MultyCaB

Power cable modelling for WIPS electromechanical chain

State of the art – Background

The main focus of demonstration in Clean Sky (CS) will be the validation and maturation of the aircraft technologies and sub-architectures, related to the concept of 'All Electric Aircraft' (AEA). Several promising technologies are being explored and developed by CS, ranging from power generation, distribution, and conversion systems, resulting in an architecture that became more and more complex and have to be optimized to substantially reduce the consumption of non-propulsive power. One of such technologies likely to be optimized is the electrical Wing Ice Protection Systems (WIPS), which protect against the build-up of ice on structures of the aircraft.

Such systems include ice protection systems (de-icing, anti-icing or a combination of both systems) coupled to ice detection systems, usually located at the leading edge of the exposed surfaces. De-icing systems are reactive and commonly consist in mechanically deformable membranes or electro-impulse devices. Such systems are used periodically to remove already accreted ice. Anti-icing systems, such as hot-bleed-air circulation systems or electro thermal devices, are pre-emptive and designed to prevent ice accretion by evaporating the impinging droplets. De-icing requires less power than anti-icing because of a short but periodic energy input that is used to melt the ice-airfoil interface.

Anti-icing systems are mainly categorized into two methods: passive and active. Passive anti-icing systems such as black paint and so-called “ice-phobic” and super hydrophobic coatings do not require energy supply for ice removal. Active anti-icing systems require an energy supply, and mainly categorized into two types of anti-icing systems including chemical system and thermal systems.

Thermal anti-icing systems including hot-air and electro-thermal systems, which are based on an electrical resistance heating, should provide enough energy to maintain the surface temperature of a structure above freezing and also melt the ice formed at impact of super cooled water drops.

Among the thermal ice protection systems, electro-thermal anti-icing are simple and compact methods and their response time is very short compared to hot air or chemical systems, allowing for intermittent or cyclic heating. Electrical resistance heating systems in aircraft industry are mostly used in the form of electro-thermal pads. These electro-thermal pads are applied onto the surface of a structure or as close as possible to the skin surface to heat the surface and prevent ice accretion.

Actually, electro thermal ice protection systems typically comprise a number of electrically - powered heater elements such as heater mats applicable to both metallic and composite structures, which can be used as anti-icing zones in which a sufficient temperature is maintained at the surface of the wing in order to prevent the formation of ice.

As a summary, electro-thermal ice protection systems remove the need to bleed hot air to be extracted from the engine, and compared to this system, heat can be locally targeted and finely controlled to avoid icing in very specific areas making electro-thermal systems compatible with today’s advanced high performance critical wing designs. This increases the performance and endurance of the airframe and reduces fuel consumption significantly.

An electro-thermal system is also more fuel efficient and avoids the problems associated with channelling hot-gas tubing through complex wing and fuselage structures. As a result, the performance efficiency of the aircraft engine is increased, whilst maintenance requirements are reduced, i.e., the simplicity of the system reduces maintenance tasks, helping to limit aircraft downtimes.

These reasons make the electro thermal WIPS a good proposal to achieve the high levels of, efficiency and reliability for the new all-electric airplane design.

The generated power is high power for high load devices in the aircraft. The common High Voltage Alternating Current (HVAC) standards are three phase 115VAC 400 Hz, 230VAC frequency wild (300 to 800 Hz) three phase, and the High Voltage Direct Current (HVDC) 270V/540 VDC (floating). Futures increments are expected in these voltages up to 350VAC 400 Hz and 600 VDC. These are therefore the main power sources that can be applied to electrothermal WIPS, although the HVDC PWM will be the most usual.

On the other hand, the application of solid state technology protection and control of aircraft loads (SSPCs) introduces many advantages for the deployment of the all-electric aircraft:

- Controlled Switching
- Incorporates current limiting function (I2t)
- Modular, programmable and remote controlled
- Allows condition monitoring and rearming
- Reduced weight and volume, and improved reliability

However, the natural switched operation of solid state technology introduces new challenges related to switching frequencies, switched voltage and (sometimes) switched current on the electric and electronic circuits of the aircraft, including of course the wiring for the Electrical Wiring Interconnection System (EWIS) of the aircraft and specifically for the WIPS.

With the Power Converter operating as ON-OFF, unipolar and bipolar PWM, switched AC or DC voltage source, etc., new effects such as switching and commutation harmonics, skin effect, high dv/dt, EMI, etc., need to be considered and conveniently modelled on basic the cable model. This advanced cable model will facilitate the analysis of the complete EWIS system simulations with high degree of accuracy, and will contribute to the development of new WIPS minimizing design errors and helping to components specification.

Objectives

The analysis and evaluation of the previous commented effects will lead to define and develop a Multi Layer Cable Model, MultyCaB, able to **analyse steady state and transients, fundamental and harmonic behaviour, thermal effects, high frequency modelling and skin effect, and dv/dt effects on a power cable**.

The model could be used alone as an independent application by using an easy HMI Interface to introduce problem description, auxiliary connection and protection devices, cable and load electric parameters and electric variables at the output side of the power converter, or embedded into a general time – domain or electromagnetic simulator, which will include power source and power cables, power converter, complete wiring for WIPS, additional connectors, protections and terminals, and (non-linear) load characteristics. Temperature affects also not only because resistivity increase, but also for wiring degradation. For these reasons, thermal models of power cables for WPIS must be included into the full model, which allows for knowing not only the rate of resistivity parameter, but also the effects of long time high and variable temperatures exposures.

On the other hand, classical electric circuits for WIPS consider only continuous AC 115/230 VAC, and only fundamental frequency is considered for calculations on the circuit, which is frequently modeled with concentrated parameters. In such a model, typical cable models do not take into account the evolution of the cable parameters with frequency, so skin and proximity effects are neglected since the variation of the resistance with the frequency is not included. However, current PWM waves generated at aircraft power distribution will produce a large range of harmonics and wave effects, which must be taken into account for analyzing power cable behavior.

In this project a lumped R-L-C ladder cable model will be investigated and developed which models the evolution of the resistance and the inductance (including mutual inductance between conductors) with the frequency, as well as leakage capacitors that produce capacity effects to determine the leakage currents, dielectric losses and the high-voltage reflected waves.

So the overall improved cable model have to include **low and high frequency effects and thermal effects, and must be able to simulate reflected waves due to dv/dt, as well as transient phenomena such as temporary oscillations, cable energization and de-energization and short overvoltages**, which are the **main objectives** of the project.

It is however desirable to have as simple model as possible with as few modeling choices as possible too, to concentrate attention on the studies being conducted that with specific modeling details.

For these reasons, the proposed frequency dependent lumped parameters cell model is transformed into a constant parameter electrical cell model which together has the same frequency response as the original. The number of electrical elements to achieve this is arbitrary, and depends on the desired accuracy. The project develops a specific procedure to stablish the best option regarding cell complexity and model accuracy.

By this way, the Multi-Layer Cable Model developed includes two main levels for simulation.

The first layer contains a concentrated cable model, over a single lumped parameters cell, which allows determining general approximating cable behavior: frequency effects at the fundamental frequency, voltage drops, losses and efficiency, heating, etc. In spite of this apparent simplicity, the model will accept the effects of the commutated voltage wave, which produce fundamental, and low frequency harmonics, voltage resonances, and harmonics losses, among others.

Specific effects such as skin effect, proximity, etc., will be analyzed and modeled into the cable model at the fundamental frequency, to simulate the cable and circuit behavior and to obtain approximated parameters of operation, such as cable efficiency, oscillations, heating and others, which are the input characteristics to selection and validation of cable type chosen for application.

Once determined the global cable characteristics, and obtained the lumped parameters (with a specific methodology developed into the project), the second layer of multi cell structure allows an accurate simulation and fine analysis of high frequency specific effects, such as skin and proximity full effects, high frequency losses and critical cable length for over voltages and over currents.

Description of work

The project starts developing a general methodology for high frequency models of power cables from analytical studies of lumped model cells.

Later on, a general structure of the lumped parameters high frequency cable model for the basic two and three unshielded conductors, which includes longitudinal and transversal impedances have been specifically developed.

Finally, a specific GUIs have been developed to manage all the procedure, i.e, cable cell definitions, initial values for cable parameters, experimental inputs, GA parameters, output results, etc.

The consequent Steps for project development have been the following:

Step 1. Choose a cable configuration, two or three shielded or unshielded cables

Step 2. Determine longitudinal and transversal parameters at 500 kHz (Ll, Rl, Ct, Gt, Cs and Gs is) from short circuit and open circuit tests (several tests, the number depending on cable type).

Step 3. Perform experimental short circuit and open circuit tests at 40 Hz – 40 MHz to determine Lmeasured, Rmeasured, Cmeasured and Gmeasured. Only two tests are required, which are performed with a higher lenght of the cable samples (for instance, 10m sample cable for a 1m cable cell model). From these tests the frequency response of longitudinal and transversal cable parameters Ll, Rl, Ct, Gt , Cs and Gs can be extrapolated.

Step 4. Adjustment of calculated values of step 3 to a lower number of significant points obtained from experimental measurements. Although hundreds of Rl-f, Ll-f, GTC-s and Ctc-s data points were measured, in order to determine the components of the longitudinal impedance using a GA (Genetic Algorithm) optimization approach, only a few points are retained, to simplify the operation of GA optimization and to reduce the computational load of the next steps, since this is a complex problem demanding high computational requirements.

Once defined the basic cells structure, GA will perform the fitting of corresponding lumped parameters up to match the frequency cell response to an experimental (sub-adjusted) curves (Step 5).

Step 5. Create a single-cell cable model including longitudinal and transversal impedances with variable number of branches in both longitudinal and transversal impedances. Next, use Genetic Algorithm (GA) optimization to determine the components of the longitudinal and transversal parameters (Ri, Li, Ci and Gi with i = 1…4, 5 or 6) to match the frequency response of the single-cell model with the experimental one of Ll, Rl, Ct, Gt, Cs and Gs from data of 1 m cable. Note that when analyzing, for instance the longitudinal impedance, if the GA doesn't converge for a given number of branches, more branches have to be added to the analyzed impedance model until convergence is achieved and the single-cell model of the cable covering a length of 1 m is obtained.

By this way, lumped cells parameters are fitted and basic cell cable model is obtained.

Step 6. Generate a multi-cell circuit depending on cable length. Finally, cable model can be simulated and tested in a specific circuit with a power supply and load. Frequency and heating effects are considered.

Since modern IGBT-based converters have modulation frequencies in the range of 2 to 20 kHz with typical switching times of 50 ns or about 13 V/ns for a 460 V system, these operating conditions induce high voltage variations (dv/dt) which in turn excite the parasitic elements of the cables and mats, so to simulate the system behavior a high frequency model is required.

At high frequency, when dealing with power cables the eddy effects arise, so they have to be included in the cable model. Similarly, capacitive interactions between different cables and between cables and screen also happen. Therefore, to include these effects in the cable model, both longitudinal impedance and transversal impedance are included in the cable model, as explained former.

The parameters of these impedances have to be measured by means of a precision high-frequency impedance analyser by applying two test types, that is, short circuit and open circuit tests to a short sample of the cable to be characterized in order to ensure that the model is able to reproduce the real cable response for a wide range of frequencies of 40 Hz – 30 MHz.

An estimation of the computational burden has been also provided when considering different cable models and different number of cells, as an example to know the necessary time for simulations. Results provided are based on an Intel® Core™ i7-2600 – 3.40GHz computer processing unit, 8.00 GBytes RAM computer.

A PWM modulated output voltage of the switching power converter has been used as an input, for a time-step of 10-10 seconds and a simulation interval of 0-44·10-6 seconds. Simulations times for different cable configurations are shown in the following table. All analysed models assume five branches in the longitudinal impedance and seven branches in the transversal impedances.

GUI Interfaces

In order to facilitate the user to simulate the transient behavior of the cable two GUIs (Graphical User Interface) have been created with Matlab R2013b®.

The goal of the first GUI or GA_GUI is to determine the parameters R, L and C of the transversal and longitudinal impedances of the cells composing the cable model from the experimental short circuit and open circuit tests. The second GUI or CABLE_GUI is intended to simulate the transient behavior of the cable.

Results

Project describes how to model a high frequency power cable, taking into account all the frequency and no frequency effects, by means of single lumped parameters cell connections. After designing this basic cell, project presents a methodology based on a GA optimization algorithms to fit basic cell parameters up to adjust frequency cell response to a real cable frequency behaviour. After that, cable model are ready to be used in system simulations including continuous or discontinuous (PWM) power supply and any kind of power load, especially, mats for a WISP systems.

Main results of the project are:

- A general methodology for high frequency models of power cables from analytical studies of lumped model cells, experimental measurements and characterization and artificial intelligence (GA) based approach for fitting the lumped cell parameters has been developed and validated.

- A general structure of the lumped parameters high frequency cable model for the basic two and three unshielded conductors, which includes longitudinal and transversal impedances have been specifically developed.

- Specific GUIs have been developed to manage all the procedure, i.e, cable cell definitions, initial values for cable parameters, experimental inputs, GA parameters, output results, etc.

a) Timeline & main milestones

The Project started August 2014 and ended January 2016.

The main milestones and its achievements are:

- A methodology for power cable modelling, for its use in switched electric energy distribution.

- High frequency models of power cables, experimental set up for cable’s parameters determination.

- GA-based interactive algorithm to adjust the coefficients of the impedance networks of cable models to measured frequency response of the cable.

- Publication of Project Web Page: http://multycab.upc.edu/en.

b) Environmental benefits

The project appears to be in line with the environmental targets of the Strategic Research Agenda (SRA) for aeronautics in Europe –the SRA of the Advisory Council for Aeronautics Research in Europe (ACARE). On the other hand, the Clean SKY SGO initiative aims to meet the increasing social demand to reduce fuel consumption, emissions and noise through the adoption of a new approach when designing systems which will optimize use of engine power when aircraft is on ground and provide silent taxing capabilities and will be able to fly green missions from start to finish.

The project is in line with this general objective as it aims to develop an optimized design tool for power cables transporting energy into the aircraft, and specifically, for WIPS systems. This design has to take into account the new challenges for cable operation because the high frequency related to switched electronic converters. For example, the resistance to 2 kHz of Aluminum AWG000 is doubled in comparison with DC resistance. Moreover, high frequency signals are also transmitted by power cable and more specifically to switching frequency on the level of the order several 10 kHz. It is necessary to construct a precise model and manufacturing power cable, taking into account the various phenomena that appear when the frequency increases.

Electro-thermal systems usually use electro-thermal heaters embedded into the solid to heat protected surfaces where anti-icing/de-icing hot air is not available, such as propellers, spinners, and center windshield panels. On this so-called all-electric airplane, electric heat is used for the anti-icing of the wing, which needs a large electrical load of approximate 200 kW. Optimal design and accurate prediction of cable behavior in order to speed and reduce the time for developing the new electro thermal WIPS will help to accomplish the required specifications for electro thermal WIPS efficiency. In fact, the project has developed a design tool optimized for electric cables, which allows a more rapid design, with better performance than the approximate packages used hitherto and faster to apply than more complex FEM simulation suites.

The Multi Layer Cable Model MultyCaB tool has as target the improvement of the overall cable efficiency of around 50% by optimal design compared with basic pi-models, which, in turns, implies a saving of 2.5 kW per day of operation, apart from of course, superior safety against cable, inverter and load damage due to standing waves.

The project will highly contribute to the RTD European targets for strengthening the European competitiveness in the Aeronautics sector. The Multy Layer Cable Model developed in the project could potentially be applied to several other industrial sectors, including:

- The manufacturing industry, helping to model quickly and efficiently productive plants and motion systems that require high power.

- The industry for design and manufacturing of electric cables for industrial applications, electric energy production and distribution, energy management, electric transport, etc.

- The industry of renewable energy generators (wind, tide, water, etc..), including all energies using an electrical machine which should provide energy trough an electrical cable

- The deployment and installation of Smart Grids for industrial and tertiary sector.

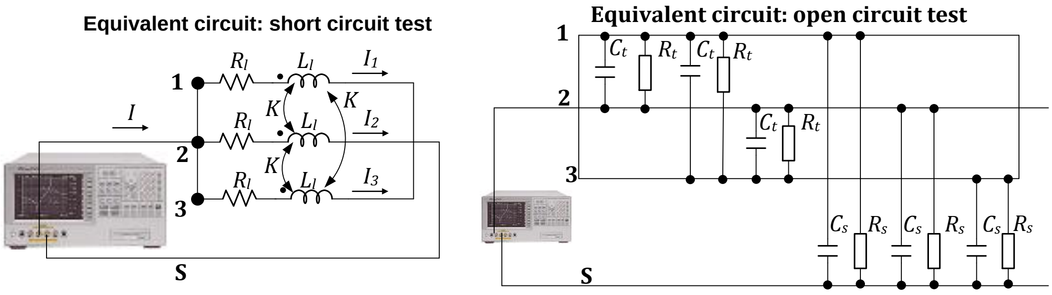
- Any stage of electric energy conversion by using power converters.

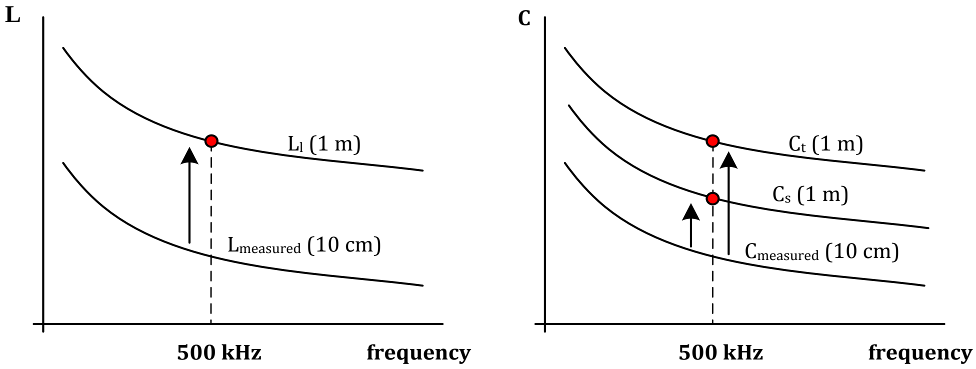
Regarding safety of passengers, the need to improve all-weather flying safety is absolutely necessary and beyond of any discussion. Airframe icing continues to be a serious aviation hazard, but following certain precautions and procedures can considerably reduce the probability of having an icing related mishap. On this extent, the newest electrothermal WIPS solutions can help to increment the operational life of primary flight controls and the passengers' safety, because electro thermal anti icing and deicing allow more direct actuation on the affected icing zones can be performed, allowing for higher safety of operation.

Summarizing, the development of specific tools for improving the design and operation of thermal anti icing and deicing in terms of efficiency and weight of the cabling will lead to a safer operation of electrical WIPS and improved safety regarding electrical behaviour and disturbances for high frequency switching at the power supply.

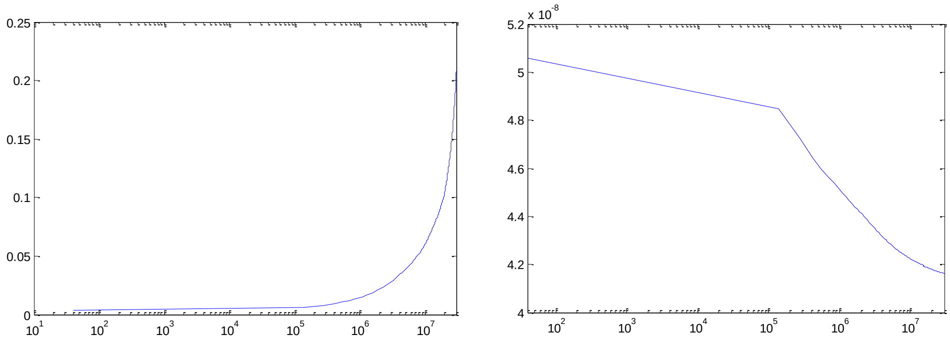
By this way, the new electrical technologies together the tools for modeling and simulation here developed and taken as a part of the design process will improve the safety of planes and passengers.

Pictures and illustrations

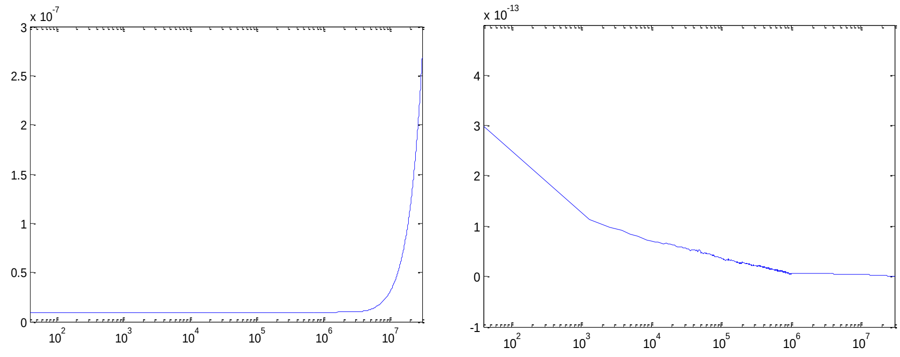




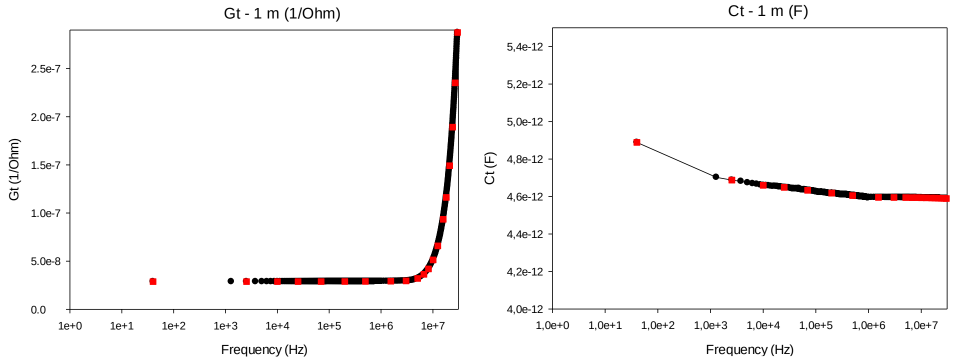
The data obtained in the 10 cm open circuit test among tree conductors is shifted to coincide at 500 kHz with data of 1 m cable as indicated in the figure



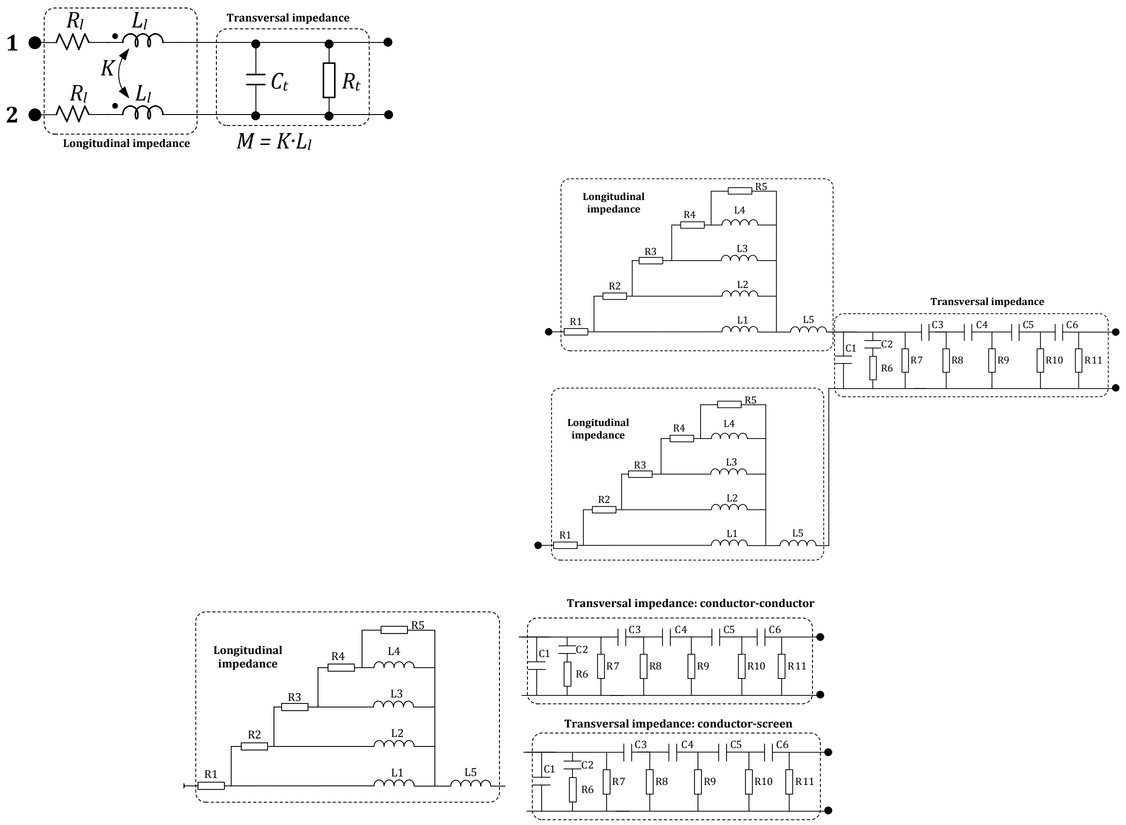
Calculated values of Rl (Ohm) and Ll (H) in the range 40 Hz-30 MHz from the measurements performed with the Agilent 4294A impedance analyzer. Short Circuit test



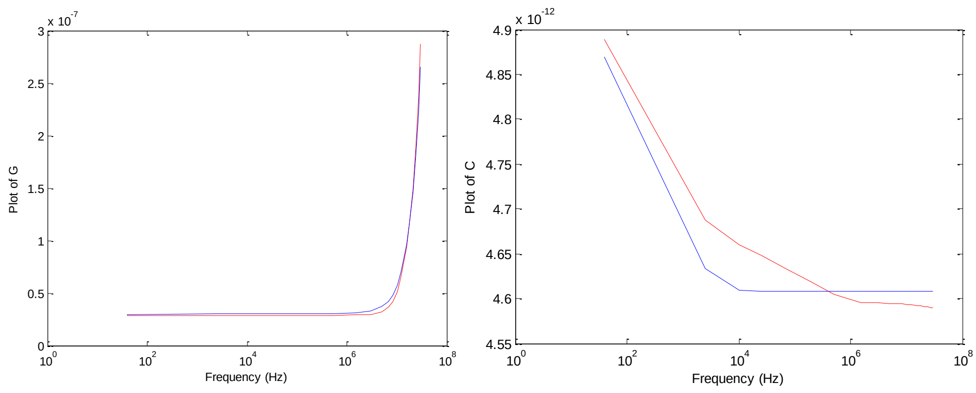
Calculated values of Gtc-s (1/Ohm) and Ctc-s (H) in the range 40 Hz-30 MHz from the measurements performed with the Agilent 4294A impedance analyzer. Open Circuit test



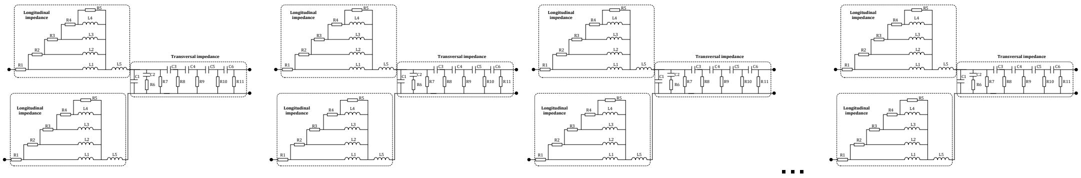
Results derived from the two short circuit experimental tests.



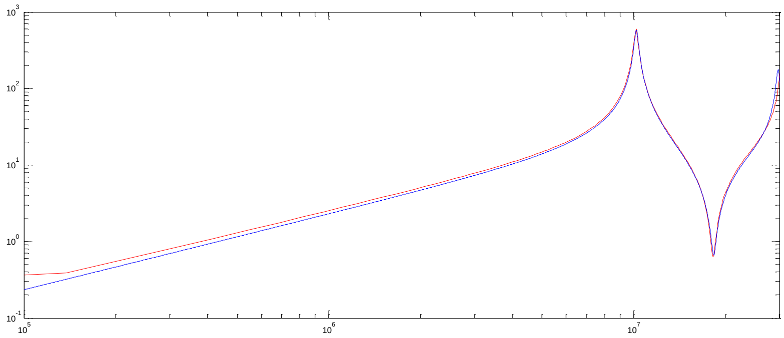
Longitudinal and transversal impedance models



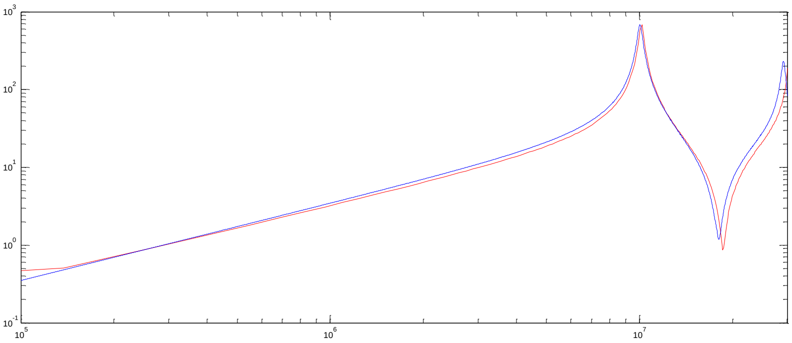
Rtc-c and Ctc-c. Red = experimental values. Blue = values fitted by means of the GA algorithm.



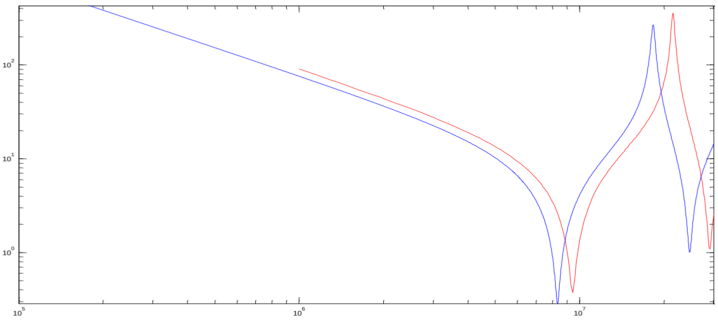
Cable model containing 4 cells for a cable length 4f 5 m



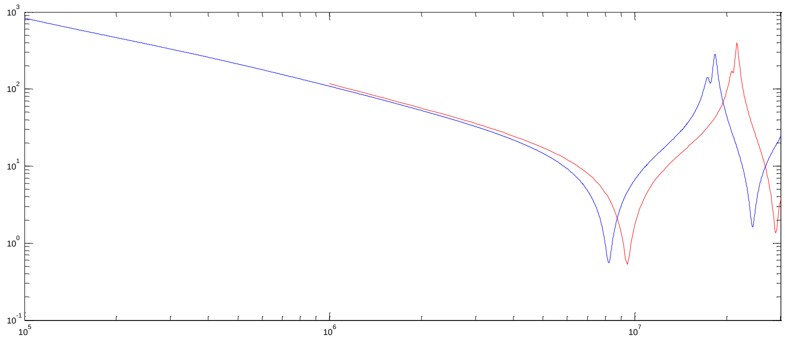
Three conductors in short circuit.



Two conductors in short circuit.



Three conductors in open circuit.



Two conductors in open circuit

Project Summary

Acronym:	MultyCaB
Name of proposal:	Power Cable Modelling for WIPS electromechanical Chain
Technical domain:	Electric modelling
Involved ITD:	Systems for Green Operations
Grant Agreement:	632458
Instrument:	Clean Sky JU
Total Cost:	287.494,78 €
Clean Sky contribution:	215.621,09 €
Call:	SPI-JTI-CS-2013-02
Starting date:	01/08/2014
Ending date:	31/01/2016
Duration:	18 moths

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