# A Stationary Reference Frame Current Control for a Multi-Level H-Bridge Power Converter for Universal and Flexible Power Management in Future Electricity Network

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*Abstract* — **More "green" power provided by Distributed Generation will enter into the European electricity network in the near future. In order to control the power flow and to ensure proper and secure operation of this future grid, with an increased level of the renewable power, new power electronic converters for grid connection of renewable sources will be needed. These power converters must be able to provide intelligent power management as well as ancillary services. This paper assesses a control method based on the stationary reference frame with Proportional-Resonant current controllers for a multi-level cascaded H-bridges power converter used for grid applications. The proposed method is tested in terms of harmonic content in the Point of Common Coupling (PCC), voltage amplitude and frequency excursions as well as system response for bidirectional power flow.**

*Keywords* — **Distributed Generation and Renewable Energy Systems; Power Quality and Utility Interface Issues; Converter Control Techniques; Modeling, Analysis and Simulation.**

## I. Introduction

The establishment of a new paradigm for electricity networks in Europe in which there is large-scale integration of distributed energy resources is major element of the key strategic objective of the EU to secure a supply of energy that is clean, sustainable and economical [1]. The impact of this will be to reduce the dependence on fossil fuels and to reduce climate change and pollution, which are of concern to all humanity. In the new system, large numbers of small and medium sized generators and energy storage elements are interconnected through a fully interactive intelligent electricity network.

In order to reach this goal, the entire architecture of the electricity network must be redesigned and the Information and Communication Technologies (ICT) will be the key factor [3]. New features added by ICT and ICT-based applications such as universal connectivity, services over internet and web, distributed intelligence, advanced fault handling, intelligent load shedding, etc. will transform the existing electrical grid into a smart one.

Different architectures of the future electricity systems have been proposed during the last years [1] e.g. micro-grids, the "Internet" model and Active Networks supported by ICT. However, the last mentioned grid architecture seems to be the natural evolution of the current passive networks [1]. These active networks can provide an increased connectivity and an intelligent control of the power flow over the network. Also, they may be the best way to facilitate Distributed Generation (DG) initially in a deregulated market. Though, in order to make possible the implementation of the active networks as well as a large integration of DG power electronics based solutions are recognized as "critical components of a future grid control infrastructure" [1].

The work presented in this paper is part of a research project (Uniflex-PM) supported by the European Community under the 6$^{th}$ Framework Programme with focus on the development of key enabling technologies to reach the DG objectives. The main objectives in this project are to research and experimentally verify new, modular power conversion architecture for universal application in the Future European Electricity Network. The target is to establish technology that provides lower cost power electronics to network architects and owners and facilitates the connection of a broader range of distributed generation sources [4].

## II. High power/high voltage Power Converters for Grid Connected Applications

Several topologies, originated from drives applications have been proposed during the last years for medium and high voltage grid applications. These topologies cover a wide range of applications e.g. FACTS, STATCOM, DVR, UPFC, IPFC, DC Transmission Systems, etc as well as the grid connection of renewable sources [5]-[8]. Most of these applications are based on the two-level voltage source power converter topology [6], [8].

However, due to advances in power semiconductor devices, particularly in the IGBT technology, there is an increasing interest in the last years, in multi-level power converters especially for medium to high-power, high-voltage [5]-[8]. Since the development of the neutral-point clamped three-level converter [9], [10] several alternative multilevel converter topologies have been reported in the literature that can be classified in the following five categories as presented in Figure 1 [8], [11], and [12].

In order to extend the applicability of the multi-level converters to higher voltage/higher power applications the interconnection of multi-level structures is proposed in [13].

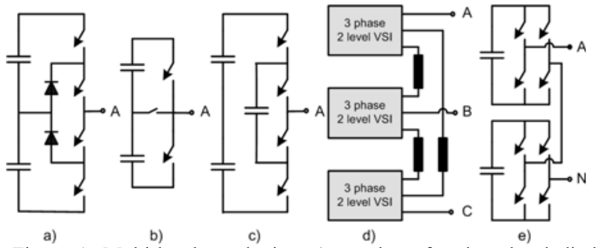


Figure 1. Multi-level topologies: a) one leg of a three-level diode clamped converter; b) one leg of a three-level converter with bidirectional switch interconnection; c) one leg of a three-level flying capacitor converter; d) three-level converter using three two-level converters and e) one leg of a three-level H-bridge cascaded converter.

Three topologies are of interests for these multi-level multi-cellular converters namely: the diode-clamped circuit (Figure 1a), the flying capacitor circuit (Figure 1c) and the series isolated H-bridge circuit (Figure 1e) [13]. These topologies are the basic "building blocks" for the multi-cellular power converter.

The generalized structure for such a three-phase multi-cellular converter is shown in Figure 2 [13].

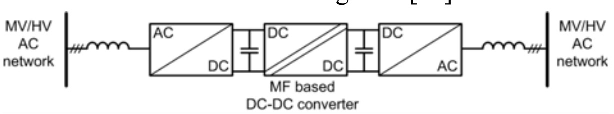


Figure 2. Generalized multi-cellular power converter structure.

The topology consists of two AC to DC power conversion stages and a DC to DC conversion stage based on Medium Frequency (MF) transformer to achieve the galvanic isolation between the AC terminals. Using the basic "building blocks" many possible implementations are possible [13].

## III. UNIFLEX-PM SYSTEM

The main target of the Uniflex-PM system is to provide a universal and flexible power electronic interface for grid connection of DG including storage facilities [14]. A possible structure of a three-port Uniflex-PM system used for grid integration of the DG into MV networks is shown in Figure 3.

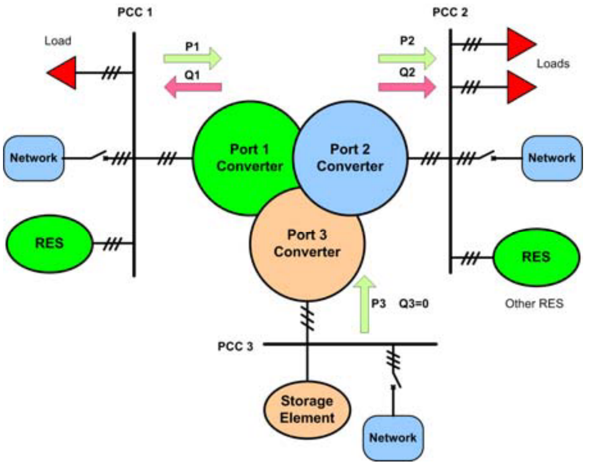


Figure 3. Structure of the Uniflex-PM system for grid integration of DG including storage facilities.

Each port can be connected at different voltage levels. A multi-level cascaded H-bridge topology has been selected for the implementation of the Uniflex-PM system. A two port based structure with three series power modules per phase is considered in the analysis, as shown in Figure 4.

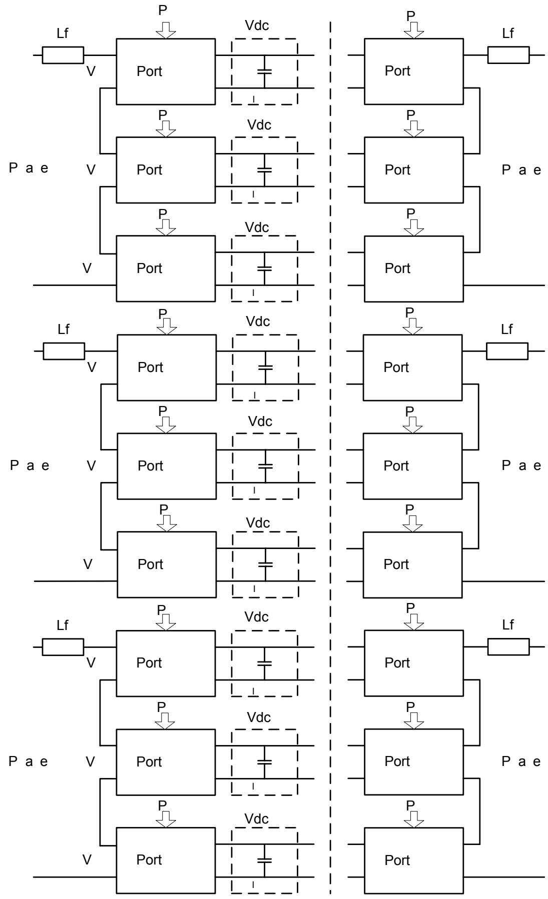


Figure 4. Two port structure of the Uniflex-PM with DC-link interleaving.

This system must be able to support bi-directional power flow in all ports and basically should comply with most of the existing grid codes for connection of DG in terms of power quality, active and reactive power control abilities and low voltage ride-through capabilities. Therefore, the converter control is one of the key elements in achieving the increasing interconnection requirements of the DG into the MV networks.

Since the isolation module (IM) for each branch has an independent control an equivalent capacitor is used instead. Thus, just the AC to DC modules are used in this paper.

The structure of a single phase H-bridge cell is shown in Figure 5.

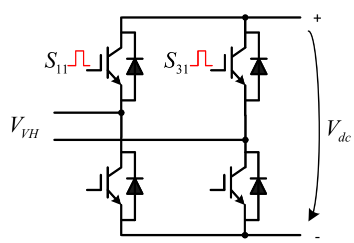


Figure 5. Structure of a single phase H-bridge cell.

In order to balance the DC voltages and to allow power exchange between phases the interleaving of the DC-link circuits is also considered for this Uniflex-PM system. A chart with the connection of the DC-link circuits for Port 1 and Port 2 is given in Table 1.

A horizontally phase-shifted multicarrier modulation is used for the Uniflex-PM system.

Table 1. Connection chart of the DC-link circuits for the two port system (in connection with Figure 4)

| Port 1 | Connection | Port 2 |
|---|---|---|
| Port 1 A1 | → | Port 2 A1 |
| Port 1 A2 | → | Port 2 B1 |
| Port 1 A3 | → | Port 2 C1 |
| Port 1 B1 | → | Port 2 A2 |
| Port 1 B2 | → | Port 2 B2 |
| Port 1 B3 | → | Port 2 C2 |
| Port 1 C1 | → | Port 2 A3 |
| Port 1 C2 | → | Port 2 B3 |
| Port 1 C3 | → | Port 2 C3 |

## IV. Control strategies for the Uniflex-PM System

Different control strategies are under consideration for the Uniflex-PM system e.g. synchronous reference frame with PIR controllers, stationary reference frame with Proportional Resonant (PR) controllers, natural reference frame control (ABC) and predictive control. All these control methods are evaluated in terms of power quality, response to unsymmetrical and unbalance voltages in the network, low voltage ride-through capabilities, grid support during the faults, etc. In this paper a control strategy based on the stationary reference frame with PR current controllers is presented as shown in Figure 6. The stationary reference frame controller has been chosen as a possible alternative to the “classical” synchronous reference frame control due to the fast current control provided by PR controllers. Thus, the Uniflex-PM system can increase its dynamic response under different grid events or sudden change in the power flow.

As it can be noticed from Figure 6, this control includes PR current controllers. The PR controller has been chosen due to the fact that it gives better performances compare to the classical PI. The two well known drawbacks of the PI controller (steady-state errors and poor harmonics rejection capability) can be easily overcome by the PR controller. The PR controller is able to remove the steady-state error without using voltage feed-forward, which makes it more reliable compared with the “classical” synchronous reference frame control. However, a three-phase PLL (Phase-Locked Loop) system is used to obtain the necessary information about the grid voltage magnitude and its angle.

In order to support the bidirectional power flow through the system, the current reference in *d*-axis is obtained based on the active power set-point and the average voltage (provided by PLL) and a correction given by the DC-link voltage control loop. This controller controls the average value of the nine DC links as presented in Figure 4. The reactive power is controlled using a PI controller which provides the current reference in the *q*-axis. One of the drawbacks of this control is the transformation of the control variables from synchronous reference frame to the stationery one. Based on the grid voltage angle the current references in synchronous reference frame are transformed into the stationary frame and then applied to the PR current controllers.

## V. Study cases

The two ports of the Uniflex-PM system, as shown in Figure 4, have been simulated using the MATLAB-Simulink environment in order to test the effectiveness of the chosen control strategy. The control strategies and the PWM generators of the Uniflex-PM system has been implemented using Simulink discrete S-functions while the grid and converter models have been implemented using PLECS toolbox in continuous time domain.

The considered control strategy is evaluated in different grid conditions and situations. The following study cases are presented in this paper in order to evaluate the proposed control strategy:

Case 1: Reverse power flow between Port 1 and Port 2 and leading/lagging operation at 0.9 power factor in Port 1;

Case 2: Reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1;

Case 3: Reverse power flow between Port 1 and Port 2 and phase jumps of ± 60° in all phases at Port 1;

Case 4: Reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1.

For all the simulations presented in the following, an inductance of 16 mH has been used as output filter of the each phase of the Uniflex-PM system.

The switching frequency per H-bridge (as shown in Figure 5) was set to 300 Hz. The sampling frequency of the control was set to 5 kHz. The PR controller was tuned in order to give a standard damping ratio of 0.7. The root-locus and the open-loop Bode diagram of the current loop are presented in Figure 7.

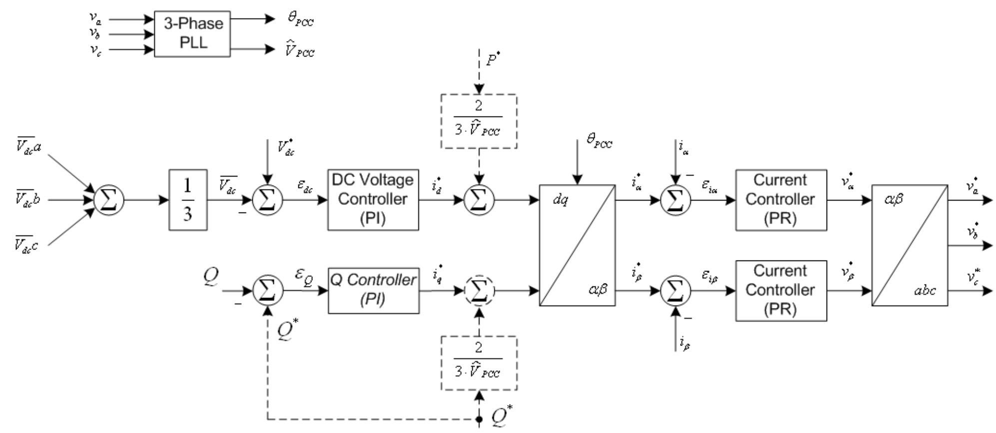


Figure 6. Stationary reference frame control strategy with global DC-link voltage control for the UNIFLEX-PM system.

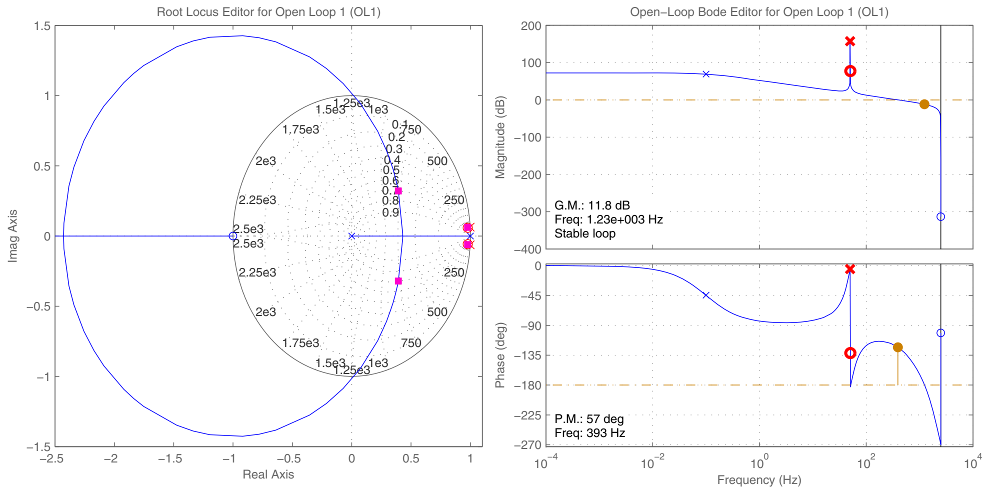


Figure 7. Root-locus and the open-loop Bode diagram of the current loop including the PR controller.

The step response of the current loop is shown in Figure 8. In the Case 1, a reverse power flow is simulated using a profile as shown in Figure 9.

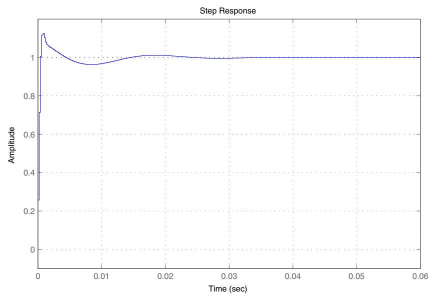


Figure 8. The step response of the current loop using PR controllers.

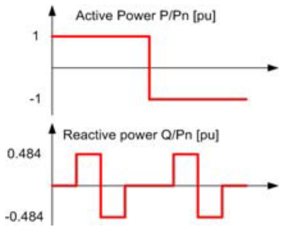


Figure 9. Case 1 - Reverse power flow between Port 1 and Port 2 and leading/lagging operation at 0.9 power factor in Port 1.

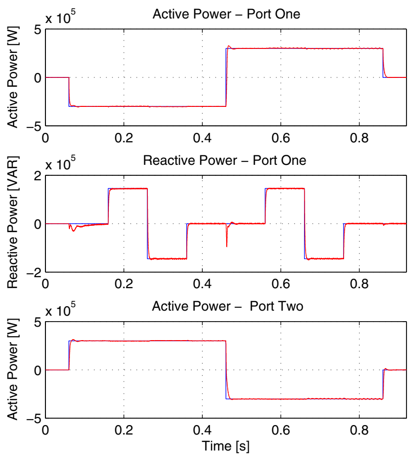


Figure 10. Case 1 - Reverse power flow between Port 1 and Port 2 and leading/lagging operation at 0.9 power factor in Port 1.

This also corresponds to a leading/lagging operation at 0.9 power factor. The response of the system for Case 1 in Port 1 and Port 2 can be seen in Figure 10.

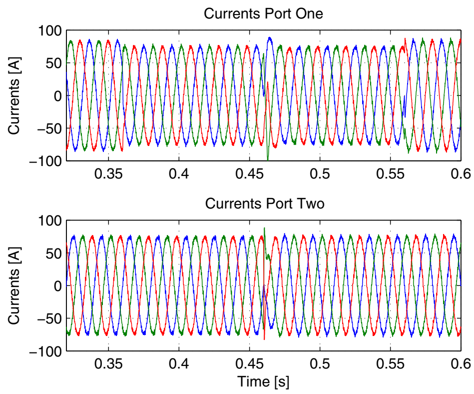


Figure 11. Case 1 – Currents in Port 1 and Port 2.

The currents in Port 1 and Port 2 at reversing power are shown in Figure 11. As it can be noticed, a good transient response is obtained at reverse power flow. The DC voltage overshoot at reverse power is about 1.1% of nominal value as shown in Figure 12.

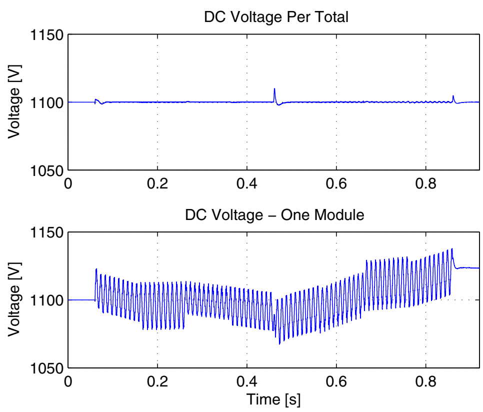


Figure 12. Case 1 - DC-link voltage response.

The start up currents and PWM voltages in Port 1 and Port 2 are presented in Figure 13 and Figure 14, respectively. As it can be noticed, a fast current controller response is obtained using the proposed control strategy.

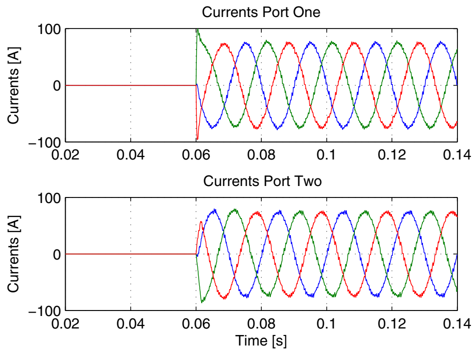


Figure 13. Case 1 – startup currents in Port 1 and Port2.

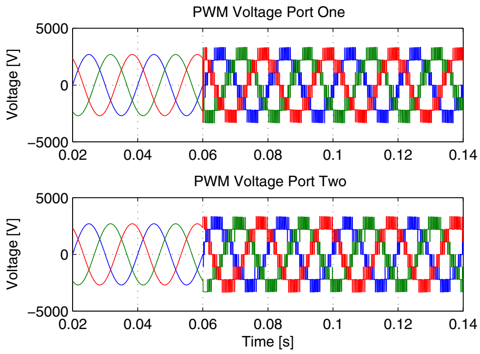


Figure 14. Case 1 – startup PWM voltages in Port 1 and Port2.

In the Case 2, a reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1 are simulated using a profile as shown in Figure 15.

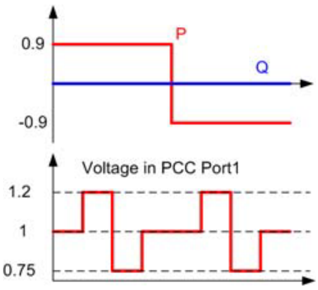


Figure 15. Case 2 - Reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1.

The response of the system for Case 2 in Port 1 and Port 2 can be seen in Figure 16.

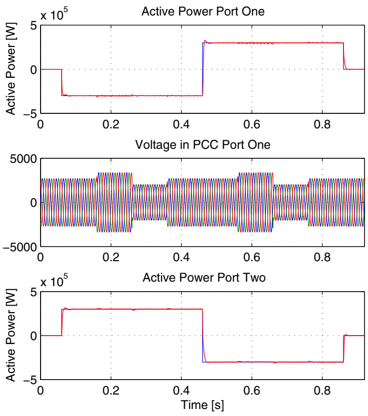


Figure 16. Case 2 - Reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1.

The currents in Port 1 and Port 2 are shown in Figure 17. As it can be noticed, a good track of the active power is obtained at voltage excursions of 75% and 120%. The DC voltage overshoot at voltage excursions is about 1% of nominal value as shown in Figure 18.

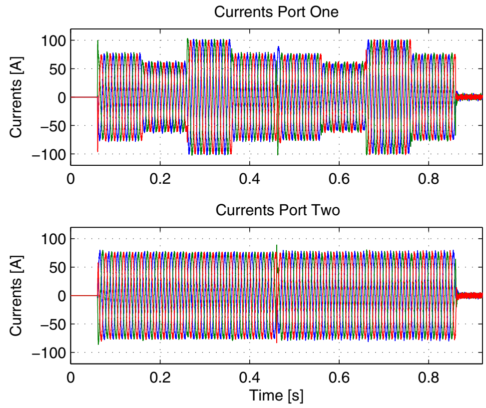


Figure 17. Case 2 – Currents in Port 1 and Port2.

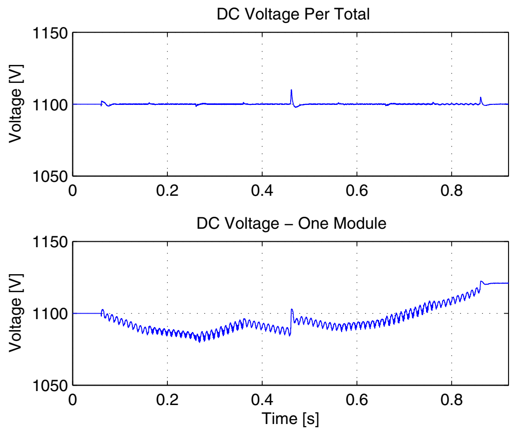


Figure 18. Case 2 - DC-link voltage response.

In the Case 3, a reverse power flow between Port 1 and Port 2 and phase jumps of ± 60° in all phases at Port 1 are simulated using a profile as shown in Figure 19.

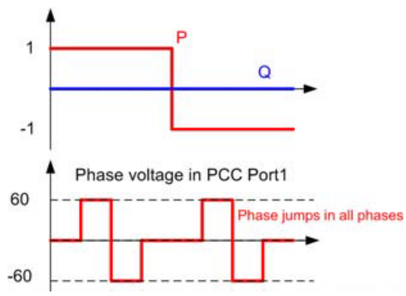


Figure 19. Case 3 - Reverse power flow between Port 1 and Port 2 and phase jumps of ± 60° in all phases at Port 1.

The response of the system for Case 3 in Port 1 and Port 2 can be seen in Figure 20. The currents in Port 1 and Port 2 are shown in Figure 21.

As it can be seen, even under a phase jump of 120° from +60° to -60° the system is able to track the changes. However, this is a hypothetical case which does not exist in a real power system.

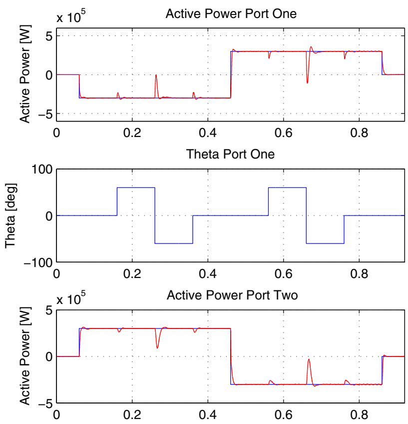


Figure 20. Case 3 - Reverse power flow between Port 1 and Port 2 and phase jumps of ± 60° in all phases at Port 1.

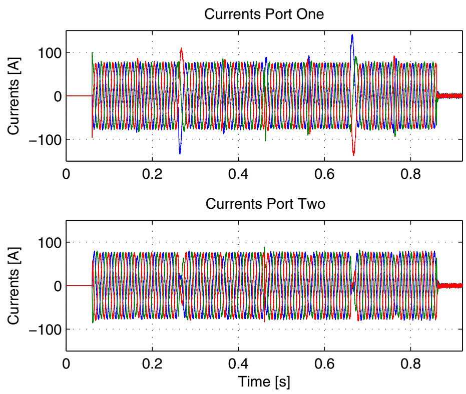


Figure 21. Case 3 – Currents in Port 1 and Port2.

This case of 120° phase jump was to show that the proposed control strategy is robust even under such of extreme disturbances. The maximum DC voltage overshoot at 120° phase jump is about 5.4% as presented in Figure 22.

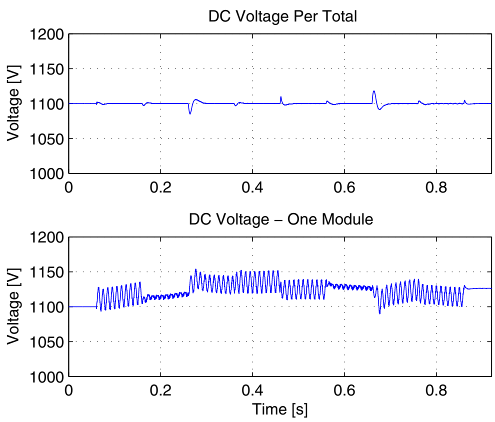


Figure 22. Case 3 - DC-link voltage response.

In the Case 4, a reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1 are simulated using a profile as shown in Figure 23.

The response of the system for Case 4 in Port 1 and Port 2 can be seen in Figure 24. The currents in Port 1 and Port 2 are shown in Figure 25. As it can be noticed, the system is slightly affected by the frequency excursions. This is due to the standard three-phase PLL that provides the resonant frequency to the PR current controller [15]. The maximum DC voltage overshoot at ± 3 Hz frequency excursion is less than 1% as presented in Figure 26.

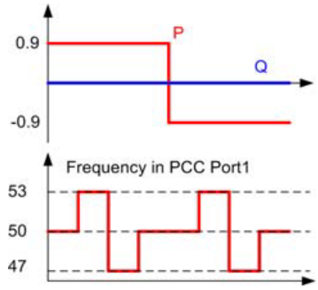


Figure 23. Case 4 - reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1.

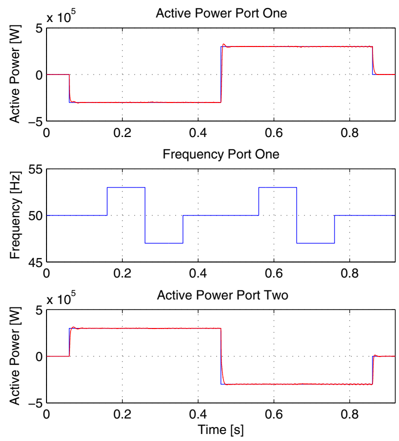


Figure 24. Case 4 - reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1.

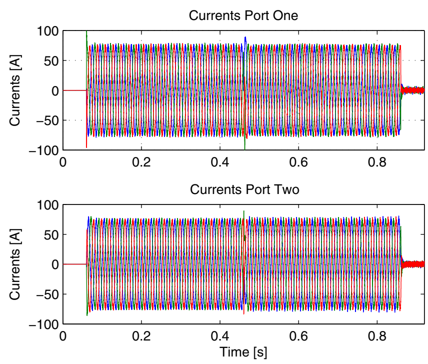


Figure 25. Case 4 – Currents in Port 1 and Port2.

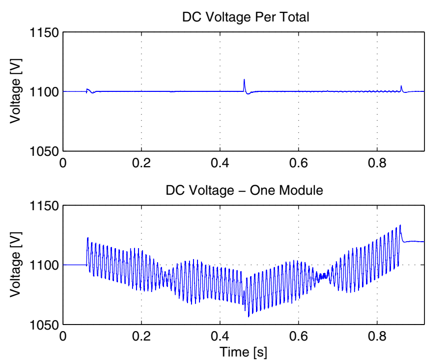


Figure 26. Case 4 - DC-link voltage response.

The THD of the current was below 4% for all of the presented cases.

## VI. Conclusions

Advanced power electronic converters and control are needed in order to facilitate a high penetration of DG in the future European electricity network. These converters shall be able to provide an intelligent management of the renewable sources including storage technologies as well as system services. Currently, all existing solutions are addressed to particular technologies and a universal and flexible power converter is needed. This paper presents the structure and a control method of such a power converter. The power converter has a modular architecture based on MF transformer isolation modules incorporating advanced magnetic and insulating materials. This modular approach leads to high reliability and low cost due to a feasible large scale production. Because the galvanic insulation is made at a frequency higher than the network frequency, the reduction of raw material utilization, like copper which is getting more and more expensive, is also possible. Connection at different voltage levels and powers is made possible by series/parallel connection of modules. This power conversion system can connect different sources and/or loads including energy storage with different characteristics and power flow requirements.

It has been proven by simulations that the proposed control strategy based on the stationary reference frame gives good results. Using the PR current controllers advantages such as: very fast reversal of power flow, robustness to voltage amplitude, phase and frequency excursions, good balancing of the DC-link voltages without any additional DC voltage compensators, small DC-link voltage overshoot during different disturbances are obtained.

Currently, the low voltage ride-through capability of the proposed control strategy is studied and a comprehensive analysis is expected soon.

## Acknowledgment

The authors acknowledge the support from the European Commission through Contract no. 019794 SES6. More information about the UNIFLEX-PM project can be found at: http://www.uniflex-pm.org.

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