Trackside Static Converter Fed by Overhead Line

Branimir Puškarić[1], Miroslav Macan[2]
Power Electronic Devices BU
KONČAR – Electronics and Informatics, Inc.
Zagreb, Croatia
bpuskaric@koncar-inem.hr[1]; mmacan@koncar-inem.hr[2]

Nenad Težak[3]
Power Electronics and Control dept.
KONČAR – Electrical Engineering Institute
Zagreb, Croatia
ntnenad@koncar-institut.hr[3]

***Abstract*—A two-cell interleaved boost converter for railway applications is described. Some special considerations regarding disturbances in the catenary line voltage are pointed out. Principal operation of the controller is presented with emphasis on feed-forward compensation of input voltage disturbances. Presented results are verified through simulation and through measurements in the laboratory.**

Keywords*— *railway application, boost converter, interleaved operation, converter control, DSP

I. Introduction

A novel trackside static converter fed by overhead line (Fig 1.) is presented, with special emphasis on some considerations, which have to be taken into account when designing such a converter for railway applications.

The converter is a result of continuous development of converters for railway applications in Končar [1]-[6] and is used in electric traction substations (transformer feeding stations) in order to supply various loads inside the substation facilities (power supply for integrated lighting and information systems, railway signaling and protection systems, etc.). The converter is primarily intended to be used as backup energy source (in case of power outage from the distribution network). Nevertheless, in projects where poor or no distribution network is available at site, this converter can be implemented as a primary power source as well.

The railway supply voltage very often contains transient phenomena which are not usually present in the line voltage of regular power distribution networks (severe distortions of the line voltage by high content of higher order line harmonics, voltage sags/swells, multiple zero-crossings, etc.). On this topic, in the second section, some examples and corresponding analysis, based on measured data from considered trackside locations, is presented.

Considered circuit configuration is discussed in more detail in section 3. The focus is on the line-side boost converter which is used as the input stage. Boost converters are well known and widely used in single-phase traction applications [7, 8] because of their sinusoidal shaping effect on the input current, which is controlled to be in phase with the input voltage, and featuring near unity power factor operation.

Description of implemented control structure is given in section 4. The control structure provides interleaved operation [1, 2, 9, 10] of two parallel boost input stages resulting in effective 16 kHz switching operation in the input stage. Phase angle estimation of input voltage is performed using a modified EPLL supported by sliding DFT which was introduced in [1] and [2] and has proved to provide fast response of the phase, frequency and amplitude during sudden changes in input voltage [3]. The control structure is implemented on a new DSP-FPGA core based embedded controller which is responsible for all control, monitoring, conditioning and communication tasks [11].

In section 5 a more detailed consideration of the implemented voltage feed-forward compensation is given. The implemented solution provides sinusoidal input current and stabilized DC-link voltage even in case of heavily distorted input voltage. The presented solution is a simplified version of the method presented in [1], and special considerations are discussed which justify the presented approach. Simulation data is provided to show effectiveness of the solution.

In section 6 experimental results are presented which show voltage and current in real operation.

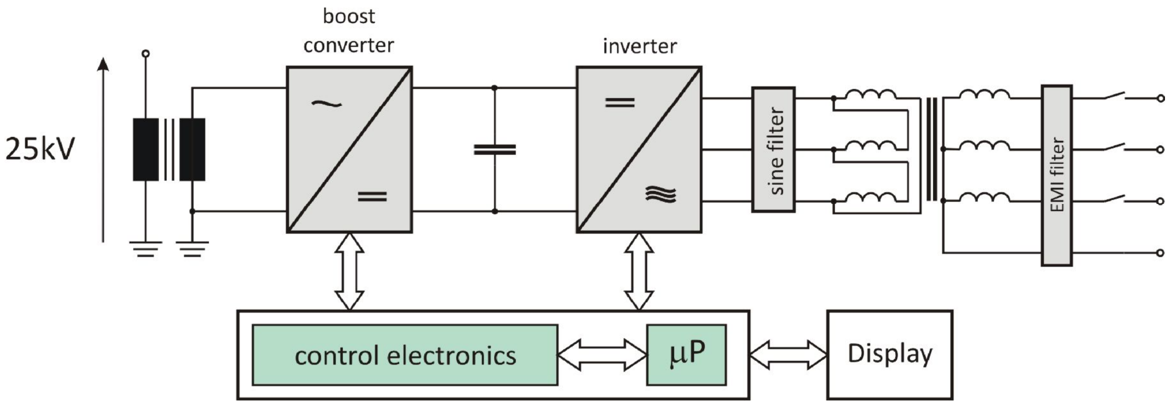

Fig. 1. Shematic of the presented converter

II. TRACKSIDE VOLTAGE CONDITIONS

On the 25 kV, 50 Hz overhead line voltage disturbances such as voltage spikes, sags and surges can occur frequently. Disturbances are caused by the current drawn from locomotives. Conventional design considerations and restraints, usual for industrial applications powered from the distribution grid, are therefore not sufficient. Besides frequent disturbances, a wide input voltage operating range has to be allowed. According to EN 50163:2004 for the 25 kV grid voltage variations of +20%, and -30% are allowed. In the case considered, a 50 kVA (25 kV/220 V) single phase step down transformer is used to connect the converter to the grid.

In Fig. 2. and Fig. 3. typical voltage waveforms from the secondary side of the transformer are shown. The voltage waveforms have been recorded at the commisioning site in Čapljina (BiH) on the secondary winding of the step-down transformer.

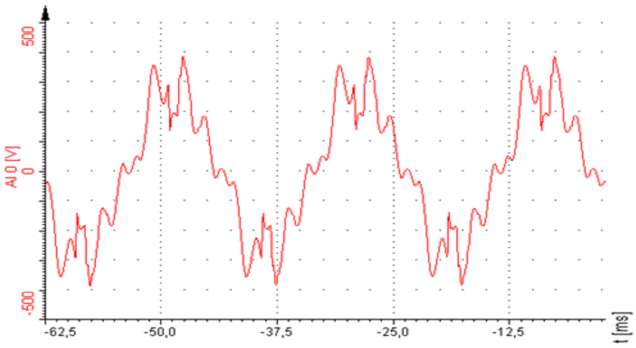

Fig. 2. Voltage waveform recorded at transformer secondary at no load condition – example 1.

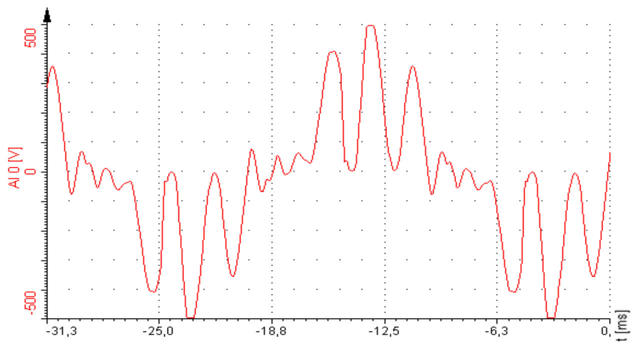

Fig. 3. Voltage waveform recorded at transformer secondary at no load condition – example 2.

Disturbances generated by classical line-commutated converters, although significant in amplitude, are multiples of the grid frequency (Table 1.). The impact of such disturbances on signaling and other communication systems along railway tracks is therefore somewhat easier to control and to predict. For instance, most track control circuits operate at frequencies that are not multiples of the fundamental grid frequency [12] (e.g. 75 Hz, $83^1/_3$ Hz, 125 Hz, etc.). Classical locomotives with line-commutated converters and DC motors will therefore not produce disturbances at frequencies that are critical for such equipment.

Modern pulse-width controlled converters can generate disturbances which are not multiples of the grid frequency, so this has to be taken in consideration. If not taken proper care of, presented disturbances in the line voltage, caused by nearby locomotives with line-commutated converters, could affect the control structure to generate non-harmonic disturbances.

The presented control structure avoids such behavior by ensuring accurate synchronization of converter to fundamental grid frequency [1-3, 13, 14], and effective compensation of harmonic voltage components.

TABLE I. HARMONIC COMPONENTS OF THE VOLTAGE WAVEFORMS SHOWN IN FIG 2. AND FIG. 3.

Frequency	U_{sec} [Vrms] (Fig.2)	U_{sec} [Vrms] (Fig. 3)
50	197	181
150	8,56	17,1
250	36,2	17,4
350	41,8	71,1
450	16,8	106
550	26,6	33,9
650	10	21,2
750	2,92	13,5
850	2,1	6,71
950	0,0751	1,86
1050	2,27	4,97
1150	4,55	1,81
1250	5,92	9,16
1350	3,33	2,03
1450	3,44	5,92

III. CIRCUIT CONFIGURATION

The presented converter (Fig. 1) is supplied from the railway catenary line (25 kV, 50 Hz) via a single phase step down transformer (50 kVA) and has a rated input of 230 V_{RMS}. The converter is designed to operate continuously for voltages from 175V_{RMS} AC (19 kV line voltage) up to 253 V_{RMS} AC (27.5 kV line voltage) at full power (30 kVA).

The input voltage is rectified using a full bridge single phase rectifier. The input stage of the converter consists of two paralleled boost legs which operate in interleaved mode. The DC link voltage is held constant in order for the output inverter to have a smooth 3×400 V_{RMS} output voltage. The output voltage is filtered using sine and EMI filters and provides voltage supply quality in accordance with EN 50121-3-2:2006.

In this paper, focus is put on the input stage of the converter, so a more detailed schematic of the input stage is given in Fig.4.

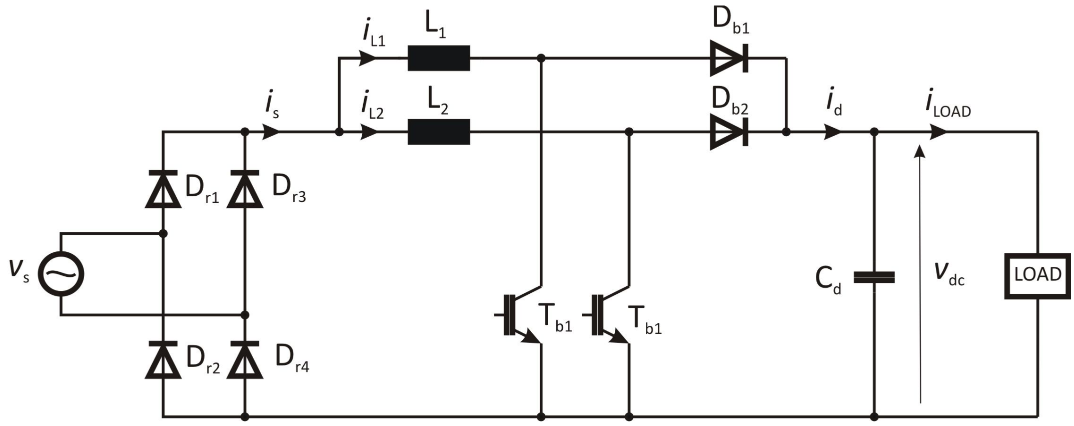

Fig. 4. Schematic of the two-cell interleaved boost converter

IV. CONTROL STRUCTURE

Since the primary objective of the control system of the boost converter is to stabilize output DC-link voltage, the obvious starting point for feedback controller is a single PI voltage regulator. The PI controller, based on the error signal from the outer voltage loop, together with the output from phase angle estimator, builds the reference current i_b^*. The inductor currents i_{L1}-i_{L2} are forced to follow the reference current i_b^*, which is proportional to the rectified fundamental component of the input voltage, so that near unity power factor is achieved. The bandwidth of voltage control loop should be much lower than the double line frequency (100 Hz). Otherwise, the inductor current waveform would be distorted and the higher harmonic components of the input current would be amplified or even new components would be injected via reference i_b^* (intermodulation with estimated fundamental grid frequency).

Simplified control structure of the input two-cell interleaved boost converter, implemented by DSP based module, is shown in Fig. 5.

All feedback signals are synchronously sampled, and all corresponding measuring chains feature auto-calibration (e.g. zero-offset adjustment) during startup of the converter. Offsets cancellation is particularly important, in order to minimize odd harmonics in input currents (otherwise injected by a possible raw implementation of the phase estimator and consequently the current controller). However, implemented modified EPLL, featuring sliding multiple DFT filtering at the input is immune to the DC offset in the input signal, thus resolving all related issues while retaining extremely robust and very high dynamic performance [1]-[3].

Since the input stage of the auxiliary power converter consists of two boost stages connected in parallel, current reference is common to both of them. Each current controller has its own respective current feedback loop, so each current controller determines desired duty-cycle.

Following the design guidelines from previous projects [1, 2, 4], duty-cycles for both phase-shifted PWMs are recalculated and readjusted after each execution of the cyclic program task (T=62.5 µs), resulting in true 16 kHz (2×8 kHz) dynamic behavior regarding the responses to step changes of the input voltage and/or the load (attached to the DC link).

The implemented feed-forward compensation ensures sinusoidal input current even in case of heavy disturbances in the input voltage waveform (Fig 6.).

All control, monitoring, conditioning and sequence handling is implemented on a newly developed DSP-FPGA core based embedded digital system controller [11].

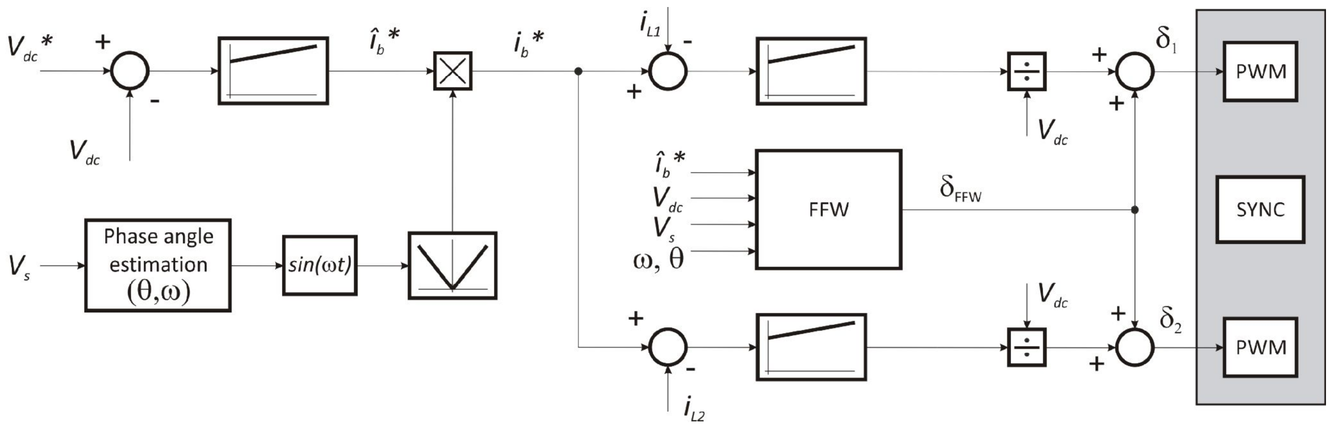

Fig. 5. Simplified block diagram of the implemented control structure

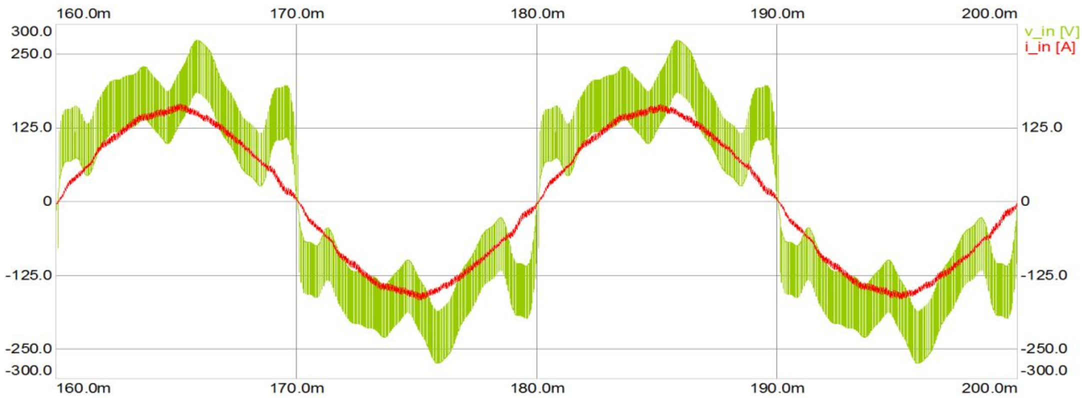

Fig. 6. Simulated voltage and current waveforms in case of heavily distorted input voltage

V. Principles Of The Proposed Feedforward Compensation

The converters input inductances, due to demands of minimum cost and weight, are kept as low as possible. In the considered case the input reactance is only an order of magnitude higher than the equivalent input impedance of the step down single phase transformer at the converter input. A simplified schematic of the considered circuit is shown in Fig. 7. As a result of low converter input reactance, the voltage on the secondary side of the step down transformer (25kV/230V), during converter operation, has significant harmonics at the effective switching frequency which results from the pulse-width modulated converter input voltage (Fig. 8). In case of interleaved operation, the fundamental frequency of the resulting voltage ripple can be higher than the fastest cyclic task used in the digital control system. This has to be taken into account when designing systems with discrete computing intervals in order to evade possible aliasing effects. Proper adjustment of the analogue section of the voltage measuring chain has to be performed.

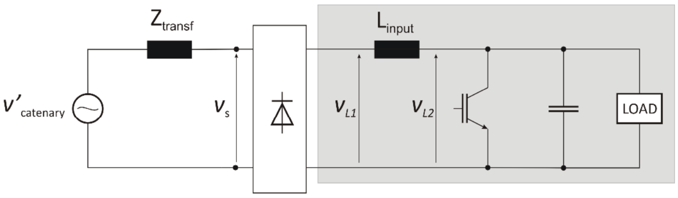

Fig. 7. Simplified schematic of the input circuit

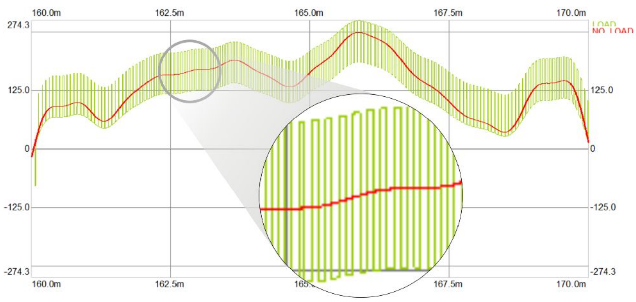

Fig. 8. Transformer secondary voltage with converter in operation (LOAD) and without converter (NO LOAD – straight line)

In Fig. 9 a block structure of the proposed feed-forward sheme is presented. The idea of feedforward compensation becomes obvious from Fig. 7. In the ideal case if voltage V_{L1} and are V_{L2} equal, then the current through L_{input} will be zero. If we apply a phase shift in the fundamental line component only (50 Hz), then we will have a sinusoidal current at the input of the converter (neglecting effects of the diode bridge and the current rise time defined by the inductor). In this ideal case, the voltage drop over L_{input} is a result of the fundamental component only. This part is shown in Fig. 9 in the shaded area. The estimated line frequency ω, the known inductivity of the input reactors L and the current reference $\hat{i}_b$* are used to estimate the fundamental voltage drop on the input reactor [1, 2, 3, 15].

For compensation of higher order harmonics in the input voltage $V_{L1,i}$ it would be necessary to form an equal counter voltage $V_{L2,i}$ for every ***i-th*** component. For the fundamental component of the converter input voltage v_s we have the relation:

$$v_s(t)=[1-\delta(t)]\cdot V_{dc};\quad \delta(t)=m\cdot\left|\sin(\omega t+\varepsilon)\right| \qquad (1)$$

Simulation results show that the same reasoning is valid also for higher harmonics as long as their period is at least 3 to 4 times higher than the switching period of the boost stage [4].

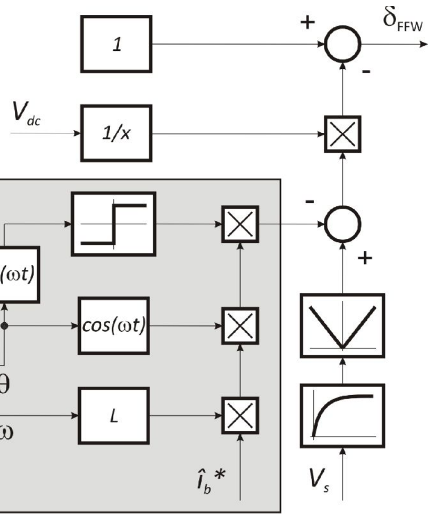

Fig. 9. Block structure of the implemented feed-forward control scheme

Of course, in order for this assumption to be true, converter parameters have to be chosen accordingly as to allow such dynamic changes. For example, if the inductivity of the input reactor is too high, then it is not possible to effectively track such dynamic changes (sometimes less is more!).

Practical implementation of the presented feed-forward compensation of higher line harmonics depends on the application and the given resources.

In railway applications on rolling stock the input voltage exhibits additional phenomena related to e.g. pantograph bouncing, section breaks, etc., that are not present in fixed applications. In such applications it is suitable to assess and control each dominant harmonic component separately using some sort of harmonic estimation [1, 2, 3]. In such applications the dynamics of the output stage of the converter can seriously influence the behavior of the input stage which is not the case in the presented situation. Additionally, as the power of the converter goes up, the switching frequency has to be reduced, so the number of harmonics that can be compensated is lower.

In the given case the input voltage V_s is filtered using an analog low pass filter and this signal is used for the feed-forward compensation of higher harmonics. The analog section was tuned so that aliasing effects are omitted and to allow a sufficient bandwidth for the feed-forward control.

Simulation results of the proposed control sheme are shown in Fig. 6.

VI. Experimental Results

Major parameters of the considered converter are presented in Table 2.

TABLE II. Boost converter prototype parameters

Circuit parameters	Value
Rated power	30 kVA
Rated input voltage	230 V over transformer (25kV/230V)
Minimum input voltage	160 V (equivalent to 17.5 kV of overhead line voltage)
Maximum input voltage	270 V (equivalent to 29 kV of overhead line voltage)
Minimum continuous input voltage	175 V (equivalent to 19 kV of overhead line voltage)
Maximum continuous input voltage	253 V (equivalent to 27.5 kV of overhead line voltage)
Input frequency	50 Hz ±5%
DC link voltage	680 V
Rated output voltage	3 ×400V / 230 V
Rated output frequency	50 Hz ± 1%
Switching frequency of one-cell	8 kHz

Actual input current and input voltage waveforms recorded at a testing site inside the factory are shown in Fig. 10. The voltage at the testing site is only slightly distorted (slightly trapezoidal shape), and from the figures it can be seen that the current remains sinusoidal.

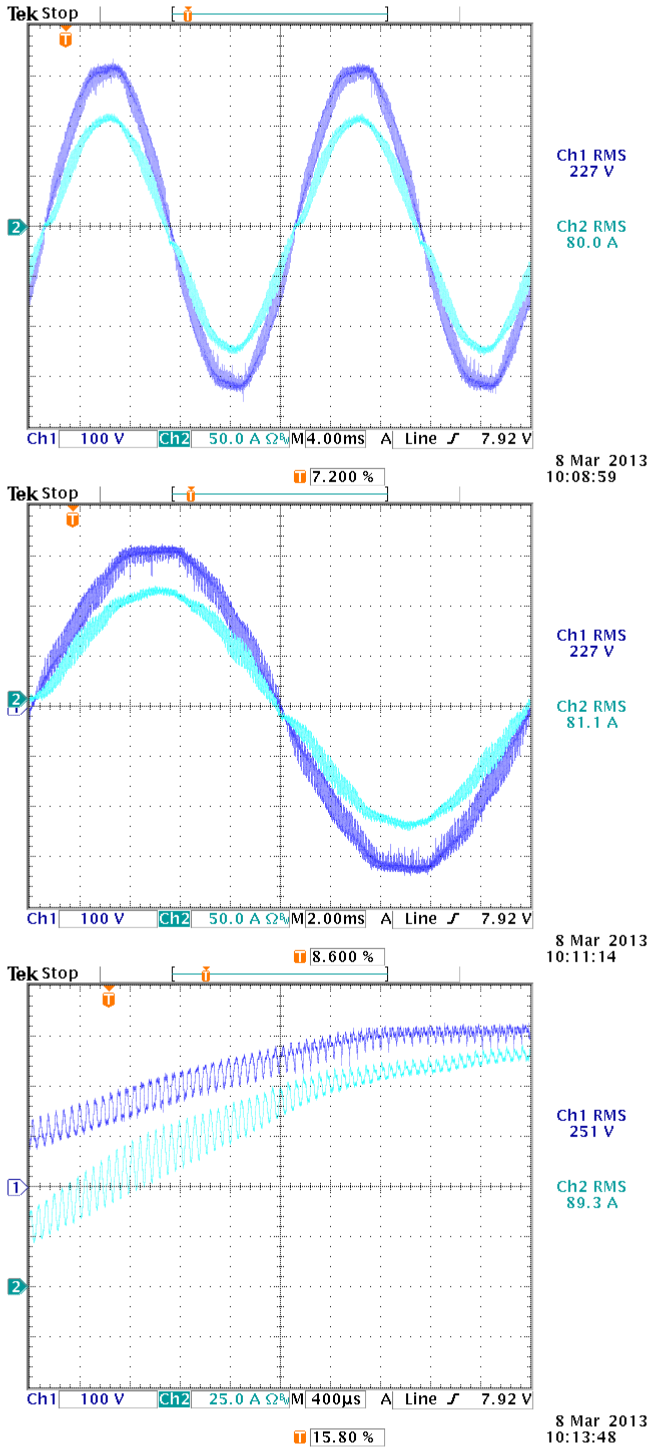

Fig. 10. Actual voltage and current waveforms recorded using prototype in the laboratory

VII. Conclusions

A newly developed converter for electric traction substations is presented. It is shown how interleaved operation of parallel input legs can lead to aliasing effects in the input voltage measurements when using discrete control structures. In order to avoid such effects, an analogue low pass filter has to be tuned to at least 2.5 times less than the resulting input switching frequency.

Feed-forward compensation of AC/DC type boost converters is discussed. It is shown how higher order harmonics can be effectively compensated using their actual value scaled by the DC link voltage as input signal for the PWM controller. It is shown that a reasonable bandwidth for feed-forward control is 3 to 4 times smaller than the switching frequency of each individual boost leg. Another boundary for feed-forward control is set by the converter parameters. In the presented case simply a filtered value of the measured input voltage is used as feed-forward signal. Application specific circumstances which allow such an approach are presented, and experimental results show the effectiveness of the presented solution.

Fig. 11. Disposition of equipment in trackside converter

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