# DOTTORATO DI RICERCA NAZIONALE IN INGEGNERIA DEI SISTEMI, ENERGETICA, INFORMATICA, E DELLE TELECOMUNICAZIONI XXXII CICLO

Brainstorming day
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# ADVANCED DIGITAL CONTROL TECHNIQUES OF SIC BASED FRONT-END POWER CONVERTERS


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## MIXED SIGNALS BASED CONTROL OF A SIC VIENNA RECTIFIER FOR ON-BOARD BATTERY CHARGERS

The main aim of this work is to investigate the feasibility of implementing a low-cost mixed-signal based control solution for a SiC three-level Vienna rectifier addressing electric vehicle on-board battery charger applications. The proposed solution allows to achieve almost unitary power factor operation as well as higher control loop bandwidths and lower total harmonic distortions in comparison with standard all-digital implementation using low-cost digital platform. A detailed description of the combined digital-analog approach is provided, as well as an experimental validation of the proposed solution for a 12kW on-board battery charger.
This work deals with the implementation of a suitable control strategy for the AC/DC stage, realized by a three phase Three-Level Vienna Rectifier (3L-VRECT), whose circuital scheme is shown in Fig. 1a ,according to the four modes of operation displayed Fig. 1b. Being a multilevel topology, the 3L-VRECT has the advantage of reducing the electrical stresses on the power devices, ensuring small current distortion.

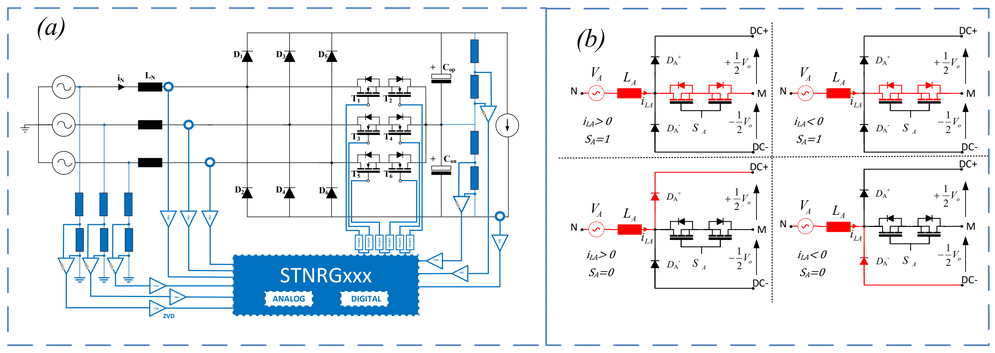
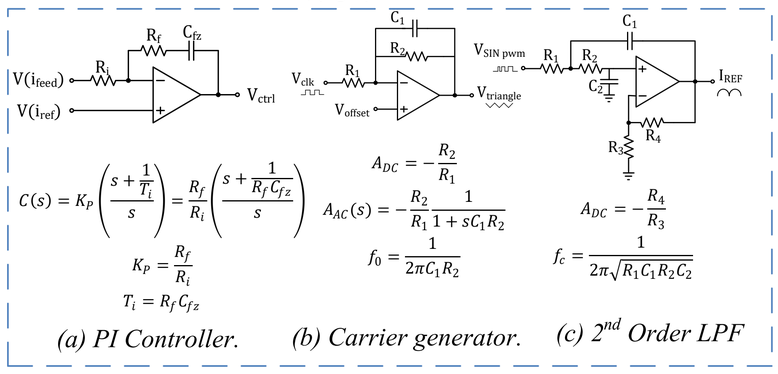



*Fig. 1 Circuital scheme of the three phase Three-Level Vienna Rectifier (a), and modes of operation of the phase A as example (b).*

## PROPOSED MIXED-SIGNAL CONTROL

The block diagram of the proposed mixed-signal controller architecture is shown in Fig. 2. The proposed control scheme has been implemented in a digital controller, a STNRG388A by STMicroelectronics (Table I) based on low cost 8bits microcontroller (STM8) and includes six SMEDs "State Machine Event Driven"; (Fig. 3).




*(a) PI Controller. (b) Carrier generator. (c) 2nd Order LPF*

*Fig. 6 Main blocks of the analog current controller.*

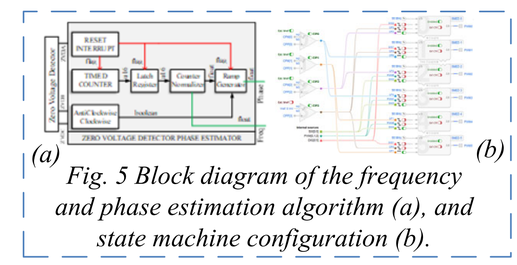



*Fig. 5 Block diagram of the frequency and phase estimation algorithm (a), and state machine configuration (b).*

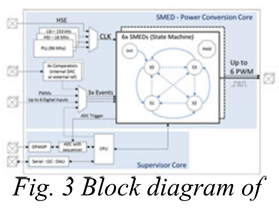



*Fig. 3 Block diagram of STNRG388A*

*Table I Technical specifications of the STNRG388A*

| |
|---|
| 6 programmable SMED "State Machine Event Driven" |
| High Resolution PWM Generation (1.3ns) |
| Transactions triggered by sync/async ext. or int events |
| 4 analog comparators |
| 4 ADC analog to digital converters |
| low propagation time (50ns) |

The block diagram of Fig. 4 provides a graphical representation of the functions implemented in the SMED, in the microcontroller and by the external analog circuit. The algorithm carrying out the phase and frequency estimation of the grid voltage vector is implemented in the STNRG388 according to the scheme shown in Fig.5. The voltage control loop is sequentially executed in the STNRG388 as well as the generation of the reference currents irefj (with j=a,b,c).

The sinusoidal waveforms of the reference currents are determined by means of a Look Up Table (LUT). The PWM signals applied to the bidirectional switches of the power converter are generated by comparing the with a carrier signal from an analog wave generator, as it is shown in Fig. 6b. The other three SMEDs are exploited to produce PWM signals whose fundamental harmonic features same frequency and phase of , with . The signals irefj (with j=a,b,c) from the SMEDs are filtered by using three analog Sallen-Key second order low pass filters. The Sallen-Key architecture is displayed in Fig. 6c. Finally, the PI controller of the current loop has been realized according to the circuital scheme of Fig. 6a.




*Fig.2 Block diagram of the proposed controller architecture.*

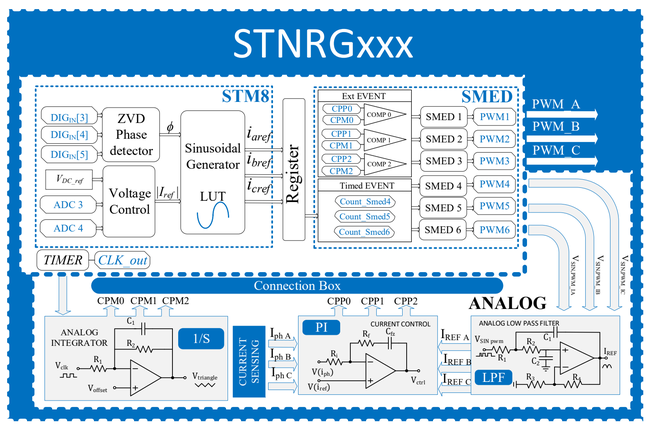



*Fig. 4 Block diagram of the proposed mixed-signal control implementation.*

## TEST BENCH

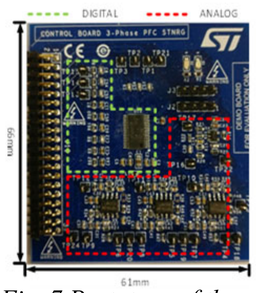



*Fig. 7 Prototype of the control board used in the proposed mixed-signal control architecture.*

The mixed-signal control strategy presented in the previous section has been tested on the 12kW battery charger prototype including a 3L-VRECT able to convert a balanced three-phase power supply featuring 400V–50Hz AC in a DC output voltage of 800V. This first power stage is PWM operated at fs=70kHz and driven by the control board shown in Fig. 7, specifically designed for this application. The power section has been realized using SiC diodes, STPSC20H12 (20A-1200V), as input rectifier and SiC MOSFETs, SCTW35N65G2 (55mΩ – 650V), as bidirectional power switch in the three legs of the converter.

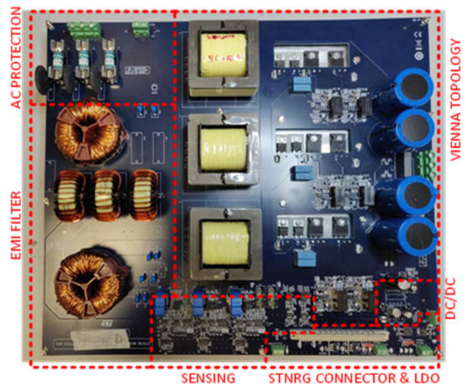



*Fig. 8 Battery Charger Prototype.*

## EXPERIMENTAL RESULTS

Fig. 9 shows the start-up of the power converter, the pre-charging operation of the DC link capacitors via a passive current limiter circuit and the burst packet can be noted. Then, an active charging is performed to increase the dc-link voltage to the rated value. Finally, a load step is applied to verify the effectiveness of the PFC control. The active rectifier is operated according to the working conditions listed in Table II. Fig. 10 displays a sequence of load transients, from no load to full load and back.In Fig.11 an overview of analog current regulator signals is shown.Addressing the steady state of the experimental test shown in Fig. 11, the measured THD of the phase currents is equal to 4,7%, while the power factor is equal to 0.992 and the efficiency is about 98,4%. Fig. 12 displays the efficiency and power factor curves vs the DC output power, with constant DC output voltage.
The sensing circuits needed by the control unit are integrated in the battery charger board displayed in Fig. 8.

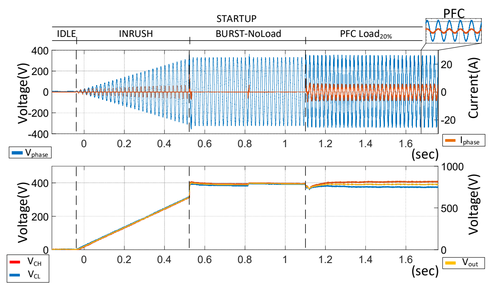



*Fig. 9 Startup followed by a 20% load step.*

*Table II*

| | |
|---|---|
| $V_{AC_{ph,n}}$ | 230 $V_{rms}$ |
| $I_{ACref}$ | 17.5 $A_{rms}$ |
| $f_{sw}$ | 70 $kHz$ |
| $L_{AC}$ | 514 $\mu H$ |
| $R_{eqL}$ | 20$m\Omega$ |
| $I_{satL}$ | 26$A$ |
| $I_{Load}$ | 15$A$ |
| $f_{AC}$ | 50 $Hz$ |
| $S_{AC}$ | 12 $KVA$ |

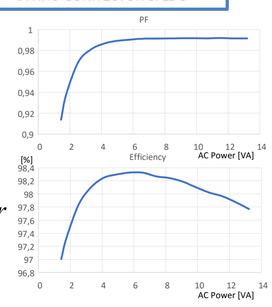



*Fig. 12 FoM of converter efficiency and PF at $400V_{LL}|800V_{DC}$*

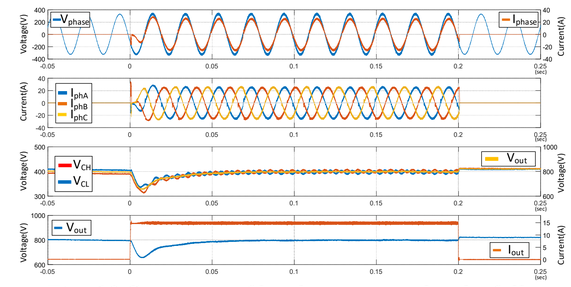



*Fig. 10 Sequence of load tests: zero load - full load – zero load.*

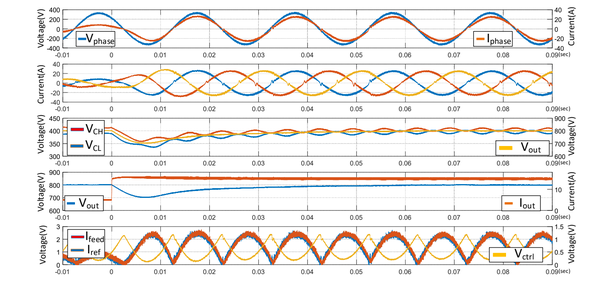


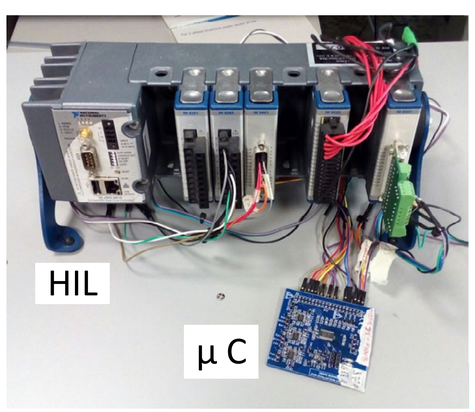

*Fig. 11 Overview of current control analog signal during a load transient.*

## CONCLUSION

A three-phase PFC AC/DC converter with SiC is implemented considering its use as front-end in EV battery charger with an interesting control strategy based on a mixed signal implementation that allow to match at the same time the advantages of analog cycle by cycle regulation and the flexibility of a digital system.
Theoretical aspects have been investigated, the analog current control loop is discussed and a design procedure for the control implementation is provided.
A prototype of the complete system has been realized in order to verify the performance of the proposed control scheme. As major results, input current waveforms are not affected from grid voltage distortion and test results show very good performances for both steady-state and dynamic conditions featuring THD of 4,7% and PF well above 0.99 at the rated power as well as a efficiency higher than 98%.

## REAL-TIME EMULATION OF A THREE-PHASE VIENNA RECTIFIER

The activity deals with the accomplishment of a FPGA-based dynamic model of a three-phase Vienna Rectifier controlled in order to feature unity power factor operations. Such a model has been developed for the Hardware In the Loop (HIL) implementation of a test rig in which the power converter is replaced with an embedded system using a FPGA board. The proposed approach has been fostered mainly to test different converter control algorithms in a fast and safe way. Such solution is based on a software platform environment with a high-level abstraction that ensures a good trade-off between accuracy and hardware resources, also allowing a fast prototyping procedure. The results obtained by the HIL implementation have been compared with those of a fully hardware experimental rig, confirming a very good agreement in terms of accuracy and dynamic behavior.



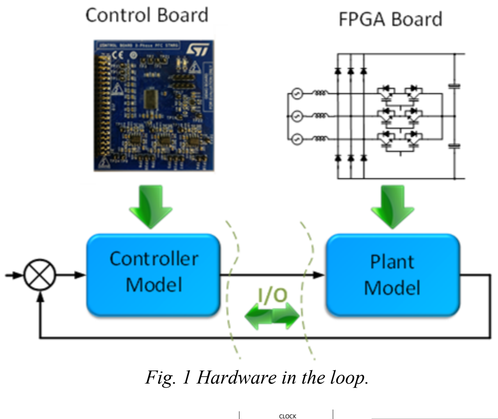
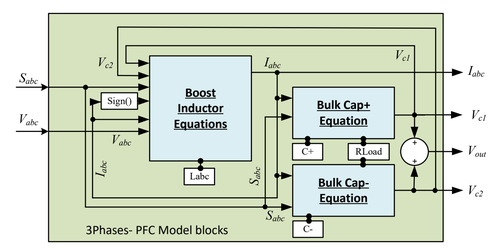




*Fig. 1 Hardware in the loop.*



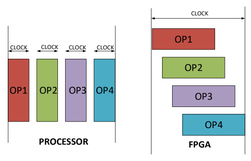
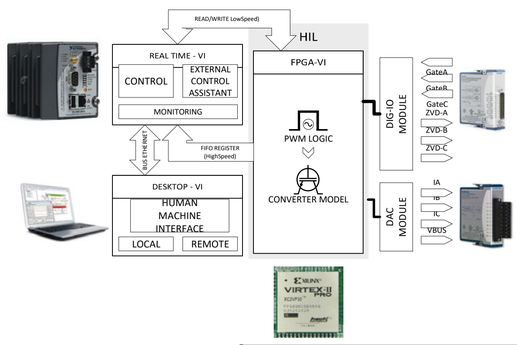



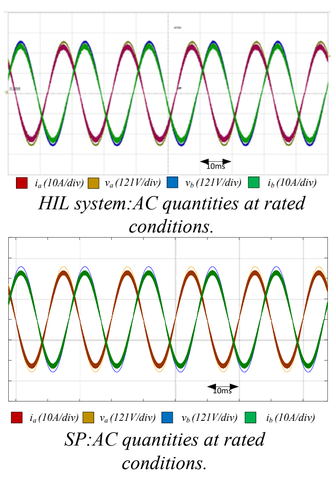

*Fig. 2 Comparison task Processor vs FPGA.*

| | µC | DSP | FPGA |
|---|---|---|---|
| **Embed** | Easy | Easy | Easy |
| **Low Power** | Yes | Sometimes | Sometimes |
| **Float operations** | No | Excellent | Possible |
| **Integer Operations** | Average | Excellent | Excellent |
| **Pipelining** | No | No | Yes |
| **Programmability** | Easy | Medium | Challenging |
| **Timing control** | Fair | Fair | Excellent |
| **Control Flow** | Excellent | Fair | Challenging |

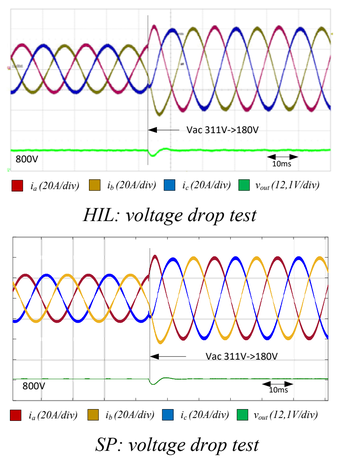
*Table 1 Hardware comparison*

The HIL shown in Fig. 1 combines the mathematical model of the power converter with actual control board, such that the control algorithm performs as though it were integrated into the real system. For testing and development of the control algorithms, the control board and associated software are connected to the mathematical model of the power converter, which is executed on the FPGA board in real time. Both boards are interfaced by electrical signals representing in the forward path the switching commands to drive the Vienna rectifier. The plant model calculates the physical variables that represent the outputs of the plant, which are converted into electrical signals which are sent back to the control board.

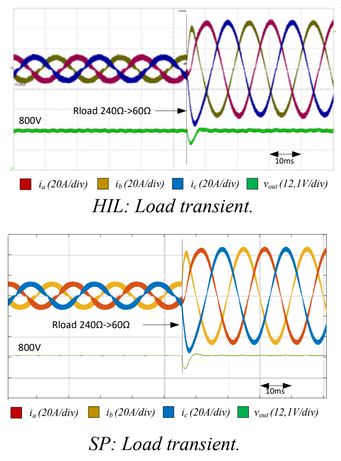


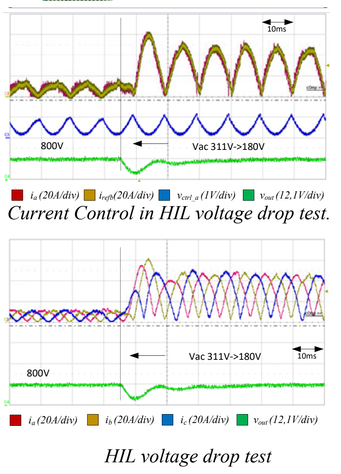

*HIL system:AC quantities at rated conditions.*



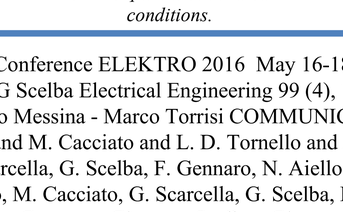

*HIL: voltage drop test*



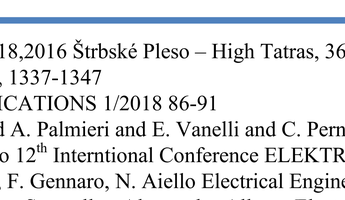

*HIL: Load transient.*




*Current Control in HIL voltage drop test.*

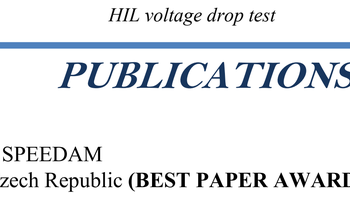



*SP:AC quantities at rated conditions.*




*SP: voltage drop test*


*SP: Load transient.*




*HIL voltage drop test*

## PUBLICATIONS

- Hardware in the loop for failure analysis in AC motor drives G Scelba, G Scarcella, M Cacciato, G Aiello 11th Interntional Conference ELEKTRO 2016 May 16-18,2016 Štrbské Pleso – High Tatras, 364-369 **(BEST PAPER AWARDS)**
- Failure analysis of AC motor drives via FPGA-based hardware-in-the-loop simulations G Aiello, M Cacciato, G Scarcella, G Scelba Electrical Engineering 99 (4), 1337-1347
- A high efficiency interleaved PFC front-end converter for EV battery charger Giuseppe Aiello - Mario Cacciato - Sebastiano Messina - Marco Torrisi COMMUNICATIONS 1/2018 86-91
- Real-time emulation of induction machines for hardware in the loop applications G. Aiello and G. Scelba and G. Scarcella and M. Cacciato and L. D. Tornello and A. Palmieri and E. Vanelli and C. Pernaci and R. Di Dio 2018 International SPEEDAM
- RealTime Emulation of a Three-Phase Vienna Rectifier with Unity Power Factor Operations G. Aiello, M. Cacciato, G. Scarcella, G. Scelba, F. Gennaro, N. Aiello 12th Interntional Conference ELEKTRO 2018 May 21-23,2018 Mikulov, Czech Republic **(BEST PAPER AWARDS)**
- RealTime Emulation of a Three-Phase Vienna Rectifier for the Development of Control Unit with PFC Capability G. Aiello, M. Cacciato, G. Scarcella, G. Scelba, F. Gennaro, N. Aiello Electrical Engineering 2018 – Springer
- Modelling and Simulation of a Bidirectional SiC-based Battery Charger for V2G Giuseppe Aiello · Mario Cacciato · Alex La Cognata · Giacomo Scelba · Giuseppe Scarcella · Alessandro Allegra Electrimacs 2019 21-23 May, Salerno (Italy)
- FPGA-Based Design and Implementation of a real Time Simulator of Switched reluctance motor Drives Aiello G., Tornello LD, CACCIATO M., DI DIO R., PALMIERI A, PERNACI C,SCARCELLA G., SCELBA G., VANELLI E. EPE19 2-6 2019 Genova (Italy)
- Mixed Signals Based Control of a SiC Vienna rectifier for On-Board Battery Chargers, AIELLO G., AIELLO N., CACCIATO M., GENNARO F., SCARCELLA G., SCELBA G.,EPE19 2-6 2019 Genova (Italy)
- Analysis of PCB parasitic effects in a Vienna rectifier for an EV battery charger by means of Electromagnetic Simulations, PALOMBA F., AIELLO G., AIELLO N.,CACCIATO M., GENNARO F., PAVONE M.,EPE19 2-6 2019 Genova (Italy)
- Analyse der parasitären Leiterplatteneffekte eines EV Batterieladesystems mit Gleichrichter durch Simulation , PALOMBA F., AIELLO G., AIELLO N.,CACCIATO M., GENNARO F., PAVONE M,Muff S. DESIGN & ELEKTRONIK (submitted)
- Modelling and Simulation of a Bidirectional SiC-based Battery Charger for V2G applications, Aiello G.,Cacciato M., Scelba G., Scarcella G., Gennaro F., MATCOM (submitted)

## COURSE & SCHOOL

- EUREOPEAN PHD SCHOOL «Power Electronics, electrical machines Energy control and Power Systems 21-25 May 2018 Gaeta (Italy)
- ECPE Tutorial «Power semiconductor devices and technologies» 4-5 October 2018 STMicroelectronics Catania (Italy)
- ISI&DCN «International school on Informatics and Dynamic Complex Systems» 15-19 October 2018 Catania (Italy)
- PCIMTutorial «High performance Control of Power Converters» 6 May 2019 Nuremberg (Germany)
- EPE Tutorial «Model predictive Control of Power Converters: Principle, Design and Applications» 2 September 2019 Genova (Italy)
- CMAEL «Riunione annuale congiunta GUSEE-CMAEL» 16-17 Settembre 2019 Cagliari (Italy)

## REFERENCE DESIGN

- During the period of studies, in collaboration with ST Microelectronics of Catania, a power conversion system was studied and developed, based on the latest wide bandgap (SIC) devices.
- In detail, this is a 12kW three-phase AC / DC stage multi levels power converter for Electric Vehicles Battery charger.
- This prototype has been presented during the PCIM Europe 2019 international event 7-9 May 2019 Nurnberg