The product between the derating factor due to the altitude and the number of wires in a bundle is reported in Fig.1.

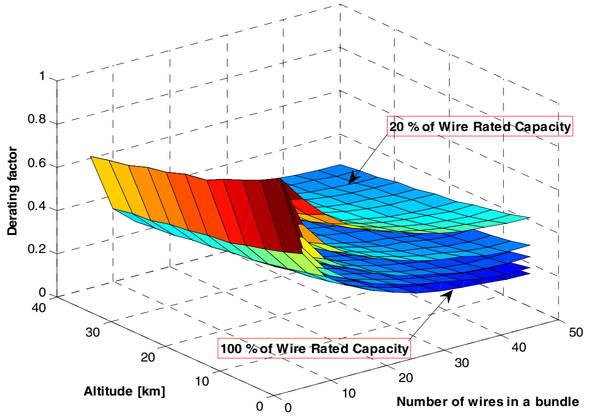


Fig. 1. Total derating factor due to the number of wires in a bundle and the altitude

The final derating factor is reported for a certain percentage of wire rated capacity (starting from the 20% until the 100 %). For an aluminum wire, it is necessary to reduce the total capacity of the 20% respect to the copper wire.

The difference between the operating temperature of the wire and the ambient temperature influences directly the rated capacity of the cable. The Fig.s 2 and 3 report the maximum current for AWG sizes in the range 8 to 4/0 (related to copper and aluminum wires):

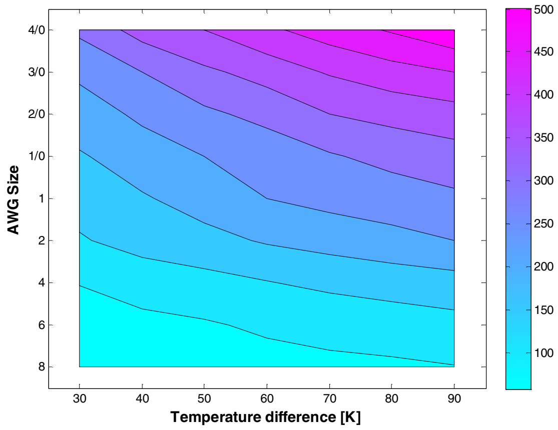


Fig. 2. Maximum current respect to the AWG size and the temperature difference: copper wire

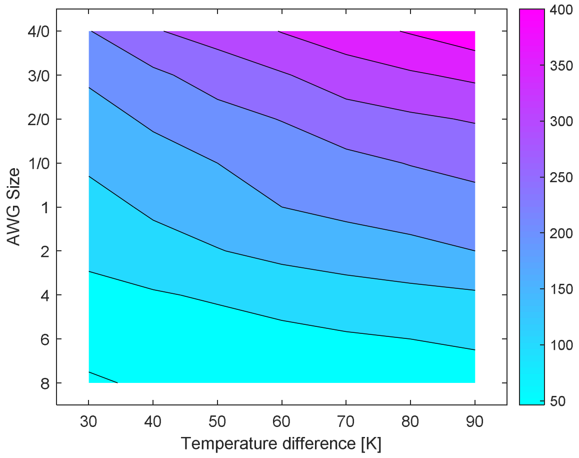


Fig. 3. Maximum current respect to the AWG size and the temperature difference: aluminum wire

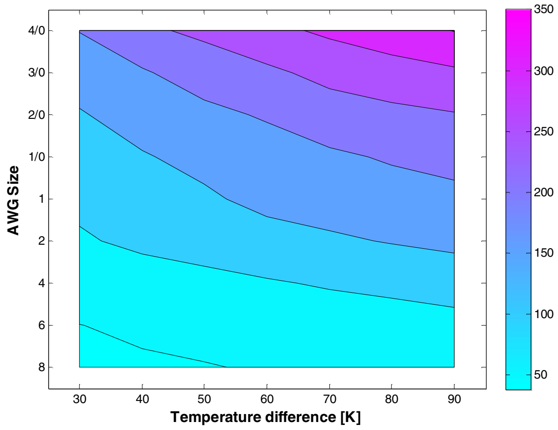


Fig. 4. Maximum current respect to the AWG size and the temperature difference at 10 km of altitude, 100% of load and 3 wires in a bundle : copper wire

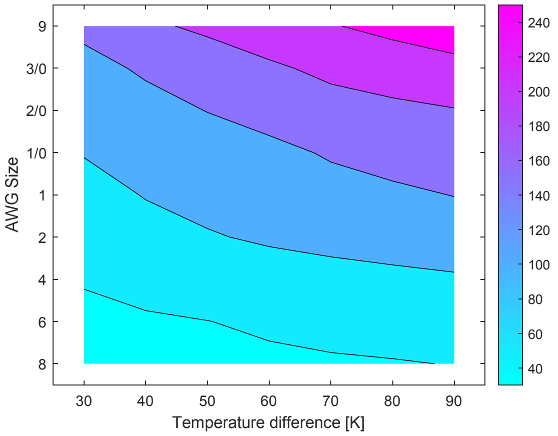


Fig. 5. Maximum current respect to the AWG size and the temperature difference at 10 km of altitude, 100% of load and 3 wires in a bundle: aluminum wire

Joining the results of Fig.1 and Fig.2, it is possible to obtain the maximum current respect the AWG size for a certain altitude, percentage load and number of wires in a bundle. For example, the Fig.s 4-5 show the maximum current respect to the AWG size and the temperature difference for an altitude of 10 km, the wire load at 100% and three wires for bundle referred to the copper and aluminum wire.

IV. DISTRIBUTED PROPULSION SYSTEM ANALYSIS

The distributed propulsion system is proposed in some recent technical paper and prototype design [14]. From an electrical point of view, it is possible to schematize the supply systems as shown in Fig. 6.

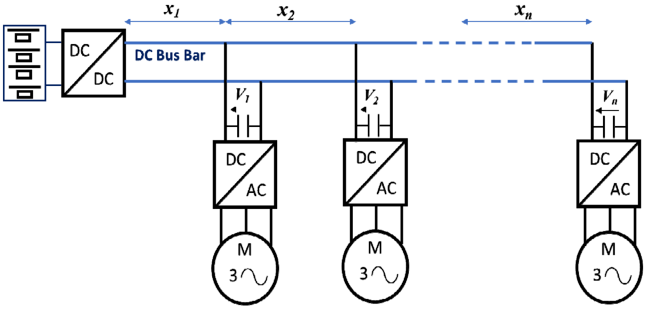


Fig. 6. Distributed propulsion system suppied from a battery storage system

The electric motors are supplied or by a generator (for example in the case of turboelectric propulsion) or by an energy storage system, usually based on batteries. In both the cases, it is considered the advantage to have a DC distribution and therefore the use of a power converters for the voltage regulation of the DC bus bar. Considering the particularity of the application, it is considered a bus bar with a single side fed and with consecutive loads. The electric scheme used is the similar proposed in [15,16] and depicted in Fig. 7:

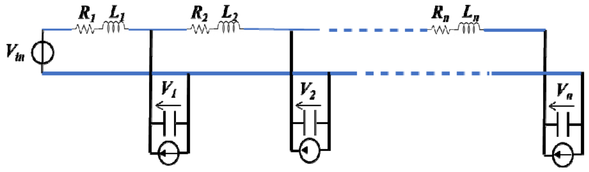


Fig. 7. Electric scheme of the distribution propulsion system

Assuming the steady state performance and neglecting possible discontinuous operation mode, the mathematical model of the electrical power system is reported in (1):

$$\begin{cases} V_{in} - V_1 = 2r_c x_1 \left(\dfrac{P_{mot,1}}{V_1} + \dfrac{P_{mot,2}}{V_2} + \ldots + \dfrac{P_{mot,n}}{V_n} \right) \\ \vdots \\ V_{h-1} - V_h = 2r_c x_h \left(\dfrac{P_{mot,h-1}}{V_{h-1}} + \ldots + \dfrac{P_{mot,n}}{V_n} \right) \\ \vdots \\ V_{n-1} - V_n = 2r_c x_n \dfrac{P_{mot,n}}{V_n} \end{cases} \tag{1}$$

Where V_{in}, V_1, …V_n are the voltages in the DC-Link, $P_{mot,h}$ are the powers absorbed by the electrical drives (inverter and motor) and r_c is the resistance for unit length [Ω/m] of the wire. The value of r_c is considered depending by the wire size and the ambient temperature. The unknown variables are the voltage in the nth node and the powers of electrical drives, that in this case are assumed equals and must be maximized. Globally, the problem has n equations in n+1 unknown variable. For an acceptable solution, the values of voltages must be contained in the range imposed by the standard, while the total current of the propulsion system (the sum in the bracket of the first inequality) must be below the rated capacity of the wire calculated according to the derating factor of Fig.1. Therefore, the solution of the problem (1) is carried out considering an optimization problem with a single objective function reported below and using the Matlab© function "fmincon":

$$\max\left(P_{mot,h}\right) \tag{2}$$

Subject to:

1) Eq.s (1)

$$2)\begin{cases} \left(\dfrac{P_{mot,1}}{V_1} + \dfrac{P_{mot,2}}{V_2} + \ldots + \dfrac{P_{mot,n}}{V_n} \right) \le I_c \\ V_1, V_2, \ldots, V_h \in [540, 560] V \\ V_1 < V_{in} \\ V_2 < V_1 \\ \vdots \\ V_h < V_{h-1} \end{cases} \tag{3}$$

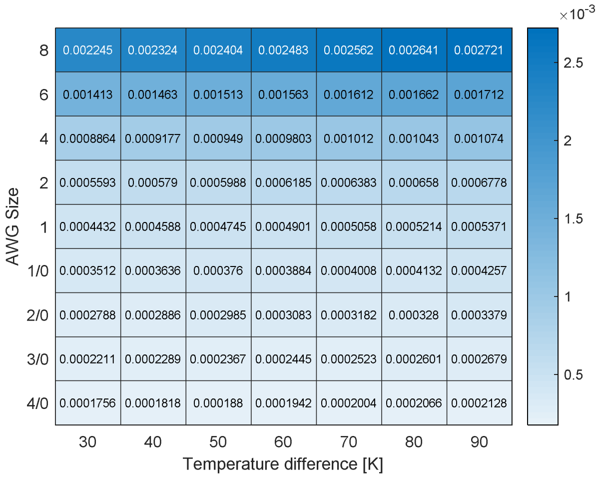
V. SIMULATIONS AND RESULTS

The proposed analysis is applied to the following distributed propulsion systems below reported:

- *Case1*: three motors with equal power and and a DC bar length of 5,10,15 meters;
- *Case 2*: four motors with equal power and a DC bar length of 10 meters;
- *Case 3*: five motors with equal power and a DC bar length of 10 meters;

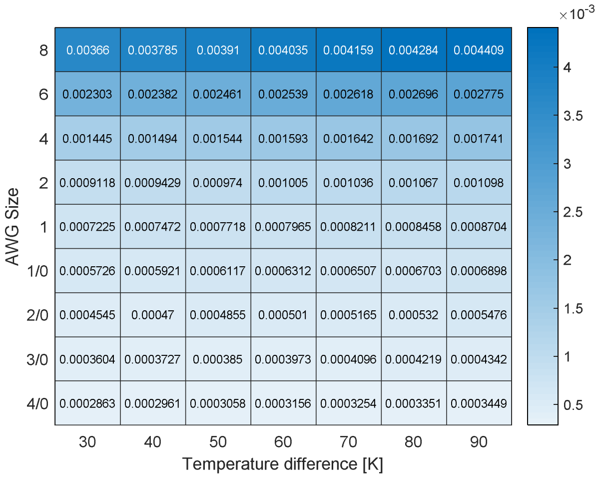
For each of the previous cases, the use of one, two and three wires for bundle is analyzed. The common case of 10 meters is supposed considering the possibility to apply this consideration to a wing of a regional aircraft. The distance between the motors and the power supply x_1, is fixed equal to the 50% of total length, while all the drives (inverters + motors) are equidistant (therefore $x_2 = x_3 = \ldots = x_n$).

As previous mentioned, the resistance of the copper and aluminum wires used for the calculation of losses depend by the working temperature. The Fig.s 8 and 9 show the variation trends of the resistivity and the values which are used in the simulations:



AWG Size	30	40	50	60	70	80	90
8	0.002245	0.002324	0.002404	0.002483	0.002562	0.002641	0.002721
6	0.001413	0.001463	0.001513	0.001563	0.001612	0.001662	0.001712
4	0.0008864	0.0009177	0.000949	0.0009803	0.001012	0.001043	0.001074
2	0.0005593	0.000579	0.0005988	0.0006185	0.0006383	0.000658	0.0006778
1	0.0004432	0.0004588	0.0004745	0.0004901	0.0005058	0.0005214	0.0005371
1/0	0.0003512	0.0003636	0.000376	0.0003884	0.0004008	0.0004132	0.0004257
2/0	0.0002788	0.0002886	0.0002985	0.0003083	0.0003182	0.000328	0.0003379
3/0	0.0002211	0.0002289	0.0002367	0.0002445	0.0002523	0.0002601	0.0002679
4/0	0.0001756	0.0001818	0.000188	0.0001942	0.0002004	0.0002066	0.0002128

Fig. 8. Resistance per unit length (Ω/m) for the different AWG size and temperature: copper wire



AWG Size	30	40	50	60	70	80	90
8	0.00366	0.003785	0.00391	0.004035	0.004159	0.004284	0.004409
6	0.002303	0.002382	0.002461	0.002539	0.002618	0.002696	0.002775
4	0.001445	0.001494	0.001544	0.001593	0.001642	0.001692	0.001741
2	0.0009118	0.0009429	0.000974	0.001005	0.001036	0.001067	0.001098
1	0.0007225	0.0007472	0.0007718	0.0007965	0.0008211	0.0008458	0.0008704
1/0	0.0005726	0.0005921	0.0006117	0.0006312	0.0006507	0.0006703	0.0006898
2/0	0.0004545	0.00047	0.0004855	0.000501	0.0005165	0.000532	0.0005476
3/0	0.0003604	0.0003727	0.000385	0.0003973	0.0004096	0.0004219	0.0004342
4/0	0.0002863	0.0002961	0.0003058	0.0003156	0.0003254	0.0003351	0.0003449

Fig. 9. Resistance per unit length (Ω/m) for the different AWG size and temperature: aluminum wire

Using the optimization problem explained in the previous paragraph, the maximum power transferrable for wires with AWG sizes of 8, 6, 4, 2, 1, 1/0, 2/0, 3/0, 4/0 and with a difference temperature variable in the range 30°C and 90°C has been calculated. During the calculation it is assumed that the value of voltage V_{in} is equal to the maximum value obtained in steady state condition (in our case 280 V) and the minimum value admissible for the DC-Link of the electric motor is the rated value of 270 V.

The results related to the three cases and for a DC bar length of 10 meters are reported in Fig.10 (copper wires) and Fig. 11 (aluminum wires). For sake of simplicity, only the results obtained for a temperature difference of 90°C are reported.

The blue, red and green colors indicate respectively the case of three motors, four motors and five motors; while the continuous line is related to the use of one wire in a bundle, the dashed line is the case of two wires and the dashed-point line is the case of three wires in a bundle.

The trends are inherent to the maximum power of the single motor admissible for each case. For both aluminum and copper wires, the maximum value is obtained for the case of the three motors and three wires for bundle.

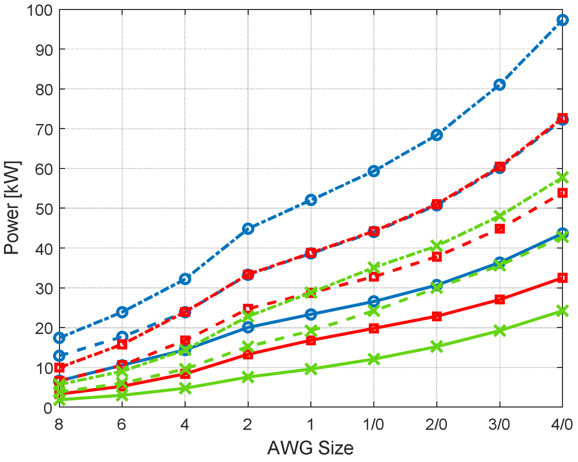


Fig.10 Motor power obtained with copper wire and a temperature difference of 90 °C: three motors (blue lines,), four motors (red lines), five motors (green lines)

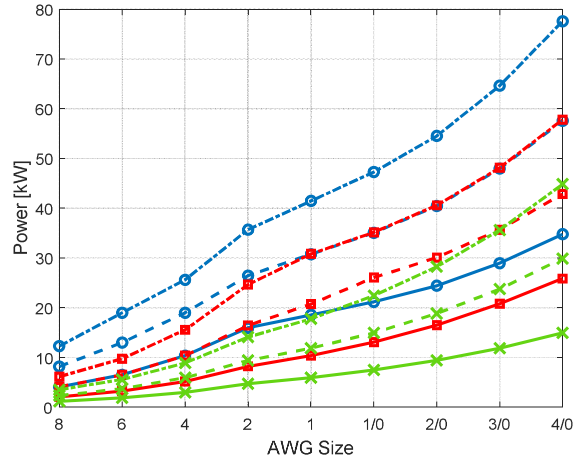


Fig.11 Motor power obtained with aluminum wire and a temperature difference of 90 °C: three motors (blue lines,), four motors (red lines), five motors (green lines)

In fact, this condition is favorable for the low number of motors and for the respect of the maximum drop voltage, due to the use of high number of wires for bundles.

It is interesting to highlight that the derating factor due to the presence of more wire in a bundle penalizes the maximum power obtainable (with three wires for a bundle is obtained a double power respect to the use of one wire for a bundle), and this is highlighted by the fact that the variation of power between the same motor configuration with different wires for bundle is not linear.

The Fig. 12, 13 and 14 show the trend of the total power obtainable with one, two and three wire for bundle respectively. The differences of the three cases are very little for high AWG sizes, while increase with low wire sizes and with the aluminum wire.

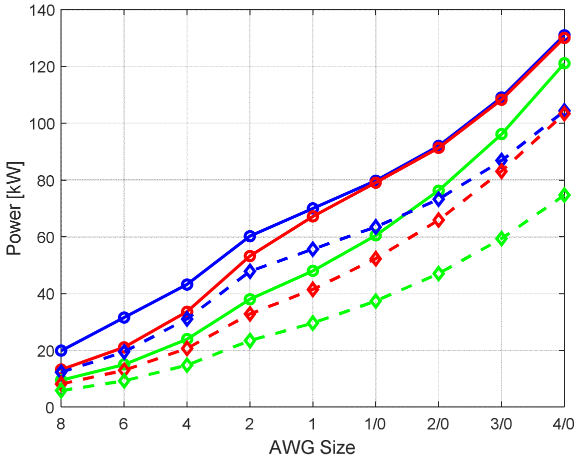


Fig.12 Maximum propulsion power obtained with 1 wire in a bundle: continous line and dashed line are used for copper wire and aluminum wire; blue, red and green indicate the case of 3, 4 anf 5 motors.

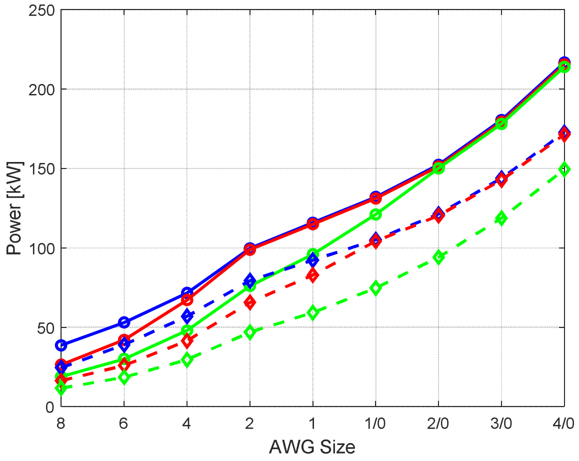


Fig.13 Maximum propulsion power obtained with 2 wires in a bundle: continous line and dashed line are used for copper wire and aluminum wire; blue, red and green indicate the case of 3, 4 anf 5 motors.

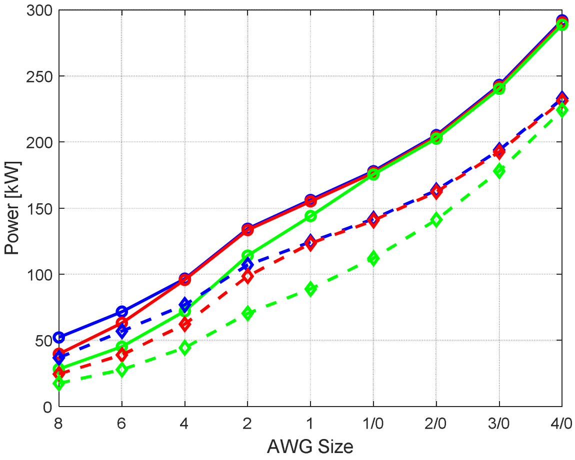


Fig.14 Maximum propulsion power obtained with 3 wires in a bundle: continous line and dashed line are used for copper wire and aluminum wire; blue, red and green indicate the case of 3, 4 anf 5 motors.

The Fig.s 15,16,17 show the comparison between the obtainable power for each motor configurations and the different length of the DC bus bar previous mentioned (the values are expressed in in p.u. respect to the case of 5 meters length). The cyan color is the case of three motors, the brown is the case of four motors and the other is related to five motors. For sake of brevity, only the results with one wire for bundle are shown and the aluminum case is not presented because the behavior is quite similar.

The simulations highlight that the effect of the motor configurations and the length of dc bus bar are not negligible; in fact, the for low wire size the transferrable power is quite difference between the three configurations, while for short length and high wire size the power is practically the same for each configuration.

An increase of the difference between the transferrable power is obtained with an increase of length (with a reduction of 40 % of power for a 4/0 AWG size between the three distributed motor and the five distributed motors).

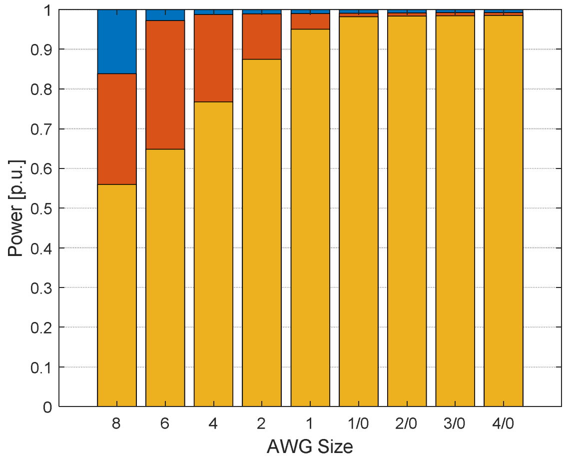


Fig.15 Obtainable power for a bar length of 5 metres and one wire in a bundles

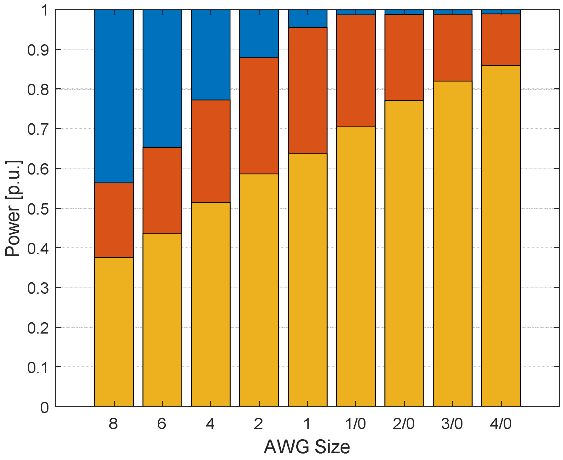


Fig.16 Obtainable power for a bar length of 10 metres and one wire in a bundles

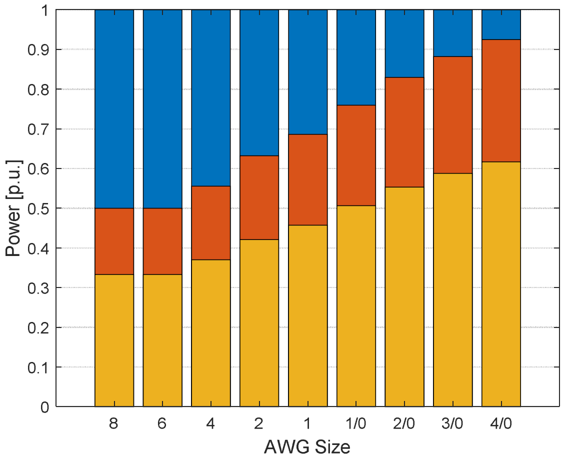


Fig.17 Obtainable power for a bar length of 15 metres and one wire in a bundles

The main results obtained show a different power allowable with the different size, the type of material and the number of wires in a bundle. In particular:

- propulsion influence considerably the maximum power obtainable; the only case where the results are similar is during the use of one wire for bundle and with a high value of wire sizes;
- the length of DC bus bar influences also the maximum transferrable power, with a high reduction related to the increase of length and number of distributed motors

VI. CONCLUSION

The paper deals with some considerations about the power transferred in a wiring system used to feed an electric distributed propulsion system. The investigation is carried out considering all the factors which affected the performance of a wire used in aircraft (derating due to the number of a wires in a bundle, derating due to the altitude, etc…). The results obtained demonstrate that using a methodology which promote the achievement of the maximum power for a certain cable sizes doesn't guarantee the minimization of weight. Therefore, future works will contemplate the use of an optimization procedure in order to find a global optimum between the transferred power and the weight of the distributed propulsion wiring system.

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