Description and Efficiency Comparison of Two 25 kVA DC/AC Isolation Modules

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Abstract

In the frame of the European project UNIFLEX-PM, two AC/AC converter topologies have been studied and implemented. Both converters, rated for 25 kVA, are isolated by a medium frequency power transformer. The first topology is based on a dual active bridge containing two additional voltage source inverters for the connection of both DC links to the interfaced grids. The second topology is based on a cycloconverter for the connection of the secondary side of the transformer to the grid without a DC link capacitor. Both topologies have an identical primary side so the efficiency study is focussed on the chain link from one DC link to a 25 kW output load. Experimental efficiencies are compared to theoretical expectations. Due to soft-switching operation in the dual active-bridge, the cycloconverter based solution shows a lower efficiency than in the symmetrical topology.

Introduction

In a general frame where energy production is to be performed on a more localized scale due to the multiplication of renewable sources, the distribution network will see a growing number of micro-grids containing sources, storage units and users. The connection of those sub-networks becomes a challenging task since a bidirectional power flow is to be managed. Various factors are involved, including changing weather and users demand. In that view, a flexible unit based on isolation modules has been designed for the control of the power flow, independently of possible frequency deviations between the grids [1, 2].

The proposed topology in UNIFLEX-PM for the grid connection is a three phase three port modular converter allowing medium frequency conversion and isolation, along with a power flow control between the grids. The use of intelligently driven semiconductors together with medium frequency power transformers allow drastic reductions in terms of size and materials needed by the large low frequency transformers. As illustrated in Fig. 1, each phase contains four AC/AC chain converters with a galvanic isolation between the ports.

As a contribution, two 25 kVA chain converters have been investigated by EPFL for the implementation of a down-scaled demonstrator, rated for 300 kVA. Both solutions consist on the series connection of three elementary converters indexed as A, B and C. The two investigated solutions are defined on the composition of the mentioned elements, connected together through DC link capacitors and line inductors on the grid sides. As illustrated on Fig. 2, converter A and B are full bridges operated at different frequencies since the first is designed for the grid connection and the second for the medium frequency transformer connection. Converter C is a cycloconverter connecting directly the grid to the transformer. The investigated converters are the CBM (cycloconverter based module) which is a composition of the three mentioned elements and the VSIBM (voltage source inverter based module) which is a symmetrical solution based on a dual active bridge topology including both A and B converters on each side of the transformer.

Both converters are fully described and implemented in order to experimentally validate each operation principle. The efficiency evaluation is performed on partial chain converters from one DC link capacitor to a 25 kW load on the grid side [3].

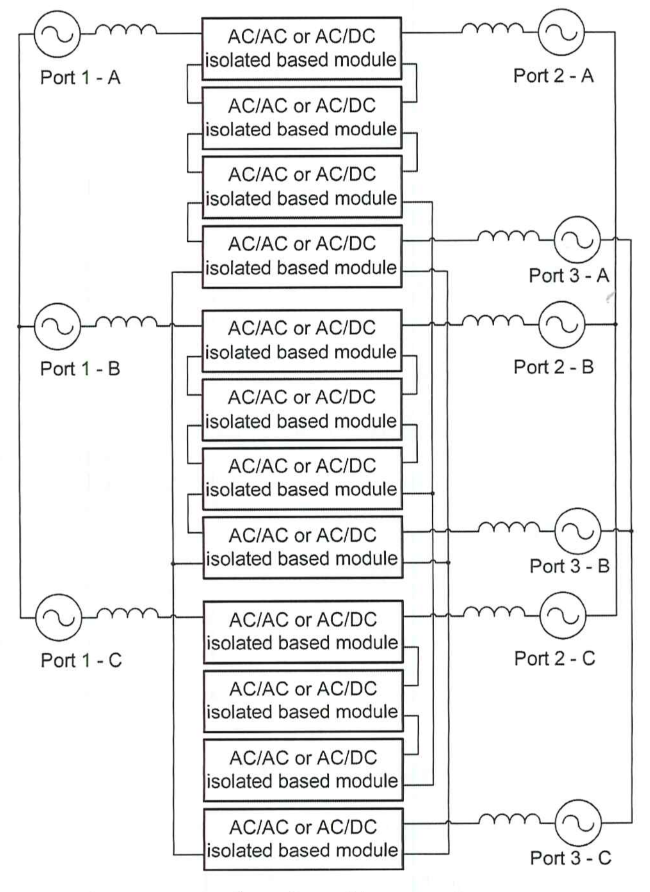

Fig. 1: Three port topology for grid connection

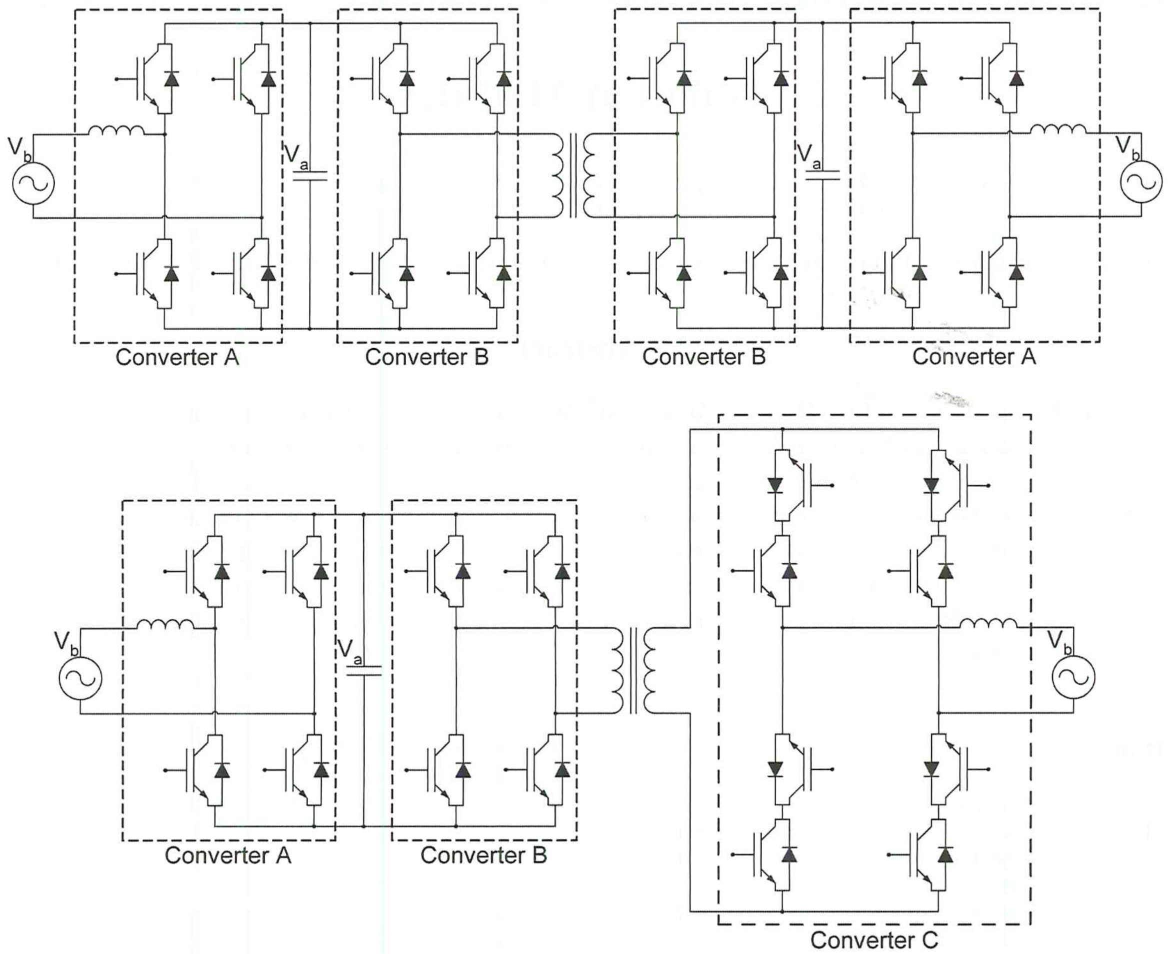

Fig. 2: Chain converters for grid connection (VSIBM and CBM)

Converters operation principle

The operation principle is different for both investigated solutions. In the case of the VSIBM, the active power flow is defined by the DC/DC dual active bridge and the DC link voltages are regulated through the grid connection. The CBM has only one DC link and its control relies on a matrix type operation with a similar principle for the power flow through the medium frequency transformer.

Connection to the grid

The connection to the grid is done through an inductor which value is chosen in order to minimize the current ripple at low switching frequencies. Its value is limited though and depends on the DC link voltage, the power and the grid. Its design is also different between a single phase application and the whole multilevel converter. The voltage V_L applied to the grid inductor, as illustrated on Fig. 3, is a spatial vector whose phase shift $\pi - \beta$, defines the proportion between the active and the reactive power. V_L is obtained by applying a voltage V_x, which is proportional to the DC link voltage V_a and has a phase shift θ when referenced to the grid. The control of the vector parameters allows the control of the power flow.

Control of the power flow through the transformer

The control of the power flow through the transformer relies on the phase shift difference δ of the rectangular voltages on the primary and the secondary side [4, 5, 6, 7]. In a simplified transformer model where parasitic capacitances, winding resistances and the magnetizing inductance are not considered, the current flow is defined by the voltage applied on the leakage inductance L_σ. As illustrated on Fig. 4, a higher phase shift allows a higher power flow and the phase shift polarity defines the direction.

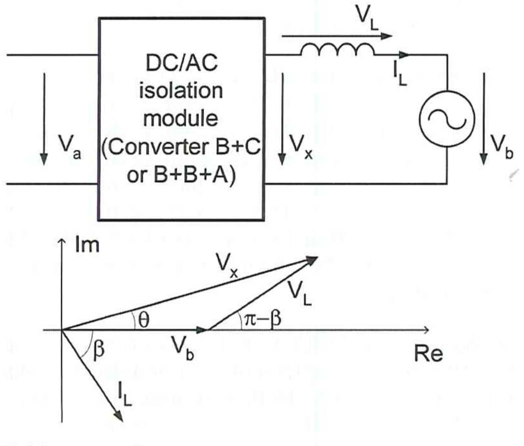

Fig. 3: Grid connection

The value of the phase shift remains in a range of a few degrees since the value of the leakage inductance is small. In case of a variation of the power flow, the change of the phase shift may create a DC component in the current which may eventually result on additional losses. As illustrated on the same figure, a variation of the phase shift must be done in two equal steps at each half period of the applied alternating voltage in which case no DC component appears.

Operation of the dual active bridge

The operation principle of the VSIBM relies on the control of the active power flow through the DC/DC dual active bridge and the control of the reactive power flow through the grid side inverters. Assuming that the DC link voltages have a small difference, the converter is run in soft-switching conditions. The switches turn-on is made under zero voltage condition since the anti parallel diodes are always in a conducting situation. On the other hand, the losses due to the switches turn-off are reduced by the use of parallel snubber capacitors. The switch turns off with a reduced value of current since most of it goes through the snubber capacitors.

The detailed soft-switching mechanism is presented in Fig. 5 in the case where the active power flows from the primary side to the secondary. Only one switching sequence is detailed since the three other mechanisms in the whole period can be directly deduced.

1. With a positive current when V_P and V_S are positive, the current flows through the switches on the primary side whereas the current flows in the diodes on the secondary side. The snubber capacitors of the open switches have a positive voltage.
2. In order to apply a negative voltage on the primary side, the conducting switches are turned off. A circulating current in the full bridge brings the charges from one snubber capacitor to the other.
3. The diodes on the primary side start conducting since the current is still positive. When referring to Fig. 4, the current decreases to eventually reach zero.
4. Finally, when the current changes its polarity, switches on the primary and the secondary side start conducting under zero voltage since their corresponding diodes were conducting.

The snubber capacitors are included in the mechanism in order to reduce the turn-off losses. However, it is not compulsory to physically add capacitors in parallel to the switches since the medium frequency transformer has a parasitic capacitance on each of its sides. If this parasitic value is large enough, namely in the range of the nano Farads, the snubber capacitance can be omitted.

Operation principle of the cycloconverter

The cycloconverter operates with bidirectional switches, consisting of two active devices with two parallel diodes. In a similar way as in matrix conversion, the active device to operate, in case of a switching, depends on the direction of the conducting current. However, the operation of the cycloconverter doesn't allow the two active switches to be conducting in order to avoid short-circuit. The zero crossing of the alternating current is therefore an issue, since it has to be detected in order to switch the two devices in the bidirectional switch. This issue is not discussed any further but more details are available in [7, 8, 9].

The voltage applied to the primary side of the transformer is identical to the secondary side. As illustrated on Fig. 6, the cycloconverter applies this voltage to the inductor on the grid side with a varying pulse width τ in order to produce the 50 Hz output current. In order to reduce the current ripple, a three level modulation is obtained by applying a fixed negative voltage during τ and a zero voltage during $\lambda - \tau$ as described in [10].

Experimental set-up

The two 25 kVA converters have been built in order to validate the operation principles and to measure the power efficiency. The ratings that are common for both solutions are given in Table 1. The converters are implemented with the same transformer tank filled with oil for cooling. The switches are IGBTs based modules provided by Dynex Semiconductor and the two medium frequency transformers have been designed and produced by ABB Sécheron.

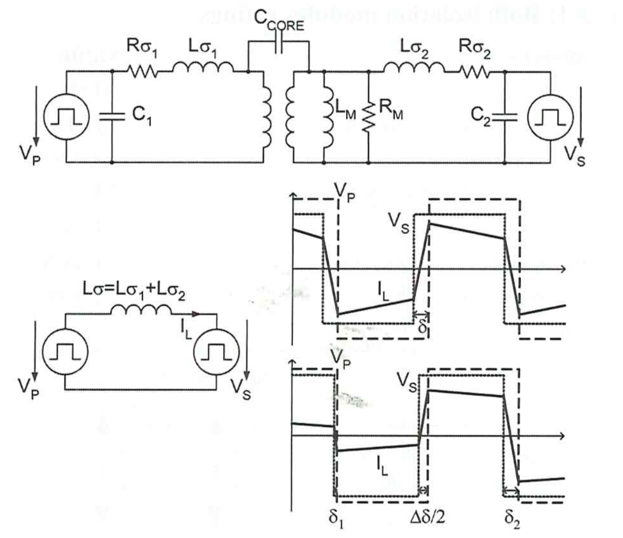

Fig. 4: Transformer model and control principle

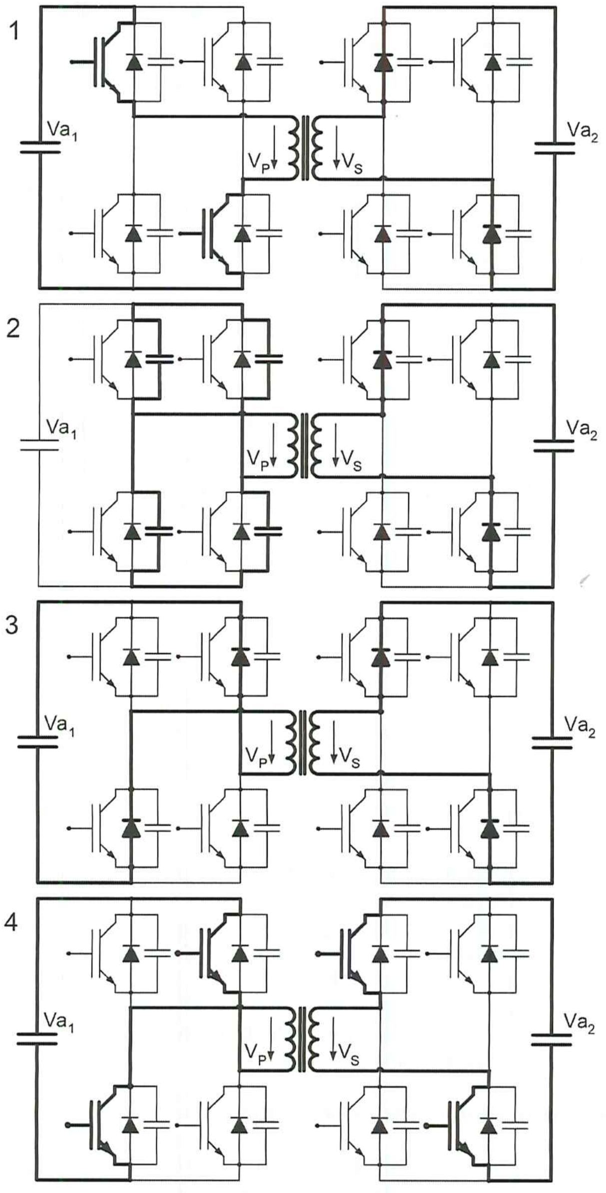

Fig. 5: Soft-switching mechanisms in the VSIBM

Table 1: Both isolation modules ratings

Parameters	Value
Grid frequency	50 Hz
Grid side switching frequency	150 Hz
DC link voltage	1.1 kV
MFT switching frequency	2 kHz
Grid voltage	480 V
Apparent power (4 quadrants)	25 kVA
Chosen inductance value	12 mH
DC link capacitors	3.1 mF

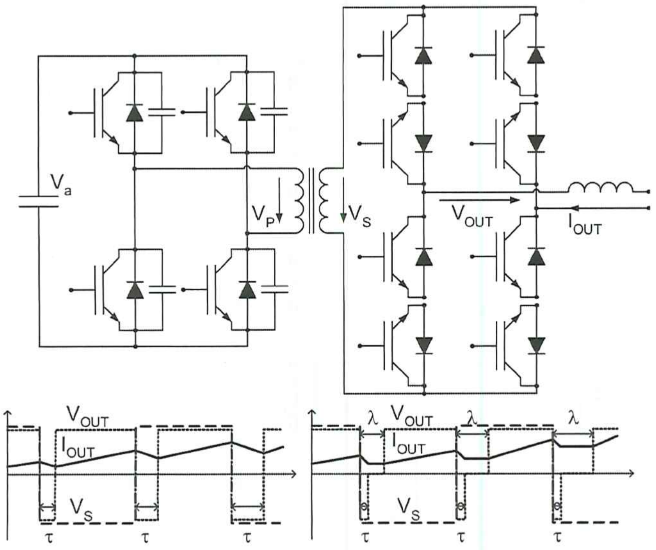

Fig. 6: Two and three level modulation in the CBM

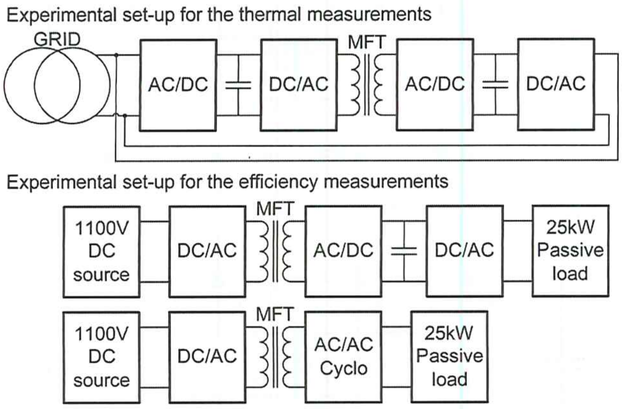

Fig. 7: Experimenal set-ups

Two experimental set-ups are illustrated on Fig. 7. Thermal measurements are performed on the transformer tank when connected to the whole converter. Both ports are connected together, so even at full active power flow, the grid only provides energy to compensate conversion losses. For efficiency measurements, partial converters are implemented. A 1100 V DC source provides the energy to a 25 kW passive load which has been built out of several commercial electric fans.

Implementation of the isolation modules

The prototype of the VSIBM, shown on Fig. 8, is similar to the CBM since they are implemented with the same transformer tank. Converters A and B are implemented on the same board together on the same heat sink and placed on each side of the tank. In the case of the CBM, the whole cycloconverter is placed alone on the secondary side of the transformer. The differences between the ratings of the converters are given in Table 2.

Dimensioning of the transformers

Due to the difference in operation principle of the two conversion topologies, the specifications for the two medium frequency power transformers are different (see Table 3). The CBM requires a transformer with a very low short-circuit impedance. On the one hand, the primary and the secondary windings are interleaved and, on the other hand, the number of turns is limited so as to reduce the short circuit inductance, leading to a high cross sectional area within the magnetic core. The VSIBM lets more dimensioning

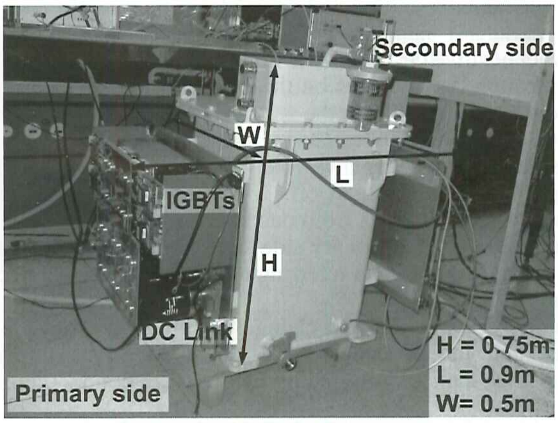

Fig. 8: 25 kVA VSIBM prototype

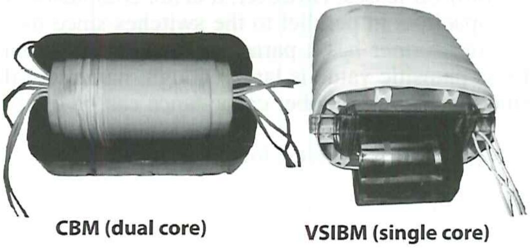

Fig. 9: Active part of the transformers

Table 2: Isolation modules properties

Parameters	VSIBM	CBM
Snubber capacitors	4.1 nF	-
Rated RMS current	56 A	33 A
Rated transformer power	61.6 kVA	36.3 kVA
Main inductance	0.1-0.2 H	0.1-0.2 H
Leakage inductance	0.032 mH	0.48 mH

Table 3: Medium frequency transformers specifications

Parameters	VSIBM	CBM
Number of cores	1	2
Core weight	21.5 kg	43 kg
Core losses	129 W	259 W
Copper weight	11 kg	10 kg
Number of turns	76	38
Total number of layers	2	3
Current density	2.9 A/mm^2	2.4 A/mm^2
Ohm losses	232 W	162 W
Short circuit impedance	480 µH	15 µH

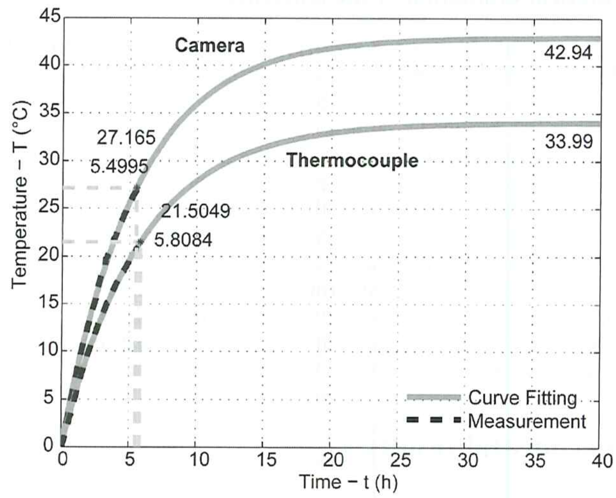

Fig. 10: Thermal time constant for the tank

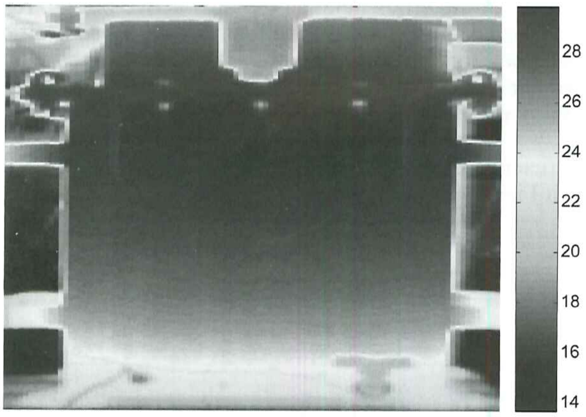

Fig. 11: Thermal view of the tank in operation

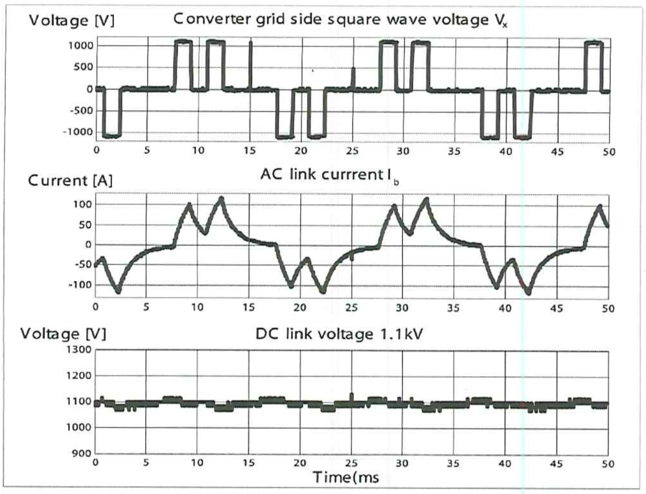

Fig. 12: Currents and voltages in converter A

freedom for choosing number of turns and core cross sectional area. In order to reduce costs both transformers have the same magnetic core made with amorphous magnetic materials. While the VSIBM has a single core, consequence of the fixed and relatively high short-circuit inductance, the CBM has a dual core to concentrate the leakage field only within the core window (see Fig. 9).

Thermal and acoustic measurement of the transformer tank

The VSIBM is run for six hours at full power and cooled down for the same amount of time. In order to determine the most suitable thermal measurement method, they have been carried out with several means, including a thermal camera (see Fig. 10) and a thermocouple. On the one hand, the shiny and creamy taint of the tank in a highly reflective environment induces non negligible errors as illustrated on Fig. 11. On the other hand, the thermocouple of type *K* used for the measurement can suffer from induced voltages introducing additional errors. However, the thermal time constants for temperature rise and fall appeared to be identical showing the accuracy of the thermocouple measurements. The temperature of the tank reaches temperature stability after an estimated time of around 20 hours deduced from the curve fitting function. The acoustic noise produced by the whole tank has been measured to be about 100 dB. The tank filled with oil for both isolation and thermal dissipation doesn't reduce the inherently high acoustic noise of amorphous cores.

Operation of the VSIBM

The converter A, namely the voltage source inverter for the grid connection is run with a switching frequency of 150 Hz to fulfil the low switching loss requirements in the whole converter. The behaviour of the converter output voltage and the line current are depicted in Fig. 12. It is easy to understand that the measuring conditions have been chosen as for a low frequency multilevel operation even if the single module application leads to high cur-

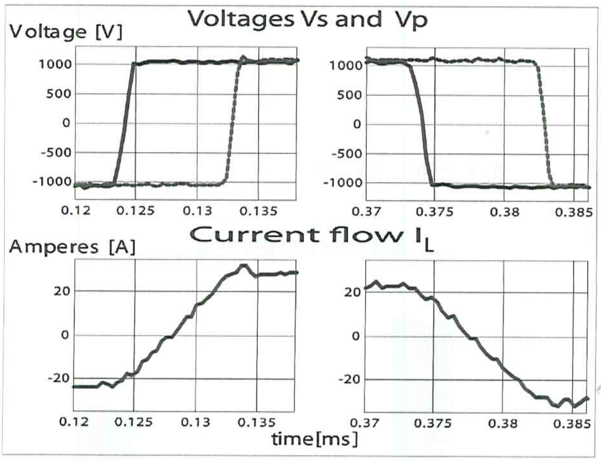

Fig. 13: Phase shift in the dual active bridge

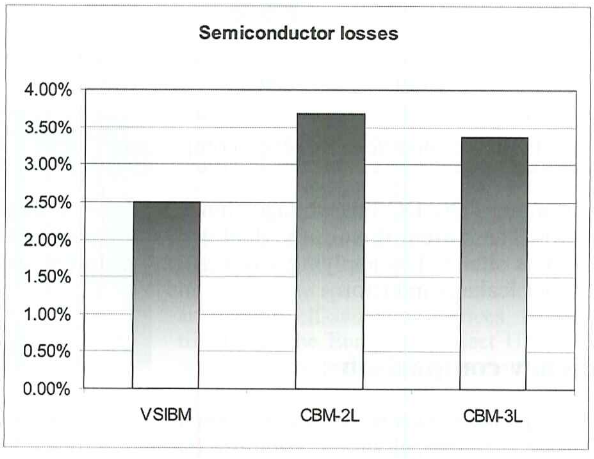

Fig. 14: Semiconductor losses comparison

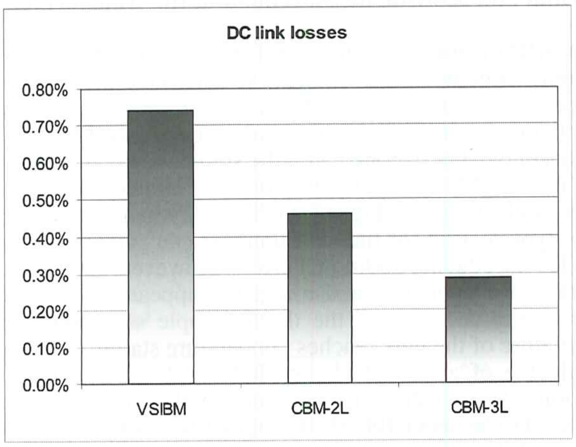

Fig. 15: DC link losses comparison

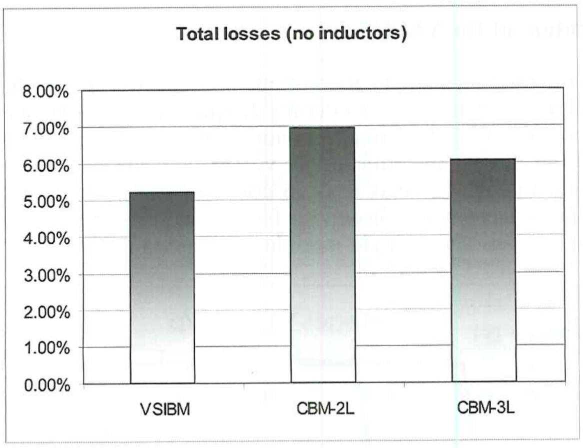

Fig. 16: Comparison of the total losses

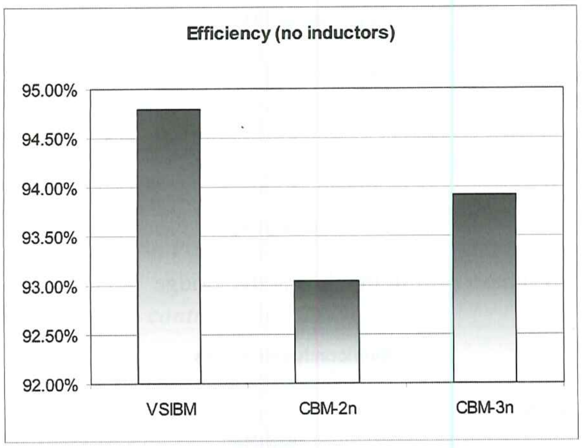

Fig. 17: Isolation modules efficiency comparison

rent harmonics. The DC link voltage shows a very low ripple at full power. The current flow in the dual active bridge, illustrated in Fig. 13, is obtained by applying a voltage phase shift across the transformer leakage inductor.

Efficiency comparison

The comparison between the two converters is focussed on the efficiencies. Theoretical values, detailing the nature of the losses in each topology, are compared to experimental measurements for validation.

Theoretical evaluation of the efficiencies

The theoretical efficiency comparison is given the VSIBM and the CBM run with two different modulations. The VSIBM shows the lower overall losses when compared to the CBM as illustrated in Fig. 16. It has higher DC link losses, illustrated in Fig. 15, due to the uses of two capacitors. However, the proportion of the DC link losses is insignificant next to semiconductor losses, illustrated in Fig. 14, which are much lower than in the CBM. When the cycloconverter is run under a three level operation, the losses are unsurprisingly lower than in a two level operation, since in free wheeling mode, the current flows through a simpler path on the secondary side. As illustrated in Fig. 17, the VSIBM is expected to have a higher efficiency than in the cycloconverter run in any operation mode.

Experimental results

Both converters are run with a 1100 V DC source and a 25 kW alternating load. The measured efficiency for the voltage source inverter alone is given in Fig. 18. As illustrated on Fig. 19, the comparison of the efficiencies in the dual active bridge, run with and without added snubber capacitors, shows a better efficiency with snubber for high power only. This results shows that the transformer parasitic inner capacitance is large enough to provide a snubbing effect to the switches.

The efficiency of the cycloconverter together with converter B is given in Fig. 20. As illustrated in Fig. 21, the CBM is constantly

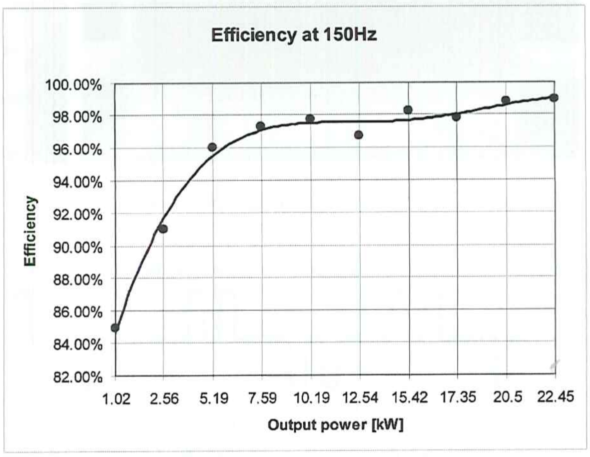

Fig. 18: Experimental efficiency of converter A

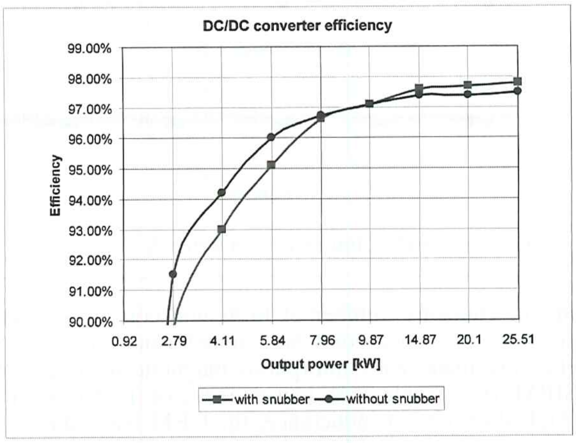

Fig. 19: Experimental efficiency of converter B

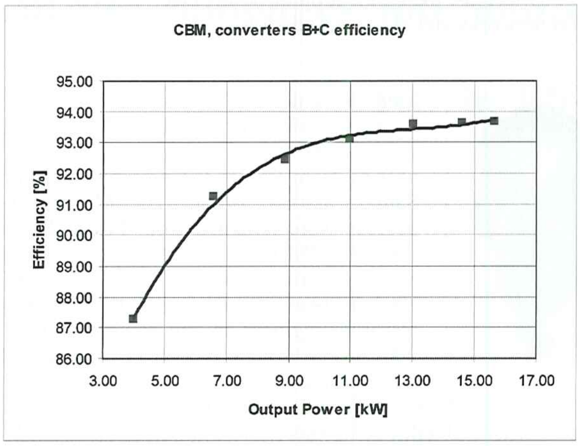

Fig. 20: Experimental efficiency of converter B+C

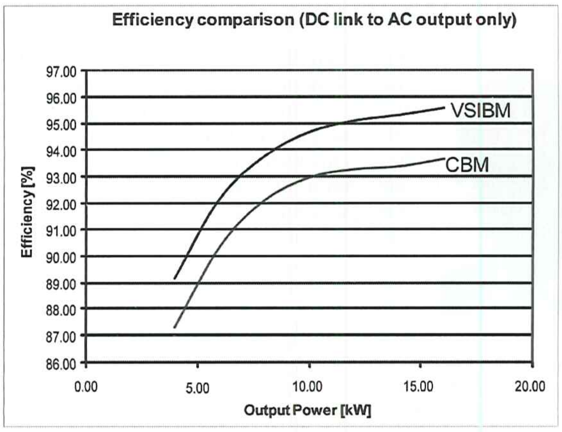

Fig. 21: Isolation modules efficiency comparison

two percent lower in efficiency than the VSIBM. This result confirms what was expected from the theoretical calculations.

Conclusions

Both proposed converters in the frame of UNIFLEX-PM were implemented and tested at EPFL. Theoretical expectations for efficiencies were experimentally validated. The VSIBM (voltage source inverter based module) has been chosen over the CBM (cycloconverter based module) for the implementation of the whole three port converter which has been fully tested at the University of Nottingham. The differences in the efficiencies are mainly due to the conducting losses in the CBM, which are more important than in the VSIBM, due to the higher current flowing from the DC link to the alternating output load.

Due to its innate characteristics, the VSIBM presents a very good behavior in terms of commutations. The voltage across all semiconductor devices is clearly clamped by the DC link voltages. Soft switching is achieved in converter B, and converter A operates in hard switching mode. However, since the whole module is to be duplicated in a multi-level topology, the switching frequency of converter A can be reduced down to 150Hz. The snubber capacitors, added to reach soft switching in the dual active bridge as well as the series inductor in the AC link can be avoided by a proper design of the medium frequency transformer, namely by increasing the leakage inductor and the input parallel capacitor.

An important remark must be done regarding efficiency results of both modules. The reached efficiency values are obviously not high enough for power systems applications since the lost energy cost is very high. However, the gain obtained by using this kind of energy processing systems in terms of power flow control, harmonic reduction and raw material economization provides unprecedented advantages for modern power systems. Moreover, the obtained efficiency is linked to the current technology, and losses are mainly related to semiconductors. This means that envisaging a possible future technology of semiconductors, probably based on silicon carbide or gallium nitride may bring much better results.

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The authors

Daniel Siemaszko was born in Fribourg, Switzerland, in 1982. He received the M.Sc. degree from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland in 2005 and the Ph.D. degree at the same institute (EPFL) at the Industrial Electronics Laboratory (LEI) in 2009. During his Ph.D. study, he was interested into special driving systems aiming for artificially self-switching devices. He also contributed in the European project UNIFLEX-PM on the study and implementation of isolation modules for a multilevel converter aiming for grid connection. After his thesis, he came to Royal Institute of Technology (KTH), Stockholm, Sweden at the Electrical Machine and Power Electronics Laboratory (EME) as a Post-Doc where he worked on the implementation of a modular multilevel converter.

Frédéric Zurkinden received the M.Sc. degree from the Swiss Federal Institute of Technology in Lausanne, Switzerland (EPFL) in 2006. He pursued with two years working at the Industrial Electronics Laboratory (LEI) of the Swiss Federal Institute of Technology in the frame of the European project UNIFLEX-PM. His researches were mainly oriented towards the study and implementation of a cycloconverter interfacing a medium frequency transformer and the grid. He joined Solvix in Villaz-St-Pierre, Switzerland in 2008. He is now part of the R&D department which is involved in developing innovative power supplies notably in the field of PVD and PECVD applications.

Lukas Fleischli was born in Luzern, Switzerland, in 1981. He received the M.Sc. degree from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland in 2006. After his degree he studied a multilevel converter for energy storage in supercapacitors. His main work was the contribution to the European project UNIFLEX-PM where he designed, implemented and tested an isolation module for a multilevel converter aiming for grid connection.

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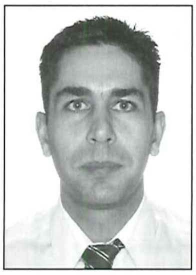

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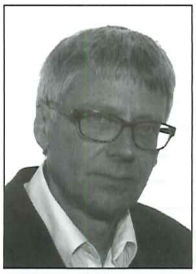

Alfred Rufer received the M.S. degree from the Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, in 1976. In 1978, he joined ABB, Turgi, Switzerland, where he was involved in the fields of power electronics and control, such as high-power variable frequency converters for 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.