

Study and Analysis of a Natural Reference Frame Current Controller for a Multi-Level H-Bridge Power Converter

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Abstract - In order to pave the way to a sustainable energy future based on a large share of Distributed Generation (DG), there is a clear need to prepare the European electricity system for the large-scale integration of both renewable and other distributed energy sources. Advanced power electronic converters for DG will be needed 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. These power converters must be able to provide intelligent power management as well as ancillary services. This paper presents an analysis of the natural reference frame controller, based on proportional-resonant (PR) technique, for a multi-level H-bridge power converter for Universal and Flexible Power Management in Future Electricity Network. 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. The presented results confirm the effectiveness of the proposed control strategy.

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

I. INTRODUCTION

The European Commission is facilitating the establishment of a technology platform for the Electricity Networks of the Future aimed at increasing the efficiency, safety and reliability of the European electricity transmission and distribution system while removing obstacles to the large-scale deployment and effective integration of distributed and renewable energy sources [1], [2]. Therefore, the impact is to reduce the dependence on fossil fuels and to reduce climate change and pollution, which are of concern to all humanity.

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 6th 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

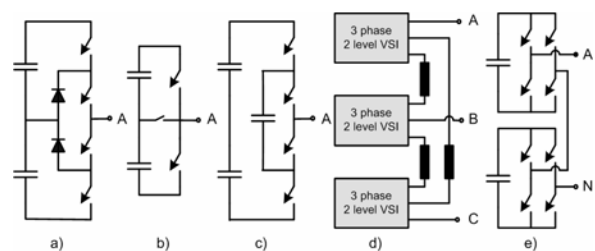


Figure 1. Multi-level topologies: a) one leg of a three-level diode clamped converter; b) one leg of a three-level converter with bidirectional switch interconnection; c) one leg of a three-level flying capacitor converter; d) three-level converter using three two-level converters and e) one leg of a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

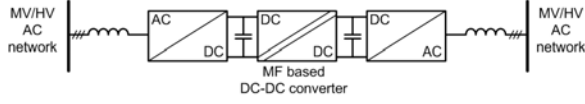


Figure 2. Generalized multi-cellular power converter structure.

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]. 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].

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.

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.

This system must be able to support bi-directional

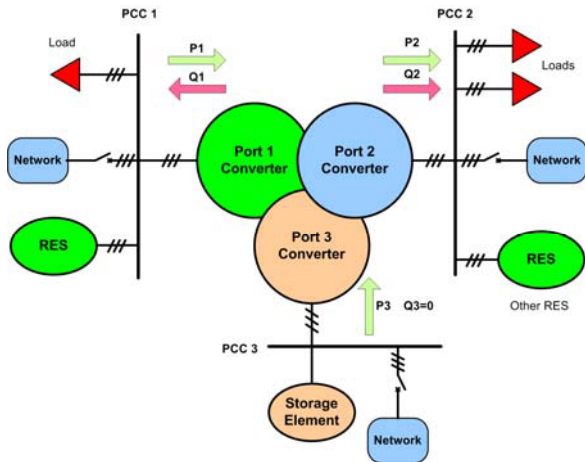


Figure 3. Structure of the Uniflex-PM system for grid integration of DG including storage facilities.

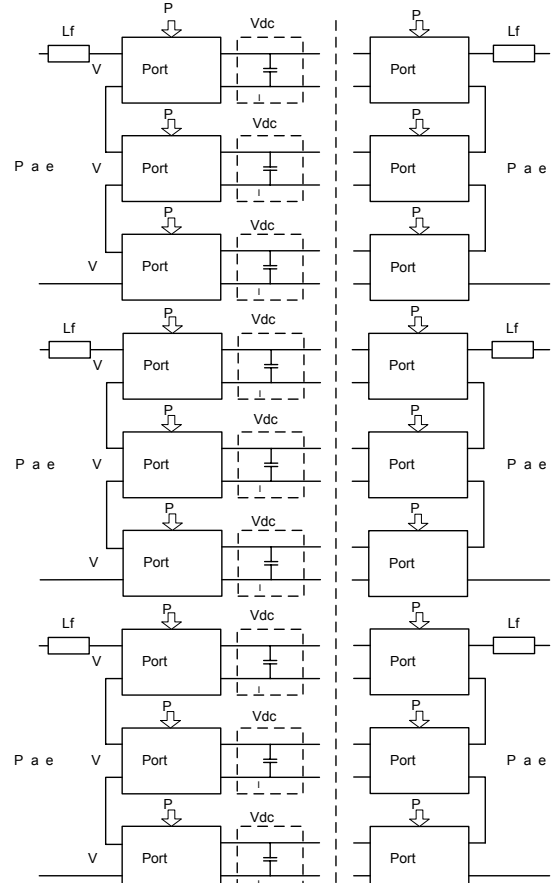


Figure 4. Two port structure of the Uniflex-PM with DC-link interleaving.

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.

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.

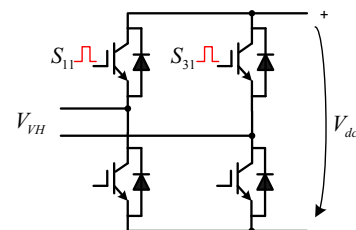


Figure 5. Structure of a single phase H-bridge cell.

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

Different control strategies are under consideration for the Uniflex-PM system e.g. synchronous reference frame with PI 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 natural reference frame is presented as shown in Figure 6. The natural reference frame controller has been chosen in order to give to the Uniflex-PM system more flexibility in controlling the currents individually on each phase. Thus, the Uniflex-PM system can increase its ride-through capabilities and it can provide a better power flow management, especially under unbalance situations. However, the natural reference frame controller requires neutral connection.

The structure presented in Figure 6 includes three independent single-phase PLLs (Phase-Locked Loop) based on the second order generalized integrator (SOGI), as presented in [16] and [17]. The advantage of using a PLL for each phase is that the voltage amplitude and phase in the Point of Common Coupling (PCC) can be provided for every phase of the three-phase system, thus improving the ride-through capabilities.

As shown in Figure 6, the active power is controlled by a DC voltage PI controller which controls the DC voltage per global (it 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 reactive currents for each phase of the system. The way it is presented, the structure shown in Figure 6 can not provide active and reactive control for each phase individually. However, the DC and the Q controllers can easily be split per each phase leading to a more flexible solution for the Uniflex-PM system. This solution is related to a later stage of the Uniflex-PM project and it is not presented in this paper. A comparison of the two solutions for controlling the active and reactive power under different grid faults will be given in a later stage of the Uniflex-PM project.

The two parts 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.

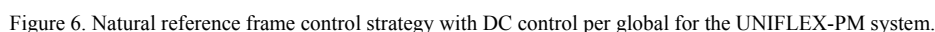
The considered control strategy is evaluated in different grid conditions and situations. The following study cases are presented in this paper in order to test the proposed control strategy:

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 $\pm 60^\circ$ 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.



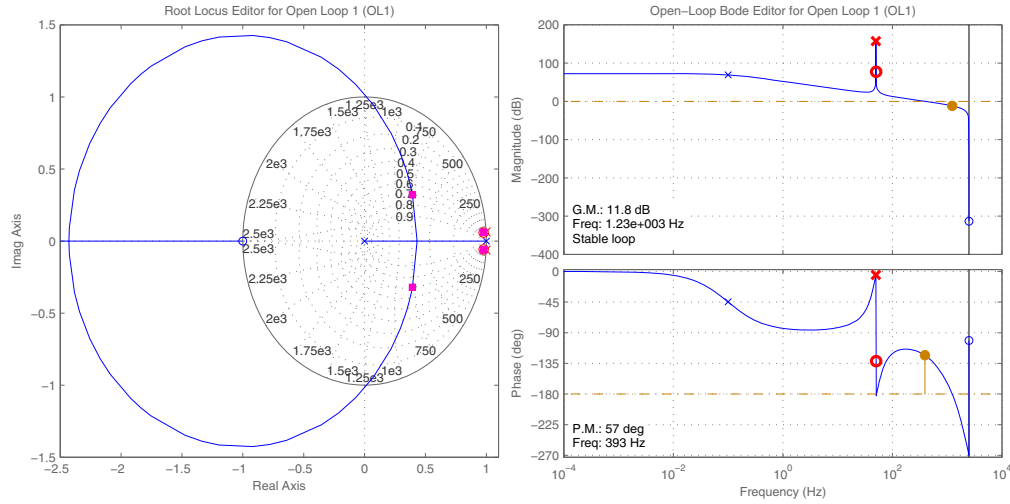


Figure 7. Root-locus and the open-loop Bode diagram of the current loop including the PR controller.

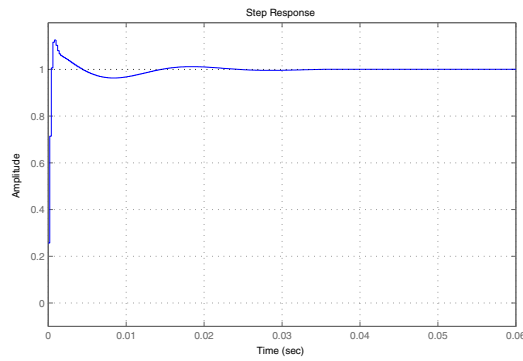


Figure 8. The step response of the current loop using PR controllers.

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. 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. This also corresponds to a

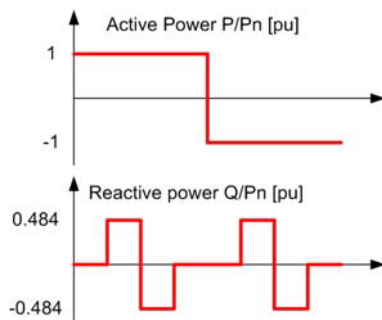


Figure 9. Case 1 - Reverse power flow between Port 1 and Port 2 and leading/lagging operation at 0.9 power factor in Port 1.

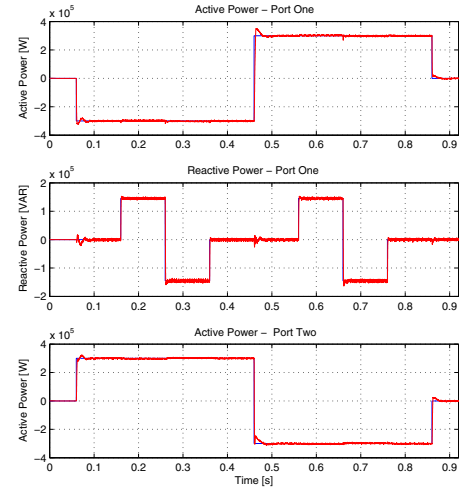


Figure 10. Case 1 - Reverse power flow between Port 1 and Port 2 and leading/lagging operation at 0.9 power factor in Port 1.

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. 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.

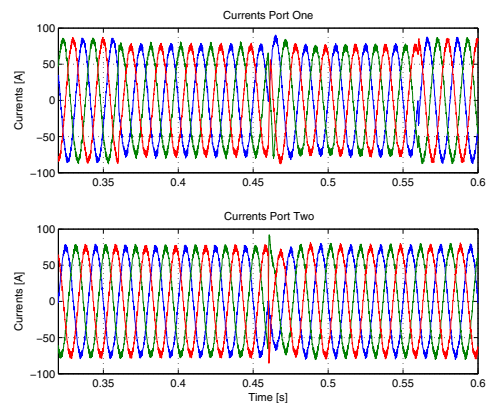


Figure 11. Case 1 - Currents in Port 1 and Port 2.

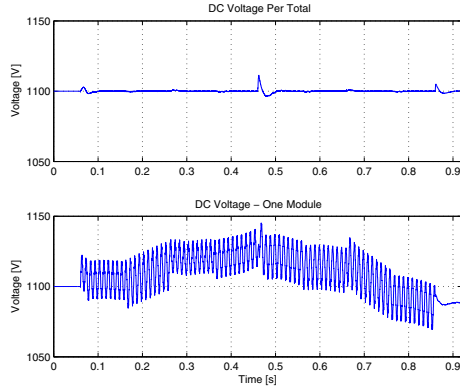


Figure 12. Case 1 - DC-link voltage response.

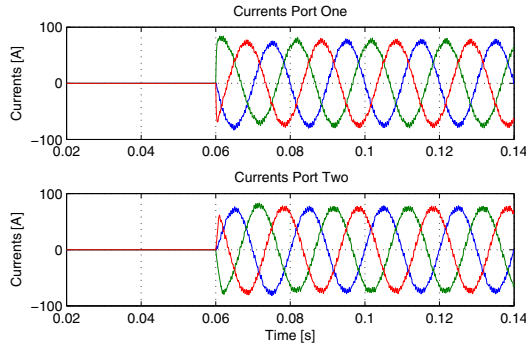


Figure 13. Case 1 – startup currents in Port 1 and Port2.

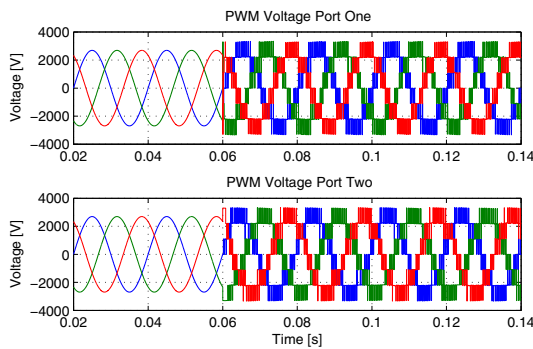


Figure 14. Case 1 – startup PWM voltages in Port 1 and Port2.

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.

In the Case 2, a reverse power flow between Port 1 and

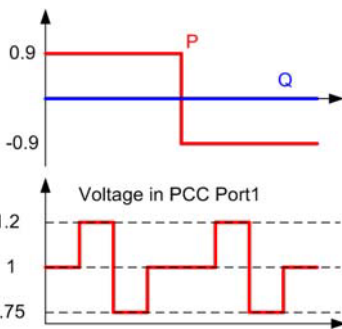


Figure 15. Case 2 - Reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1.

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.

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

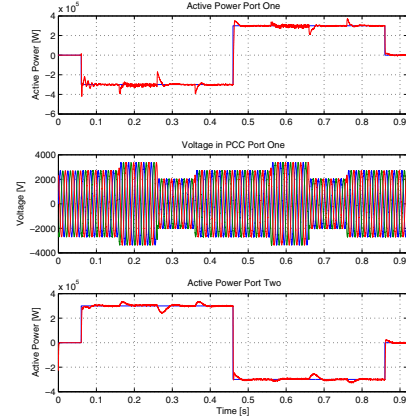


Figure 16. Case 2 - Reverse power flow between Port 1 and Port 2 and voltage excursions of 75% and 120% from the rated voltages in the PCC of the Port 1.

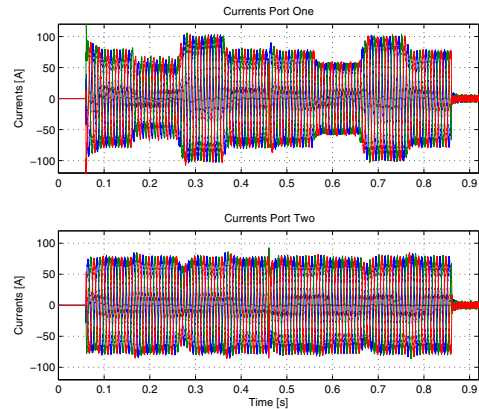


Figure 17. Case 2 – Currents in Port 1 and Port2.

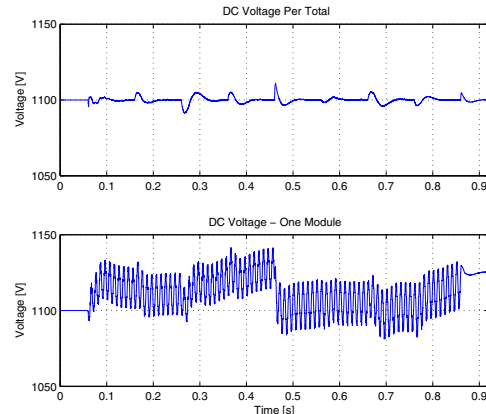


Figure 18. Case 2 - DC-link voltage response.

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

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 $+60^\circ$ 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. 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.

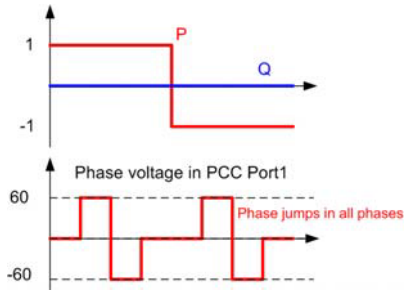


Figure 19. Case 3 - Reverse power flow between Port 1 and Port 2 and phase jumps of $\pm 60^\circ$ in all phases at Port 1.

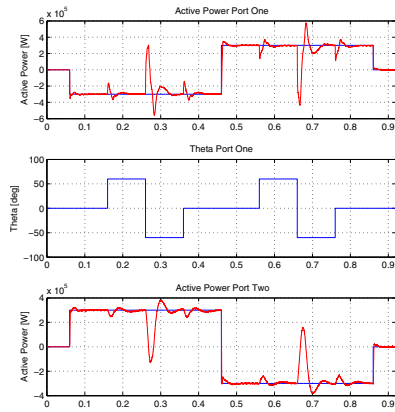


Figure 20. Case 3 - Reverse power flow between Port 1 and Port 2 and phase jumps of $\pm 60^\circ$ in all phases at Port 1.

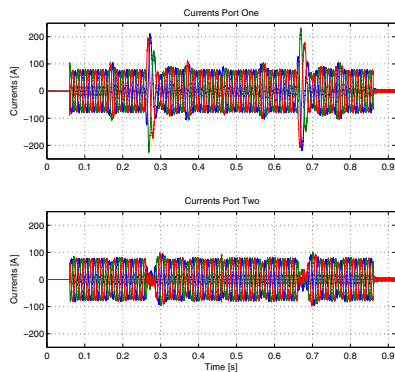


Figure 21. Case 3 – Currents in Port 1 and Port2.

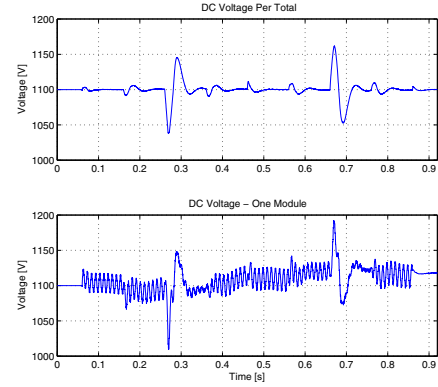


Figure 22. Case 3 - DC-link voltage response.

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 PLL based on SOGI [16] which is a frequency adaptive structure and it also fast provides the resonant frequency to the PR current controller [18]. The maximum DC voltage overshoot at ± 3 Hz frequency excursion is less than 1% as presented in Figure 26.

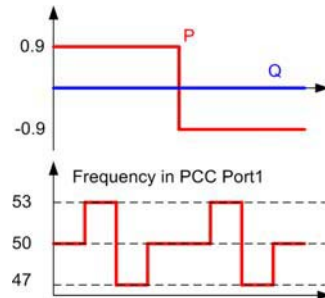


Figure 23. Case 4 - reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1.

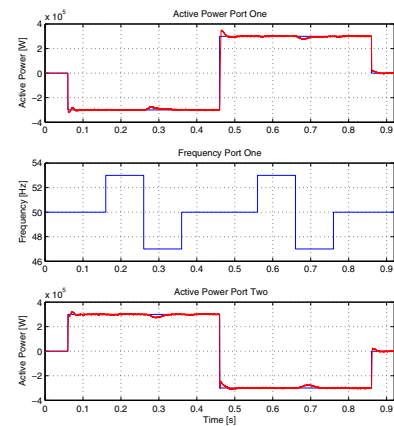


Figure 24. Case 4 - reverse power flow between Port 1 and Port 2 and frequency excursions of ± 3 Hz in Port 1.

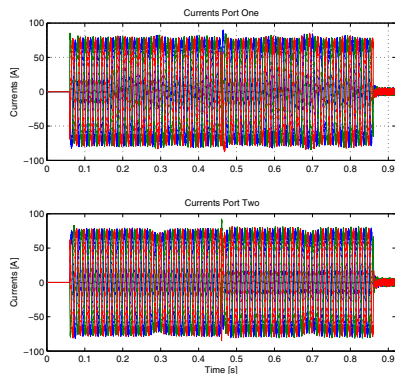


Figure 25. Case 4 – Currents in Port 1 and Port2.

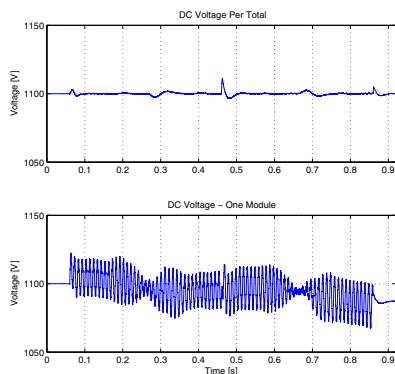


Figure 26. Case 4 - DC-link voltage response.

It is worth to mention that in all of the presented results the THD of current was about 4%.

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 natural reference frame gives good results. Using individual PR current controllers and PLLs for each phase gives 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.

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

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