Photovoltaic Converter Compatible with Real-Time Explicit Power Flow Control Framework for Micro-Grids

Evgenije Adǧiĺ, Marko Vekiĺ, Vlado Porobiĺ, Steva Grabiĺ, Milan Rapaiĺ, Zoran Ivanoviĺ, *Member, IEEE* , Lorenzo Reyes-Chamorro, *Senior Member, IEEE*

***Abstract*—This paper describes implementation of specific photovoltaic (PV) converter which is compatible with agent-based real-time explicit power flow control framework, called *COMMELEC*, proposed for future micro-grids in [1,2]. Developed converter is capable not only to track maximum power point, as conventional PV converters, but to realize specific active and reactive power, or power factor set-points which might be referenced very fast through communication network at 100 ms time-base or less. Main goal for using proposed PV converter interface within the COMMELEC organized micro-grid is to provide mechanism which supports maintaining power balance at all times (observed and influenced at 100 ms). Paper presents converter details about hardware, firmware and applied control algorithms, and at the end it gives test results obtained within working micro-grid demonstrator at *DESL Laboratory*, *EPFL*, Lausanne.**

***Index Terms*—Photovoltaics; Power Converters; Micro-grid; Smart-grid; Hardware; Control Software.**

I. Introduction

COMPARED to conventional power plants, electrical energy from renewables, like photovoltaic and wind power plants, is desirable from greenhouse gas emissions point of view. However, power output of such renewables can be highly intermittent, which is very different from conventional power plant where power production varies slowly with the time. High power volatility increases the uncertainty in distribution grid operation, which originally was not designed for supporting local and distributed power generation, and could negatively impact on power quality and power balance or even lead to blackouts [3]. One solution for mitigation of mentioned issues is to invest in grid enforcements. Increasing the grid capacity is usually unacceptably expansive, so todayĝs practice is to compensate high volatility of renewables by using a conventional fuel based generators. This is in contrary with the statement that installed renewables lead to reduction in greenhouse gas emissions.

Fortunately, these issues could be avoided by smart real-time control of power flows, which is provided by *COMMELEC* framework, proposed in [1,2]. *COMMELEC* is the control framework for managing power flows in distribution grid and it operates by explicitly controlling the generators, loads and storage elements in real-time. New control set-points are computed very fast, every 100 ms or less, due to the inertia-less resources in the system like *PV* plants, and in order to maintain grid stability.

In such framework, shown in Fig. 1, each resource in the grid is equipped with a resource agent. The resource agent performs two major tasks: verifies and shapes set-points from the grid agent before sending them to the converter, and translates the internal state of the resource into a device independent message format before sending it to the grid agent over the communication network. In such scenario, grid agent is independent on the device or resource type, and at all times aware of the grid state before taking control decisions. The device independent message format is used to inform the grid agent about the preferences of a resource and uncertainties in its operation. In particular, such preferences are expressed by means of a cost function which gives insight to the internal state of the resource.

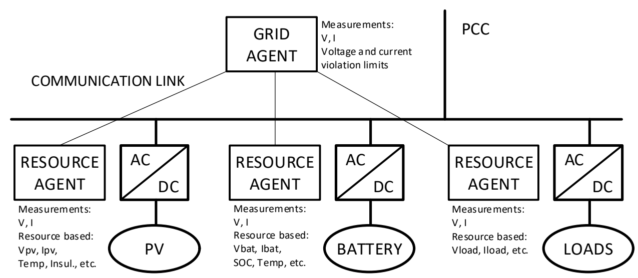

Fig. 1. Agent-based framework for real-time power flow control in distribution grid. Structure of *COMMELEC* based micro-grid demonstrator at *DESL* laboratory, *EPFL*, Lausanne.

Evgenije Adǧiĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: evgenije@uns.ac.rs).

Marko Vekiĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: vekmar@uns.ac.rs).

Vlado Porobiĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: poroba@uns.ac.rs).

Steva Grabiĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: grabics@uns.ac.rs).

Milan Rapaiĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: rapaja@uns.ac.rs).

Zoran Ivanoviĺ is with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradoviĺa 6, 21000, Novi Sad, Serbia (e-mail: zorani@uns.ac.rs).

Lorenzo Reyes-Chammoro is with the EPFL STI IEL DESL, CH-1015 Lausanne, Switzerland (e-mail: lorenzo.reyes@epfl.ch).

For example, a PV resource agent will continuously estimate available solar power based on the insolation, temperature, and other measurements or design and collected data. In the case of high insolation and low temperatures, PV resource might send to the grid agent a cost function that rewards the delivery of power, also taking into account voltage and line current violation limits in the grid determined by its construction. In that way, grid agent can compute optimal control decisions where the optimization criterion can be influenced by individual resources.

Fig. 1 also shows structure of *COMMELEC* based micro-grid working technology demonstrator at DESL laboratory, EPFL. It includes several devices such as the battery system capable of delivering up to 30 kW, load (heating system) emulator that can consume 10 kW per phase (independently), and a PV plant on the roof of the building (Fig. 2) which can cause a volatile power injection into the micro-grid of up to 20 kW. Focus of this paper is to give overview of 13 kVA *PV* converter laboratory system which is developed to meet specific requirements and to be compatible with above described micro-grid framework.

Fig. 2. PV plant on the roof of the DESL building at EPFL. Ultimate goal was to build specific power converter to make (part of) PV plant controllable in PQ-mode.

Paper is organized in five sections. First section gives short overview of micro-grid framework for which described *PV* converter was built. Second and third section gives hardware and firmware details of the converter. In fourth section, shown test results for converterôs characteristic regimes verify its operation and functionality according to set requirements. Finally, paper ends with the conclusions.

II. Hardware Details

The target requirement was to connect four independent groups of *PV* panels to the standard distribution grid 3x400 V, 50 Hz. First and second *PV* strings consists of 14 *PV* panels, and third and fourth strings have 12, and 11 *PV* panels connected in series, respectively. All *PV* panels are EC Solar Wuxi ECS-255P60 with following nominal parameters: P_n = 165 W, V_{oc} = 39 V, I_{sc} = 8,9 A (@1000W/m^2, T=25^{0}C). This gives PV plant nominal power of 8,5 kW, but taking into account insolation and temperature influence converter, and eventual future upgrade it had to be designed for continuous 13 kW operation.

Block diagram of implemented power converter is shown in Fig. 3. The core of the complete device represents two programmable three-phase power converter platforms, called *LARA* (power electronics ***LA****unch* ***RA****mp*), and coupled through the common DC link. Base of used programmable converter platforms is standard industrial three-phase power converter Hyundai N700, originally made for AC motor drive. In this way, safety regarding high voltages and high currents and related electronics was maintained, simultaneously keeping final converter compact as the original industrial drive. Standard converter power of 15 kW was selected; even that maximal designed *PV* power was 13 kW, considering that voltage level at the output of grid side converter was reduced from nominal value 400 V to 330 V by coupling transformer (within *Grid Wiring Circuit*) and considering converter nominal current capability. Reduction of the voltage level was needed, taking into account DC bus voltage constraints and voltage drop across coupling elements, especially in the case of reactive power generation. For nominal reactive power flow of 13 kVAr and used coupling transformer and inductance parameters, 700 V reference was selected for DC bus voltage reference, which lead to 330 V grid voltage level. In that case, voltage modulator linear operation and enough reserve in voltage (20%) for controlling the grid currents were achieved, even in the case of 15% grid overvoltage condition.

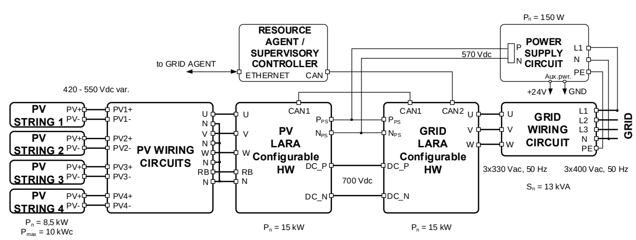

Fig. 3. Block diagram of implemented photovoltaic converter. Core of the device represents two identical configurable power converter platforms, called *LARA*, which are specifically programmed as four-phase interleaved boost converter (*PV LARA*) and three-phase grid-connected converter (*GRID LARA*).

Only small modifications to original power stage were made. Due to the requirement that the converterôs controller had to be functional even in cases when there is a grid disconnection due to an error triggering, inner power supply board for low-power electronics was disconnected from DC bus and supplied externally through independent *Power Supply Circuit* as shown in Fig.3. Besides that, considering *PV* side converter, default current measurement circuit gain is adopted by modifying number of wire turns around built-in LEM current sensors to extend range of the *PV* current measurement voltage signal and reduce noise sensitivity. Power stage of the Hyundai N700 converter applied as part of implemented *PV* and grid side converters is shown in Fig. 4a.

Industrial power stage was upgraded with four different types of interface boards, which altogether completes *LARA* converter shown in Fig. 4b. Developed set of interface boards which made industrial drive configurable and programmable is shown separately in Fig. 5. *Mainboard* is the main interface board between plugged-in TMS320F28835 DIMM100 control card and the power stage. *Communication* board contains two isolated *CAN* (*Control Area Network*) interfaces which provided communication between PV and grid side *LARA* converters, and also between master grid side *LARA* converter and dedicated *Resource Agent* controller. *Application* board was used for isolated high-voltage measurement. *PV* strings and three-phase grid voltages are conditioned from range -800 V - +800 V to 0 ï 3 V at the controller analog inputs. General Purpose Input / Output (*GPIO*) board is used for controlling power contactors states and signaling LEDs, and for accepting user commands through cabinetôs switches and buttons.

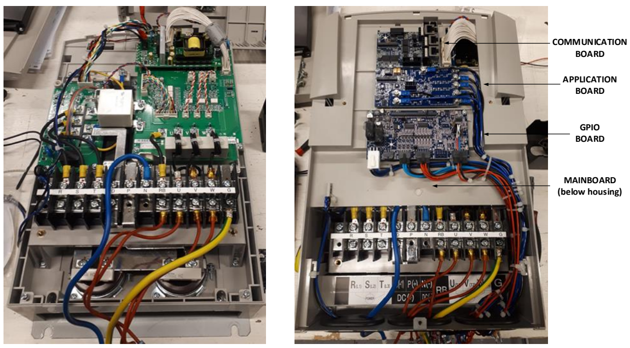

Fig. 4. a) Power stage of Hyundai N700 industrial motor drive; b) Modification to *LARA* programmable power converter platform used for implementation of *PV* side and grid side converters.

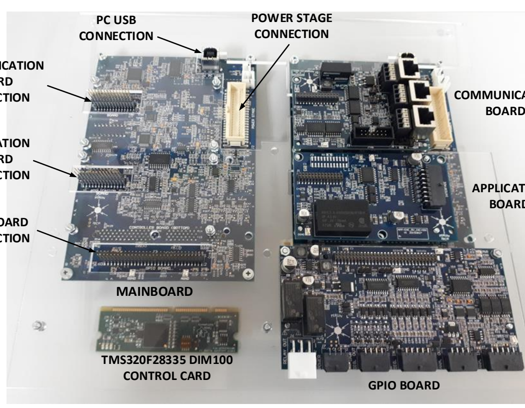

Fig. 5. Set of interface and control boards to modify standard industrial drive into configurable and programmable power converter *LARA*.

PV strings are coupled to the *PV* side converter through a *PV Wiring Circuit*. Layout of the *PV Wiring Circuit* is shown in the Fig. 6. It consists of: overcurrent and overvoltage protection, high-frequency current filter, coupling power contactor, measured *PV* voltage connections and coupling inductance which enables converter operation in *Boost* converter mode. Specially, for fourth *PV* string there is a current measurement and overcurrent detection circuit. Namely, fourth *PV* string is connected to the converterôs breaking chopper circuit which originally doesnôt have accompanying built-in current measurement. Current of fourth *PV* string is measured through *GPIO* board analog input interface. That enabled operation of the *PV* side *LARA* converter as a four-phase interleaved *Boost* converter. Boost inductances were designed to provide *PV* converter efficient operation even in the case of very low insolation in the range 150- 200 W/m^2.

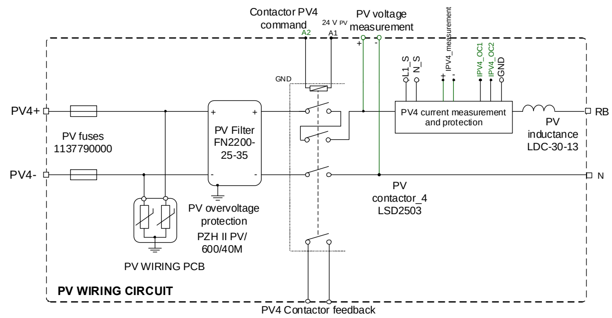

Fig. 6. Schematic of PV wiring circuit for individual PV string connection.

Connection to the grid is done through *Grid Wiring Circuit* shown in the Fig. 7. It includes following elements: overcurrent and overvoltage protection, grid current high-frequency filter, grid power contactor, pre-magnetizing/charging power contactor and in-rush current limiting resistors, coupling transformer, signaling LEDs for grid presence, measured three-phase grid voltage connections and coupling inductances with grid side *LARA* converter.

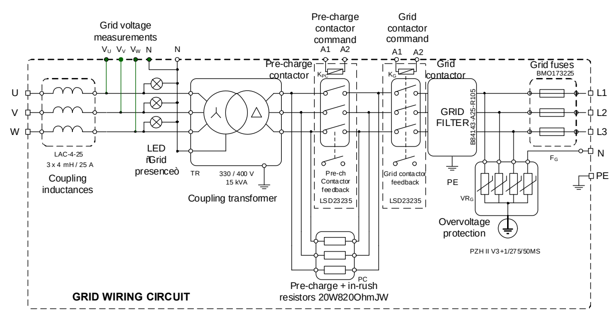

Fig. 7. Schematic of *Grid Wiring Circuit* for connection to the grid.

Layout of the finalized and completed *PV* power converter is given in Fig. 8. Main components which are previously described are designated as following:

1. Grid side *LARA* converter. It is programmed with voltage oriented control (*VOC*) algorithm to operate as grid-connected three-phase converter.
2. *PV* side *LARA* converter. It is programmed to operate as four-phase interleaved Boost converter with advanced control algorithm. It provides not only maximum power point tracking (*MPPT*), but also explicit power control.
3. Resource agent controller. It is based on LabViewôs *cRIO* system which implements requirements set by *COMMELEC* control framework.
4. Grid coupling inductances.
5. *PV* Boost converter inductances.

6. Power supply circuit. It provides power to electronic circuits within both *LARA* converters, independently of grid and *PV* strings connections. More safe and deterministic operation of complete converter is achieved, especially during error state triggering.
7. *PV* strings coupling power contactors.
8. Grid and pre-charging power contactors, and in-rush current limiting resistors. In-rush current limiting resistors role is to limit transformerĝs turn-on magnetizing current and also to limit DC bus capacitors charging current in the initial phase during building DC bus voltage.
9. Batteries (24 V) which provide auxiliary power supply for power contactors, also for the sake of more safe and deterministic turn-off during error detection, and to avoid possible DC bus overvoltage.
10. Coupling transformer. It performs galvanic isolation between the grid and *PV* strings, and also required voltage translation from 400 V at distribution grid side to 330 V at the converter side.
11. Front panel of converter cabinet. It allows manual control of the converter state by following pushbutton commands: turn-on/off, start/stop control, and manual error set/reset. Signalization of the converter states is also provided.

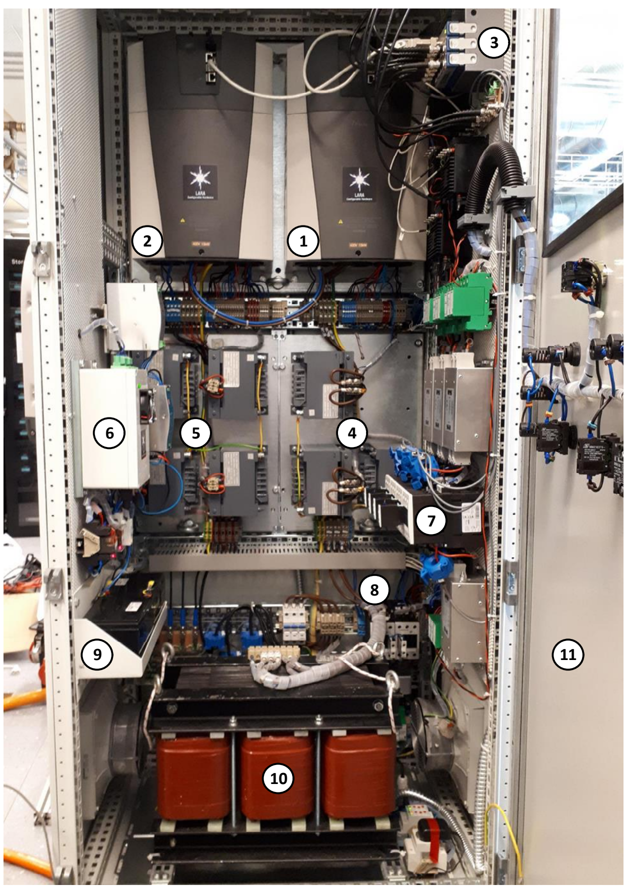

Fig. 8. Overview of developed *PV* converter and its hardware components.

III. Firmware Details

Developed firmware for controllers of both *LARA* converters can be divided according to Fig. 9 to following layers: state machine, control, communication and protection.

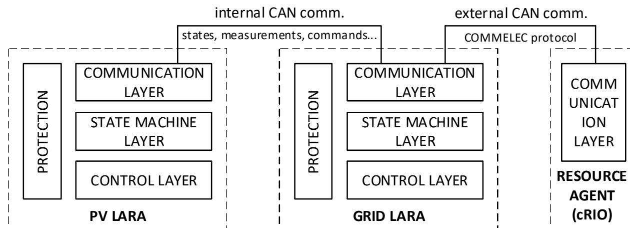

Fig. 9. Overview of the developed PV converter firmware structure.

Based on the converter actual state and user inputs, received either manually from cabinets control panel or automatically from *Resource Agent* supervisory controller, it defines transitions to next states and accompanying higher-level commands. All states and transition conditions (commands) are shown in the Fig. 10. There are four inactive states: *IDLE, BUSY, READY* and *ERROR*, and four active states: *TRACKING_Q*, *TRACKING_MPPT*, *TRACKING_PQ*, and *TRACKING_PPF*. Active states reflect operating regimes of the converter. In *TRACKING_Q* state converter operates as a STATCOM device by controlling only the reactive power flow. PV strings are disconnected in this mode. In *TRACKING_MPPT* state converter tracks maximum power point for given insolation and other working conditions. Two different explicit power flow control regimes are available. In *TRACKING_PQ* state converter accepts and implements explicit active and reactive power setpoints, while in *TRACKING_PPF* it tracks active power and power factor references.

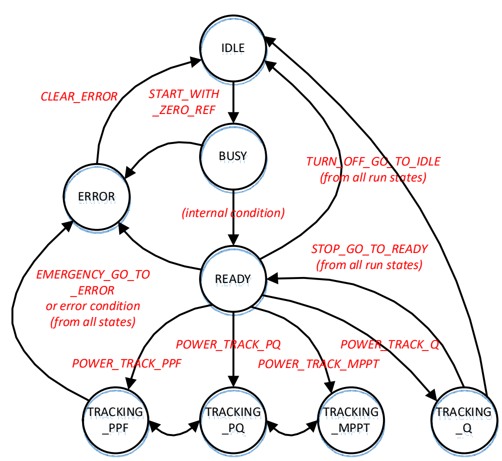

Fig. 10. PV converter states and state transition conditions/commands.

Control part is the core of the complete firmware, and it implements low-level control of the converter. Based on the measured feedback signals it implements dedicated control algorithm and generates PWM signals for controlling the converter switches. For example, grid side *LARA* converter implements standard grid-voltage vector oriented control (*VOC*) algorithm [3], and PV side *LARA* implements modified perturbation and observation (*P&O*) algorithm which allows explicit power reference tracking [4]. The *Resource Agent* sets P and Q references. The power reference is sent to the *Grid LARA*, which is responsible for regulating the DC bus voltage and the reactive power injection. The *PV LARA* is in charge of injecting the required amount of active power. The overview of control structure of the *PV LARA* is presented in Fig. 11. The power reference P_{ref} is firstly modified taking into account correction look-up table and then distributed among the PV strings, based on the ratio between the string nominal power and total nominal power of all strings. Correction look-up table is obtained during the converter test phase in order to take care of converter power losses for various P-Q setpoints, and in order to have output power equal to the referenced values. Then, the proposed algorithm decides on the next duty-cycle for each *PV LARA* converter leg (D_U, D_V, D_W, and D_{RB}), taking also into account measured string currents and voltages.

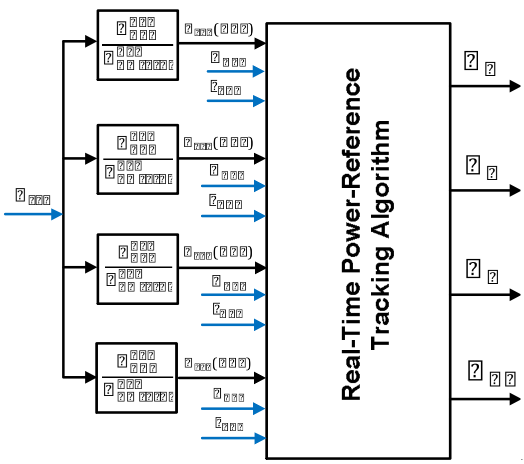

Fig. 11. PV side converter general control structure.

Communication part implements *CAN* communication protocol for internal communication between master *Grid LARA* and slave *PV LARA* systems, and also external communication between slave *Grid LARA* and master *Resource Agent* controller. It is realized as specific *CAN Mailbox IDentifier* based protocol. For example, device sends through external *CAN* communication link its state every 50 ms through mailbox ID 0x19 with 1-byte data (Byte 0) containing state code. On the other hand, device receives states transition commands in continuous loop through mailbox ID 0x18 with 8-bytes data containing command code. Interchanged messages are updated every 50 ms, due to the requirement of real-time control in *COMMELEC* based micro-grid at 100 ms or smaller time-base. Besides state and command messages there are also setpoint, measurement, error and alarm types of messages connected to particular *CAN* mailbox IDs, number of bytes and data positions.

IV. Experimental Results

In this section experimental results are shown which verifies converter operation in PQ mode. This is most characteristic regime of implemented PV converter, where user set independently active P and reactive Q power references. All presented results regarding grid voltages and grid currents are recorded using LeCroy oscilloscope, and controller variables are obtained using dedicated *LARA PowerDesk* software running on the PC connected to the converter (*Grid LARA Mainboard*) through *USB* connection.

Fig. 12 represents active power transient response, measured at the secondary of transformer (at converter side) after sending active power reference 8000 W, together with reactive power reference set to 0 VAr. Previously, it was determined in MPPT operational mode that for given moment and working environmental conditions there was available solar power of 9500 W. Settled stationary value of measured active power was around 8200 W, as seen in Fig. 12. However, measured active power by *Chauvin* power analyzer at the primary side of transformer, i.e. at the grid side, proved that 8000 W of active power was injected. In this case, active power losses on the coupling elements were around 200 W. *Chauvin* power analyzer was used for fine system calibration and determination of previously described correction look-up table. Important is to notice that active power settling time is around required 100 ms.

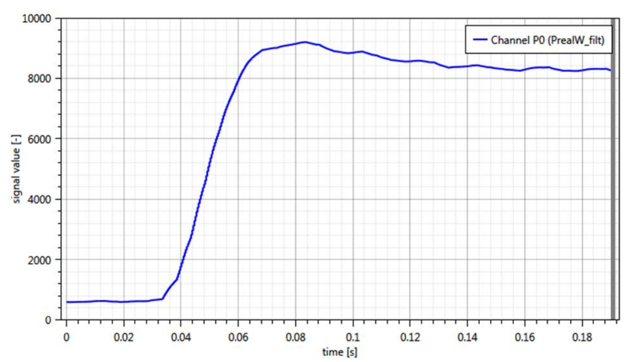

Fig. 12. PV converter active power response in PQ operational mode for Pref = 0-8000 W and Qref = 0 VAr.

Corresponding grid voltage and current waveforms, measured at the distribution grid side, are presented in Fig. 13. Only one grid phase voltage and all three grid line currents are shown. In stationary state there is an phase alignment of grid phase voltage and corresponding grid line current, indicating that it is related to active power flow. Amplitudes of obtained line currents were around 16,3 A, which corresponds to power flow of 8 kW at 400 V.

PV string currents and PV voltages are given in the Figs. 14 and 15. Only currents and voltages of two PV strings, PV string 1 consisting of 14 PV panels and string 4 consisting of 11 PV panels, are shown. One can note, as power is getting closer to reference value, PV current is increasing and voltage is decreasing according to the negative slope of current-voltage operational part of PV characteristic. Stationary current values were 5,2 A and 5,6 A, and voltage values were 460 V and 355 V for PV strings 1 and 4, respectively. It corresponds to around 2,4 kW and 2 kW of DC power flow. Time response is around 50 ms, and within set requirements.

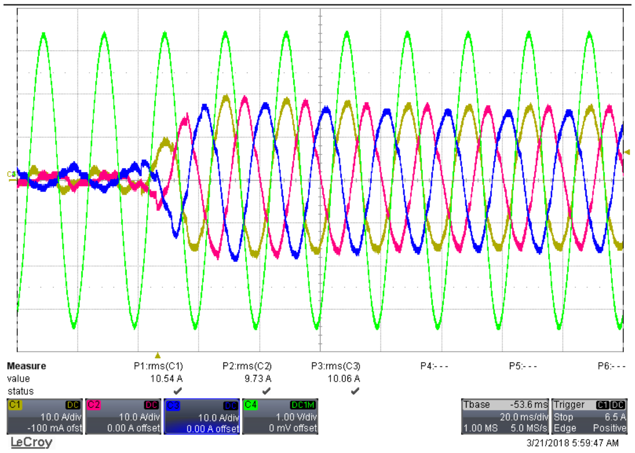

Fig. 13. PV converter grid voltage and current waveforms during active power transient in PQ mode for Pref = 0-8000 W and Qref = 0 VAr.

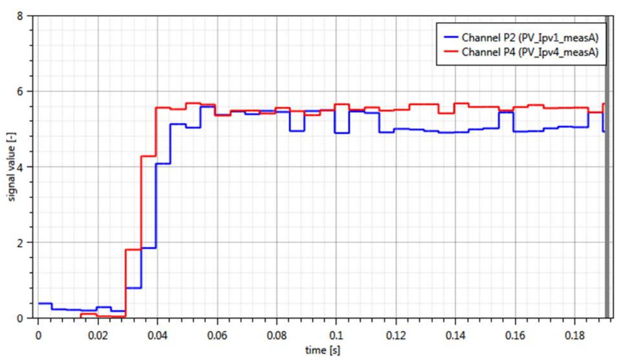

Fig. 14. Measured currents of PV strings 1 and 4 during active power transient in PQ mode for Pref = 0-8000 W and Qref = 0 VAr.

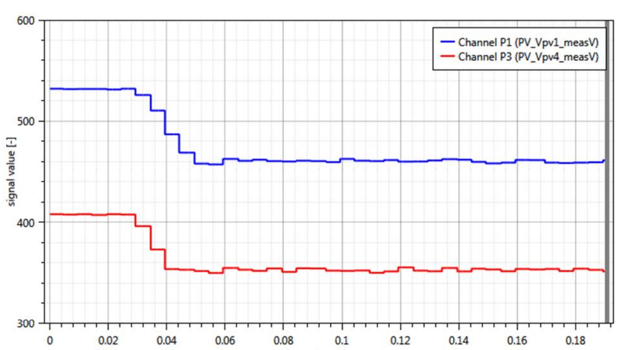

Fig. 15. Measured voltages of PV strings 1 and 4 during active power transient in PQ mode for Pref = 0-8000 W and Qref = 0 VAr.

Corresponding DC bus voltage response is presented in the Fig. 16. Referenced DC bus voltage is 700 V. One can note that this value is maintained within 100 ms. Due to the active power flow from PV side, DC bus voltage jumped to the value of 726 V, which is still considerably lower then set DC bus overvoltage limit 790 V.

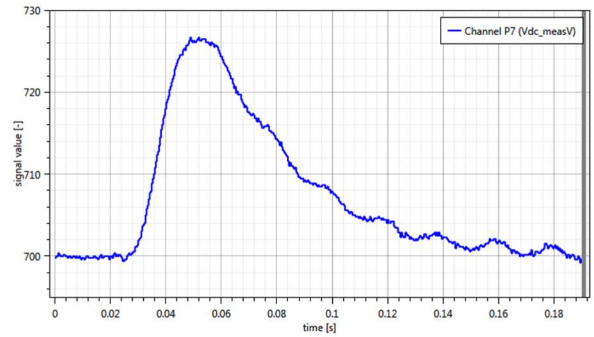

Fig. 16. DC bus voltage response during active power transient in PQ mode.

V. Conclusion

Active distribution networks and micro-grids require flexibility from energy sources for achieving a stable and smooth operation, particularly in the case where almost no inertia is present. In order to achieve such level of flexibility, specialized power electronics converters need to be employed. Therefore, in this paper a specific PV converter compatible with previously proposed real-time explicit power flow control framework suitable for future micro-grids is presented. Overview of hardware and firmware details related to the implemented PV converter is given. The main advantage of described converter comparing to standard MPPT converters is that it can operate in PQ control mode without any a-priori knowledge of PV panel characteristics. Experimental results proved efficient operation in required PQ mode.

Acknowledgment

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References

[1] A. Bernstein, L. Reyes-Chamorro, J.-Y. Le Boudec, M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part I: Framework", Electric Power Systems Research, vol. 125, pp 254-264 August 2015.

[2] L. Reyes-Chamorro, A. Bernstein, Jean-Yves Le Boudec, M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part II: Implementation and validation", Electric Power Systems Research, vol. 125, pp. 265-280, August 2015.

[3] Q. Zhong, T. Hornik, *Control of Power Inverters in Renewable Energy and Smart Grid Integration*, Chichester, UK: Wiley 2013, p.4.

[4] M. Vekiĺ, V. Porobiĺ, S. Grabiĺ, E. Adžiĺ, C. Zogogianni, " Explicit Active Power Reference Tracking Algorithm for Photovoltaic Converter ", 2017 International Symposium on Power Electronics (Ee), Novi Sad, 2017, pp.1-6.