Solid State Transformers:

architecture, control and simulation results.

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This document presents an analysis of Solid State Transformers, including hardware architectures, control strategies, and simulation results..

1 Introduction

Solid State Transformers (SSTs) are advanced power electronic devices designed to replace traditional low-frequency transformers in modern power distribution systems. By operating at high frequency and using fully controllable conversion stages, SSTs achieve a more compact size, improved energy efficiency, and enhanced functionality compared to conventional transformers. Beyond simple voltage transformation, they provide additional services such as bidirectional power flow, voltage and reactive power regulation, and seamless integration of distributed energy resources including renewables, electric vehicles, and energy storage.

A key difference from traditional transformers is the behavior of SSTs during fault conditions. Due to their electronic nature and active current limiting, SSTs inherently restrict short-circuit currents. This prevents downstream systems from relying on conventional overcurrent-based protection schemes, which depend on high fault currents for detection. As a result, new protection strategies based on advanced sensing, high-speed control, and intelligent fault identification must be implemented. This shift in protection philosophy presents both challenges and significant opportunities for the development of more flexible, reliable, and smart power networks.

2 Global Architecture

In this chapter few general architectures for SST solutions are proposed and investigated; the SST device is intended to operate between two different grids:

- a low voltage DC grid source where many contributors can be assumed are connected e.g. energy storage, photovoltaic installations, car chargers and others;
- a three phase medium voltage AC grid source;

Figure 1 shows a single phase architecture, which basically is made by a cascade of single phase inverters. Each single phase inverter is supplied by a galvanically isolated DC/DC converter.

From control point of view we could assume the following control strategy

- DC/DC power supply control can be assumed monolithic and independent;
- three phase active front end (AFE) control architecture can be assumed as follows
  - each single phase inverter is equipped by a single phase PLL (master and slaves);
  - an inverter current control (master);
  - a voltage controlled source mode (slaves).

Figure 2 a case scenario of global three phase architecture with a common communication bus which performs a global distributed control.

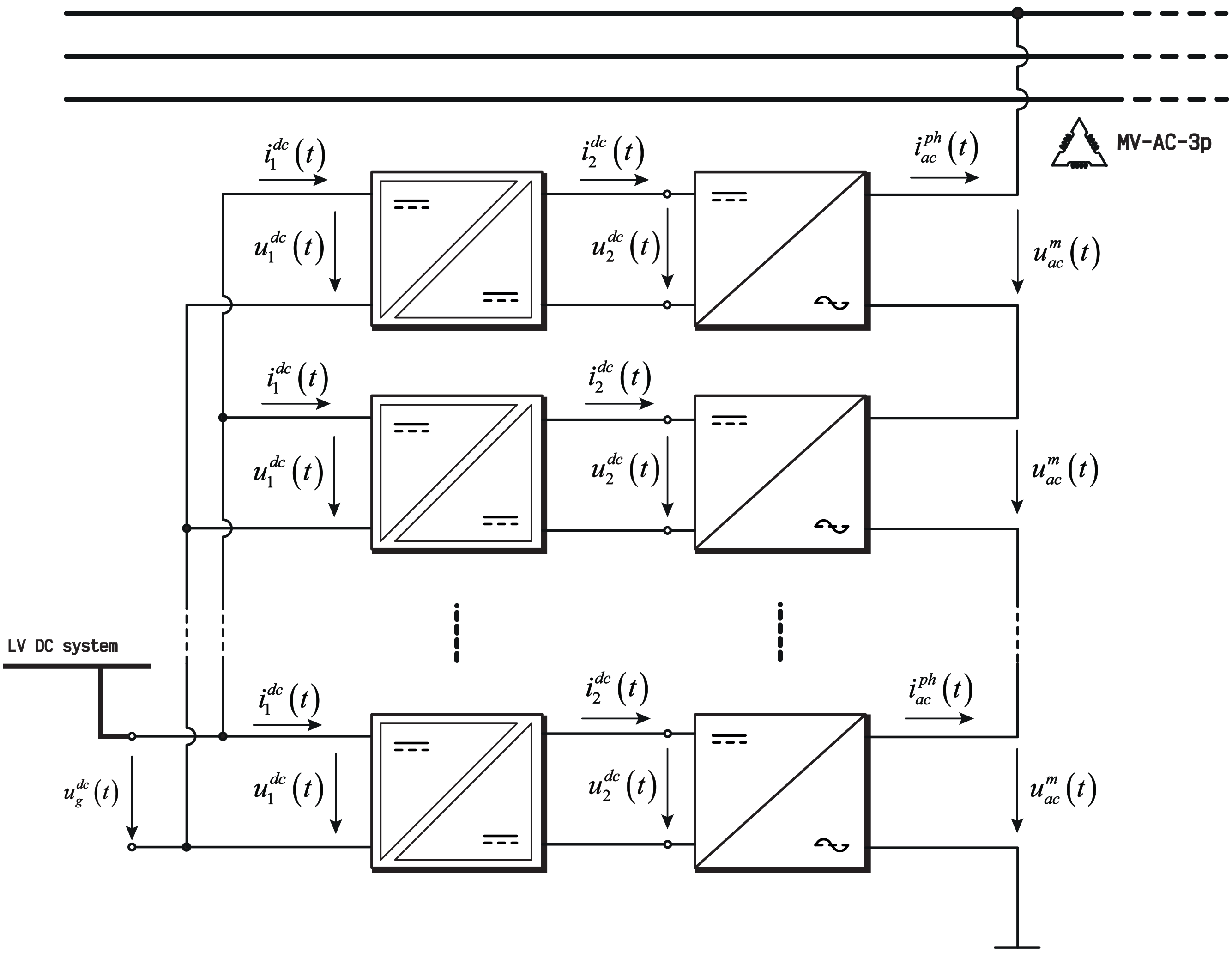


Figure 1: Single phase architecture based on galvanically isolated single phase inverter cascade.

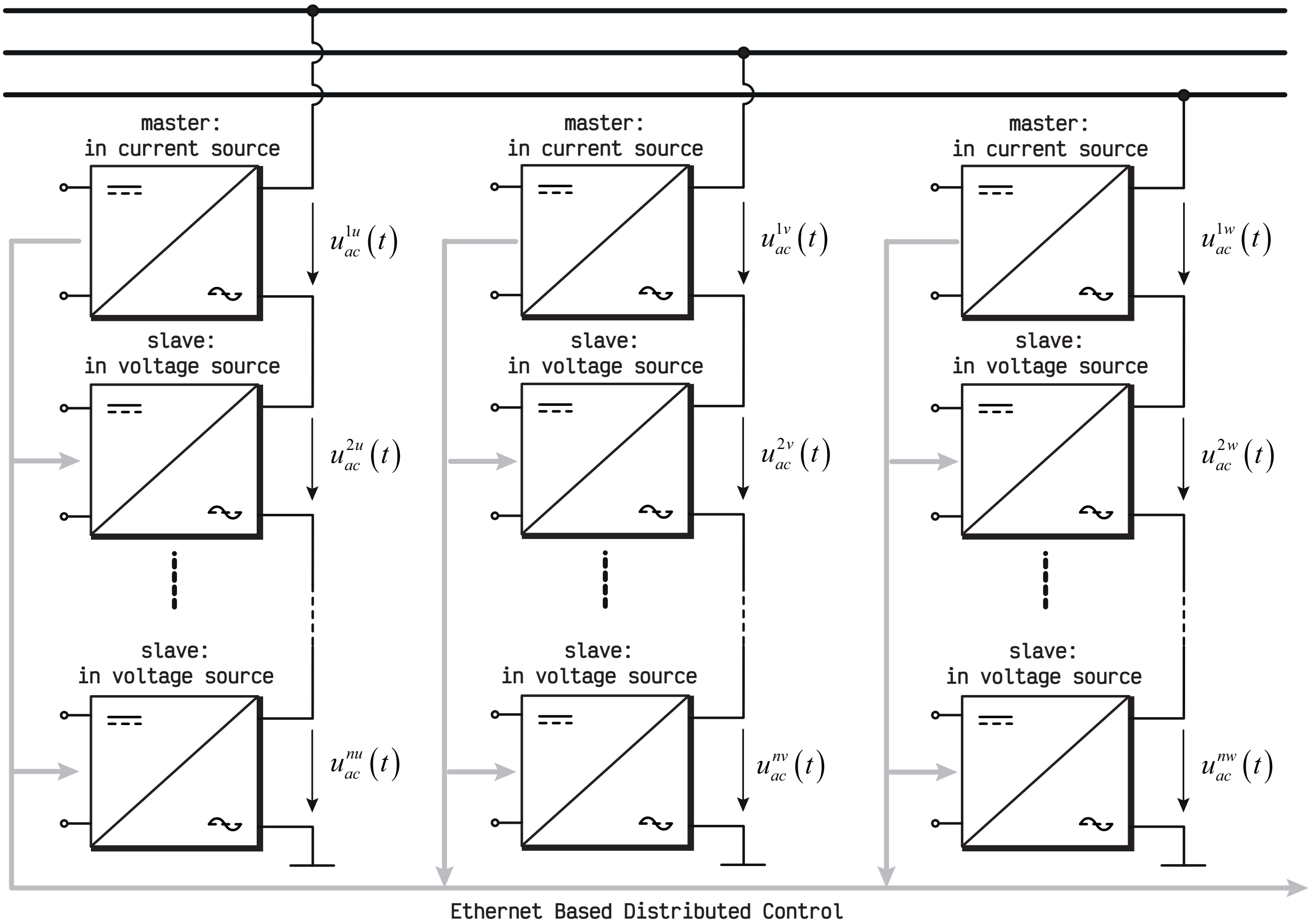


Figure 2: Global architecture for three phase system where a cascade of master/slaves single phase inverter implements the the single phase MV.

Single phase inverter will be here assumed made by a three levels NPC as shown in Figure 3. This solution permits to extend the nominal voltage of the single phase inverter and be able to operate with a dclink voltage around 1.5 kV.

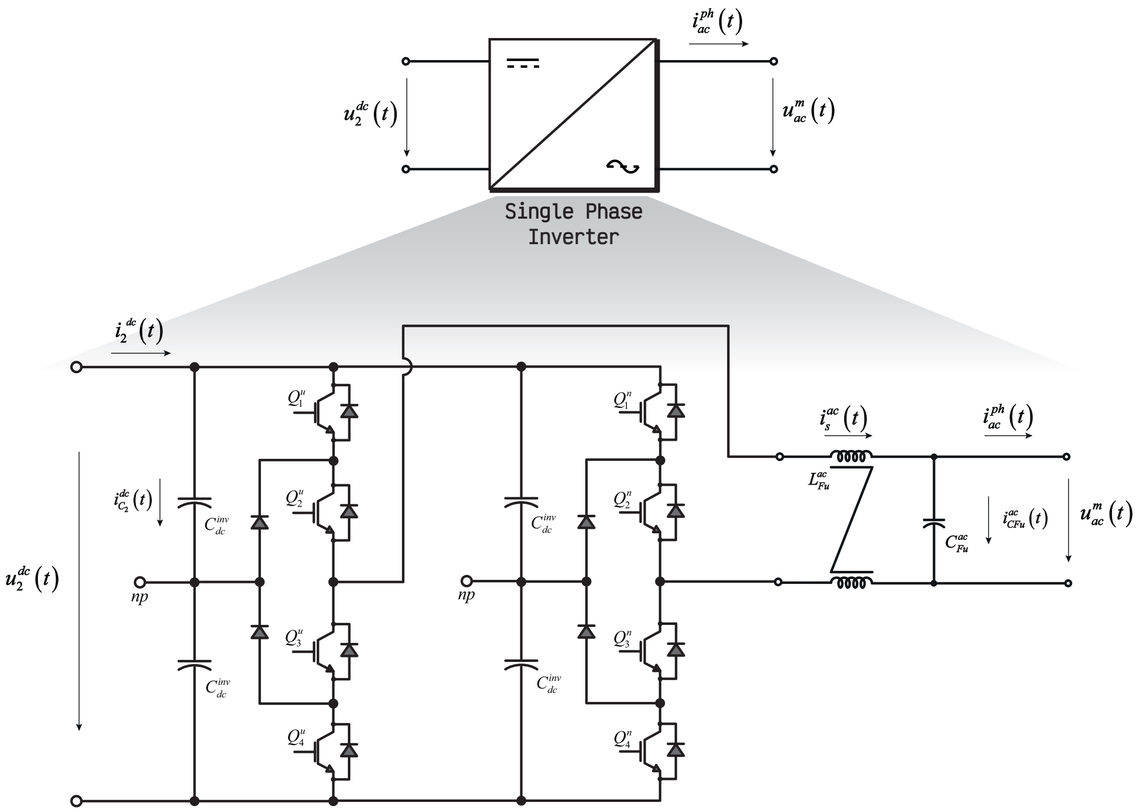


Figure 3: Single phase inverter stage: based on three level NPC.

In SST applications, the galvanically isolated DC-DC power supply plays a fundamental role in terms of global efficiency and performance. In this document three different DC/DC architectures will be investigated:

– three phase DAB;

– single phase bidirectional LLC;

– single phase DAB;

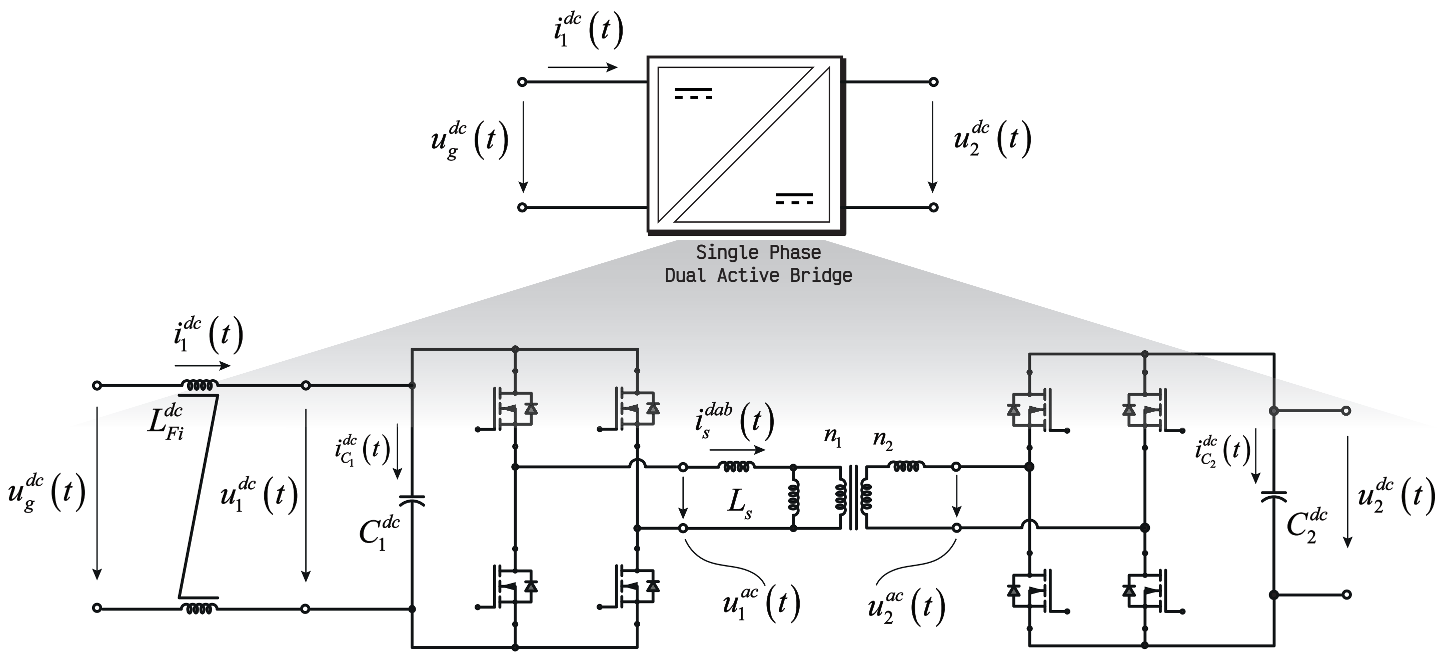


Figure 4: Single phase DAB.

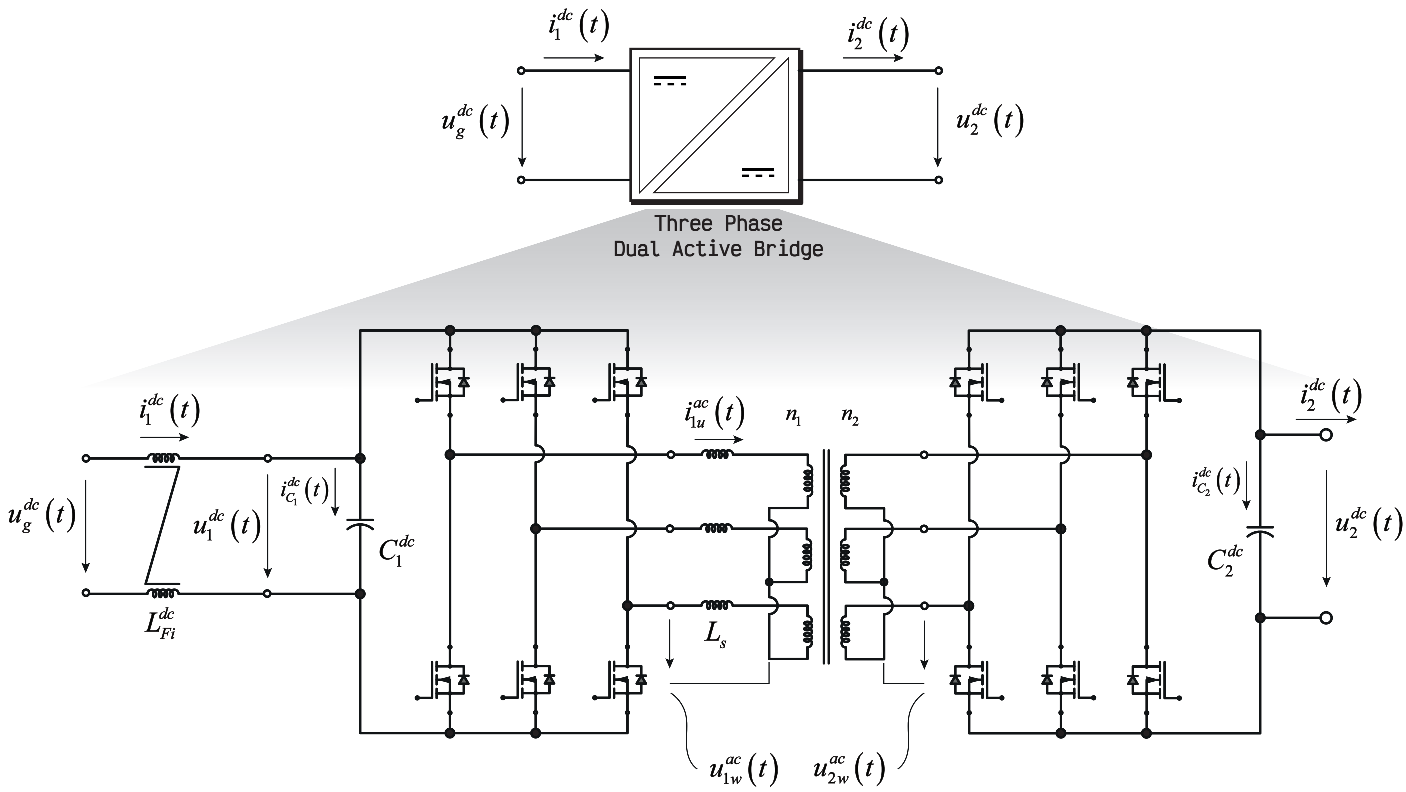


Figure 5: Three phase DAB.

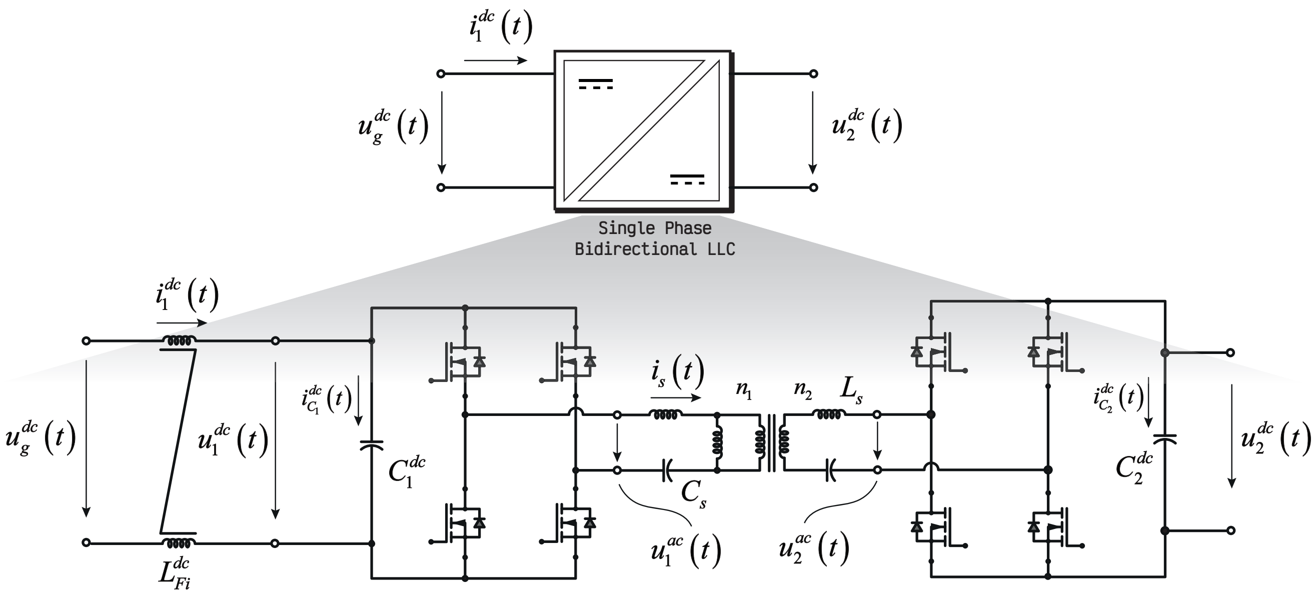


Figure 6: Single phase bidirectional LLC.

3 Control Architecture

In the control concept here proposed the aim of the DC/DC power supply is to provide a controlled DClink voltage, $u_2^{dc}(t) = u_2^{dc}\Big|_{ref}$, while the AFE will drive a current reference to the AC grid according to the status of the DC grid, Figure 7 shows a possible control principle.

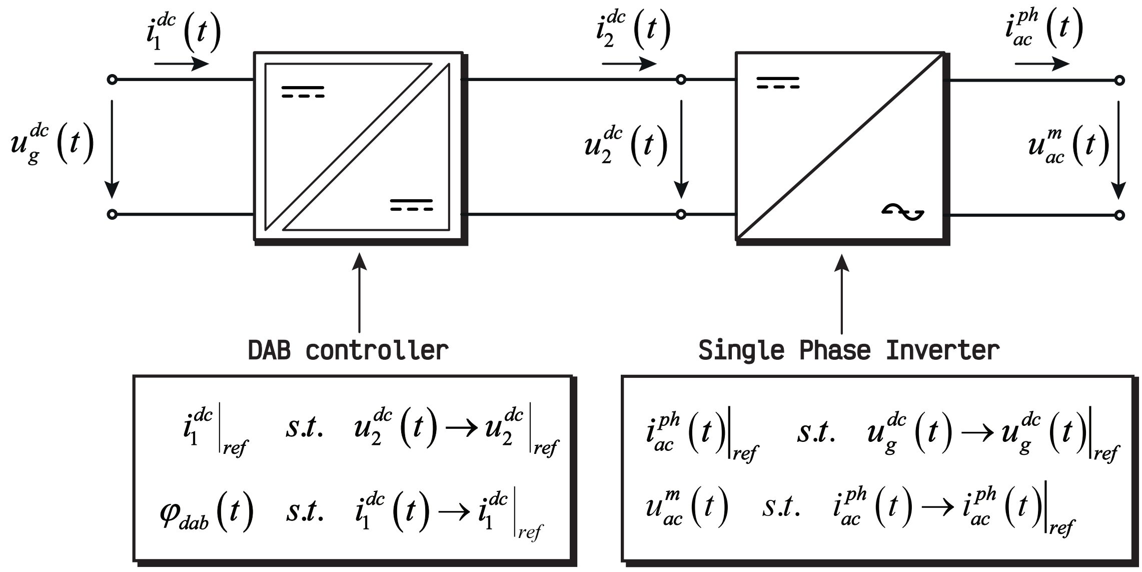


Figure 7: Fundamental control strategies of the isolated single phase inverter.

4 Simulation results

In this section simulation results of the architecture based on three phase DAB is shown, in particular the following operative conditions have been accounted:

- three phase DAB works at fundamental frequency of $f_{dab} = 4\,\mathrm{kHz}$;
- single phase LLC works at fundamental frequency of $f_{llc} = 9.6\,\mathrm{kHz}$;
- single phase DAB works at fundamental frequency of $f_{spdab} = 10\,\mathrm{kHz}$;
- single phase inverter operates at the switching frequency of $f_{inv}^{pwm} = 4\,\mathrm{kHz}$.

The three phase DAB switching devices are based on SiC MOSFET, while Si based IGBT for the three level single phase inverter, as follows

- Infineon **FF1800R12IE5** for the single phase inverter;
- Danfoss **SKM1700MB20R4S2I4** for the three phase DAB;

According to Figure 6 and Figure 3, the following components shall be accounted:

- $L_{Fi}^{dc} = 400\,\mu\mathrm{H}$ - input DAB inductance with nominal current of $I_{LFu}^{nom} = 300\,\mathrm{A}$;
- $C_1^{dc} = 3.6\,\mathrm{mF}$ - input DAB capacitor with nominal voltage of $U_{C1dc}^{nom} = 1.5\,\mathrm{kV}$;
- $L_s = 60\,\mu\mathrm{H}$ - DAB inductance (this value takes into account also the leakage inductance of the transformer) with nominal current of $I_{Ls}^{nom} = 250\,\mathrm{A}$;
- $C_2^{dc} = 3.6\,\mathrm{mF}$ - output DAB capacitor with nominal voltage of $U_{C1dc}^{nom} = 1.5\,\mathrm{kV}$;
- $C_{dc}^{inv} = 3.6\,\mathrm{mF}$ - output DAB capacitor with nominal voltage of $U_{C1dc}^{nom} = 1.5\,\mathrm{kV}$;
- $L_{Fu}^{ac} = 500\,\mu\mathrm{H}$ - output single phase inverter of $I_{LFu}^{nom} = 300\,\mathrm{A}$;

Figure 9 show the control architecture of the single phase inverter.

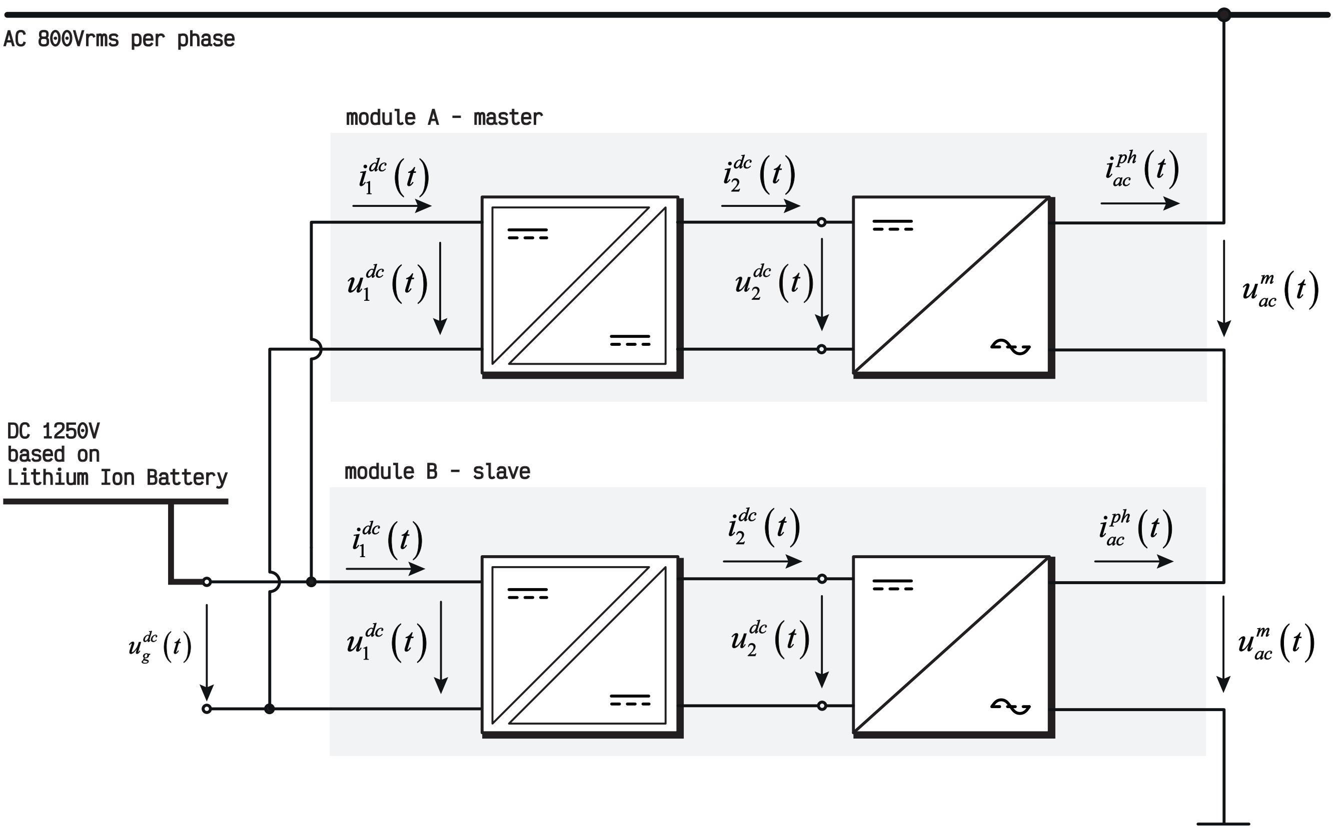


Figure 8: Simulation layout: simulation has been performance using a single phase SST composed by two single phase inverter connected in series with three difference case scenario of DCDC: three phase DAB, single phase DAB, and single phase LLC.

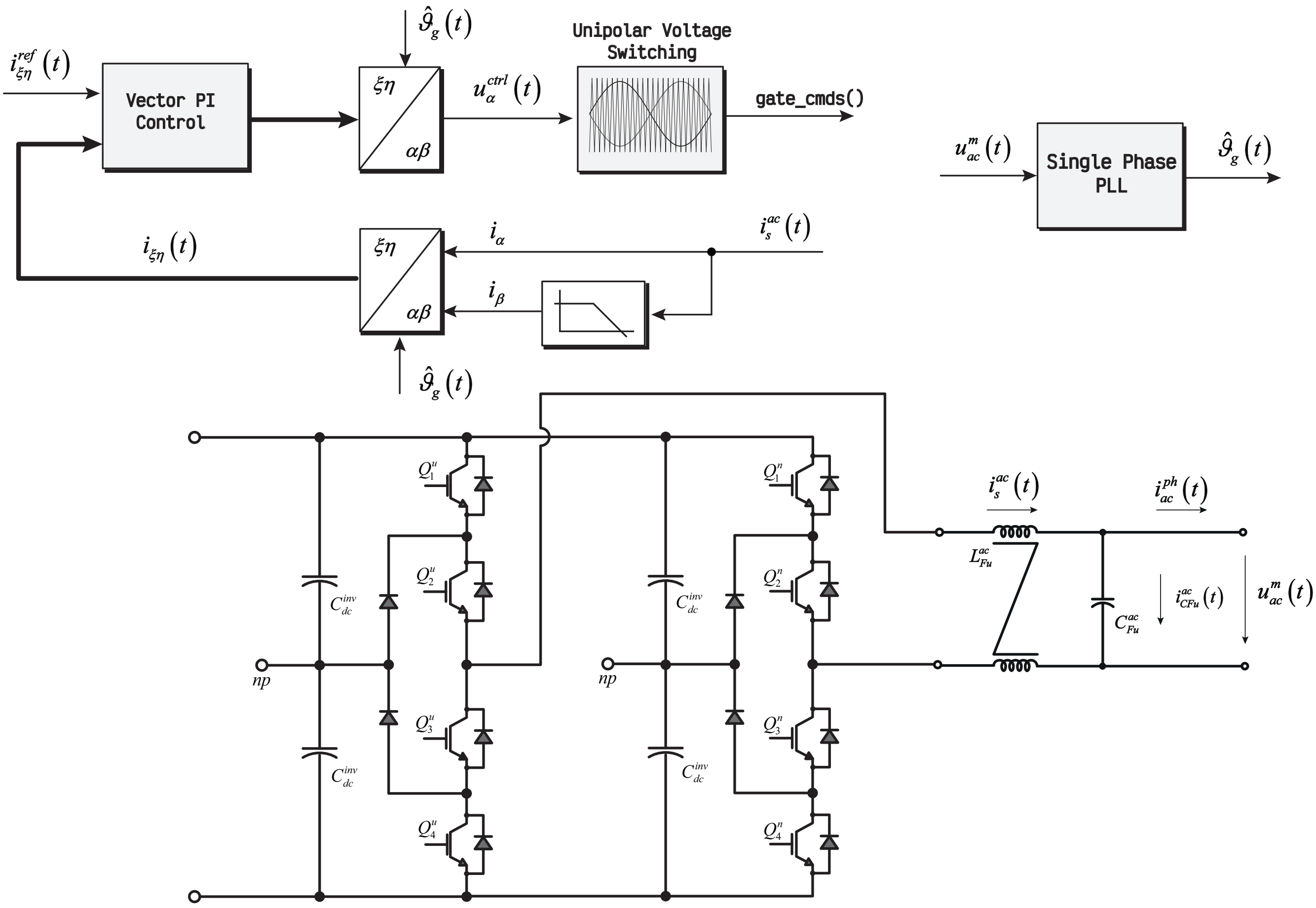


Figure 9: Control layout of the single phase inverter.

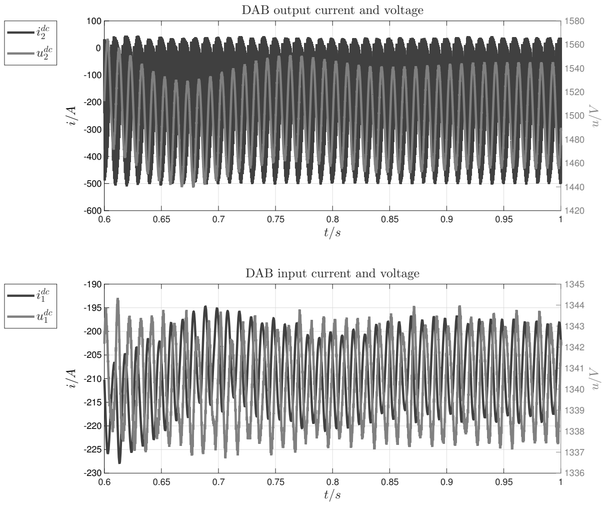
4.1 SST based on Three Phase DAB

Here performance of the SST based on three phase DAB and a cascade of two three level NPC single phase inverters.

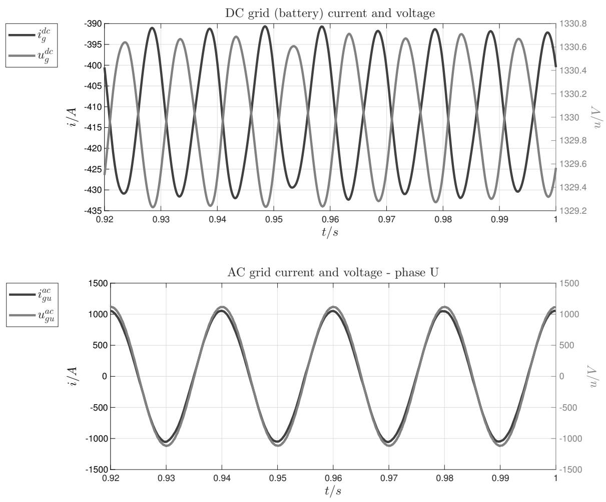
Remark - only one single phase has been simulated and total power at DC grid side is resulting in one third than in an equivalent three phase implementation.

Remark - simulations have been performed under the following condition of grids and load:

- DC grid nominal voltage (from Lithium Ion Battery) : $u_g^{dc}\Big|_{nom} = 1250\,\mathrm{V}$;
- AC grid nominal voltage : $u_g^{ac}\Big|_{nom} = 800\,\mathrm{V}$ - rms per phase-centertap;
- AC grid load current : $i_g^{ac} = 750\,\mathrm{A}$ - rms;

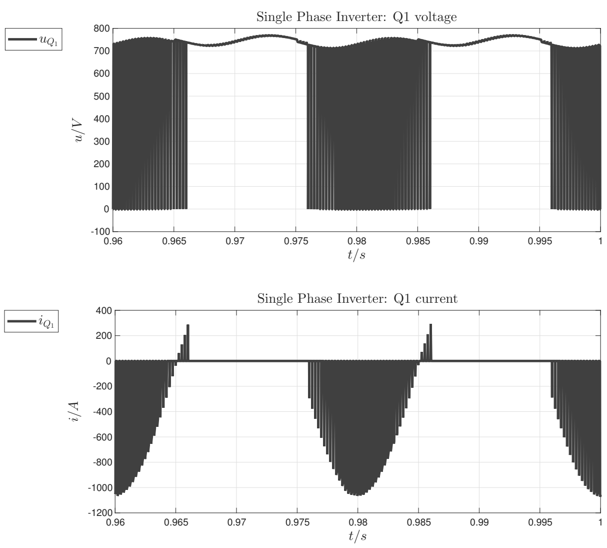


(a) Master three phase DAB input current and voltage (bottom) and outputs (top).

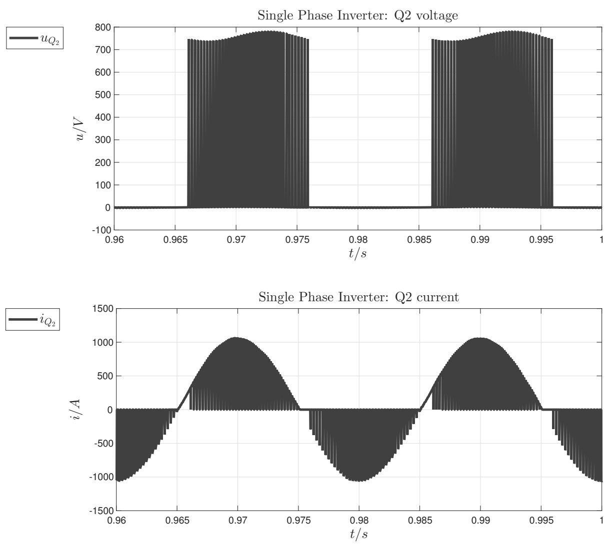


(b) DC grid current and voltage (top) and AC grid current and voltage (bottom).

Figure 10: Performance of two stages single phase SST: three phase DAB input/output and grids.

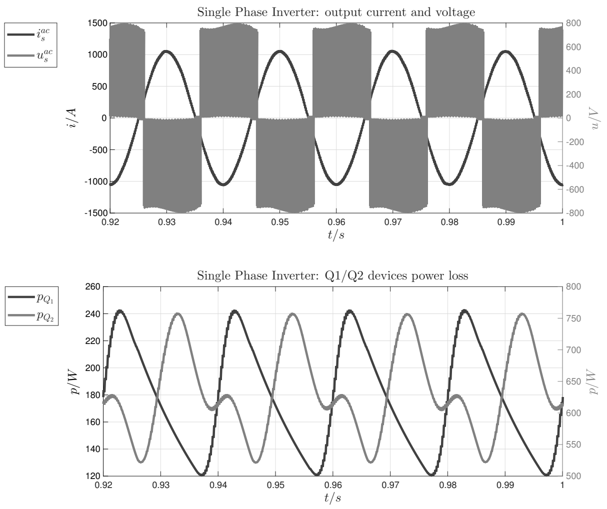


(a) Single phase inverter: Q1-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

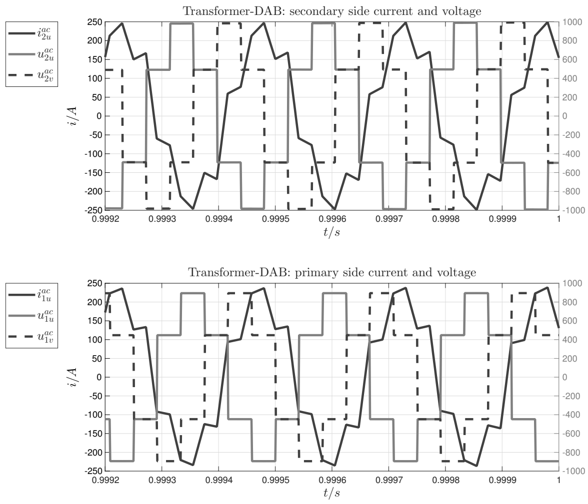


(b) Single phase inverter: Q2-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

Figure 11: Single phase inverter NPC: IGBTs voltage and current.

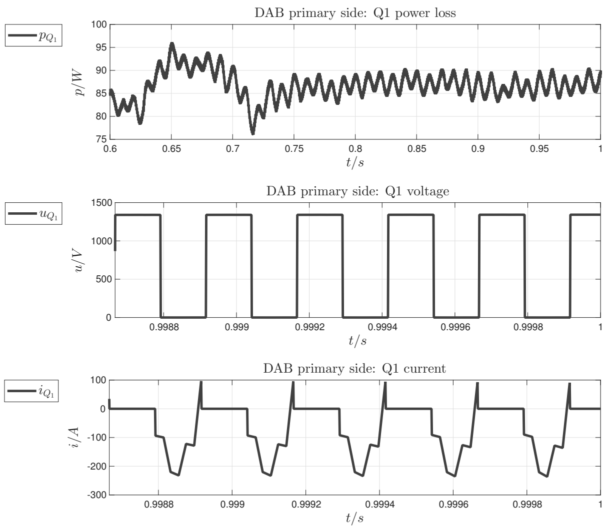


(a) IGBT Q1 and Q2 power loss (bottom). Single phase output current and voltage, before the output filter (top).

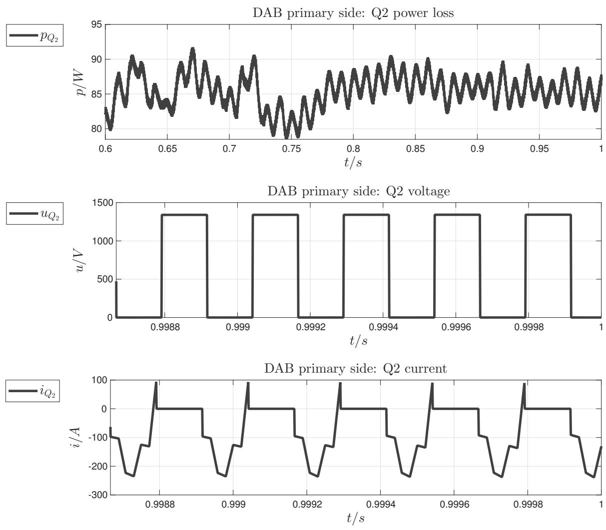


(b) Three phase DAB operative condition at nominal flow power.

Figure 12: Single phase inverter and three phase DAB performances.

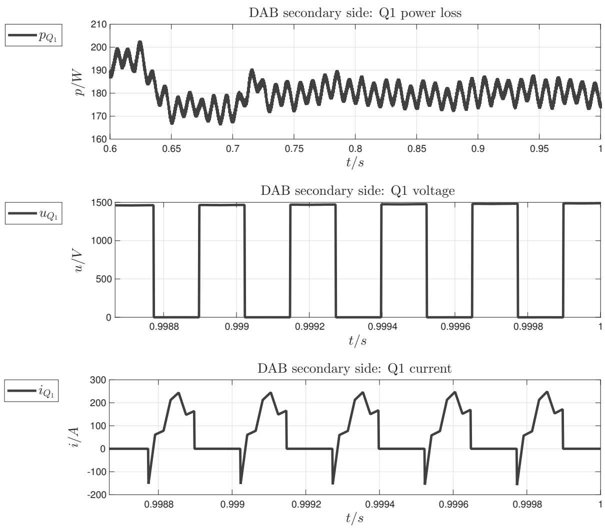


(a) Three phase DAB - primary inverter: Q1-MOSFET power loss, voltage and current.

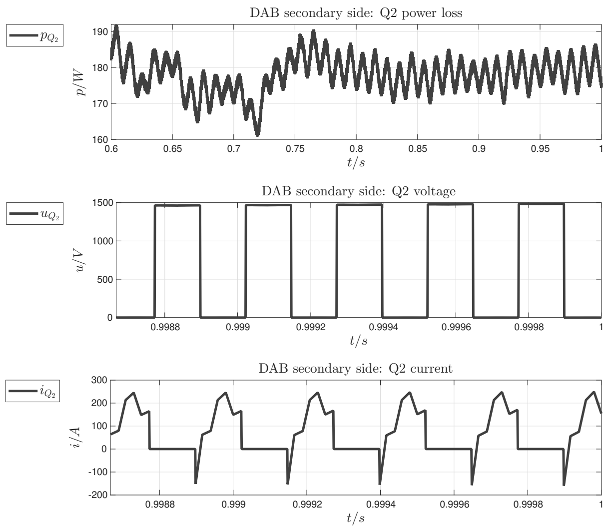


(b) Three phase DAB - primary inverter: Q2-MOSFET power loss, voltage and current.

Figure 13: Three phase DAB - primary inverter devices performances.



(a) Three phase DAB - secondary inverter: Q1-MOSFET power loss, voltage and current.



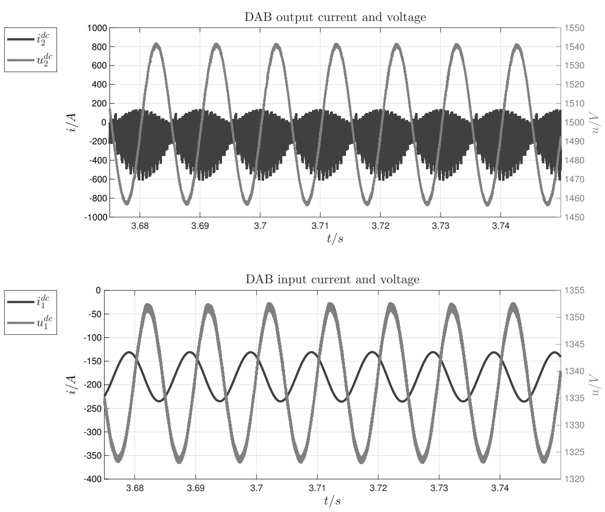
(b) Three phase DAB - secondary inverter: Q2-MOSFET power loss, voltage and current.

Figure 14: Three phase DAB - secondary inverter devices performances.

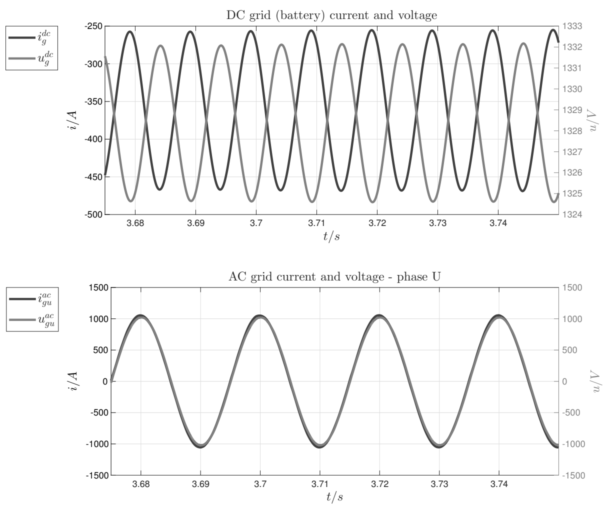
4.2 SST based on Single Phase LLC

In this section the performance of the LLC has been investigated. The control strategy of the LLC DCDC converter has been assumed as follows

- single phase LLC is operating at constant frequency of $f_{\text{llc}} = 9600\,\text{Hz}$;
- power flow direction as well as amplitude is controlled by phase shift between primary and secondary side H-bridges;
- the above control law keep the LLC conversion in a constant condition of zero current switching;

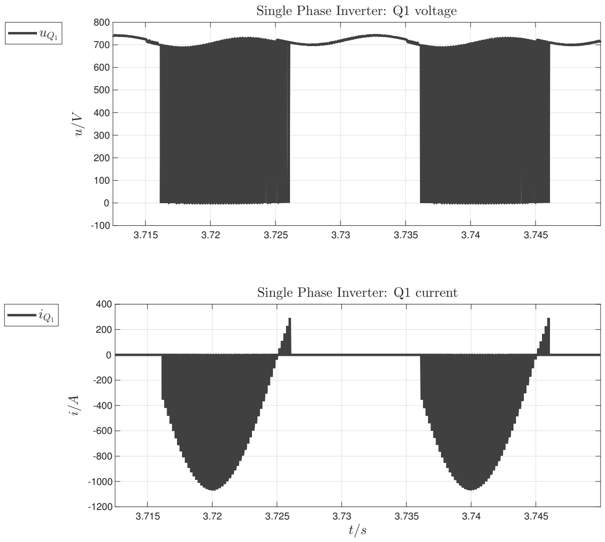


(a) Master single phase LLC input current and voltage (bottom) and outputs (top).

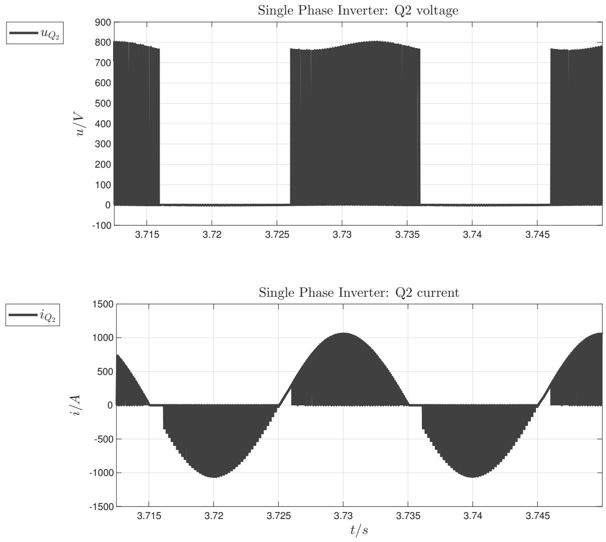


(b) DC grid current and voltage (top) and AC grid current and voltage (bottom).

Figure 15: Performance of two stages single phase SST: single phase LLC input/output and grids.

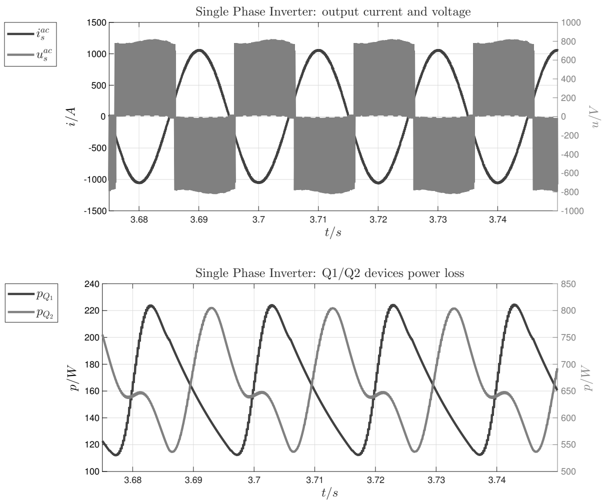


(a) Single phase inverter: Q1-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

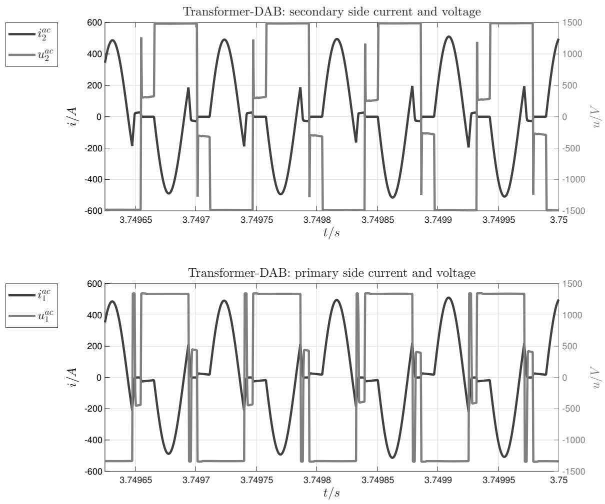


(b) Single phase inverter: Q2-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

Figure 16: Single phase inverter NPC: IGBTs voltage and current.

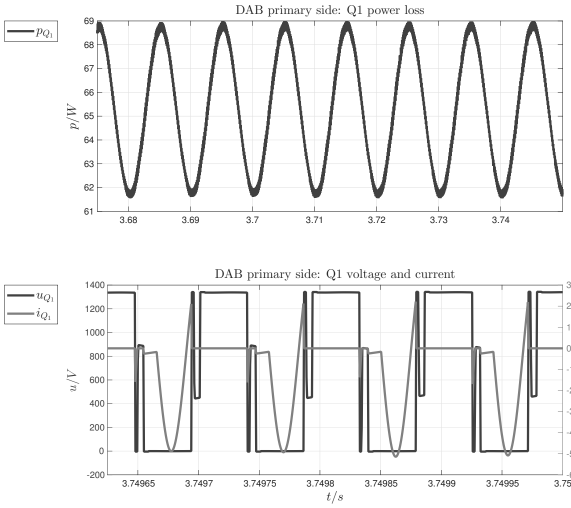


(a) IGBT Q1 and Q2 power loss (bottom). Single phase output current and voltage, before the output filter (top).

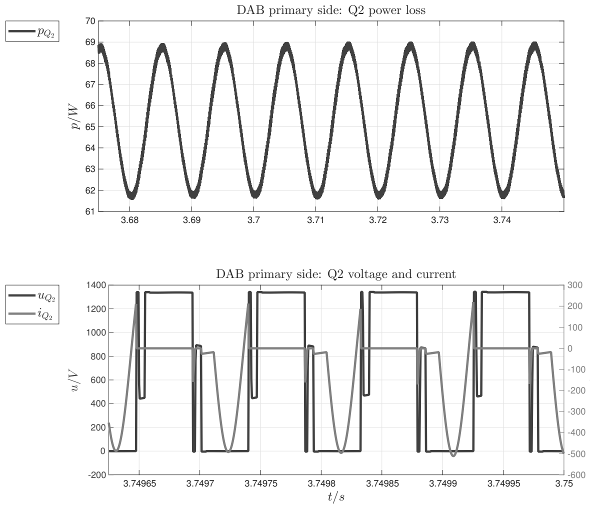


(b) Single phase LLC operative condition at nominal flow power.

Figure 17: Single phase inverter and single phase LLC performances.

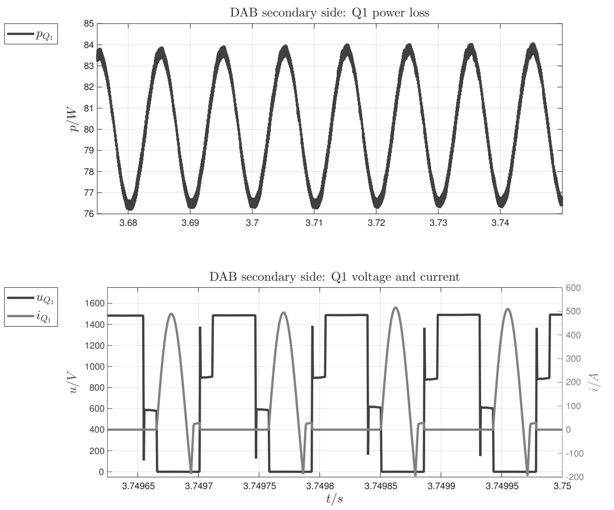


(a) Single phase LLC - primary inverter: Q1-MOSFET power loss, voltage and current.

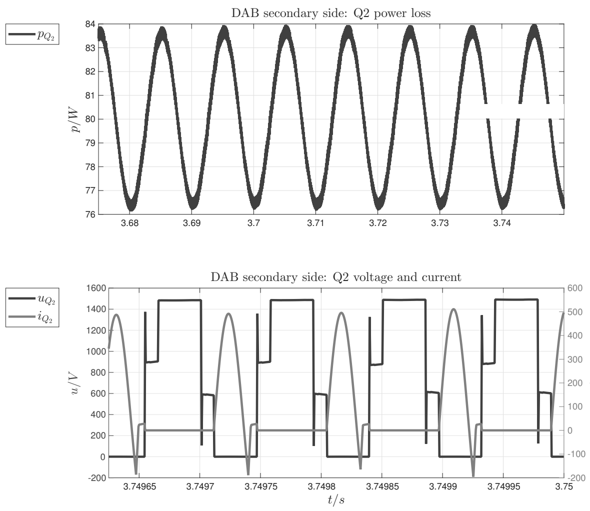


(b) Single phase LLC - primary inverter: Q2-MOSFET power loss, voltage and current.

Figure 18: Single phase LLC - primary inverter devices performances.



(a) Single phase LLC - secondary inverter: Q1-MOSFET power loss, voltage and current.

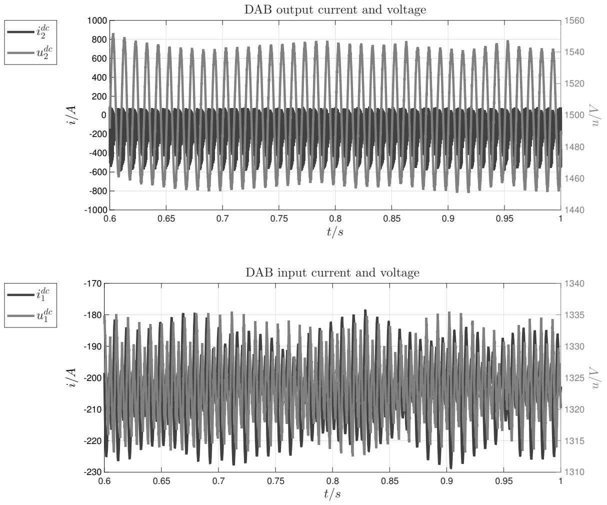


(b) Single phase LLC - secondary inverter: Q2-MOSFET power loss, voltage and current.

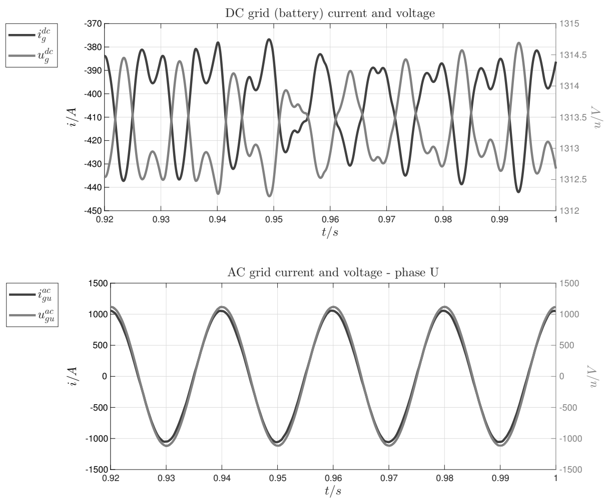
Figure 19: Single phase LLC - secondary inverter devices performances.

4.3 SST based on Single Phase DAB

Single phase DAB performance.

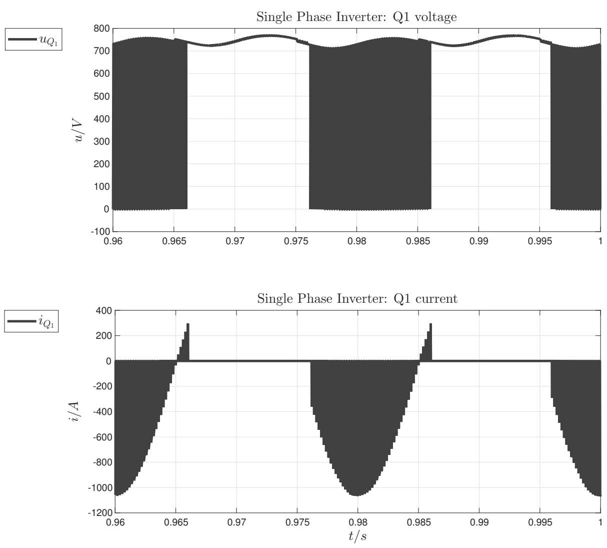


(a) Master single phase DAB input current and voltage (bottom) and outputs (top).

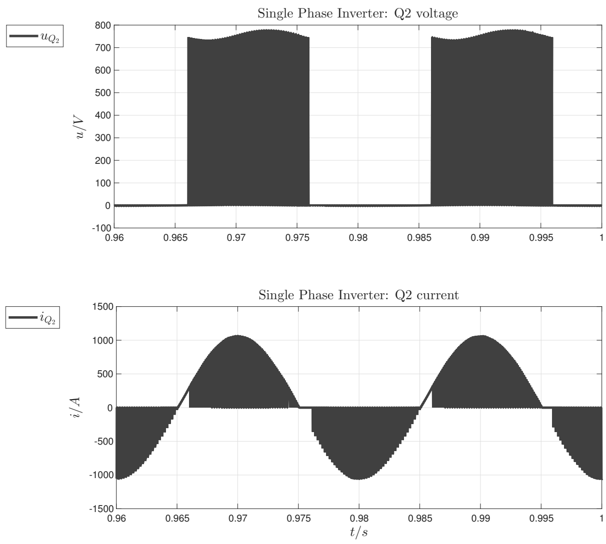


(b) DC grid current and voltage (top) and AC grid current and voltage (bottom).

Figure 20: Performance of two stages single phase SST: single phase DAB input/output and grids.

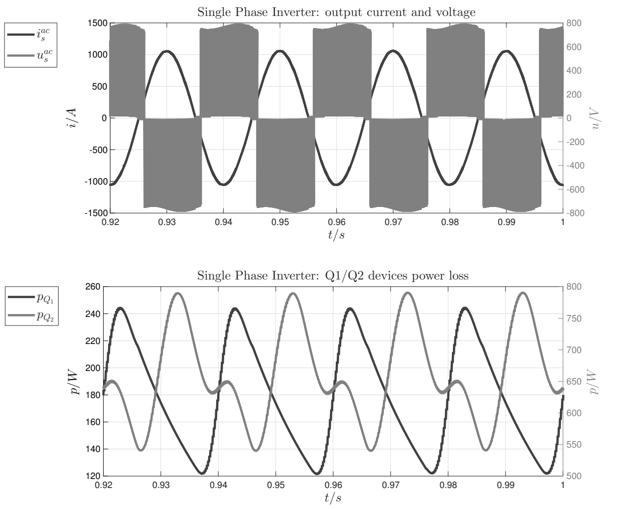


(a) Single phase inverter: Q1-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

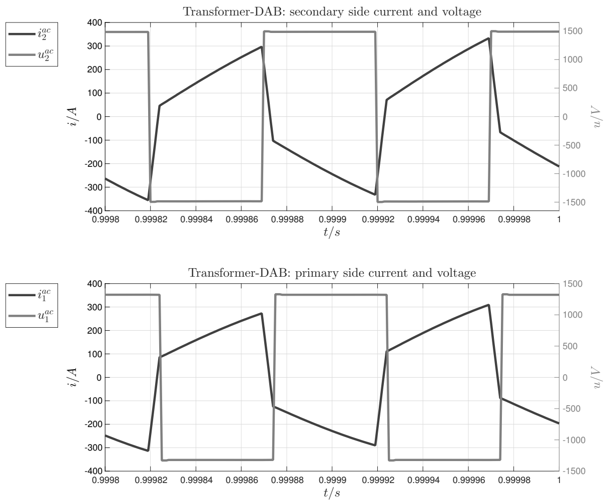


(b) Single phase inverter: Q2-IGBT voltage and current. The aim of this image is to proof the effective operative working of the three level NPC single phase inverter.

Figure 21: Single phase inverter NPC: IGBTs voltage and current.

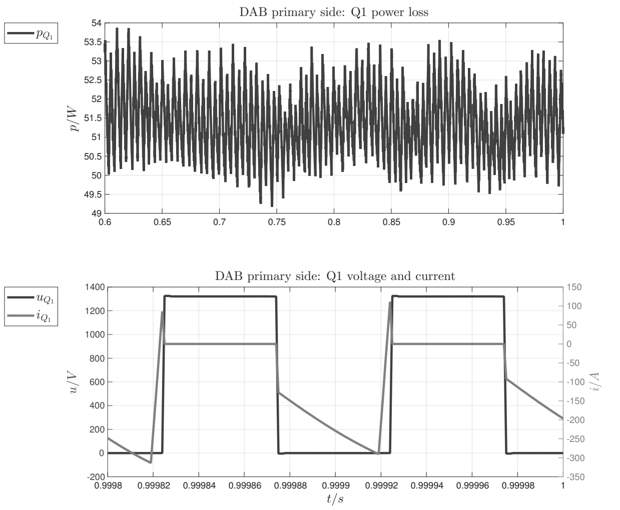


(a) IGBT Q1 and Q2 power loss (bottom). Single phase output current and voltage, before the output filter (top).

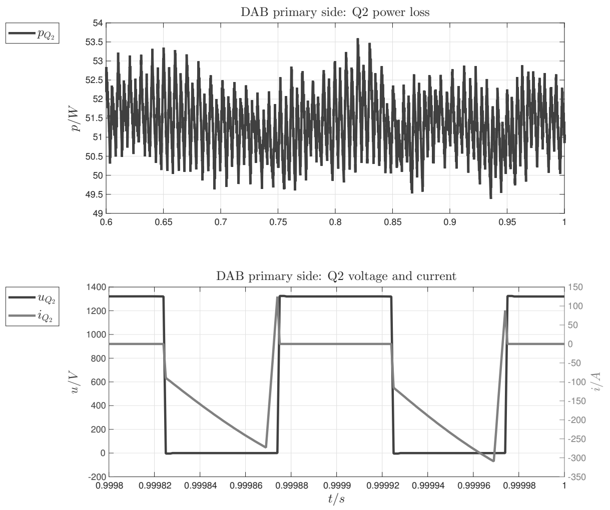


(b) Single phase DAB operative condition at nominal flow power.

Figure 22: Single phase inverter and single phase DAB performances.

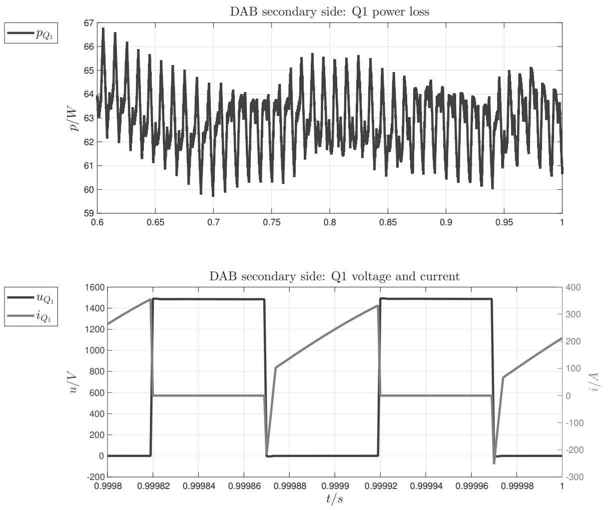


(a) Single phase DAB - primary inverter: Q1-MOSFET power loss, voltage and current.

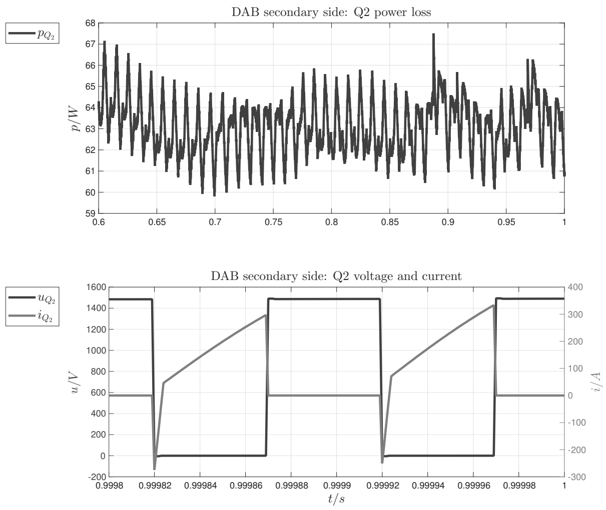


(b) Single phase DAB - primary inverter: Q2-MOSFET power loss, voltage and current.

Figure 23: Single phase DAB - primary inverter devices performances.



(a) Single phase DAB - secondary inverter: Q1-MOSFET power loss, voltage and current.



(b) Single phase DAB - secondary inverter: Q2-MOSFET power loss, voltage and current.

Figure 24: Single phase DAB - secondary inverter devices performances.

5 Summary of simulation results

In this section a summary of overall efficiency for: three phase DAB, single phase DAB, single phase LLC is shown.

The power flow through each DC/DC/AC converter is around 250 kW, in Table 1 the total power loss concerning the semiconductors components are reported. Power loss concerning capacitors and inductors gave been not accounted at this stage.

Table 1: Comparison of power loss for three different DC/DC architecture.

Architecture	f_{dab} [kHz]	f_{inv} [kHz]	p_{loss}^{dab} [kW]	p_{loss}^{inv} [kW]
Three phase DAB	4 kHz	4 kHz	1.76 kW	3.25 kW
Single phase LLC	9.6 kHz	5 kHz	0.58 kW	3.3 kW
Single phase DAB	10 kHz	5 kHz	0.485 kW	3.3 kW

From Table 1 all solution seems promising until ZVS for single phase DAB or ZCS for LLC are satisfied. Impact into magnetic has to be investigated.

In the following additional information are reported.

Table 2: DC/DC transformers rms main quantities.

Architecture	f_{dab} [Hz]	i_1 [A_{rms}]	i_2 [A_{rms}]	u_1 [V_{rms}]	u_2 [V_{rms}]	L_s [H]
Single phase DAB	10 kHz	230 A	230 A	1325 V	1500 V	35 µH
Three phase DAB	4 kHz	170 A	177 A	633 V	720 V	59 µH
Single phase LLC	9.6 kHz	390 A	390 A	1236 V	1310 V	18 µH

Remark - in Table 2 voltages for the three phase DAB represent the *per phase* voltage and not the phase to phase, on the other hand voltages for the LLC and single phase DAB architecture represent the voltage across the single phase transformer.
Remark - L_s accounts also the leakage inductance of the transformer.

References

[1] R. Teodorescu, M. Liserre, P. Rodrıguez, *Grid converters for photovoltaic and wind power systems.* Wiley, 2011.