Control Challenges and Solutions for a Multi-cellular Converter for Use in Electricity Networks

Alan J. Watson, HQS Dang, Patrick W. Wheeler, Jon C. Clare, Gopal Mondal, University of Nottingham, UK
Stephan Kenzelmann, Alfred R. Rufer, Ecole Polytechnique Federale de Lausanne, Switzerland
Yales R. De Novaes, ABB Switzerland LTD.

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Summary

This paper presents the concept of a multi-cellular power converter structure targeted towards use in future electricity networks. Control of such a converter is challenging because of the distributed energy storage intrinsic to the concept. If the energy flow through the converter is not carefully controlled poor performance and even shutdown of the converter may result. This paper details the operation of such a converter and presents an example of a control scheme which can achieve the desired performance. Validations of the converter concept and the control principles are provided by experimental results at low voltage using a two port prototype.

Introduction

Power Electronics is a key enabling technology for the electricity grids of the future [1]. "Advanced Power Converters for Universal and Flexible Power Management in Future Electricity Networks" (UNIFLEX-PM) is a collaborative European project which has aimed to develop advanced power conversion techniques capable of connection in future electrical grid systems enabling advanced functionality and direct integration of renewable sources [2, 3]. The project consortium consisted of four Universities (University of Nottingham, Aalborg University, Ecole Polytechnique Federale de Lausanne and Università degli Studi di Genova), several key Industrial partners (ABB, Dynex Semiconductor, and Areva T&D) as well as the European Power Electronics Association (EPE). The project was part funded by the EC under the Sixth Framework program.

Multi-cellular converters, capable of incorporating redundancy and being reconfigurable to meet the demands of various grid applications were considered during the UNIFLEX-PM project. An example grid connection scenario is shown in Fig. 1. Here three networks are connected together via a "multi-port" power converter and several types of renewable energy sources or energy storage systems such as fuel cells or batteries may be connected into the grid. In this example ports 1 and 2 may be connected to Medium Voltage grids whilst port 3 could be connected at Low Voltage. It is important that the converter interfacing these grid systems allows bidirectional power flow and is able to conform to grid connection standards.

This paper presents a modular power converter concept which can be configured to achieve a wide range of the expected functional requirements for future grids, including those in Fig. 1, for example. The paper concentrates on the basic operation of the topology and on energy flow control. Results from a Low Voltage prototype are provided to validate the approaches taken.

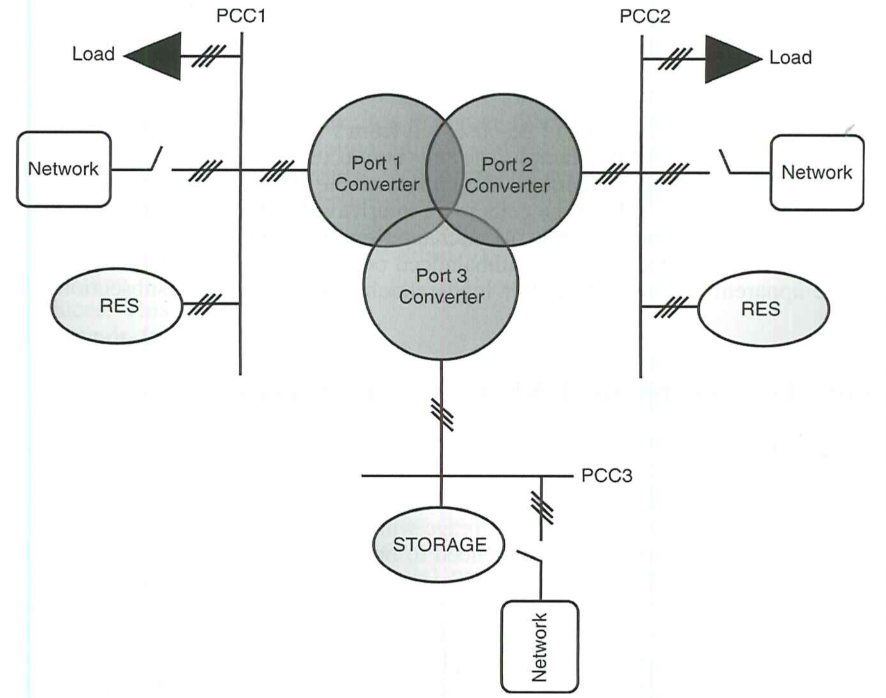

Fig. 1: Example of UNIFLEX-PM concept connecting three electricity systems together

The UNIFLEX-PM prototype converter

The underlying concept of UNIFLEX-PM is to develop a modular converter architecture using basic building blocks, employing medium frequency (MF) transformer isolation, each with single-phase AC/AC bidirectional conversion capability. A number of configurations for the building blocks can be imagined, the most obvious being an AC/DC/DC/AC structure as shown in Fig. 2. Amongst the other possibilities, the UNIFLEX-PM project has also studied an AC/DC/AC structure employing medium frequency cyclo-conversion [4]. In this paper the arrangement of Fig. 2 is assumed, where the two central H-Bridges and the MF transformer form a dual bridge bidirectional DC/DC converter. Due to the transformer isolation, the modules (cells) can be stacked in series or parallel combinations to achieve the desired voltage and power levels and overall conversion topology for a particular application. The methods for controlling the DC/DC converter are not considered in detail in this paper since they are well documented [5, 6]. The purpose of the DC/DC converter control is simply to ensure DC link voltage tracking on either side of the isolation boundary.

The outer two H-Bridge (DC/AC) converters are interfaced to the grid via a line inductance and can be connected in series with similar converters in other cells to form cascaded multi-level structures on the grid side of the converter [7]. This enables the converter to work at high voltages using low voltage switching devices and also provides the possibility to increase the waveform quality at the AC side, reducing filtering requirements to meet grid connection standards [8].

For the example shown in Fig. 1, an overall converter structure can be formed using UNIFLEX-PM cells as shown in Fig. 3. In this example there are four cells per phase in port 1, three in port 2 and one in port 3. Depending on the required functional and voltage/current ratings, different configurations are possible. In the UNIFLEX-PM project however, the structure of Fig. 3 has been assumed as the basis for the experimental investigations for validation of the concepts. The assumed ratings for the experimental prototype are 300 kVA (port1), 3.3 kV (port 1 and port 2), 415 V (port 3), with a DC link voltage for each cell of 1.1 kV. The practical results in this paper are taken at reduced voltage (415 V, ports 1 and 2). Full power testing of the prototype is reported in a companion paper [9].

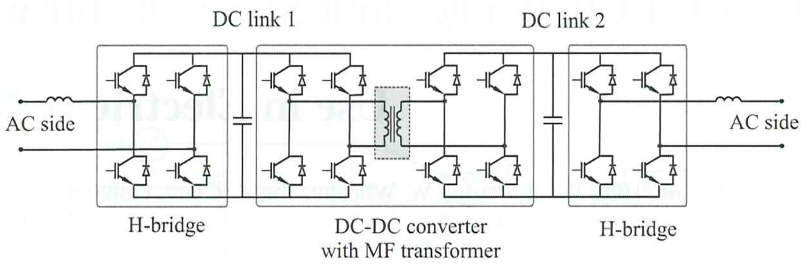

Fig. 2: UNIFLEX-PM Single AC/DC/DC/AC module with Medium Frequency Isolation

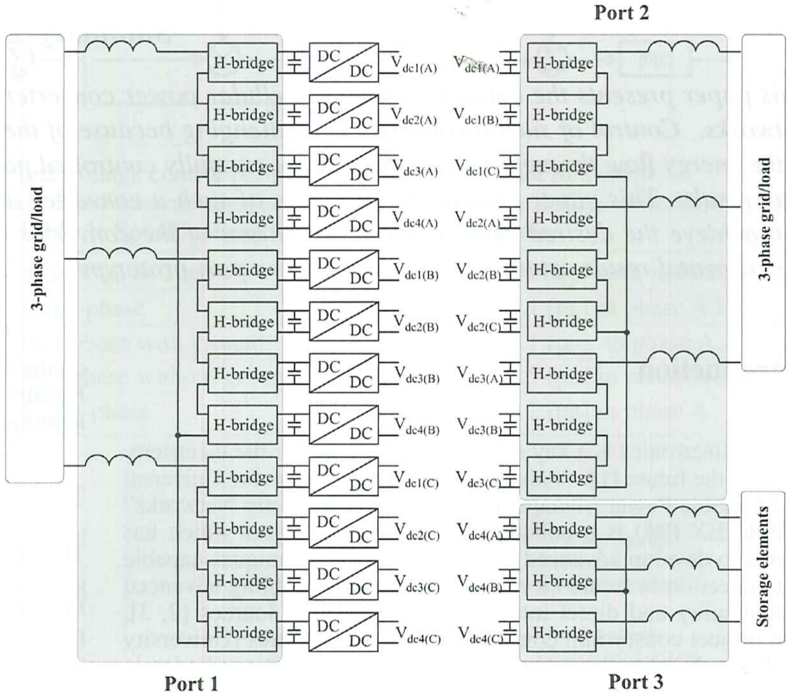

Fig. 3: UNIFLEX-PM 3 port prototype power converter utilising nine AC/DC/DC/AC cells

An important point which should be observed from Fig. 3 is that the cells are interleaved. For example, the cells connected to phase A on port 1 are distributed amongst the phases of the other two ports on the secondary side of the cells in an interleaved configuration. This enables the converter to exchange energy between phases and to deal effectively with unbalanced conditions which may be apparent in the grids and/or loads attached to the ports [10].

Control scheme for the UNIFLEX-PM prototype converter

The control scheme for the modular converter is challenging due to the distributed nature of the energy storage within the converter, and, in a multi-port configuration, the need to balance the power flows between multiple sources and loads.

For the example in Fig. 3, the power flow control for port 1 must be the master and determine the balance. This is because it is the only port which is directly connected to the other two ports inside the converter. Note that, in this configuration, power can only flow from port 2 to port 3 (and vice versa) indirectly via the cells connected to port 1. Hence, ports 2 and 3 respond to external power flow demands whilst the control of port 1 ensures overall power balance in the converter.

The control structure for port 1 is shown in Fig. 4. The control is similar to that commonly used for the active rectifier part of a back to back drive system [11], with modifications to deal with the special requirements of the UNIFLEX-PM modular structure. The subsections of the control system are described in detail below.

Global DC link voltage control

Overall power balance in the converter is achieved by controlling the total energy storage via regulation of the DC link voltages. All twelve DC link voltages on port 1 are measured and the result is averaged. A global voltage controller (PI), labelled 1 in Fig. 4, is applied at port 1 and determines the real power demand based on the deviation of the average voltage from the demanded value. This power demand is then translated into a current demand for the current controller, labelled 2 in Fig. 4. Using this method, the power demand at port 1 will always be driven to track transients in the power flows at ports 2 and 3 and achieve balance.

Current control

The current control in this example (shown in Fig. 5) is based on a rotating frame representation of the grid connected converter

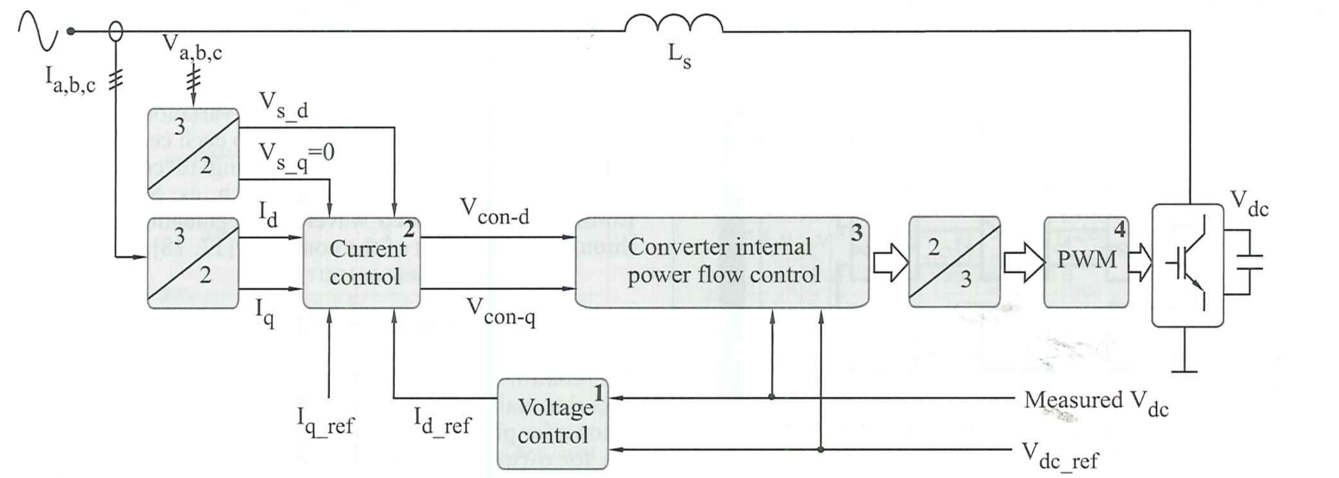

Fig. 4: Control scheme for port 1 of the UNIFLEX-PM prototype converter

and is well documented [12]. In this case the d-axis of the rotating frame is synchronised with and aligned with the supply voltage vector at port 1. Hence, current on the d-axis of the rotating frame represents real power and that on the q-axis represents reactive power. Since the converter aims to run at unity power factor at port 1, the q-axis demand, I_{q_ref}, in Figs. 4 and 5 is nominally zero. The d-axis component is derived from the overall DC link voltage control scheme (labelled 1 in Fig. 4). The current control scheme then determines the required converter voltage demands (with appropriate limitation).

It should be noted that there are several other possible implementations of current control. The method described has been chosen for its simplicity in practical implementation. Various other approaches have been researched during the project, including Resonant Controllers and Predictive controllers. These methods may offer advantages since they allow the converter to be controlled on a "per phase" basis which may be desirable when the converter is connected to a grid experiencing fault conditions [13, 14].

It should be noted that the overall power balance control described above, does not ensure power balance (and hence DC voltage regulation) of the individual cells in the converter. It is therefore necessary to augment the control strategy with a means for achieving this as described below.

Converter internal power balance control

Assuming negligible distortion in the grid currents, the power flow into each cell at port 1 can be regulated by controlling the magnitude and phase of the fundamental voltage it produces. This can be achieved through adjusting the modulation demands for each cell, but must be done under the constraint that the total voltage produced (magnitude and phase) is that required by the global DC voltage controller. The internal balance control, as currently implemented, uses a feed-forward approach (based on the external power demands) to determine a first approximation of the power split between ports 2 and 3. This split, together with the overall modulation demand is used to determine a first approximation of the desired modulation demands for each cell [15].

In practice however, the feed-forward calculations are not sufficient to ensure DC link voltage equalisation for each cell, due, for example, to non-idealities in the converter modulation and the hardware used to construct each cell. Therefore a closed-loop trim must be applied to the modulation demand for each cell to ensure equalisation. The control scheme employed to achieve this uses PI controllers. Each DC link voltage of a series chain (for example the 4 cells of phase A in port 1) is compared against the average for that series chain [16]. The PI controllers adjust the modulation demand for each cell in the string according to the individual cell voltage errors. It is important that this is done so that the individual cell modulation adjustments do not affect the total modulation demand issued by the current controller. In this way, the cell balancing action is totally transparent to the current control loop. This is essential, since the cell balancing control is much slower than the current control.

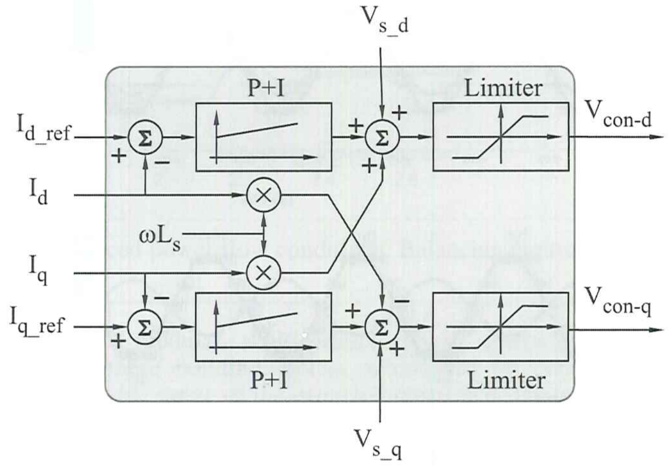

Fig. 5: Rotating frame current controller as applied in the control scheme of Fig. 4

Modulation

The control schemes described above, issue a modulation voltage demand for each cell of the converter at port 1. This is used as a reference waveform for a Pulse Width Modulation (PWM) scheme. For high power converters it is important that the device switching frequency is as low as possible, in order to minimize switching losses and achieve high overall converter efficiencies. Choice of switching frequency is a tradeoff between switching loss and the quality of the waveforms (and therefore the size of the filtering components) produced by the converter [15]. For the prototype, the device switching frequency was chosen to be 250 Hz in order to validate scalability to higher powers.

For the prototype, Phase Shifted Carrier PWM (PSC-PWM) was used as it explicitly determines the magnitude and phase of the voltage produced by each cell when applied to a cascaded H-Bridge structure. This means that only a slight alteration to the basic method is needed to implement the internal balance control described above.

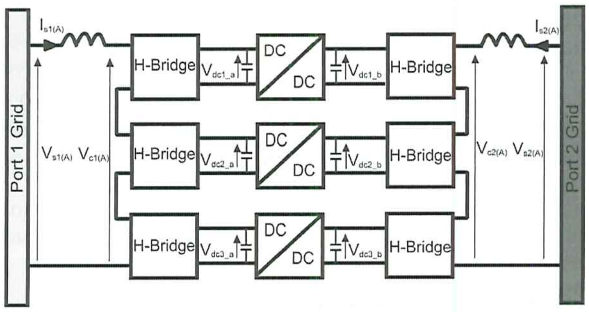

Fig. 6: Experimental per phase configuration for the two port power converter testing

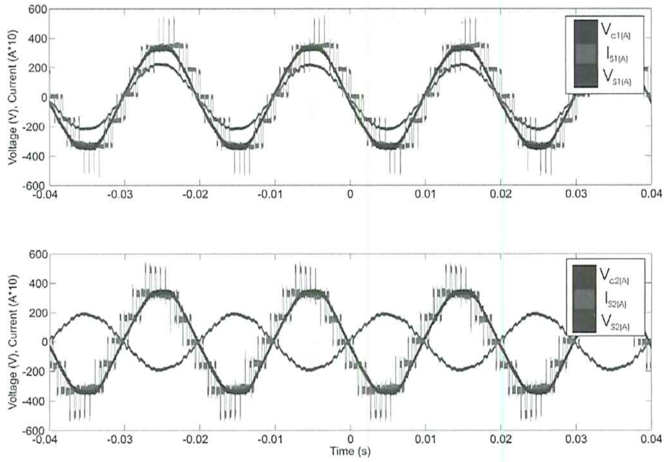

Fig. 7: (Top) Port 1 Phase A waveforms, (Bottom) Port 2 Phase A Waveforms for power flow from Port 1 to Port 2

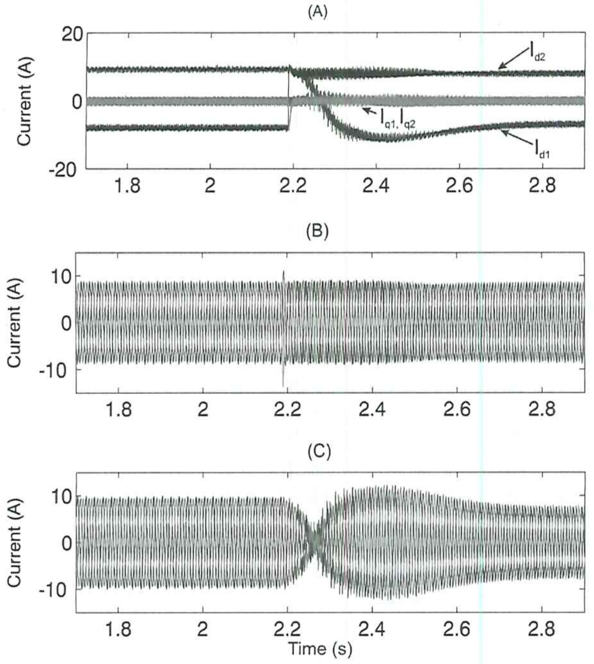

Fig. 8: Waveforms for reversal in port 2 power flow
(A) Rotating frame current components for both ports,
(B) AC current in port 2, (C) AC current in port 1

Various other methods of modulation have been reviewed as part of the evaluation [15]. One issue with PSC-PWM, when the power balance control is applied, is potential degradation of the waveform spectrum due to reduced harmonic cancellation. The level of degradation depends of the degree of variation between the individual modulation demands applied to each cell. In order to overcome this issue, it may be interesting to consider the use of optimised modulation strategies such as Selective Harmonic Elimination where such waveform degradation may be avoided throughout operation of the converter [17, 18].

Experimental test results

The control scheme presented in the previous section has been experimentally verified using the configuration shown in Fig. 6 (shown for phase A only for clarity). In this case the results shown are for a two port converter connected to a 415 V grid system (three cells per phase). A two port converter is used to simplify the experimental set-up and validate the basic principles of the control methods presented. Simulation results for the 3-port configuration have been presented previously [10].

Fig. 7 shows the AC waveforms for power flowing between port 1 and port 2. The advantages of the multi-cell approach are clearly demonstrated in the quality of the line currents, considering the low switching frequency (250 Hz) of the individual cells. The THD of the current up to the 50th harmonic is less than 5 % in both ports.

Fig. 8 shows the transient response at both ports of the converter when there is a power reversal demand at port 2. Initially power is flowing from port 1 to port 2. At t = 2.2 s, the d-axis (real) component of current in port 2 is reversed as shown in plot A of Fig. 8. Plot B shows the port 2 AC current where it can be observed that the reversal is almost instantaneous. In order to balance the power flow, the d-axis current in port 1 reverses under the action of the global DC link voltage controller as shown in Plot A. The action of this controller is also illustrated by the AC current in port 1 shown in plot C. The speed of response of the port 1 current is determined by the bandwidth of the global DC link voltage control. The q-axis current of both ports remains zero throughout this transient.

Fig. 9 shows the response of the DC link balancing control. For this test the DC/AC bridges in port 2 were disabled and resistive loads were placed directly across the DC links of the secondary

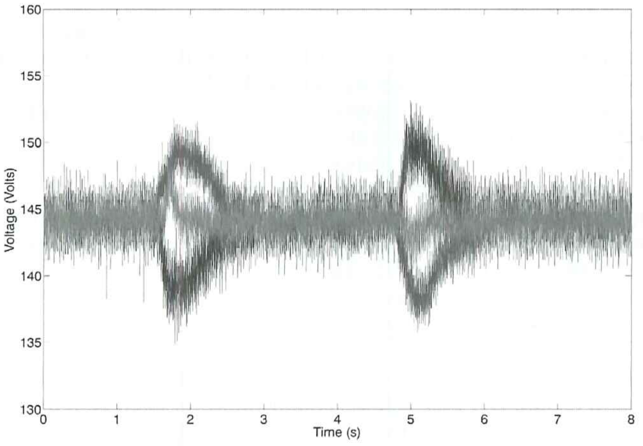

Fig. 9: DC link capacitor voltages of Phase A for the port 1 converter acting as an active rectifier with asymmetric loading step changes

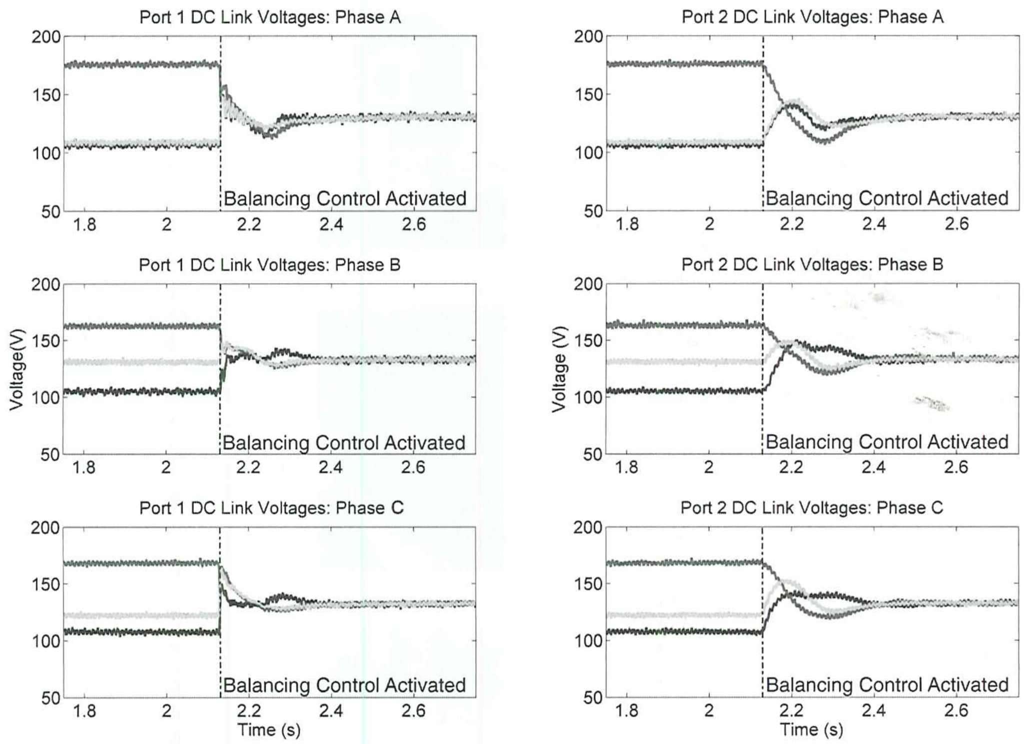

Fig. 10: DC link capacitor voltages with port 2 connected and forcing unbalanced power flow conditions. Balancing control activated at $t = 2.15$s

side of the DC/DC converters. Unbalanced conditions to test the balance control scheme can be artificially created by adjusting these loads. As illustrated in the figure, two different unbalance scenarios are applied at $t = 1.5$ s and $t = 4.8$ s respectively. In each case the capacitor voltages initially diverge due to the unbalance. The control loop then acts on the individual voltage errors and adjusts the power flow in each cell to return the capacitor voltages to the equalised condition, even though the load powers in each cell remain different.

Further results for the balancing control are shown in Fig. 10. In this case, the DC/AC bridges in port 2 are reinstated and unbalanced conditions are purposely created by adding errors to the individual cell modulation demands for port 2. This creates unbalanced DC link voltages under steady state conditions when the balancing control is disabled (before $t = 2.15$ s). At $t = 2.15$ s, the balancing control is activated. Fig. 10 shows the resulting response for all of the 18 DC link voltages (9 on each side of the isolation boundary), illustrating the effectiveness of the balancing control. This figure also illustrates the action of the DC/DC converter control strategy in achieving tracking of the DC voltages on each side of the isolation boundary.

Conclusions

Power Electronics is a key enabling technology for the electricity grids of the future. "Advanced Power Converters for Universal and Flexible Power Management in Future Electricity Networks" (UNIFLEX-PM) was a collaborative European project aiming to develop advanced power conversion techniques capable of connection in future electrical grid systems enabling advanced functionality and direct integration of renewable sources. The underlying concept of UNIFLEX-PM is to develop a modular converter architecture using basic building blocks, employing medium frequency (MF) transformer isolation, each with single-phase AC/AC bidirectional conversion capability. This paper has presented a modular, multi-cellular power converter concept, based on these building blocks, which can be configured to achieve a wide range of the expected functional requirements for future grids.

A particular feature of the UNIFLEX-PM concept is that the energy storage in the converter (in the DC links) is distributed amongst the isolated cells. Control of such a converter is therefore challenging because power balance has to be achieved for the overall converter and for the individual cells. This is essential to maintain the individual DC link voltages within limits, both for protection of the converter and to maintain the power quality performance. The paper has concentrated on methods to achieve this and a suitable control philosophy has been described.

Finally, experimental results taken during low voltage testing of the converter have been presented to validate the proposed converter control methods. It is concluded that the methods presented are effective in ensuring the desired operation of the converter. Operation of the converter at full rating (300kVA, 3.3kV), using these control approaches is described in a companion paper in this issue.

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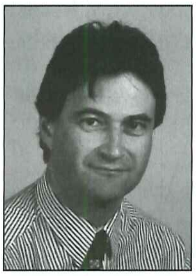
The Authors

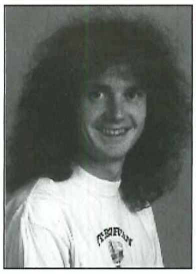
Alan Watson received the Masters and PhD degrees in Electronic Engineering and Electrical and Electronic Engineering from the University of Nottingham, UK in 2004 and 2008 respectively. He is currently a Research Fellow in the Power Electronics, Machines and Control Group at the University of Nottingham, UK. Between 2008 and 2009 he was employed on the UNIFLEX-PM project. His research interests include multilevel converters, advanced modulation schemes and power converter control.

Gopal Mondal completed his PhD at the Indian Institute of Science, Bangalore, in 2008. He was employed as a Research Fellow at the University of Nottingham, UK between 2008 and 2009 where he worked on the UNIFLEX-PM project. Currently he is working as a Research Technologist in power electronics at AREVA T&D, UK.

HQS Dang received the PhD in Electrical and Electronic Engineering from the University of Nottingham, UK in 2006. From 2006 he was employed at the University of Nottingham, UK as a Research Fellow in the Department of Electrical and Electronic Engineering where he worked on the UNIFLEX-PM project. His research interests include direct power conversion, high power converters, modulation and control strategies.



Prof. Jon Clare was born in Bristol, England. He received the BSc and Ph.D. degrees in Electrical Engineering from The University of Bristol, UK. Since 1990 he has been with The University of Nottingham, where he is currently Professor of Power Electronics and Head of the Power Electronics, Machines and Control (PEMC) Research Group. Prof Clare's research interests are in power electronic systems and applications, power electronic converter topologies and their control, aerospace electrical systems and variable speed drive systems. Prof. Clare is a Member of the Institution of Engineering and Technology (IET) England and is a Senior Member of the IEEE. He is a Member of the Editorial Board of IET Journal of Power Electronics and was formerly an Associate Editor for IEEE Transactions on Industrial Electronics. Prof. Clare is a former member of the Executive Council of the European Power Electronics Association and is currently a member-at -large of the IEEE Power Electronics Society AdCom.



Prof Pat Wheeler received his BEng [hons] in 1990 from the University of Bristol, UK. He received his PhD degree in Electrical Engineering for his work on Matrix Converters from the University of Bristol, UK, in 1994. In 1993 he moved to the University of Nottingham and worked as a research assistant in the Department of Electrical and Electronic Engineering. In 1996 he became a Lecturer in the Power Electronics, Machines and Control Group at the University of Nottingham, UK. Since January 2008 he has been a Full Professor in the same research group. His research interests are are in power conversion and More Electric Aircraft technology. He has published over 200 papers in leading international conferences and journals.

Stephan Kenzelmann (S'10) received the M.Sc. degree in electrical engineering from the Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland in 2007, where he is currently pursuing the Ph.D. degree in the Industrial Electronics Lab (LEI). His research interests include single-phase control methods, multilevel converter control, and research and development of new power electronic systems for DC power transmission.

Alfred Rufer received the M.S. degree from the Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, in 1976. In 1978, he joined ABB, Turgi, Switzerland, where he was involved in the fields of power electronics and control, such as high-power variable frequency converters for drives, and where he was a Group Leader involved with power electronic development beginning in 1985. In 1993, he became an Assistant Professor at EPFL, where, since 1996, he has been a Full Professor and the Head of the Industrial Electronics Laboratory (LEI). The LEI is active in power electronics used in energy conversion and energy storage and in the modeling and simulation of systems, including control strategies and control circuits. He has authored or coauthored several publications on power electronics and applications, such as for multilevel converters or for different energy-storage systems. He is the holder of several patents.

Yales Rômulo De Novaes was born in Indaial, Santa Catarina, Brazil, in 1974. In 1999 he received the bachelor degree in electrical engineering from Regional University of Blumenau, Santa Catarina, Brazil. The M.Eng. and Dr. degrees were obtained from Power Electronics Institute (INEP) of the Federal University of Santa Catarina (UFSC), Brazil, in 2000 and 2006, respectively. During 2001, he worked as a research engineer in the same institute. From 2006 to 2008 he was as a post-doctoral fellow with the Industrial Electronics Laboratory (LEI) at the Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, as a project leader for UNIFLEX-PM. From 2008 he is with ABB Corporate Research Ltd working in the Power Electronics Systems Group. Dr. De Novaes is member of the Brazilian power electronics society (SOBRAEP) and IEEE.