# 7 kW converter prototyping for EV charging network development supplied through rail traction power systems

Hajian Foroushani, Masood; Mir, Tabish; Tricoli, Pietro

*DOI:*
10.1109/CPE-POWERENG54966.2022.9880891

# 7 kW Converter Prototyping for EV Charging Network Development Supplied through Rail Traction Power Systems

Masood Hajian
Birmingham Centre for Railway Research and Education
University of Birmingham
Email: m.hajian@bham.ac.uk

Tabish Nazir Mir
Birmingham Centre for Railway Research and Education
University of Birmingham
Email: t.mir@bham.ac.uk

Pietro Tricoli
Birmingham Centre for Railway Research and Education
University of Birmingham
Email: p.tricoli@bham.ac.uk

***Abstract*— Electric vehicle (EV) charging is expected to impose a high loading demand on distribution systems in near future due to its fast-growing market. This will lead to an urgent need of expensive upgrades on distribution networks if no alternative energy supply is provided. Rail traction power networks benefit from substantial reserve capacity which can be used for this purpose. This paper reports on design, laboratory prototyping, and experimental testing of a 7 kW power electronic converter prototype which can be used for EV charging network development using a single-phase supply emulating AC traction system. The prototype consists of a single-phase voltage source converter (VSC) connected back to back via a DC link, to three half bridge VSCs feeding the charging network. The prototype enables connection of both single-phase and three-phase EV chargers while ensuring balanced three-phase output voltages from the grid forming converter. The converter also offers the possibility of power injection from its DC bus which is useful in DC rail traction application. Additionally, it supports reverse power flow from charging network towards traction sub-station which is advantageous for voltage support and improved stability of the traction network. Detailed design of main converter components is presented. Experimental results confirm the feasibility and appropriate performance of the studied converter.**

***Index Terms*—Power Electronic Converter, Prototype, Voltage Source Converter (VSC), Electric Vehicle (EV), Charging Network.**

## I. INTRODUCTION

EV industry is very fast developing to address challenges concerned with fossil-based combustion engines that are traditionally used in road transportation system. Relying on fossil fuels for transport is not only recognized as one of the main contributors to air pollution in large cities, but it also results in unsustainable supply chain in future. EVs can effectively address this challenge and that is why it is envisaged that they will take more than 50% of the vehicle transport market by 2050 at the latest [1].

Nevertheless, there are issues with widespread acceptance of EVs which necessitate further research and development. In the context of EV technology, further improvements are needed, such as faster charging process that competes with combustion engines. Additionally, advanced battery technologies are required to enable EVs with longer travels capabilities at lesser re-fuelling requirements. Currently, EV charging using ultra fast chargers can be achieved within 20-30 minutes which although is promising, yet it is much longer than the re-fuelling times of combustion engines. EVs with the capability of running for up to 200 miles on single charging have also been reported, and identified for scope of improvement [2].

Apart from the aforementioned component level issues, EVs can potentially impose a serious challenge to distribution systems at the system level. Considering that the number of EVs is rapidly growing and given that they normally need to be connected to distribution systems for charging, a high loading demand will be incurred on these systems. Consequently, costly upgrades on protection switch gear of such systems will be inevitable, particularly in crowded cities [3, 4]. In order to reduce the distribution system loading, several ideas have been proposed and researched so far. Electric train traction systems are one candidate for this purpose as the substations are usually designed for large reserve capacity. This practise is prevalent to address reliability issues through support of section load during faults in nearby substations, and also to support high loading on the system that occurs only during peak hours. In order to tap this reserve capacity, the feasibility of rail traction power systems for developing EV charging networks has been investigated so far in [5–8].

The feasibility of EV charging using DC traction power is studied in [6] where a DC micro grid including DC charging points, PV panels, and DC tramway lines is investigated. EV chargers and PV panels are connected to the grid via high power DC to DC converters. A downscaled lab prototype is reported in [7] wherein a high capacity DC link is connected to a supercapacitor energy storage system (ESS) and an EV battery using DC transformers. However, it is noteworthy that its realistic implementation is not feasible as all commercially available EV chargers need AC input power. Furthermore, the requirement of customized DC transformers serves as an additional impediment. In [8], a power converter comprising of an active front end single-phase VSC, connected back to back to a three-phase VSC is presented. The three-phase VSC is controlled as three independent half bridge VSCs to facilitate balanced voltage generation during unbalanced charging loads. The feasibility and effectiveness of this technique is discussed using detailed simulation results obtained from Simulink modelling in [8]. This paper reports as a continuation of [8] with design, development, and experimental testing of a 7 kW lab

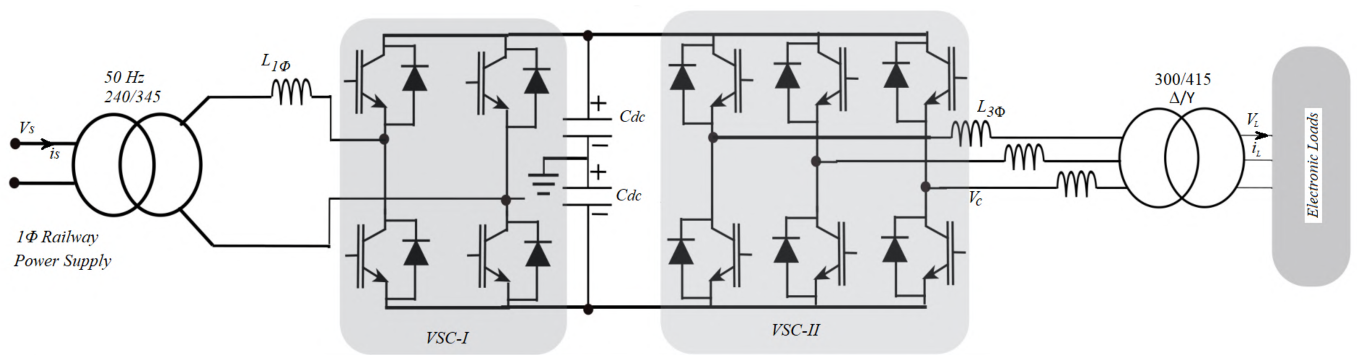


Fig. 1. Circuit diagram of back to back VSC based EV charging network generated from single-phase railway supply system

TABLE I
MAIN COMPONENTS IN THE PROTOTYPE

| Converter Components | Specification |
|---|---|
| Power switches | SKM75GB12F4 (1200V, 75 A) |
| Gate driver circuits | SKHI 23/12 |
| Snubber Resistance ($R_s$) | 1 kΩ |
| Snubber Capacitance ($C_s$) | 10 nF |
| **Passive Components** | **Specification** |
| 1-$\phi$ Transformer | 240/345 V |
| 3-$\phi$ Transformer | 300/415 V |
| $C_{DC}$ | $2 \times 8.2mF$ |
| $L_{1\phi}$ | $33mH, 22.5A$ |
| $L_{3\phi}$ | $16.5mH, 11.5A$ |
| **Load Components** | **Specification** |
| Electric Vehicle Supply Equipment | Alfen |
| Programmable Electronic Load | Chroma 63804 |

prototype which is used to link the single-phase 240 V UK grid to a mixed single-phase and three-phase EV charging network. Commercial Alfen Electric Vehicle Supply Equipment (EVSE) is connected to the converter output feeding to a three-phase electronic load. Additionally, a varistor may be used to emulate single-phase battery charging load. Power converter design is presented in detail and experimental results are provided to verify the converter performance. Table I summarizes the main components in the final prototype design.

## II. PROTOTYPE DECRIPTION

The studied power converter includes a single-phase VSC connected back to back to a three-phase VSC via a DC link as shown in Fig. 1. Three half bridge independently controlled VSCs are used for three-phase VSC development to avoid voltage imbalance issues in the event of load imbalance when both three-phase and single-phase EV chargers are connected to the same charging grid. Alternately, direct connection of single-phase chargers to the traction network via an isolation step down transformer is possible. This will not only relieve the converter from any load imbalance issues, but will also avoid unnecessary power flow through the converter, leading to an improved efficiency.

It is noteworthy to mention that the topology enables reverse power flow from charging substation towards traction network which is advantageous as far as bidirectional EV chargers are concerned. This can also fractionally support the traction network in the event of lack of enough power availability when one substation is down and a high train loading is observed. Additionally, the studied converter can contribute in traction network voltage stabilization by reactive power injection during AC faults. The single-phase VSC regulates DC link voltage level as well as reactive power circulation to the traction system. On the other hand, the three-phase VSC is controlled as a grid-forming converter, that develops the required AC voltage with specific magnitude and frequency using three independent controllers. Detailed description of this topology is given in [8] with several simulation results.

### A. Sizing of the Main Components

A DC link voltage of 600 V is rationally selected for 7 kW rated power. It is evident that both VSCs should be designed for at least 600 V using adopted two-level VSC technology.

Considering a 100% voltage safety margin, SKM75GB12F4 (1200 V, 75 A) IGBTs from Semikron are used for both VSCs' development. Note that higher voltage rating is used to protect the power switches against transient voltage spikes which is a normal practice in power electronics. The sizing of DC link capacitors is estimated using the following equation,

$$C_{DC} \geq 2S_e \frac{S_n}{V_{DC}^2} \tag{1}$$

where, $S_e$ represents the energy to power ratio which is selected at $50kJ/MVA$, and $S_n$ is the nominal power of the converter. Since the DC link is setup via the single-phase converter, a large second order harmonic content is inevitably observed on the DC link voltage. To cater to this, a double sized capacitor amounting to $4.1mF$ is used. Series inductive filters are used for both single-phase and three-phase VSCs to avoid high frequency current injection to AC grids. For this purpose, a 33 mH inductor for single-phase VSC and three 16.5 mH inductors for three-phase VSC are used. The EV battery charging load is emulated through programmable electronic loads from Chroma (Model 63804), which are operated in constant current mode. Additionally, a small 20 μF capacitor may also be connected in parallel to each phase. This will filter out high frequency components when the three-phase converter is not loaded. No resonance at main frequency of 50 Hz or main harmonic frequency of 5 kHz is expected using such small capacitors. A single-phase and a three-phase AC transformer are used at the input of the single-phase converter and at the output of the three-phase converter, respectively. These transformers not only achieve isolation between power electronic circuitry and AC grids, but also enable voltage stepping. The required voltage stepping of 240 V/345 V for single-phase and 300 V/ 415 V ($\Delta/Y$) are obtained considering amplitude modulation index of around 0.9. The three-phase transformer also enables single-phase load connection since star connection is used at its secondary. The $\Delta/Y$ transformer on the three-phase side facilitates the generation of balanced output voltages in the presence of unbalanced load currents, via a three-leg three-phase VSC [9]. Alternatively, a four-leg VSC can also be used, as discussed in [10].

### B. Controller and Power Switch Driver

The two-axis voltage-oriented control (VOC) technique is used for controlling both VSCs. In order to implement the control algorithm, a second order generalized integrator (SOGI) based single-phase phase locked loop (PLL) is employed to detect instantaneous angle of AC grid voltage phasor and a voltage-controlled oscillator (VCO) is used to generate the required angle for the grid forming three-phase VSC. External and internal PI loop regulators are used in synchronously rotating $dq$ reference frame to control the DC link voltage and reactive power exchange through the single-phase VSC. Similar voltage and current control loops are employed individually on each leg of the three-phase VSC to regulate the AC voltage magnitude and frequency. Detailed description of the control system is described in [8]. In order to implement the control algorithm, a number of voltage and current sensing units are required. As such, voltage sensors are placed on the single-phase grid, the DC link, and the secondary side three-phase output of VSC-II. Current sensors are placed on the single-phase grid current and the three-phase load current.

Two Delfino floating point F28335 Texas Instruments microcontrollers, one for each VSC, are used for real time implementation of the control logic. The suggested micro-controller unit (MCU) supports clock frequency of 150 MHz, 16 ADC channels, 88 general purpose digital I/Os, and allows floating point arithmetic. A main controller board PCB is designed to enable direct embedding of each MCU card, that facilitates the reception of analogue inputs via differential amplifiers, and transmission of PWM signals via video amplifiers. The generated PWM pattern is sent to IGBT gate drivers after signal amplification of 3.3 V to 15 V within the controller board PCB. Semikron SKHI 23/12 IGBT driver boards are used to provide IGBT gate signals. These drivers can be used for all IGBTs with collector-emitter voltages up to 1200 V and can be used for two individual power switches usually developing a phase leg. Short circuit protection using collector-emitter voltage monitoring (DESAT protection) is enabled in the gate driver cards so as to protect the devices against inadvertent short circuits. Furthermore, an active protection logic is also setup through MCU units and contactors, that is designed to trip the prototype input power in the event of any detected fault particularly over current, over voltage and under voltage on the DC link.

### C. IGBT Snubber Design

Switch snubber circuits are required to ensure limited IGBT voltage at turn off instants, that are caused by stray inductance between IGBTs and the DC link. RCD voltage clamp shown in Fig. 2 is used as a suitable choice for medium and high current VSC application which benefits from lower losses compared to RC snubbers [11]. At switching OFF instant,

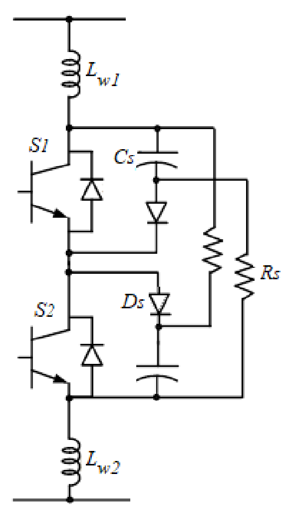


Fig. 2. RCD snubber design for each inverter leg

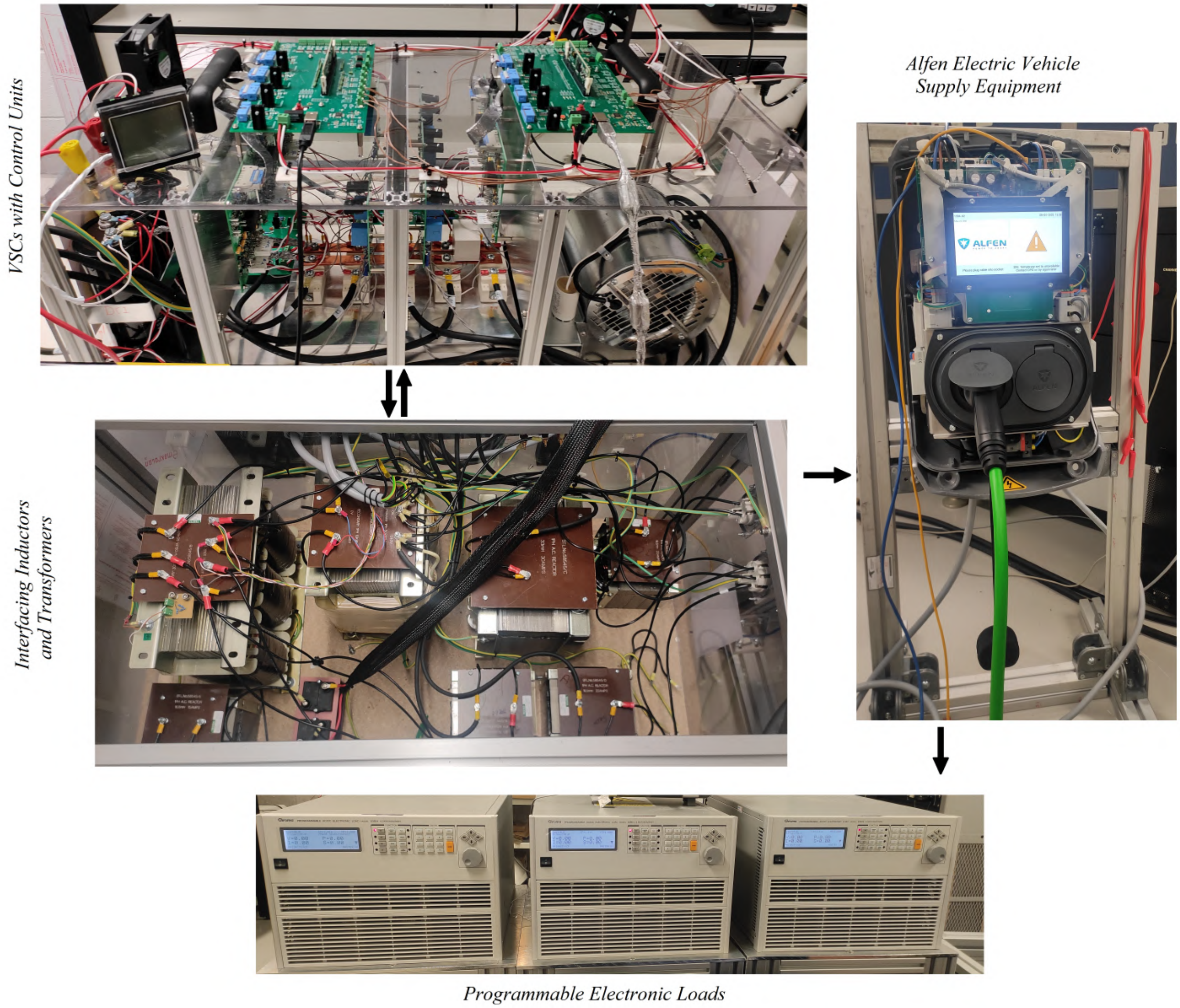


Fig. 3. Photograph of the system components and converter prototype

the stray inductance energy is transferred to the corresponding snubber capacitor increasing its voltage above $V_{DC}$. The diode prevents snubber capacitor discharge into the IGBT at the next switch ON instant. The snubber capacitor over-voltage is discharged into the DC link resulting in reduced losses. Larger the capacitor, smaller will be the over-voltage, albeit at higher total losses. The snubber resistor should be small enough to enable fast capacitor discharge to the DC voltage level by the end of switching period. Considering a 200 nH stray inductance, capacitance and resistance values of 10 nF and 1 kΩ are calculated for IGBTs of both VSCs.

## III. Experimental Results

Photographs of the power converter prototype, the interfacing inductors and transformers, Alfen electric vehicle supply equipment (EVSE) and electronic loads are shown in Fig. 3. The prototype is connected to the 240 V UK grid through a single-phase variac on its input side, while it feeds three-phase (or single-phase) EVSEs from the output side. As previously discussed, single-phase chargers can also be connected directly to the grid (railway power supply) to avoid extra losses associated with power processing. To emulate the three-phase EV charger system, three electronic loads programmed as a single three-phase load are used. The electronic load can be programmed in constant resistance, power, or current mode under AC operation. Additionally, it can also be used as a constant voltage load in DC mode which is useful for battery charging emulation in the final stage. Experimental results are recorded using Mixed Signal Oscilloscope (MSOX2024A Keysight). Current probes (Keysight 1146B) and differential voltage probes (TESTEC TTS19001 and Tektronix P5200A) have been used for measurements.

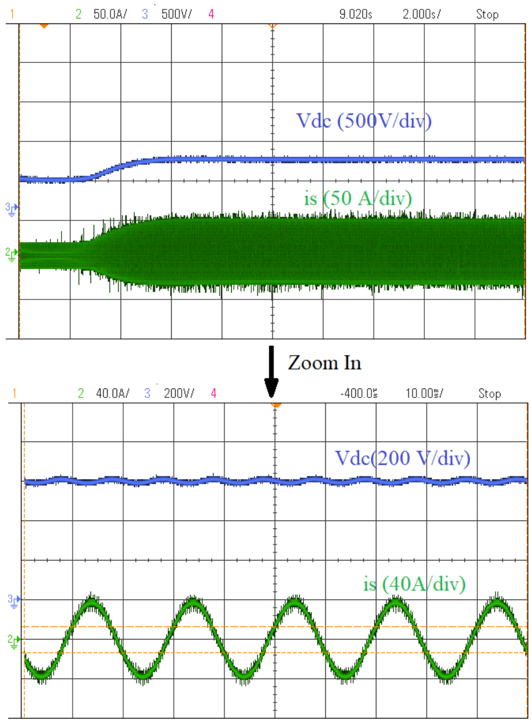


Fig. 4. Starting performance of the single-phase front end converter, VSC-I

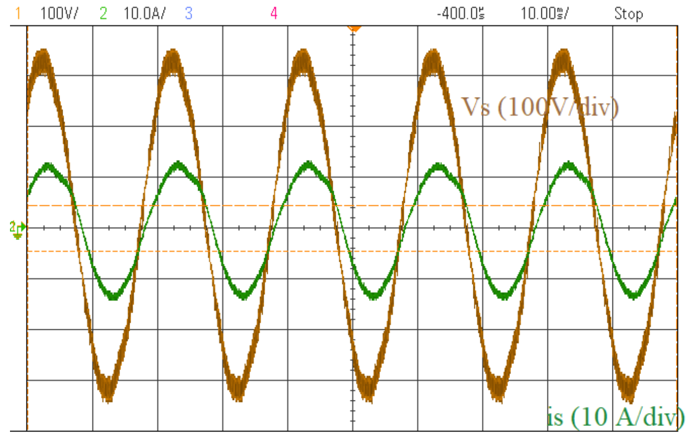


Fig. 5. Steady state power quality performance of the single-phase front end converter, VSC-I

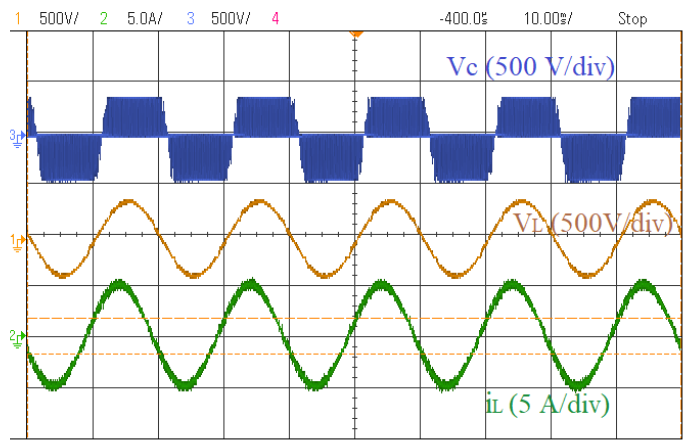


Fig. 6. Steady state performance of the three-phase grid forming converter, VSC-II

Experimental results from the prototype are demonstrated in Figs. 4-8. Starting performance of the single-phase VSC-I while establishing a DC link of 600 V is depicted in Fig.4. It shows the DC Link voltage ($V_{DC}$) and single-phase grid current ($i_s$) during start-up and in steady state. The power quality performance of the single-phase front end converter is illustrated in Fig.5, which shows the single-phase grid voltage and sinusoidal grid current at nearly unity input power factor. The slight phase shift is attributed to the positioning of voltage and current sensors, and allows scope for improvement. Performance of the grid-forming three-phase VSC-II in terms of the PWM output voltage of the converter ($V_c$), the secondary side load voltage ($V_L$), and the load current ($i_L$) for one of the phases is shown in Fig.6. Combined performance of the two back to back converters at a DC link voltage of 450 V and load power of 1.8 kW, is illustrated in Figs.7 and 8. Fig. 7 shows the steady state regulated DC link established by VSC-I, and sinusoidal three-phase load currents drawn from the grid forming converter i.e VSC-II. Finally, the dynamic performance of the back to back converter system is shown in Fig.8, which illustrates DC link regulation as the three-phase load current command is abruptly increased.

## IV. Conclusion

Design, development and initial testing of a 7 kW power converter prototype which can be used for electrification of a local EV charging grid powered from a single-phase source is presented. The main components design is presented and experimental results are shown to verify the initial performance of the converter. The converter can be used with a combination of single-phase and three-phase EV chargers with a preserved voltage balanced property against unbalanced load connection. It also enables bidirectional power flow and can be employed for input AC grid voltage and stability support using reactive power and active power injection. The converter is a low power prototype of a novel idea of EV charging network development using rail traction power and can be used with both AC and DC traction systems. Experimental results obtained using the prototype directly connected to the UK grid and feeding to two commercial EV chargers confirms the appropriate performance of the converter. Work is ongoing to add a PLC based energy management system to enable smart charging network of the EV chargers which is realistically required for such prototype connection to rail traction systems.

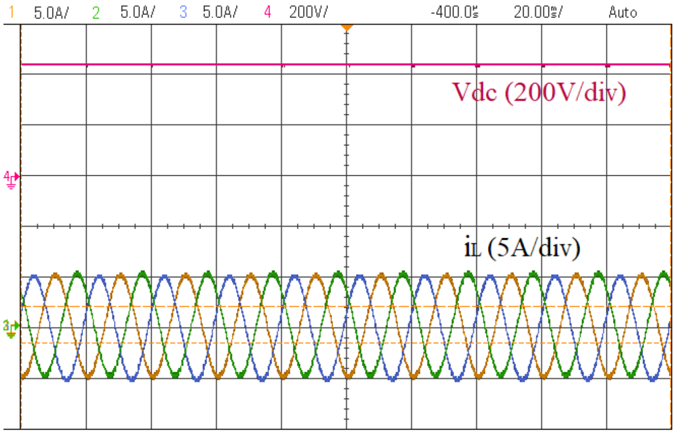


Fig. 7. Steady state performance of the back to back converter units

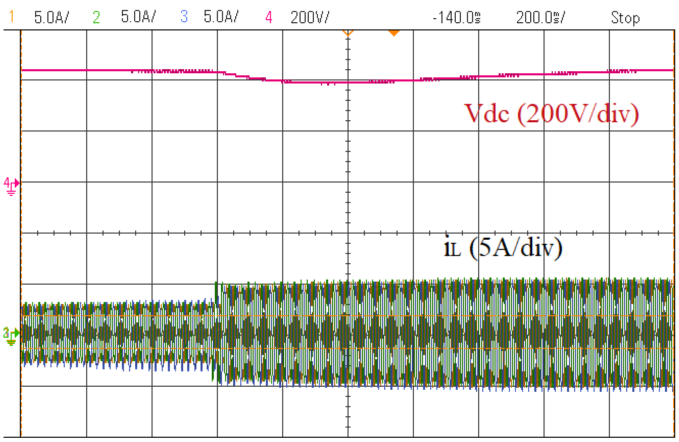


Fig. 8. Dynamic performance of the back to back converter units

## ACKNOWLEDGEMENT

The authors are grateful to Innovate UK for supporting this work under grant No. 106181.

## REFERENCES

[1] P.-Y. Kong and G. K. Karagiannidis, “Charging Schemes for Plug-In Hybrid Electric Vehicles in Smart Grid: A Survey,” *IEEE Access*, vol. 4, pp. 6846–6875, 2016.

[2] S. Taghizadeh, M. J. Hossain, N. Poursafar, J. Lu, and G. Konstantinou, “A Multifunctional Single-Phase EV On-Board Charger With a New V2V Charging Assistance Capability,” *IEEE Access*, vol. 8, pp. 116 812–116 823, 2020.

[3] M. Moschella, M. A. A. Murad, E. Crisostomi, and F. Milano, “Decentralized Charging of Plug-In Electric Vehicles and Impact on Transmission System Dynamics,” *IEEE Transactions on Smart Grid*, vol. 12, no. 2, pp. 1772–1781, Mar. 2021.

[4] X. Zhu, B. Mather, and P. Mishra, “Grid Impact Analysis of Heavy-Duty Electric Vehicle Charging Stations,” in *2020 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Feb. 2020, pp. 1–5.

[5] A. Fernandez-Rodriguez, A. Fernandez-Cardador, A. De Santiago-Laporte, C. Rodriguez-Sanchez, A. P. Cucala, A. J. Lopez-Lopez, and R. R. Pecharroman, “Charging Electric Vehicles Using Regenerated Energy from Urban Railways,” in *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Dec. 2017, pp. 1–6.

[6] J. Pouget, B. Guo, L. Bossoney, J. Coppex, D. Roggo, and C. Ellert, “Energetic simulation of DC railway micro-grid interconnecting with PV solar panels, EV charger infrastructures and electrical railway network,” in *2020 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Nov. 2020, pp. 1–7.

[7] P. Moreno-Torres, G. Navarro, M. Blanco, and M. Lafoz, “Multifunctional test bench for the emulation and testing of electric vehicle fast-charging from urban railway power lines,” in *2015 IEEE International Conference on Industrial Technology (ICIT)*, Mar. 2015, pp. 1081–1087.

[8] M. Hajian and P. Tricoli, “A Mixed 1-phase and 3-phase Vehicle Charging System from AC Rail Traction Power Network,” in *2021 IEEE 15th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Jul. 2021, pp. 1–6.

[9] D. Soto, C. Edrington, S. Balathandayuthapani, and S. Ryster, “Voltage balancing of islanded microgrids using a time-domain technique,” *Electric Power Systems Research*, vol. 84, no. 1, pp. 214–223, Mar. 2012.

[10] R. Aboelsaud, A. Ibrahim, and A. G. Garganeev, “Review of three-phase inverters control for unbalanced load compensation,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 10, no. 1, pp. 242–255, Mar. 2019.

[11] M. Hajian and D. Jovcic, “30kW, 200V/900V LCL IGBT DC/DC converter prototype design and testing,” in *IEEE PES Innovative Smart Grid Technologies, Europe*, Oct. 2014, pp. 1–5.