Solid-State Transformers for High Voltage Applications: FST Project Use Case

David Cervero García, Eduardo García-Martínez, Jesús Muñoz-Cruzado Alba, José Francisco Sanz Osorio, Juan Manuel Perié Buil, and Andrea Soto Rodríguez

***Abstract* -- Nowadays the electrical power grid is undergoing the raise of new technologies. Distributed energy resources, digitalization or the new flexibility market schemes are producing a severe change in the behavior of the electrical grid. Most of these changes specially concern distribution power grids. Consequently, there is an urgent need to provide tools to utilities to overcome the new requirements and adapt the grid structure to them. One of such emergent tools are Solid State-Transformers (SSTs). These power electronics-based devices are able not only to cope with the role of power transformers but also to provide additional features such as guiding the power flow. How to scale SSTs to operate in medium and high voltage power grids is one of the current issues of this technology. This article explains the approach of projects such as FST, TIGON and SSTAR to solve the problem of implementing a medium-frequency power stage with enough galvanic isolation levels between the primary and secondary windings.**

***Index Terms* -- high-frequency transformers, high-voltage techniques, inductive power transmission, insulation, power systems, resonant converters, solid state transformers, wireless power transmission.**

I. Introduction

THE on-going energy transition towards a decarbonized economy is changing profoundly the infrastructure of power grids worldwide as well as the management paradigms of those grids. Among other changes, electric grids are becoming progressively more interconnected, requiring bidirectional power flows in its nodes, and demanding more flexibility. This means that grids will demand different characteristics from their components.

Conventional high-power transformers are not fully prepared to overcome these challenges, as they do not have intrinsic capabilities regarding active system support [1]. Therefore, it is highly pertinent to explore power electronics solutions to address all the above-referred changes in the power grid in a potential cost-effective way, while comparing with the current state-of-the-art [2].

Solid State Transformers (SSTs) are power electronics devices designed to act in a similar way to traditional power transformers. However, SSTs are not going to substitute 50/60 Hz power transformers in all the applications. Power transformers are a cheap, mature, and very reliable technology and SSTs will not overpass them completely, at least for the incoming decades. Nevertheless, SSTs provide a series of attractive new features to use in special applications in which traditional power transformers are not an optimum solution [3]–[5].

The key concept of SSTs is that they are electronic devices that can interconnect separate electric grids with different range of voltage or frequency providing galvanic isolation between them. One of the typical SSTs configurations for AC/AC interconnection is depicted in Fig. 1: the AC input pass through a converter to establish a constant DC voltage link in the primary side. Then, thanks to a medium frequency power electronics stage, the power goes to the secondary DC-Link, and finally, a final converter adapts the signal to the output grid conditions.

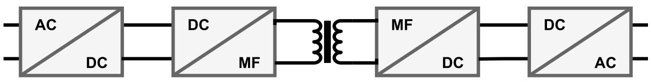

Fig. 1. Typical SST configuration with a dedicated DC-Link in each winding.

II. Solid State Transformer Capabilities

Thanks to the full control of the system given by the involved power electronics, the SST can cope with additional features respect to classic power transformers [6], [7]. Some of the more useful SST capabilities are described in the following subsections.

A. Waveform regeneration

SSTs have an independent full-controlled power converter in each side of the device. Therefore, only active power is transmitted from the input to the output of the device. As a result, possible deviations and disturbances in one side waveform are not replicated or transmitted into the other side. Consequently, imperfections in one side could be removed in the other side, producing the desired output signal.

B. Smooth voltage and frequency regulation

As described previously, SSTs have an independent full control over the output in each side. This control requires an energy balance, because SSTs cannot store energy, except for the limited energy associated to their internal passive components. Consequently, voltage and frequency excursions in the primary side could be removed in the

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D. Cervero, E. García, J. Muñoz-Cruzado and J. M. Perié are with the Electronic Systems group, CIRCE-Technology Centre, Zaragoza, 50018 Spain (e-mail: dcervero@fcirce.es; egarcia@fcirce.es; jmunoz@fcirce.es; jmperie@fcirce.es)

J. F. Sanz is with the Research Institute CIRCE, University of Zaragoza, Zaragoza, 50018 Spain (e-mail: jfsanz@unizar.es).

A. Soto is with the Electromagnetic Analysis RD Team, EFACEC, Porto, 4466-952 Portugal (e-mail: andrea.soto@efacec.com).

secondary terminal, producing an output signal at its nominal values.

C. Reactive power injection

In SST systems the active power reference is controllable but must be the same for both terminals, to keep the energy balance of the whole system. However, SSTs allow an independent control over the reactive power reference for each winding. Therefore, thanks to their full controlled converter in each side, SSTs can set different reactive power working points without restrictions. Hence, each side could work in any point of the capability curve regarding the reactive power, only considering the constrains established by the active power flow.

D. Power flow control

As most full-converter power electronics devices, SSTs have the availability to work as a voltage or a current source. Furthermore, SSTs are capable of performing a control over the grid power flow, which depends upon its mode of operation.

On the one hand, when SSTs work as current source, they cannot control directly the voltage and frequency outputs of the converter. However, they have a complete control over the active power transmission from the primary to the secondary side, and the reactive power injection could be selected freely.

On the other hand, when SSTs work as voltage source, they are not able to control the active and reactive power working point of the converter. Nevertheless, they have a total control over the voltage and frequency imposed at the secondary side, allowing a smooth regulation of these parameters. Additionally, an indirect control regarding the transmitted power is still possible regulating at a convenience voltage and frequency.

E. Protection and black start features

SSTs are fully controllable devices with an actuation time in the order of microseconds. Therefore, several timing and instantaneous thresholds can be programmed according to the use-case requirements. Besides, the disconnection can be performed instantaneously or progressively, thanks to the controllability performance of the device. These features allow SSTs to act as a protection device, isolating a section of the electrical grid by means of their disconnection.

In the same way, after the clearance of faulty conditions or after a blackout of the primary side, the reconnection of the secondary side can be regulated with a desired ramp, in order to avoid undesirable load peaks that could lead to a new fall of the system.

III. SOLID STATE TRANSFORMER APPLICATIONS

The aforementioned capabilities allow using SSTs in different fields. The main applications in which SSTs are nowadays being developed are described in the following subsections [8], [9].

A. Traction

Currently, SSTs are being applied to traction applications due to their advantages regarding volume and weight, having a technology development status of TRL 7-9. First commercial prototypes appeared one decade ago, and it is possible to find some examples in the market up to date. Still, the solutions lack from some refinement and the products have plenty of space to be improved.

B. Smart grids

There have been many initiatives to apply SSTs to Smart Grids applications. Nevertheless, due to the high technical requirements they have not break into the market yet. Currently, there are some international research projects that try to level up the technology maturity from TRL 3 to 6, installing the first prototypes in representative controlled scenarios to evaluate the performance of the device.

C. Electric vehicles

SSTs have not been applied to Electric Vehicles (EVs) until recently [10]. However, some possible configurations have been proposed with interesting features. Besides, the flexibility and compactness of SSTs make them very attractive for this sector. Therefore, it is expected a rapid development in the following years.

D. HV application

SSTs applied to the transmission and distribution power grids are very interesting in areas such as power transformers and Flexible AC Transmission Systems (FACTS). Some studies have been carried out and most of the research about SSTs in Smart Grids could be applied to this sector. However, the technology must face new challenges before a successful implementation of the technology: development of very high voltage Wide Band Gap (WBG) power semiconductors, capacitors for medium voltage applications, provide isolation between windings, etc.

E. Others

Apart from the applications exposed above, SSTs could be applied to numerous fields, and they could break into the market through them in the following decades: medical application [11], electric planes and ships [12], large data centers, etc.

IV. FST PROJECT USE CASE

A. Project Description

FST stands for Flexible Smart Transformer. The project aims to design a power electronics SST for very high voltage applications, providing galvanic isolation between the primary and the secondary side [13]. The FST is made up by a set of modules which allow to achieve very high voltages by means of parallel and serial interconnections. Each module itself supports high voltage between its terminals. Therefore, a serial configuration increases the whole rated voltage, reaching usual transmission line values.

For the selected studied application, the primary side of the FST is a shunt connection and the secondary side is a series connection, both being built up by the interconnection of the individual modules. In the shunt connection all the converters are connected in a series-cascade configuration for reaching the line voltage. On the other hand, in the serial connection a matrix association of serial-parallel allows a current capacity equivalent of the rated line current and simultaneously, provides enough voltage to allow the operation.

Fig. 2 shows a conceptual scheme of the proposed modules interconnection and the grid insertion. This module configuration enables SST to work as a Unified Power Flow Controller (UPFC) device. It can be seen that the high voltage isolation between the primary and secondary side is done by the medium frequency power electronic stage. This isolation gives a DC floating voltage that allows the possibility to configure the modules of the system in many ways, depending on the necessity in voltage and current of every application.

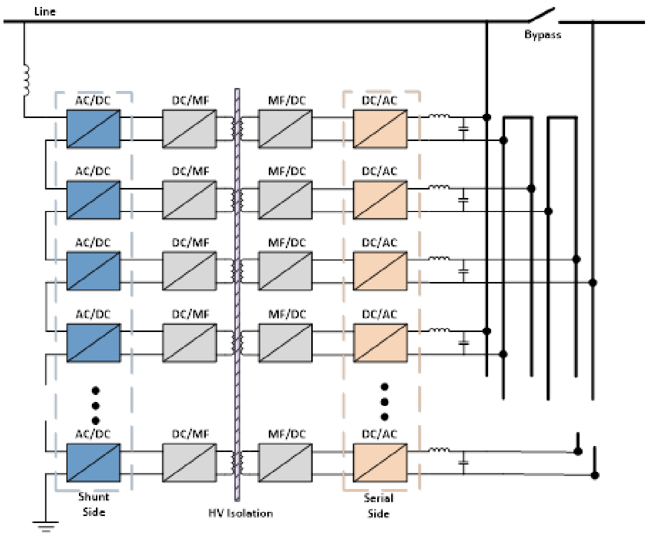

Fig. 2. Conceptual scheme of the interconnection of the modules and the grid insertion.

B. Unified Power Flow Controllers

The chosen use-case for the FST project is an UPFC [14]. UPFCs are systems which provide the following control actions [15]:

- Reactive power injection to the system.
- Introduction of a series voltage source in the installed line, which is controllable in module and in argument.

Fig. 3 depicts an UPFC model and its integration in the electrical grid. This interconnection and the aforementioned actions, enable UPFC to fulfill the following functionalities:

- Mitigation of inter-area oscillations: an introduction in the line of a series/parallel impedance with a controlled value helps to stabilize the system in scenarios in which the grid stability is compromised.
- Controlling power flow among power transmission lines: an introduction in a power transmission line of a series voltage source affects the power flow in parallel connections among different parts of the electrical system.
- Smooth voltage regulation: a reactive power injection to the electrical power network could be useful to hold the rated voltage of the grid.

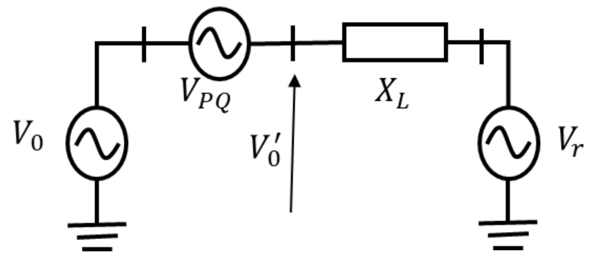

Fig. 3. Ideal UPFC unifilar model based on a series voltage source V_{PQ}.

FST project aims to obtain a UPFC to be installed in a transmission power line located in Bescanó-Sentmenat, in Spain. Table I shows the power line characteristics and the target features for the UPFC. A capacitance impedance of 20 Ω for a power line load of 1000 MW is considered to be suitable to mitigate the inter-area oscillations and hold the power grid stability in that transmission line.

TABLE I
BESCANÓ-SENTMENAT POWER LINE PROPERTIES

Parameter name	Value	Units
Rated voltage	400	kV
Transmission line power	2400	MW
Reactive power of the shunt side	150	MVAr
Equivalent serial impedance	20	Ω
Power at maximum equivalent impedance	1000	MW

TABLE II
SPECIFICATIONS FOR THE DESIGN OF THE FST

Parameter name	Value	Units
Rated line-to-ground voltage	230	kV
Rated frequency	50	Hz
Rated line-to-ground current	1444	Arms
Maximum line-to-ground current	3465	Arms
Rated reactive power available at primary (shunt) side	±150	MVAr
Rated active power available at primary (shunt) side	±30	MW
Rated reactive power available at secondary (serial) side	±150	MVAr
Rated active power available at secondary (serial) side	±30	MW
Modules primary (shunt) configuration	207/1	S/P
Modules secondary (serial) configuration	23/9	S/P
Total number of modules per branch	207	NA

C. Prototype module

Each FST module is divided in two functional parts: the inverter/rectifier converter to supply a constant DC voltage in both primary and secondary sides and the medium frequency stage. This medium frequency converter, where the SSTs controls the power transfer, has been designed and built during the project.

A resonant coupling has been selected between the primary and the secondary winding. This topology has better EMI behavior and a higher efficiency level respect to a dual active bridge circuit. Moreover, a series-series resonant topology with split capacitors has been chosen because it has fewer recirculating currents respect to parallel topologies and no problems with dealignments are expected. Regarding power electronics, a Neutral Point Clamped (NPC) semi-leg has been chosen to be able to manage higher voltage levels and reduce the total number of modules.

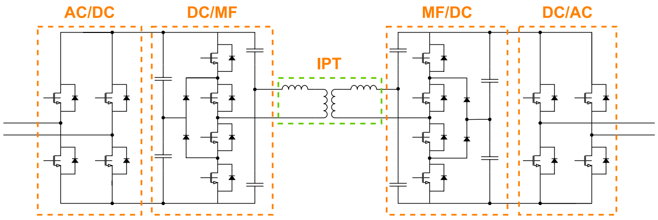

Fig. 4. FST chosen topology configuration: An AC/DC inverter/rectifier is used to provide a stable DC voltage at both sides – primary and secondary; besides, a half-bridge NPC module is used to build a series-series resonant tank in the medium-frequency stage of the SST.

The selected control strategy consists in creating a phase shift between the primary and secondary voltages. An active and reactive power flow can be set up as a result of that phase displacement. The module working range is from -45 ° to 45 ° sexagesimal degrees. This interval allows regulating the power flow between -50 kW to 50 kW.

D. Bench tests and results

The Flexible Smart Transformer is a power grid system which is expected to work integrated in the electrical power grid. Therefore, this device must work with the highest standards of reliability. An exhaustive inspection must be carried out over each FST module. Thus, an ad-hoc test bench was built in the CIRCE electrical laboratory, in order to test the module performance. Fig. 5 shows the module prototype installed in the test bench.

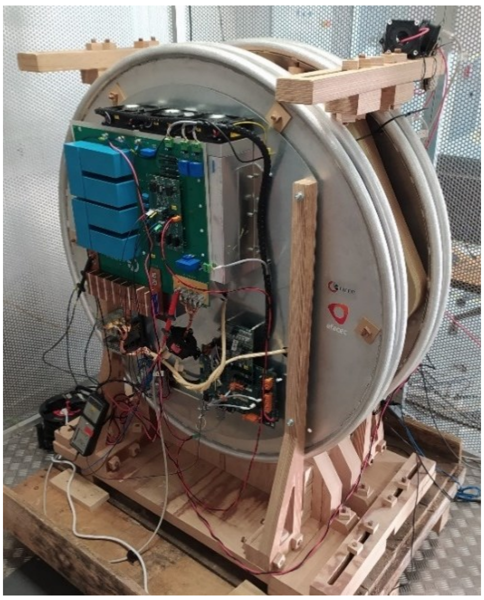

Fig. 5. 50 kW – 2.2 kV SST module prototype installed in the power test bench: power electronics NPC is placed on the top of the aluminum plate of one of the windings (secondary winding is a twin one in the back).

Each FST module is a 2,2 kV and 50 kW rated power device, that implies a high-power supply requirement to test the module in the whole working range. A circular connection was wired, connecting the primary and the secondary side, to obtain the required power flow through the inductive coupling while reducing the supply requirements. This electrical scheme allows all the transferred power through the inductive coupling going back to the emitting coil (ignoring the electrical losses). A DC power supply provides the required power but, due to the circular scheme, it only must supply power losses during the working state.

Furthermore, one of the most important results is the efficiency of the entire module. So, these tests were made to measure the power flowing from the supply and moving around the module, which is used to return the transferred power from the receiving side to the sending one. The prototype performance can be calculated comparing the percentage of power needed from the DC power supply with the power transfer measured from one coil to another.

Fig. 6 depicts the voltage and current waveforms when the FST prototype works at its rated voltage. Phase shift between primary and secondary voltages is 45 degrees. Current achieves peak values of 100 A and the power transferred reaches 50 kW (the rated power). The waveforms reveal a nice resonant behaviour.

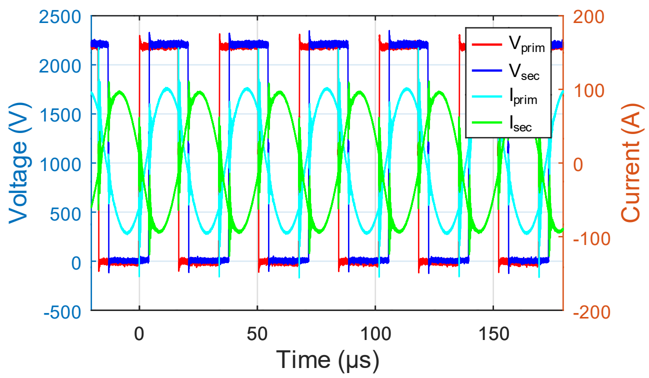

Fig. 6. Experimental results of transient electric behaviour of the SST module: Voltage (red and blue lines) and current (cyan and green lines) waveforms at rated power transfer.

The parameters and results of the power transfer tests are listed in Table III. Losses is the amount of power depleted at power electronics (primary and secondary side) and transferring power through the inductive coupling. The percentage of losses has been calculated considering the power from the DC power supply regarding the effective power transfer from the sending winding to the receiving one.

TABLE III
EFFICIENCY RESULTS FROM POWER TRANSFER TESTS

Phase shift (º)	Power (kW)	Losses (%)
25	26.69	3.4
45	51.18	4.6
-25	26.63	3.2
-45	50.78	4.7

V. Pathway to High Voltage Solid State Transformers

Two additional projects continue the research in the application of SST technology to very high voltage applications, TIGON and SSTAR projects [16], [17].

A. MV DC/AC hybrid grid applications – TIGON Project

Resilient hybrid alternating AC/DC power grids represent a potential future solution for distribution power grid flexibilization to boost a high share of Renewable Energy Sources (RES) and DC-based loads, because they allow the connection and management of these new assets in an efficient an easy way. Besides, the appearance of hybrid DC/AC grids represents an opportunity to reinforce existing grid parts respect to their power capacity and power quality [18], [19].

TIGON project demonstrates innovative DC technologies in two real demo-sites located in France and Spain. Each demo is built up with a Medium Voltage (MV) DC power line that establishes a link between the power grid and a hybrid DC/AC low-voltage grid. Therefore, the project pursues to increase the efficiency and robustness of the integration of RES and DC loads such as batteries and electric vehicles.

TIGON proposes a four-level approach aiming at improving (i) reliability, (ii) resilience, (iii) performance, and (iv) cost efficiency of hybrid grids through the implementation of novel hardware and software solutions. The SST creates a bridge between the AC point of coupling and DC MV power line, enabling both controllability and ancillary services in the new configuration, bringing into reality s use-case where the power transformer has to be substituted by an SST.

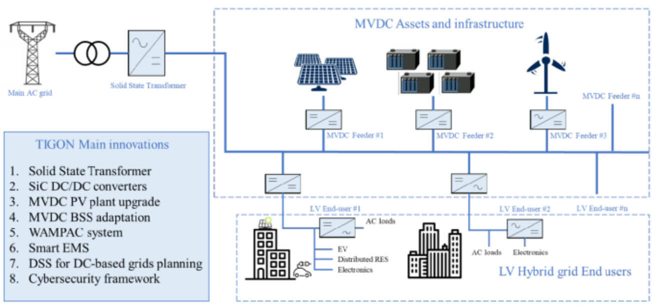

Fig. 7. TIGON main innovations and location of SST in the DC/AC hybrid grid.

B. Improving Galvanic Insulation – SSTAR Project

On the other hand, SSTAR project has recently started and continues the work done in FST. In this context, the aim of SSTAR is to increase the current operation voltage level of SSTs to enlarge their applications within the energy power sector while improving its performance in a reliable, cost-optimized and sustainable way, placing particular focus on triggering their deployment in the energy distribution and transmission grids. To do so, three main R&I Lines will be developed: 1) Sustainable biobased dielectric fluid able to increase the SST modules insulation voltage while achieving up to 50% of CO2 saving compared to traditional oils 2) Design of a new SST high isolated module based on SiC with a bidirectional Inductive Power Transfer (IPT) system able to increase the individual voltage and switching frequency of SST modules up to 1.5 kV and 50 kHz respectively with a total efficiency of 98,5% and 3) Decentralized control cascade H-bridge (CHB) converter to scale-up the number of modules in a single SST device to achieve the voltage levels of transmission grids.

VI. Conclusions

Distribution and transmission power grids need new tools to undertake the incoming transformation of the energy sector. This paper focuses in one of the most promising new technologies, SST devices, and how to overcome current insulation voltage operation limits.

The scope and main results got from FST project has been presented, showing the designed SST module and experimental results. The project has successfully demonstrated a new way to provide isolation between the primary and secondary windings by means a dielectric continuous layer between the two parts.

Besides, the paper shows the path to follow to apply SST devices with the developed presented technology to new configurations of the distribution power grid, introducing the concept of MV DC/AC hybrid grids and how to use SSTs to manage, increase the capacity and improve the robustness of the power grid in TIGON project.

Furthermore, the paper also presents SSTAR project where a dielectric fluid is proposed to increase smoothly the isolation between windings and enable to reach very high voltage operation with relatively small MF transformers based in the aforementioned technology presented in FST project.

VII. Acknowledgment

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I. BIOGRAPHIES

David Cervero García received the B.Sc. degree in industrial engineering (specialized in electric systems), and the M.Sc. degree in Renewable Energies and Energy Efficiency from the University of Zaragoza in 2009 and 2011, respectively. Currently, he is working as Project Manager in the Electronic Systems group at CIRCE Technology Centre. He has a deep expertise in power quality (PQ) assessment in electrical systems, data acquisition and, specially, in digital signal processing, developing dedicated software for measuring PQ in electrical distribution networks and performance of renewable energy sources. Fault location and power systems monitoring, with application in predictive maintenance, are among his research fields of interest. Currently, his main research field is focused on designing resonant converters for high voltage applications.

Eduardo García-Martínez received the Technical Industrial Engineer degree in Electronic from University of Zaragoza, Spain, in 2010, the Electrical Engineer degree specialization in Mechatronic from Hogeschool Zeeland, Netherland, in 2011 and the M.S. degree in Electronic Engineering from the University of Zaragoza, Spain, in 2013. Since 2011, he has been with CIRCE Technology Centre, where he works on the research and development of electronics and power electronics systems for renewable energy integration, battery energy storage systems, V2G fast chargers and Wireless Power Transfer systems. He is currently doing a Ph.D. in Renewable Energy and Energy Efficiency at the University of Zaragoza, focused on the electric power test systems for the development of the Smart Grid.

Jesús Muñoz-Cruzado Alba was born in Cádiz, Spain, in 1984. He received the B.S. and M.S. degrees in telecommunications and electronics engineering and the Ph.D. degree in power electronics from the University of Seville, Seville, Spain, in 2007, 2011, and 2016, respectively. In 2009, he joined GPTech, Seville, where he was a part of the Research and Development Department developing power converters for renewable energies applications. Since 2017, he has been a Power Electronics Researcher with Fundación CIRCE, where he is currently a Leader of the Power Electronics Team for Grid Integration Applications.

José Francisco Sanz received the Ph.D. degree in industrial engineering from the University of Zaragoza. From 2000 to 2016, he was the Director of the Research group for "Renewable Energy Integration and Power Electronics Configurations," CIRCE Foundation. He is currently a Senior Lecturer with the Electrical Department, University of Zaragoza; the Director of the "Endesa Red" Chair of Aragón; and the Director of the Research Laboratory of Charging Solutions for Electric Vehicles and Impact on the Electricity Grid. His main research interests include renewable energy integration and storage systems, power electronics for grid connection systems, microgrids, smart grids, and development of charging solutions for electric vehicles, both conductive and inductive.

Juan Manuel Perié Buil, B.Sc. on Industrial Technical Engineering (specialized in Industrial Electronics) in 2010, M.Sc. on Computer Science Engineering in 2011 and M.Sc. on Electronics Engineering (specialized in Power Electronics) in 2015 from University of Zaragoza. Researcher in CIRCE Technology Centre from 2009 to 2011 in the Renewable Energies Integration Area. Technical Responsible in this area from 2011 to 2016. Technological Expert of the Electronics Systems Group of CIRCE Technology Centre since 2016. Engineer with an experience of more than seven years in R+D+i activities related with power electronics designs and its control. Involvement in all the development cycle stages (design, implementation, testing and commissioning) of power electronics equipment from 2 kW up to 250 kW. Participation in several Spanish and European research projects. His interest areas are power electronics, control engineering and embedded systems.

Andrea Soto Rodríguez has graduated in Industrial Technical Engineering, specializing in Electrical Engineering, from the University of Vigo, in 2006. She has joined Efacec in 2007 as a researcher in the area of electromagnetic fields of Power Transformers. She currently leads the Electromagnetic Analysis RD Team and coordinates several R&D funding projects