EcosimPro/PROOSIS aircraft electrical system modelling ELECTRIC SYSTEMS LIBRARY

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1. INTRODUCTION

The concern about climate effects, the limit amount of fossil fuels and the high cost of them, leads aircraft manufacturers to develop the More Electric AirCraft. It is necessary for that purpose to develop simulation models which allows the user to run simultaneously such different systems, propulsion and aircraft electric system.

The PROOSIS [1] modelling and simulation tool can be used not only to simulate the motor of the aircraft (with the TURBO library [2]), but also to perform a joint simulation with the main systems of the motor and the aircraft. The electrical system (ELECTRIC SYSTEMS library [3]) has been modelled in this case. The model of the motor and of the electrical system of the aircraft (B767) is shown, indicating the most relevant elements and the results of the main actuations analysed: generator startup at no load, simultaneous connection of all the loads to check the limitations demanded by standard MIL-STD-704F [4], study of various short-circuits and their protections, as well as harmonics contents and harmonics reduction with the installed filters.

2. AIRCRAFT ELECTRICAL SYSTEM

The aircraft electrical system [5] typically receives the mechanical power required to move the electrical generators from the motors that propel the aircraft themselves. This power is adapted to the needs of each load by means of electrical converters to power the electrical loads in the system: these loads are of DC, three-phase AC and single-phase AC type, as shown in figure 1, for B767 analysed case.

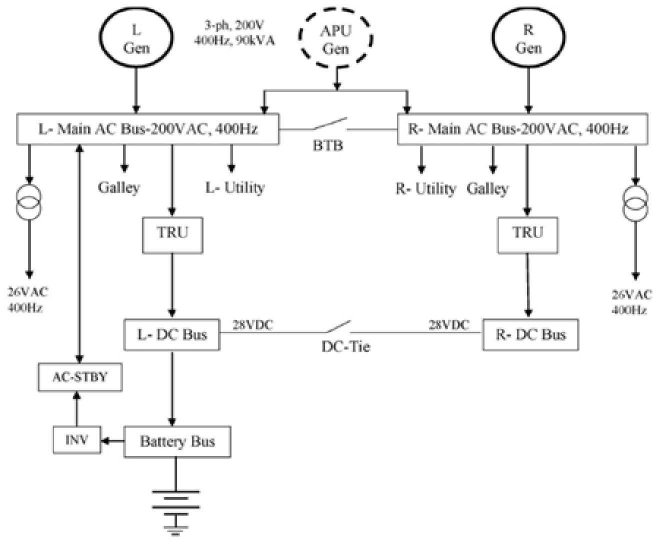

Figure 1 Aircraft electrical system

The electrical generators shall normally be of synchronous type and shall operate at a line RMS voltage of 200V and a frequency of 400Hz that is distributed by means of a step-down transformer to power the LV alternating loads.

In parallel, the DC loads in the aircraft are fed through a transformer-rectifier unit (TRU). These rectifiers are typically of '12-pulse' type. In general, they are formed by transformers with two secondary windings. The output voltages of both transformers are rectified and applied to a condenser. On the other hand, 200 Vac loads are fed directly. Lastly, the system is completed with several backup batteries that feed the main network through inverters in case of a malfunction of the main generators, or that maintain their optimum charge level under normal operation when they are connected to the DC network.

3. MODEL OF THE AIRCRAFT ELECTRICAL SYSTEM

The electrical system described in the above paragraph is modelled by means of PROOSIS [1] and the ELECTRIC SYSTEMS library [3] (for the electrical system) and the TURBO library [2] (for the aircraft motor and the corresponding gearbox). The study is limited to one of the two almost identical branches of the system.
Electrical power is produced by means of a three-phase synchronous, brushless generator modelled by cascade connection of three common synchronous generators. The synchronous generator is controlled by means of a PID system that attempts to

maintain the voltage in the three-phase system at around a reference value by means of the field excitation voltage. The rectification required to power DC loads is done with a transformer-rectifier unit modelled by means of transformers and rectifiers. In addition, the system includes several filters required to mitigate harmonics 11, 13, 23 and 25, which are the main reason behind the harmonic distortion in the systems with 12-pulse units. These filters shall be connected to the output of the synchronous generator.

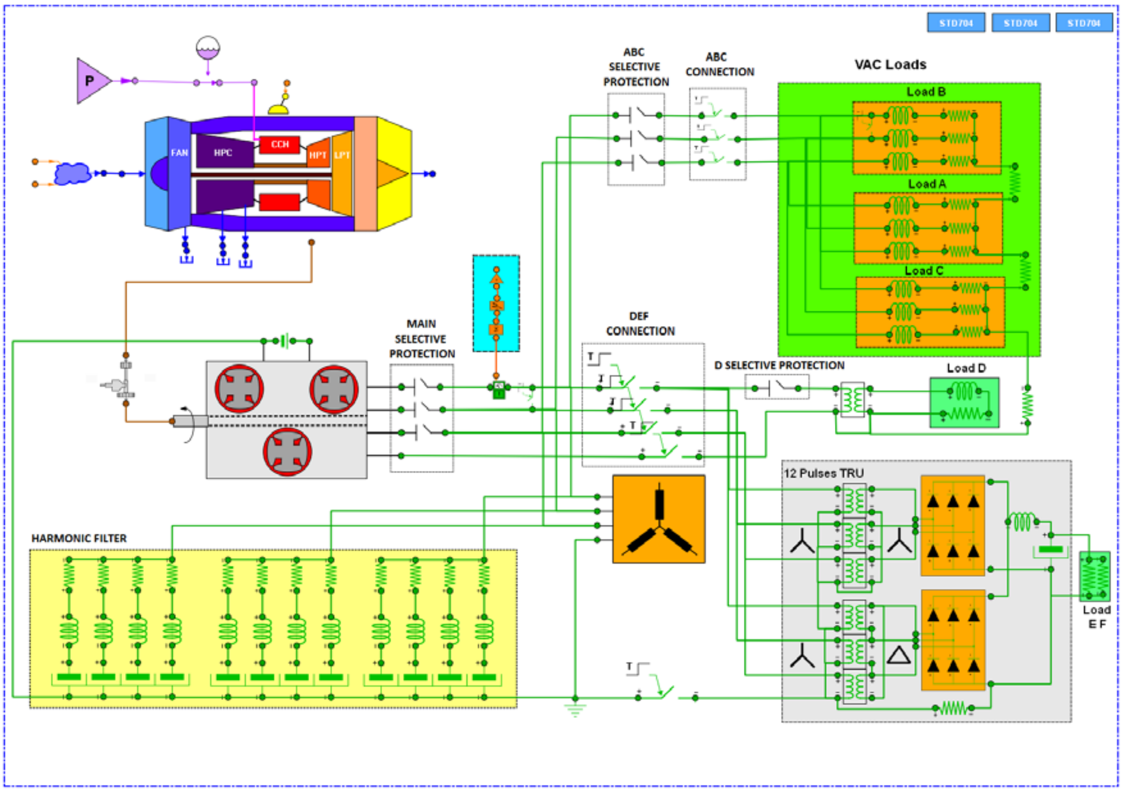

Figure 2 Model of the aircraft electrical system with EcosimPro/Proosis

The models of the most interesting elements are analysed in greater detail: Three-phase brushless synchronous generator, 12-pulse transformer-rectifier unit and protection switches.

3.1. THREE-PHASE BRUSHLESS SYNCHRONOUS GENERATOR

The developed model is formed by three synchronous generators connected to the same shaft. The voltage generated by each of them is rectified and used as excitation voltage for the following one. In addition, the first one has permanent magnetic excitation, and the voltage generated by the last one is considered the system output.

In addition, the voltage generated by the second one is rectified, regulated and used as excitation for the third one and therefore the control action is applied.

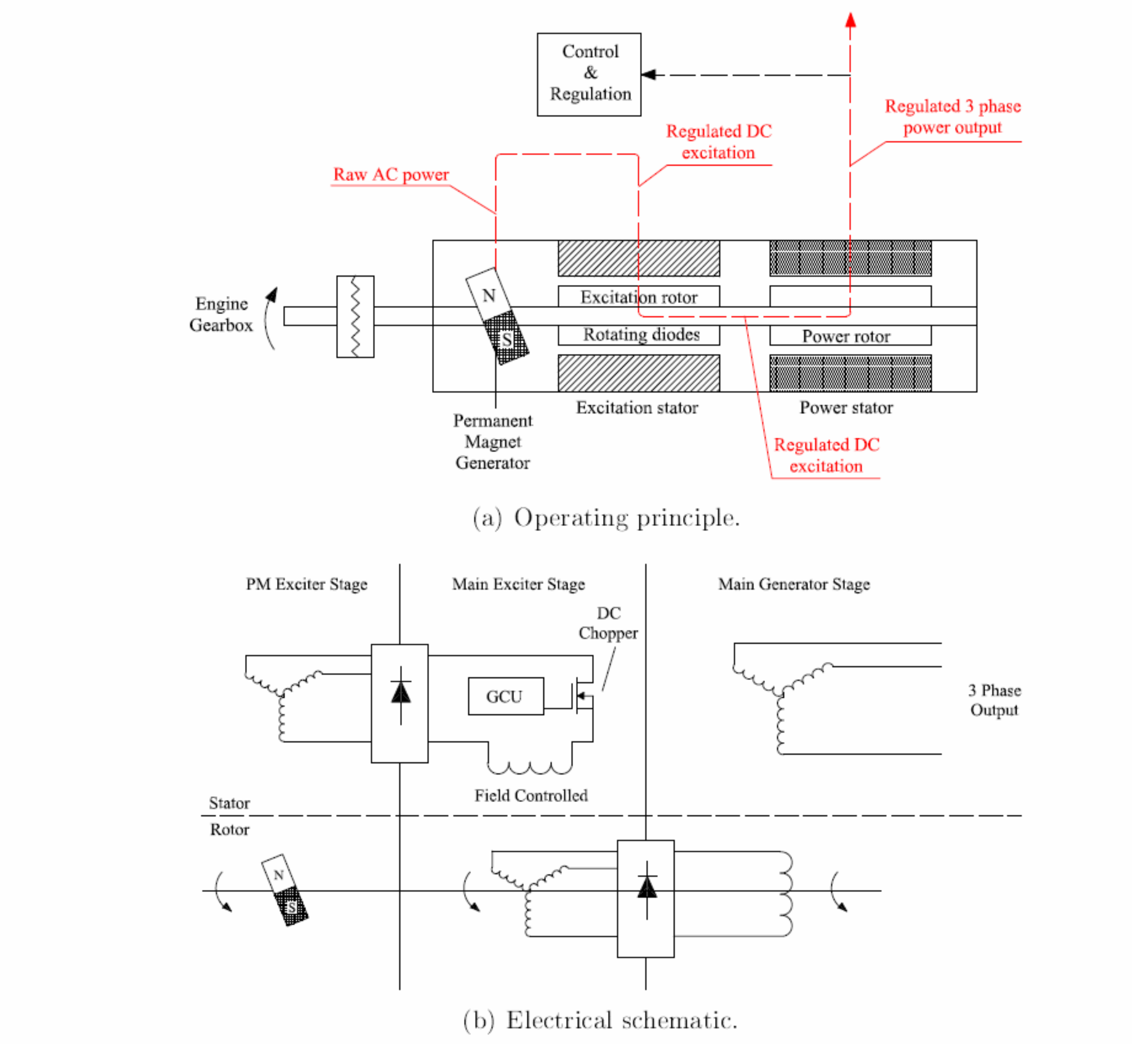

Figure 3 Three-phase brushless synchronous generator

In the developed model, three common synchronous generators have been connected through their shaft. When voltage is generated as a result of the relative motion between the rotor and the stator, this technique is equivalent to the one shown in the above figure for the purpose of the modelling. Voltage control is done by means of a Zener voltage regulator and a rheostat that serves to regulate the excitation of the central phase (main exciter), although several alternatives can be used. Figure 4 shows the structure of this generator with the model developed in PROOSIS [1].

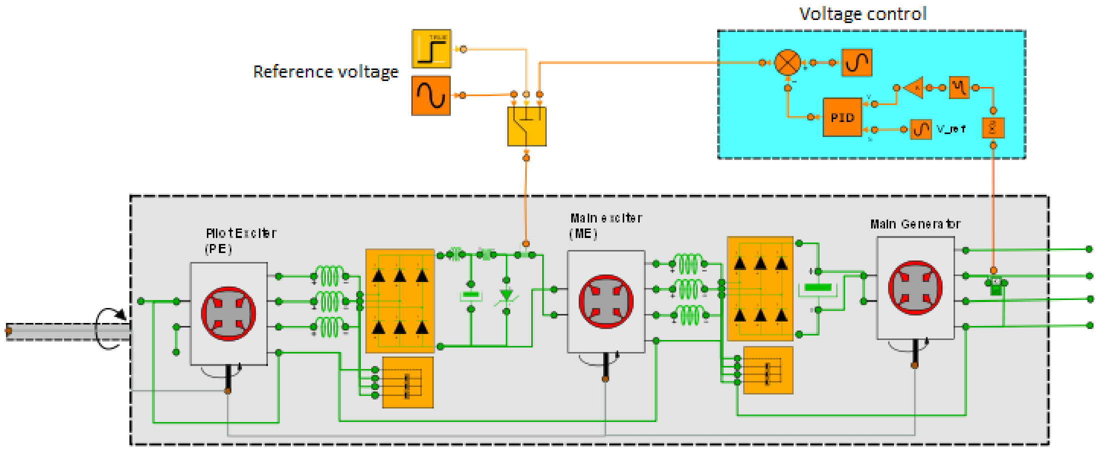

Figure 4 EcosimPro/Proosis ELECTRIC SYSTEMS library Model of generator.

3.2. 12-PULSE TRANSFORMER-RECTIFIER UNIT

The system includes several loads that operate under DC voltage conditions. One of the most widespread rectifier units for this type of system is used to generate this voltage from the AC power. It is a 12-pulse rectifier that is extremely common for this type of application and whose structure is well-known and available for consultation in specific documentation. Figure 5 shows the topology of this type of system.

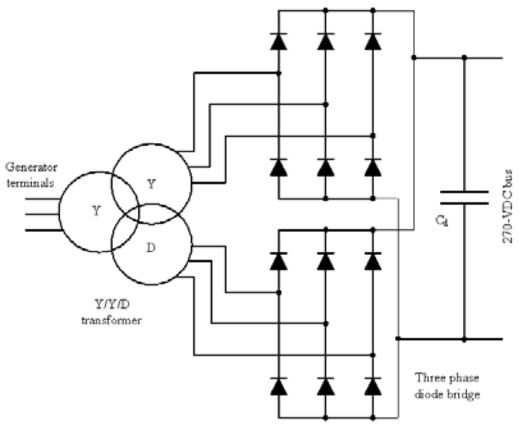

Figure 5 12-pulse transformer-rectifier unit (TRU).

A 12-pulse transformer-rectifier unit (TRU) has been modelled using six single-phase transformers. The primary windings of three of them have been connected in a star connection, as have their secondary windings. The primary windings of the others have been connected in a star connection, but their secondary windings have been connected in a delta connection. Three ideal three-phase transformers with Y-Y and Y-D connections are therefore created. The outputs of each of these three-phase transformers are rectified by means of three-phase bridges with diodes. Finally, the resulting voltage difference at the output of both rectifiers is applied to the ends of an LC filter. The output voltage thus generated is used as the supply for DC resistive loads E and F.

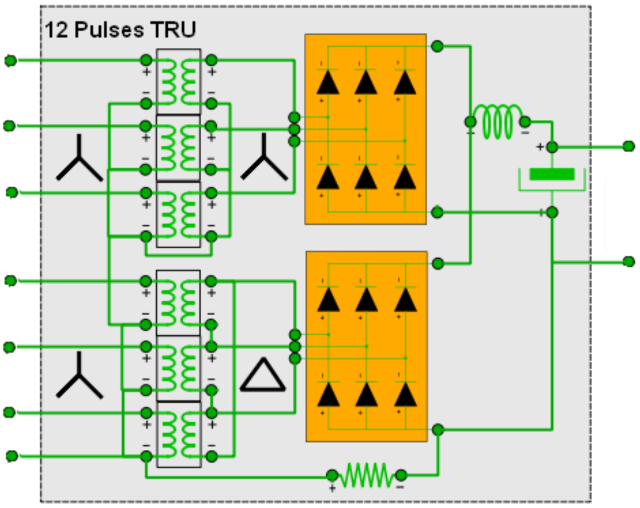

Figure 6 TRU model in EcosimPro/Proosis with the ELECTRIC SYSTEMS library.

3.3. SELECTIVE PROTECTION SYSTEM

The ELECTRIC SYSTEMS library [3] has a set of protection circuit breakers that can selectively isolate short-circuits or any other type of malfunction. If this selective protection system works according to what is expected, the points where the short-circuits have occurred shall be adequately isolated depending on the location of the system malfunction. To do this, protection circuit breakers with an adequate configuration shall be used. The switchgear can be adequately designed based on the estimated consumption for each part of the facility.

The operation of this type of device is based on the generation of current-time tables. A maximum delay is established on the basis of the current through the device. If this delay is reached, the opening of the device is triggered. Smaller delays are allowed for greater currents. Drop-down menus can be used to configure the current-time curves of each component depending on the needs of the system or on the real breaker whose behaviour is to be reproduced. Obviously, in order to guarantee the selectivity, the top switchboard needs to be configured for greater current values and the same delays than the lower switchboard.

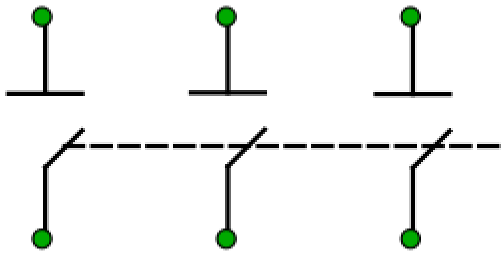

Figure 7 Model of the selective protection circuit breaker with EcosimPro/Proosis.

4. ANALYSED ACTUATIONS

Several actuations have been performed on the model of the electrical system developed so as to verify its behaviour under several scenarios and to analyse the response of the main components. The use of programmable connection breakers allows a chronological pattern to be established. This pattern can be summarised as follows:

Generator startup at no load until the rated speed is reached.

Connection of the loads in TIME = 0.3 seconds.

Short-circuit 1 in TIME = 0.5 seconds, downstream from the protection switchboard of the section of loads A, B and C, where the rest of the loads still receive power.

Short-circuit 2 in TIME = 0.7 seconds immediately downstream from the general switchboard, which interrupts the power supply to the whole system.

The location of the short-circuits can be checked in figure 9.

5. RESULTS

5.1. STARTUP OF THE GENERATOR AND SUBSEQUENT SIMULTANEOUS CONNECTION OF THE LOADS

When it starts up, the generator accelerates up to the established speed that allows generation at 400 Hz, 12000 rpm, which corresponds to a unit with two pairs of poles. It is possible to see the stabilisation of the voltages at the unit output and the voltages applied to the loads through the various power supply systems once the unit has reached its steady-state speed and the voltage of the load has reached its setpoint value.

The later simultaneous connection of all the loads shows how the generator and the configuration of the controls allow the voltages to be kept within the margins established for this purpose by standard MIL-STD-704F [4]. As expected, the voltage in the generator tends to drop once all the loads are connected simultaneously. However, the excitation control of main exciter unit actuates, and the reference values for the output voltages are recovered.

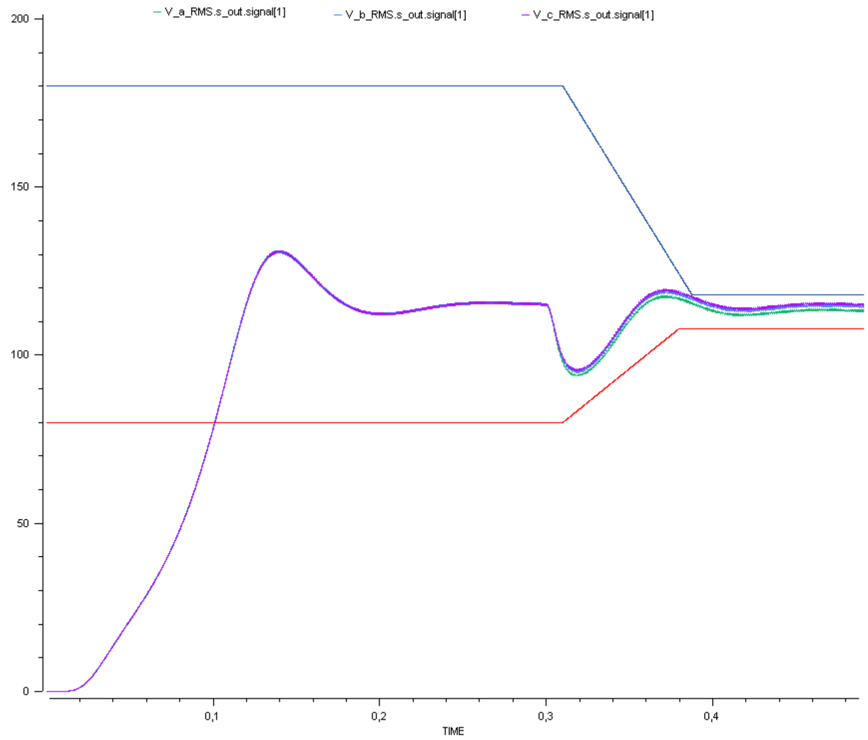

Figure 8 Evolution of the voltages during startup and load connection (RMS).

5.2. SHORT-CIRCUITS

Two phase-to-phase short-circuits at different levels of the circuit were analysed to verify the system response and the correct operation of the protections.

- Short-circuit 1: Short-circuit between phases a and b at the level immediately below the protection switchboard that corresponds to loads A,B, and C.
- Short-circuit 2: Short-circuit between phases a and b at the level immediately below the general protection switchboard.

Figure 9 shows the exact location of both short-circuits in the system.

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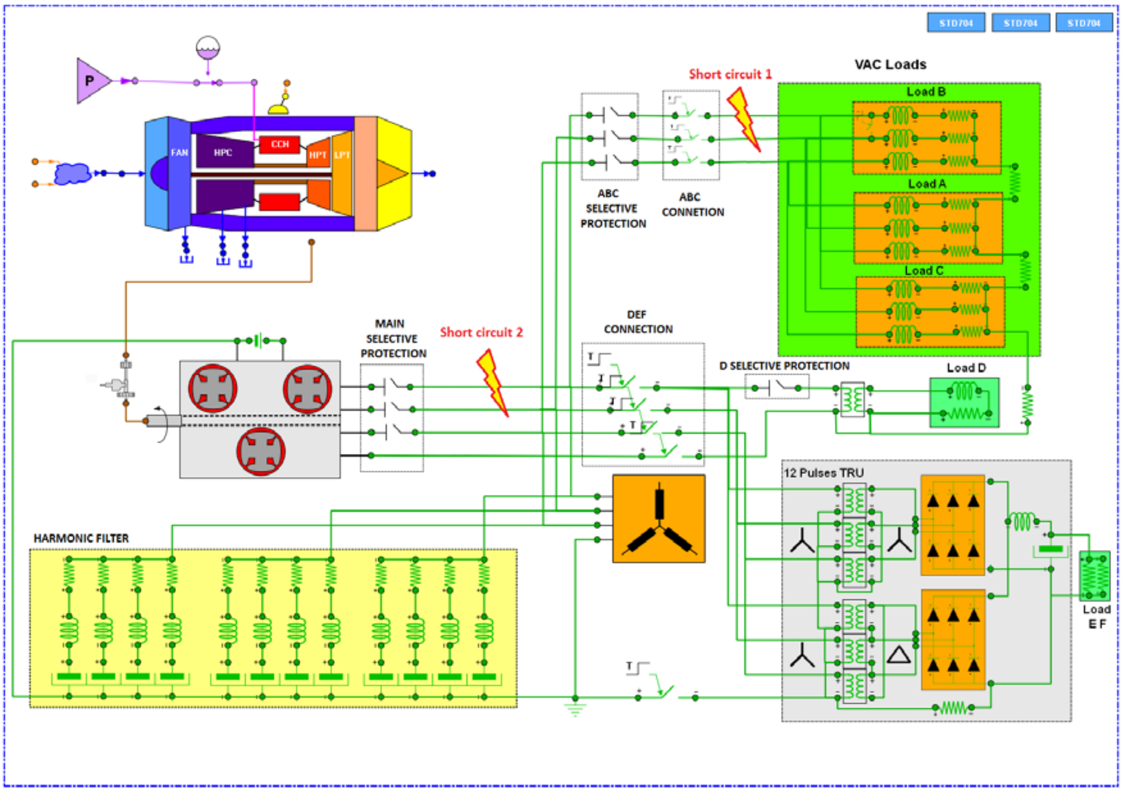


Figure 9 Location of the system short-circuits.

This serves to check the short-circuit current and confirm that a short-circuit that occurs downstream only interrupts power supply to the affected area, so the upstream section continues operating correctly thanks to the selectivity of the protection system. However, an upstream short-circuit shall require the disconnection of the main branches and, consequently, of the whole circuit.

The selected system to model short-circuits is based on the connection of the points to be short-circuited by means of a normally open circuit breaker (high resistance). At a given moment, this breaker closes (low resistance) and thus establishes an electrical connection between the points to be short-circuited.

The effects of a short-circuit of this kind appear as a strong phase unbalance. Thus, the short-circuited phases shall show very high current levels that will make their voltage drop. On the other hand, the voltage in the rest of the phases tends to rise. However, the protections and the voltage control limit the currents and recover the voltages.

Figures 10 and 11 show the effective value of the voltages generated for phases a, b and c. Upon the first short-circuit (TIME = 0.5 seconds), the value of the short-circuited phases tends to drop whereas the third phase, on the other hand, shows a voltage rise. However, the actuation of the protections prevents the voltage drop in the short-circuited phases from progressing. In addition, once the protections have isolated the short-circuited area, the voltages tend to rise because the connected load is smaller. Under these conditions, the generator excitation control actuates making the voltage recover its setpoint value after a transient that corresponds to the configuration of the PID regulator.

The second short-circuit occurs at the general protection switchboard once the system has recovered its stability. The consequences are similar: voltage drop in the short-circuited phases and voltage rise in the third phase, activation of the protections with the resulting voltage rise due to load drop and, finally, actuation of the generator excitation control and recovery of the reference value.

Figure 10 shows a detail of the first short-circuit. Although the oscillations of the voltages can be seen to exceed the margins in the standard, these margins shall not be considered because they are not defined for short-circuits, but instead for startup and load connection processes.

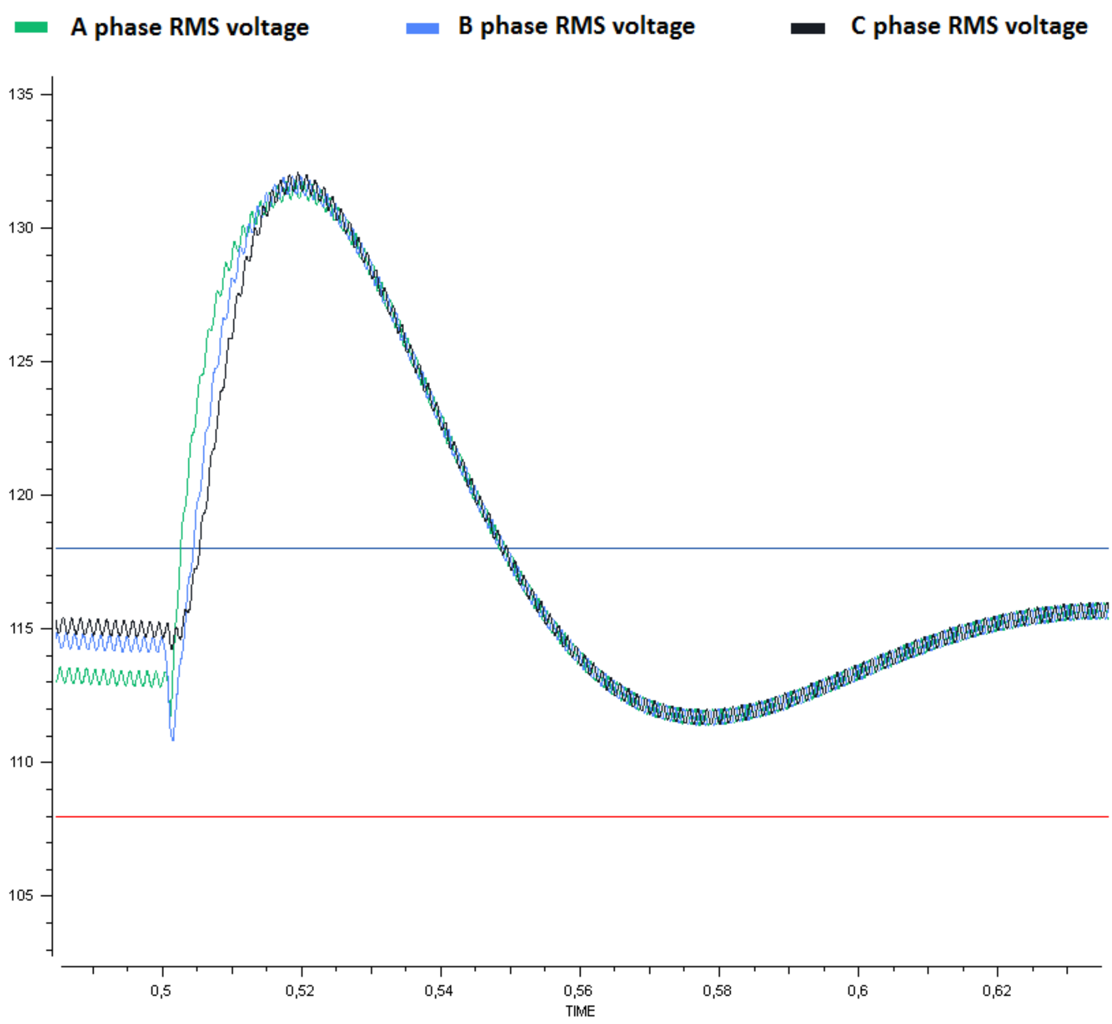


Figure 10 Detail of the voltages upon a short-circuit in the ABC protection switchboard

Finally, figure 11 shows a detail of the progress of the voltages in the second short-circuit.

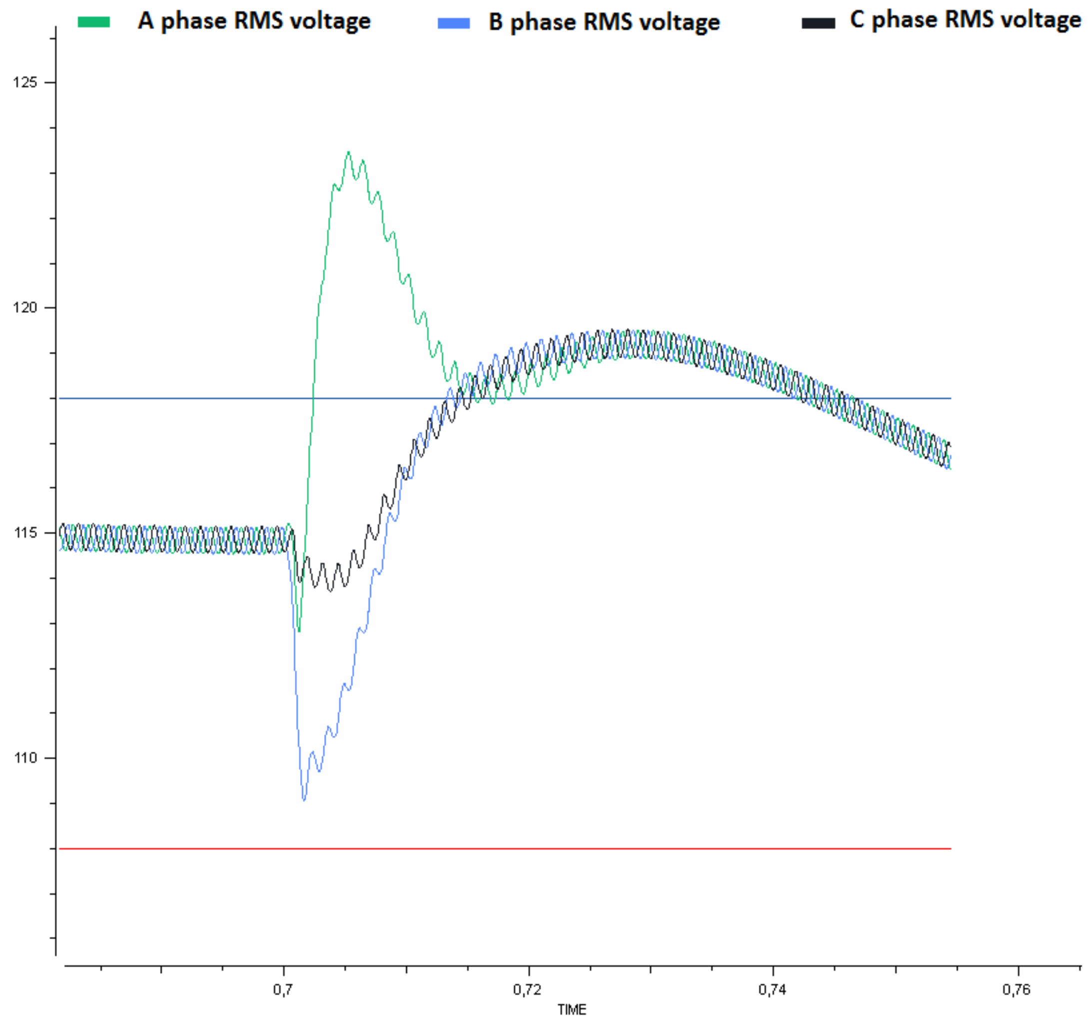


Figure 11 Detail of the voltages upon a short-circuit in the general switchboard

The operation of the protections used to isolate potential network short-circuits is based on a given current-time curve. It is therefore interesting to show the behaviour of the currents under short-circuit conditions. The following figures show the transients of the currents in RMS values.

Figure 12 shows the behaviour of the currents in the ABC switchboard during the first short-circuit. The current in phases a and b trips once the malfunction occurs. Once the set time for these current values has elapsed, the protection actuates and the currents become zero, since the area is isolated.

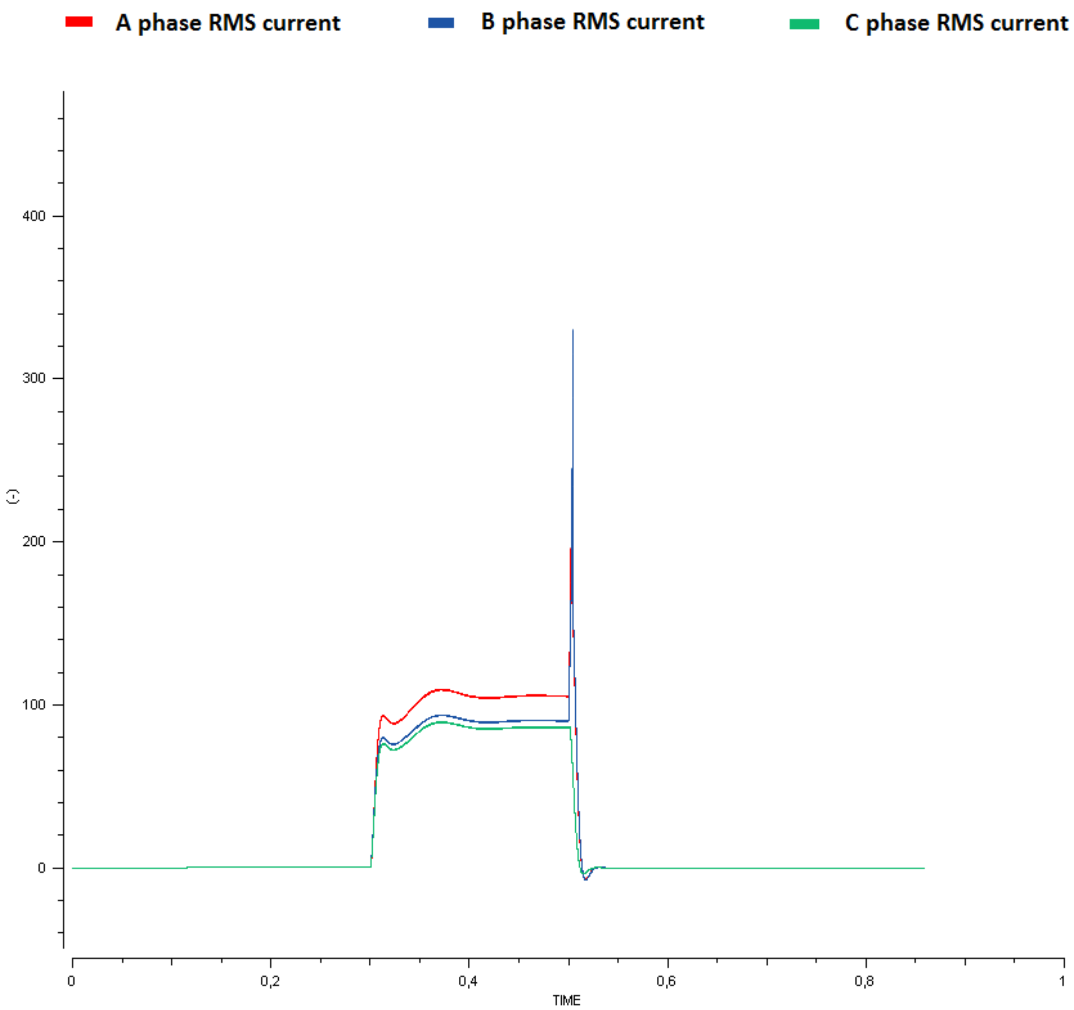
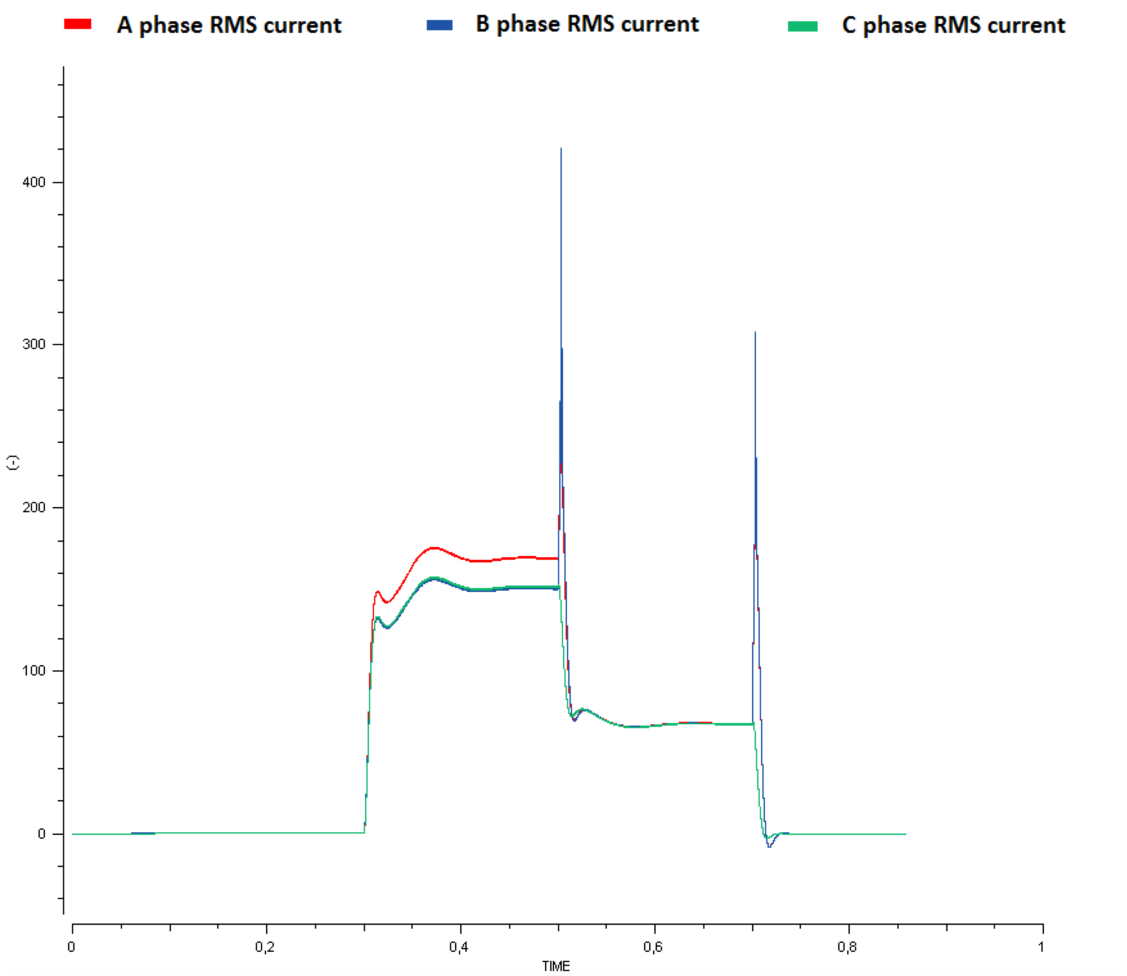


Figure 12 Detail of the currents upon a short-circuit in the ABC switchboard (RMS).

In addition, the first short-circuit also affects the behaviour of the generator output currents. This is clearly seen in figure 13, which analyses the currents through the general switchboard. Their values also trip, since once section has been short-circuited. However, the configuration of the selective protections activates the lower protections earlier and maintains the power supply to the rest of the facility. A drop in consumption is also evident after the first short-circuit. This reduction corresponds to loads A, B and C that have been isolated.

The second short-circuit then occurs after TIME = 0.7 seconds. The process is the same as the one described for loads A, B and C in the first short-circuit, but at the level of the main protection switchboard. In this case, the protections of this switchboard are the ones that completely isolate the system.



TIME

Figure 13 Detail of the currents upon a short-circuit in the general switchboard (RMS).

5.4. HARMONICS AND FILTERING

In addition, the possibility of analysing the instantaneous values of the electrical magnitudes highlights the effect of using tuned filters on the generated voltages and the mitigation of the harmonics generated by the switching of the transformer-rectifier unit.

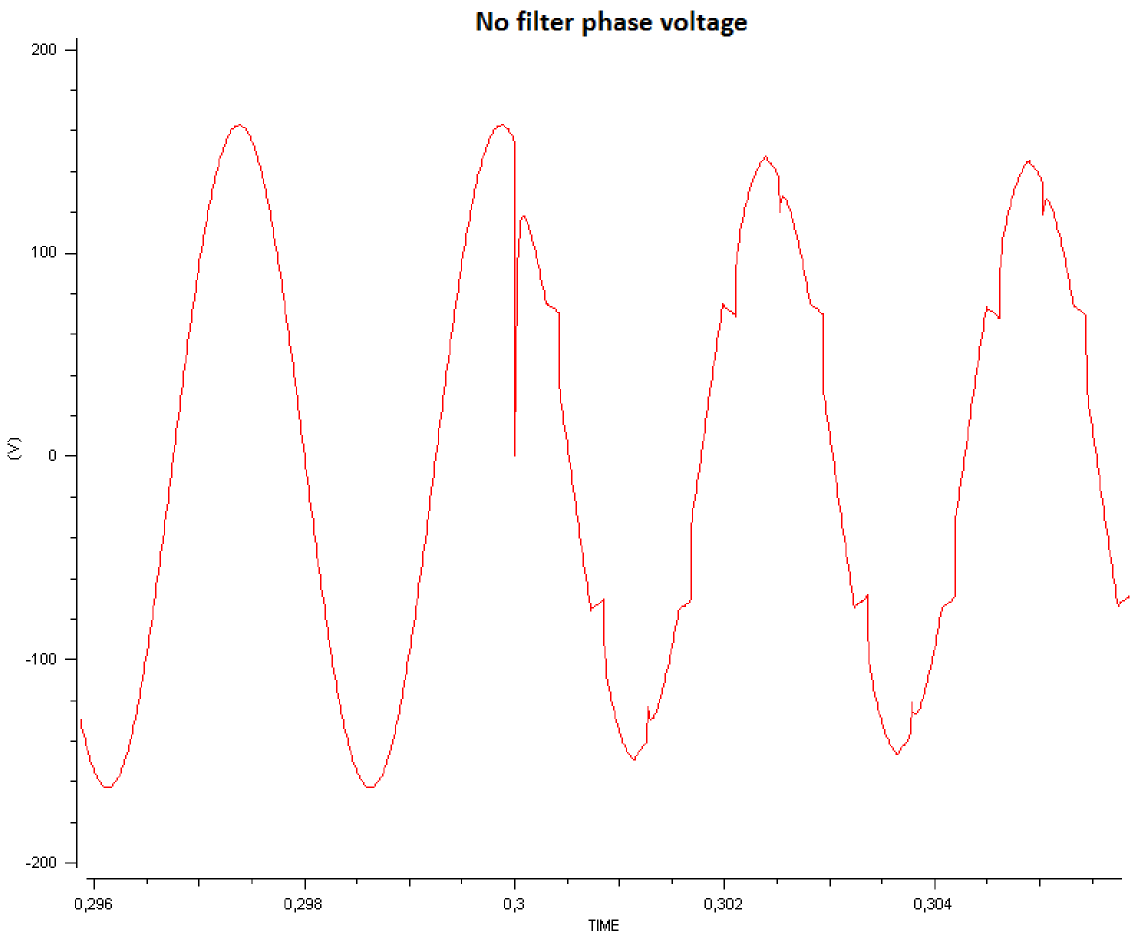


Figure 14 Generated voltages without filters.

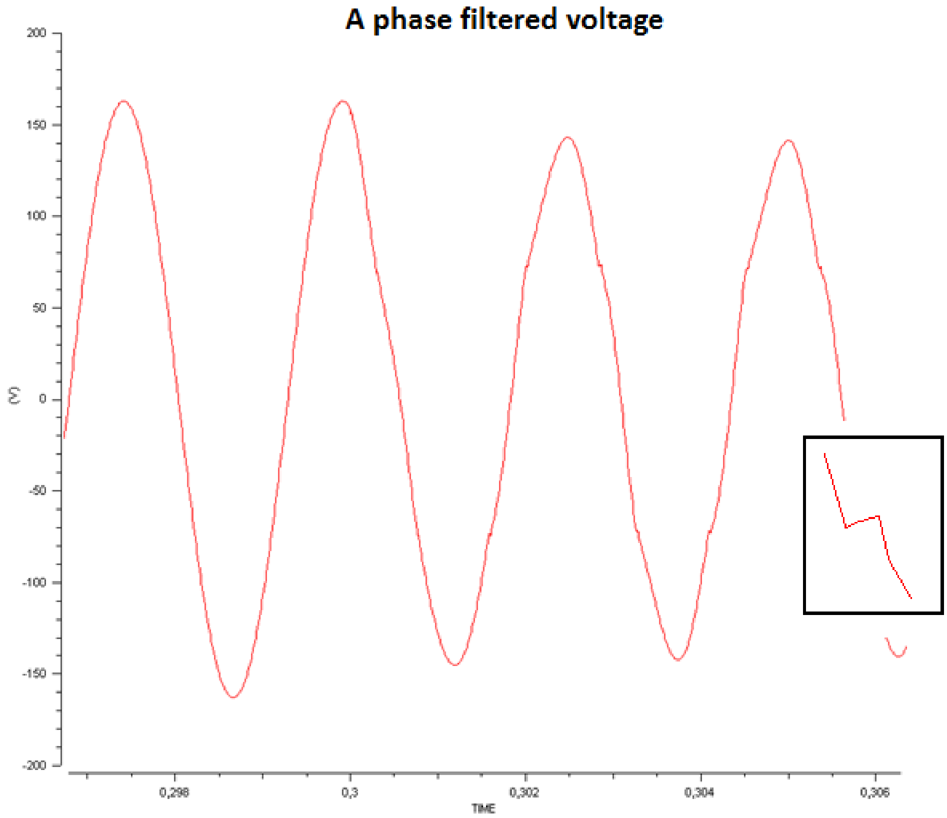


Figure 15 Generated voltages with filters.

6. REFERENCES:

- [1] PROOSIS: Propulsion Object Oriented Simulation Software, Empresarios Agrupados Internacional (EAI).
- [2] TURBO: Gas Turbine Performance Simulation Library, Empresarios Agrupados Internacional (EAI).
- [3] ELECTRIC_SYSTEMS: Electric, Electronic and Power Systems Simulation Library, Empresarios Agrupados Internacional (EAI).
- [4] Aircraft Electric Power Characteristics, MIL-STD-704F.
- [5] A. Eid, M. Abdel-Salam, H. El-Kishky, T. El-Mohandes, “Simulation and transient analysis of conventional and advanced aircraft electric power systems with harmonics mitigation”.