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Development of high-current power supplies for the TCABR tokamak

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ABSTRACT

An upgrade is being conducted on the *Tokamak à Chauffage Alfvén Brésilien* (TCABR), which is a small tokamak ($R_0 = 0.62$ m and $a = 0.2$ m) operated at the University of São Paulo, Brazil. An important part of this upgrade is the installation of additional poloidal field coils to allow for the generation of various divertor configurations, such as single-null, double-null, and snowflake divertor. The control of these various magnetic configurations requires the development of 17 robust and high-performance power supplies. To identify the most appropriate solution, thyristor-based and IGBT full-bridge converter are being considered as possible power electronic topologies. In this work, a comparison between these two topologies in terms of controllability and complexity is presented.

1. Introduction

An upgrade of the *Tokamak à Chauffage Alfvén Brésilien* (TCABR) is being carried out [1]. TCABR is a small tokamak of major radius $R_0 = 0.62$ m, with plasma minor radius $a \leq 0.2$ m, operated at the Institute of Physics of the University of São Paulo (IFUSP), Brazil. TCABR uses 18 toroidal field coils to create a toroidal magnetic field $B_0 \leq 1.45$ T and can drive plasma currents $I_P \leq 120$ kA for up to 100 ms of pulse duration. In its current hardware configuration, TCABR uses 7 magnetic coils connected in series to drive the plasma current, namely the central solenoid and 6 stray-field compensation coils. In addition, TCABR has other 14 poloidal field (PF) coils for plasma radial and vertical position control and plasma shaping, but only 8 of them are used. The main goal of the upgrade of TCABR is to make it capable of creating a well controlled environment where the effect of resonant magnetic perturbations (RMP) on edge localized modes can be investigated over a wide range of RMP coil geometries and spectra. This will allow for a detailed validation of ideal/resistive MHD and fluid-kinetic transport codes in several plasma configurations, such as wall limited and diverted configurations. After the upgrade, all the 14 PF coils will be used and, to allow for a more flexible control of the plasma configurations envisaged for TCABR, two additional PF coils will be installed. To control the current in each of the 17 coils (Ohmic + shaping) independently, 17 high-performance power supplies are being designed and will be constructed. These power supplies must provide direct current (DC) and follow pre-programmed waveforms. The power supplies must be able to operate in the four quadrants and, therefore, they must be able to provide positive or negative voltages and currents. The main reason for that is to reduce the maximum amplitude of the current needed during operation. In TCABR, the Ohmic (OH) current variation needed during the plasma current ramp-up and a flat top of 150 kA for 0.5 s is about 23 kA. By reducing the initial value of the current by half and making it to invert direction, the maximum current that must be supplied is reduced to 11.5 kA. This has several advantages, namely reduction of mechanical forces between coils, reduction of the apparent power and current drained from electrical grid, among others. It also relaxes the requirements on the choice of the thyristors. Given the various subsystems required for these power supplies to work effectively, such as modular energy storage, reactive power compensation, safety, control and operation, these supplies represent a complex system of pulsed power supplies. In addition, the power electronic topologies usually chosen in the design of such systems are determined by the use of inertia flywheels for energy storage, and by thyristor converters operating at high frequencies [2,3]. To identify the most appropriate solution for TCABR, different power electronic topologies are being considered, namely thyristor-based and IGBT full-bridge converter. In this work, a comparison between these topologies in terms of controlability and complexity is presented. The

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terms controlability and complexity here do not refer to their holistic concept though, but to their general meaning. For instance, when the term complexity is used, it refers to the number of electronic subsystems needed for synchronism, firing, tripping and the correct monitoring of the several semiconductors involved in the operation. The term controlability, however, is associated to the performance of the controler, i.e. which topology best follows the pre-established set point signals. In this work, disturbances caused by the magnetic coupling between the OH coil and the PF coils will not be considered. However, a more realistic approach with such a coupling will certainly be considered in a future work.

2. Power supply requirements

Due to constraints associated to the electrical substation of IFUSP, the electrical supply of TCABR is limited to approximately 80 MVA (13.2 kV/3.5 kA). The power supply responsible for driving the plasma current, i.e. the OH power supply, must be composed by a static converter of 24 MW of rated power (1.5 kV/ ± 16 kA), while the other 16 power supplies responsible for shaping the plasma, are divided in two groups: internal and external. They must be composed by 10 static converters of 5.6 MW of rated power (700 V/ ± 8 kA) for the internal PF coils and 6 static converters of 11.2 MW of rated power (1.4 kV/ ± 8 kA) for the external PF coils. In addition, the power supplies must be able to archive current ramp rates of up to 3 MA/s. To minimize the cost, space and electric power involved in the operation of these systems, a very detailed re-designing of the laboratory electric grid is being carried out. Given the challenges mentioned above, a study of the technical feasibility of different possible solutions will be carried out to define the most appropriate control strategy, taking into account the different possibilities of technology, topologies and semiconductor switches. Based on the specifications of complex and large machines providing DC current, the power electronic converter responsible to supply each of the 17 coils should have the following characteristics [4]:

- the converter should allow both output voltage and current to reverse in order to allow for four-quadrant operation;
- the converter should be able to operate in current-controlled mode by respecting pre-programmed waveforms. The dynamic current limit must be several times higher than the continuous steady-state current rating of the coil;
- for accurate control of position, the average voltage output of the converter should vary linearly with its control input, independent of the plasma scenario;
- the converter should produce a current with a good form factor to minimize the fluctuations in the electromagnetic fields;
- the converter output should respond as quickly as possible to its control input, thus allowing the converter to be represented essentially by a constant gain without a dead time in the overall plasma control transfer function model.

3. Results of the simulations

All simulations were performed using the code PSIM 64-bit Professional, Version 9.0.3.464 and were carried out on a time step of 10 µs. The electrical parameters used in these simulations for the OH coil and the plasma can be found it Table 1. Due to the stronger requirements of the OH power supply, with respect to those used for plasma shaping, the simulations were based on the specifications of the OH power supplies, which is considered the most complex and challenging. The electrical circuit used to simulate the coupling between the OH coil and the plasma in the PSIM simulation code can be seen in Fig. 1.

In this section the specific aspects associated to the power electronic topologies studied are presented, namely 12-pulse thyristor-based and IGBT full-bridge rectifiers. Among the line-frequency controlled converters, we studied the topologies of 12-pulse thyristor rectifiers, connected in anti-parallel formation, and associated in series and in parallel. In order to adjust the lag specifications and the voltage levels required for the topologies, three-phase isolating transformers were considered. Each transformer was composed of one star winding primary and two secondaries, namely a star winding and a delta winding. To equalize the line voltage levels at the input of the converters, the convenient ratios of 2000:175 and 2000:303 are considered, resulting respectively in 667 V for the star windings and 1.15 kV for the delta windings. At this first moment, due to the comparative character of the studies, no type of filter or device to minimize harmonics was considered. For the same reason, approximate values were used for the reactances adopted in the simulations.

Table 1
OH coil and plasma electrical parameters.

Parameters	Values
Ohmic inductance	11 mH
Ohmic resistance	0.123 mΩ
Plasma inductance	1.5µH
Mutual inductance between OH coil and plasma	50 µH

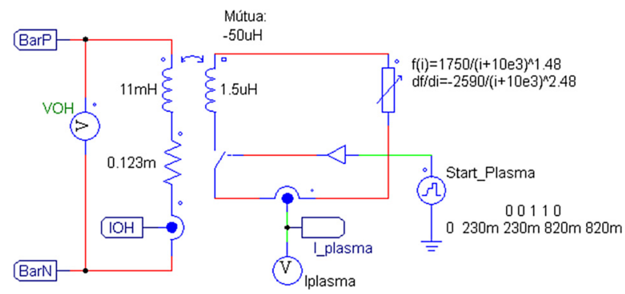

Fig. 1. Schematic of the electrical circuit used to simulate the coupling between the OH coils and the plasma in the PSIM simulation code.

3.1. The 12-pulse thyristor rectifier: series associated

The schematic electrical circuit used to simulate the series-connected 12-pulse thyristor can be seen in Fig. 2. As shown in Fig. 3(a), the control of Ohmic and plasma currents in the series association presents a satisfactory performance. However, the Ohmic coil voltage has high negative values due to regenerating trips. As a reference for the maximum and minimum values, Fig. 3(b) displays the line voltages

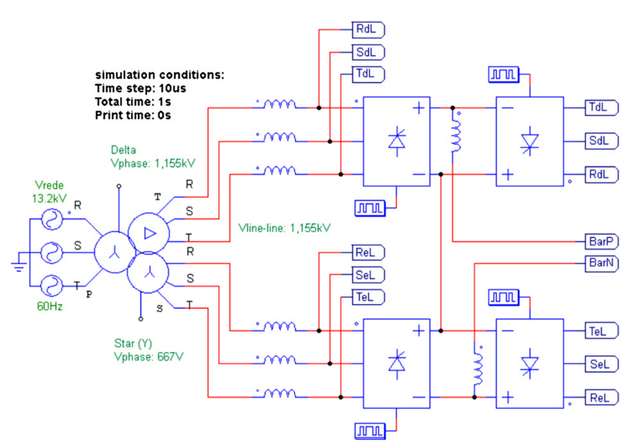

Fig. 2. Schematic of the electrical circuit used to simulate the 12-pulse thyristor-based converter, connected in anti-parallel and in series-associated topology.

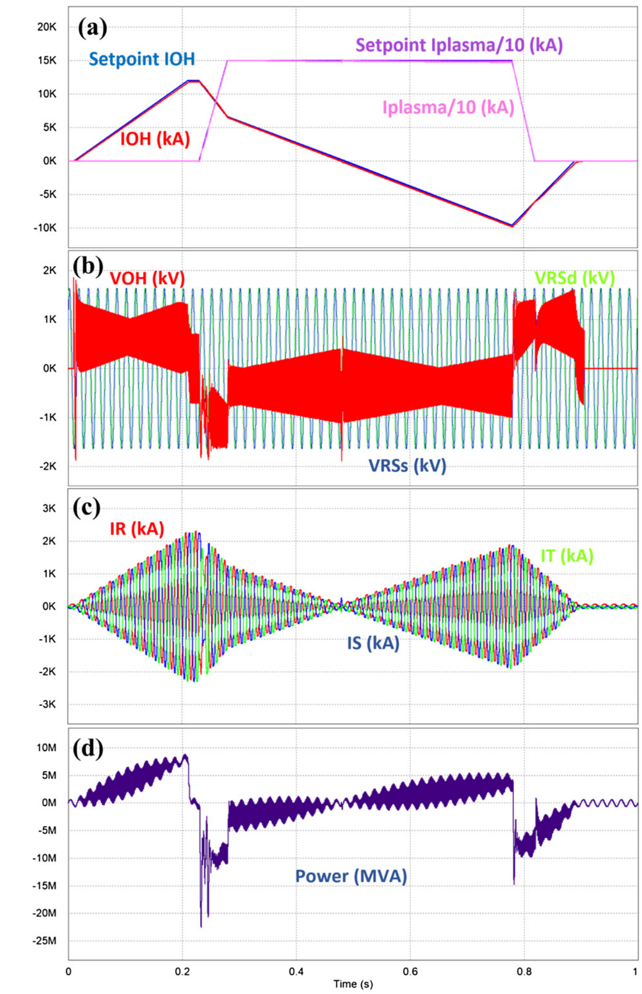

Fig. 3. (a) Waveform of OH current (red), setpoint of OH current (blue), plasma current (purple) and setpoint plasma current divided by 10, for the series-associated topology. (b) OH voltage (red), star secondary winding output line voltage RSs (Blue) and delta secondary winding output line voltage RSd (green). (c) Line currents R (red), S (blue) and T (green). (d) Instantaneous power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

V_{RS} at the converter inputs. Line currents consumed during a standard discharge remained within the specified maximum value of 3.5 kA, Fig. 3(c). Even with a sharp oscillation at 720 Hz, the peak of power reached values below 10 MVA and power consumption of 25 MVA in regeneration, Fig. 3(d).

3.2. The 12-pulse thyristor rectifier: parallel associated

The schematic electrical circuit used to simulate the parallel-connected 12-pulse thyristor can be seen in Fig. 4. As shown in Fig. 4, the control of Ohmic and plasma currents in the series association presents a satisfactory performance as the simulated current setpoint is followed very closely. As shown in Fig. 5(a), the control of both the Ohmic and the plasma current in the parallel association also presents a satisfactory performance. The DC currents at the output of the converters showed to be balanced. However, there were small imbalances during transitions in the control loops, Fig. 5(b). The moment at which this transient begins corresponds to the beginning of the plasma current. At this moment, the slip in the firing angle imposes the application of a negative voltage to the OH coil, forcing the current derivative to become negative thus causing the plasma current to raise. Until that particular time, the reference used by the control loop was set to the OH

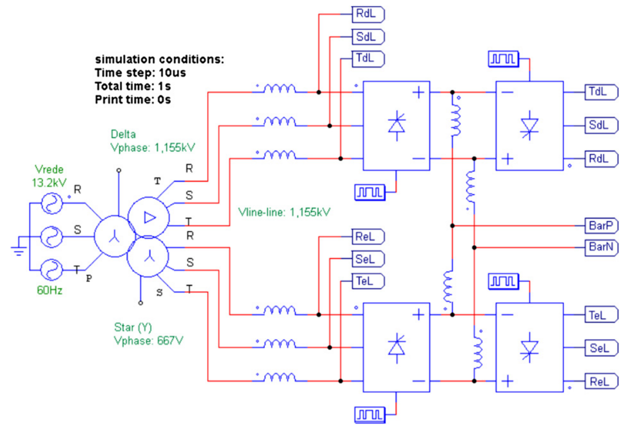

Fig. 4. Schematic of the electrical circuit used to simulate the 12-pulse thyristor-based converter, connected in anti-parallel and in parallel-associated topology.

current, which is increased to charge the OH coil. The OH coil stays constant for a short time. From this point onwards, the reference of the control loop changes to the plasma current, and the OH coil current is considered a secondary variable that is monitored only for security reasons. As the controllers used were simple proportional compensators without performance optimization, the transition between the control loops did not present the ideal dynamics. However, as the intention was to study the performance of topologies without the interference of complex controllers, the elimination of these small imbalances was not a priority. In parallel-associated topology, the line currents were, as expected, reduced to half of its value in the series connected and remained within the specified maximum value of 3.5 kA, Fig. 5(c). In this topology, the voltage at the OH coil showed a stronger stability even in the transitions between control loops. It also demonstrated that the high negative values due to the regenerating trips never exceeded the maximum and minimum values of the bus bar, Fig. 5(d). In the parallel association, the peak of instantaneous power approached a little more than 10 MVA, but it moved away from the previous 25 MVA, remaining below 15 MVA during regeneration, Fig. 5(e). In terms of complexity, both the series and parallel association of the 12-pulse rectifiers are practically equivalent since their operational structures require exactly the same circuits and subsystems. However, there is a major difference in the parallel topology, as the value of the current drops by half in each rectifier, which would also cut in half the number of thyristors per rectifier. In terms of controlability, the parallel topology presents a slightly better performance, because even by using a simple controller, composed of just a proportional compensator, it presented the least stationary error in maintaining its set point. The parallel topology was found to be more stable compared to the series topology due to the operation with more favorable firing angles, i.e. to impose the necessary voltages, the parallel topology needs longer conduction intervals.

3.3. The IGBT full-bridge converter

IGBT full bridge converters are not normally used in high power regenerative applications. However, as there is a trend in technological evolution for semiconductors and, in addition, IGBTs are notoriously known for presenting a level of controlability significantly higher than thyristors, the opportunity was considered to investigate the possible existence of significant advantages in these alternative topologies. For the simulations of the full-bridge converter topology, a three-phase isolating transformer consisting of a star-arranged primary winding and a delta-arranged secondary winding was chosen. During these studies it was observed that this topology operated better with higher input voltage levels. Thus, the line voltage level adopted at the converter input respected the ratio of 1000:303, resulting in a line voltage of

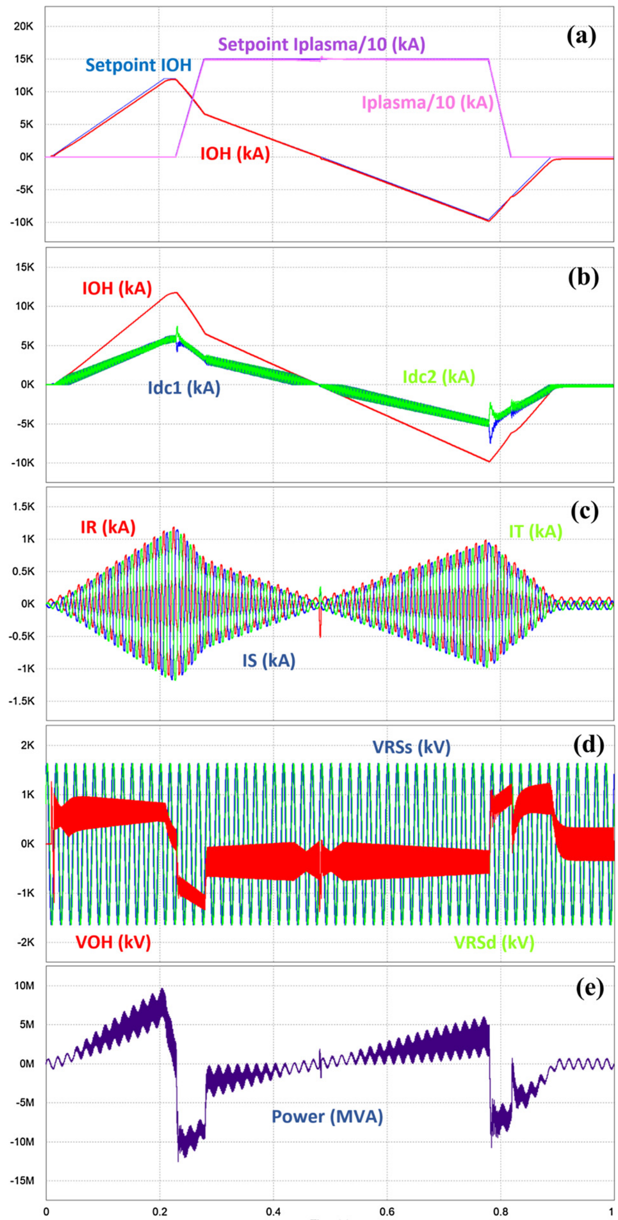

Fig. 5. (a) Waveform of OH current (red), setpoint of OH current (blue), plasma current (purple), and setpoint plasma current divided by 10, for the parallel-associated topology. (b) OH current (red), DC output currents dc1 current (blue) and dc2 current (green). (c) Line currents R (red), S (blue) and T (green). (d) OH Voltage (red), star secondary winding output line voltage RSs (Blue) and delta secondary winding output line voltage RSd (green). (e) Instantaneous power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3 kV. For the DC bus bar, a capacitor bank of 4700 µF was considered. Both converters involved in the topology operated at 5 kHz PWM mode at their respective switching frequencies. Specifically, for full-bridge modulation, the bipolar modulation technique was used. The proposed setpoint for the input controlled rectifier has been adjusted to provide maximum voltage. Again, at this first moment, due to the comparative character of the studies, no type of filter or device to minimize current distortion at the input was considered. For the same reason, approximate values were used for the reactances adopted in the simulations. The studies regarding the operation of this topology were also divided into two parts. However, in this case, the variant was the presence or absence of a parallel chopper converter on the DC power bus bar. The

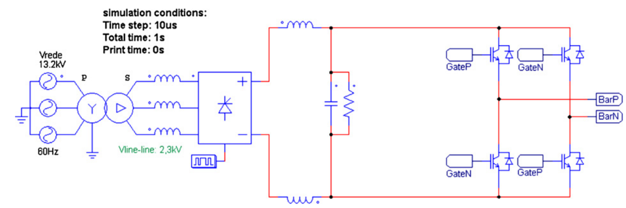

Fig. 6. Schematic of the electrical circuit used to simulate the IGBT full-bridge converter topology.

schematic electrical circuit used to simulate the IGBT full-bridge converter topology can be seen in Fig. 6. As shown in Fig. 7(a), as with other topologies, the full-bridge converter also showed excellent performance in the control of both the OH and plasma currents. Disregarding the initial transient instabilities, it is observed that the currents decreased reasonably in this topology, Fig. 7(d). Regarding the power peaks, under operation, it was observed that the approximate value remained close to 10 MVA and, as expected, there was no regeneration, since this topology does not allow for such condition, Fig. 7(e). Analyzing specifically the topology in question, from the results presented so far, no major changes in the behavior of the set in relation to the presence of the chopper converter in the DC bus bar were observed. However, the whole scenario changes when analyzing bus bar voltages and chopper current. As shown in Fig. 7(f), bus bar voltage reaches prohibitive values during power regeneration back to the DC bus bar. This fact can be easily observed by analyzing the OH voltage waveform, which indicate overvoltages well above the maximum expected values for the bus bar, Fig. 7(b). As can be seen in Fig. 7(g), when the chopper converter is present on the DC bus bar, the overall performance of the set improves considerably. This fact can also be observed in the OH voltage waveform, Fig. 7(c). However, even though the presence of the chopper converter on the DC bus bar apparently solves all the problems, there is a major drawback for the project engineering, i.e. one must deal with the huge currents resulting from chopper operation, Fig. 7(h).

4. Summary

The lack of a reliable physics model that well describes the response of plasmas to RMP fields is a fundamental issue when trying to predict the response of ITER plasmas to these fields. To provide a better insight into the physics processes responsible for the response of tokamak plasmas to RMP fields, an upgrade of the TCABR tokamak is being carried out. During this upgrade an advanced set of RMP coils will be used to investigate whether ideal/resistive MHD and fluid-kinetic transport codes accurately describe RMP effects over a wide range of coil geometries and spectra. To validate RMP models over a wide range of plasma configurations, a series of plasma scenarios have been created. To allow for a more flexible control of the plasma configurations envisaged for TCABR, two additional PF coils will be installed on TCABR increasing the number of coils (OH + shaping) to 17. To control the current in each of these 17 magnetic coils independently, 17 high-performance power supplies will be constructed. To identify the most appropriate solution for TCABR, different power electronic topologies are being considered, such as 12-pulse thyristor-based and IGBT full-bridge converter. This work presents preliminary results of simulations of the performance of these power electronic topologies performed using the code PSIM. The results indicate that the 12-pulse thyristor converters with parallel association is the most appropriate. The voltage and current levels required to perform the standard shot were relatively much lower than other topologies. From the point of view of fidelity in maintaining setpoints, the IGBT full-bridge topology showed the best results, however, other aspects such as the excessively high currents in the chopper and the interaction of the high frequency plasma current ripple with magnetohydrodynamic modes with

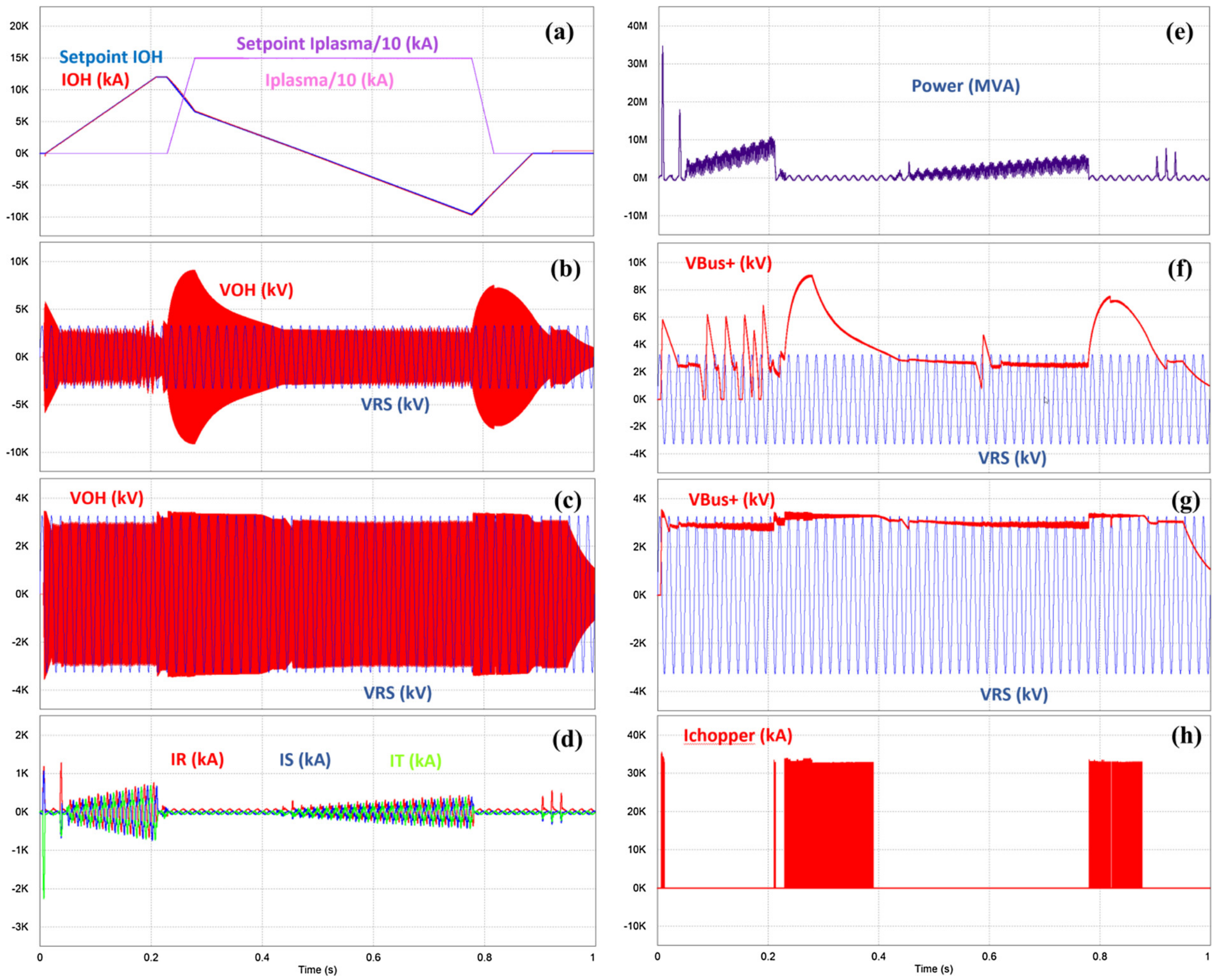

Fig. 7. (a) Waveform of OH current (red), setpoint of OH current (blue), plasma current (purple), and setpoint plasma current divided by 10, for IGBT full-bridge topology with chopper on the DC bus bar. (b) OH voltage (red), line voltage RSs (Blue) and RSd (green) without chopper. (c) OH voltage (red), line voltage RSs (Blue) and RSd (green) with chopper. (d) OH current (red), DC output currents dc1 current (blue) and dc2 current (Green); (e) power consumption. (f) bus bar voltage (red) and line voltage RS (blue) without chopper. (g) bus bar voltage (red) and line voltage RS (blue) with chopper. (h) chopper current (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

frequencies in the same range makes this topology not so attractive.

Authors' contributions

A.O. Santos: Software, Writing – Original Draft, Investigation, Conceptualization, Formal Analysis, Project administration;
W. Komatsu: Writing – Review & Editing, Formal analysis, Resources, Validation Methodology;
G.P. Canal: Writing – Review & Editing, Formal analysis, Data Curation, Project administration, Funding acquisition;
J.H.F. Severo: Supervision, Resources;
W.P. de Sá: Conceptualization, Formal analysis, Resources;
F. Kassab: Conceptualization;
J.G. Ferreira: Funding acquisition;
M.C.R. de Andrade: Funding acquisition;
J.R.C. Piqueira: Project administration;
I.C. Nascimento: Resources;
R.M.O. Galvão: Project administration, funding acquisition.

Conflicts of interest

The authors declare no conflicts of interest.

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