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Digital Object Identifier (DOI): 10.1109/PEDG.2017.7972557

International Symposium on Power Electronics for Distributed Generation Systems

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**Suggested Citation**

L. F. Costa, G. Buticchi and M. Liserre, "Modular Smart Transformer architectures: An overview and proposal of an interphase architecture," 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Florianopolis, 2017, pp. 1-7.

# Modular Smart Transformer Architectures: An Overview and Proposal of a Interphase Architecture

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**Abstract**—Several Smart Transformer (ST) architectures have been discussed in literature and the modular approach proved to be interesting because of its advantage of fault tolerance associated to the possibility to use low voltage/current rated devices. In this context, this paper presents an overview and classification of the modular ST architectures, in which the topologies, connections and building block converters are discussed. Furthermore, a ST architectures named "interphase ST architecture" is proposed and described in detail. The main characteristic is that the phases of the three-phase system are connected to the same building block converter, in such way that a single module controls the power exchange among the phases. Therefore, this solution offers higher power control capability. Finally, simulation results are provided and the power transfer capability among the phases of the three phase system is demonstrated.

**Index Terms**—Dc-dc onverter, multiple active bridge converter, modular system, smart transformer, power management.

## I. INTRODUCTION

The increasing proliferation of renewable energy resources and new sizeable loads like electric vehicle (EV) charging stations has posed many technical and operational challenges to distribution grids [1], [2]. Among them, the reverse power flow requirement, storage integration, management of hybrid grids (dc and ac) and power quality improvement are highlighted [1]–[5]. The power electronic system, already used in most of the power conversion involving the new loads and sources connected to the network, plays a significant role in the improvement of the electric grid [2]–[5]. Among the power electronics-based solutions, the Smart Transformer is a promising solution to the aforementioned problems. This system, also called as Power Electronics Transformer (PET) and Solid-State Transformer (SST), is defined as a power electronics based system operating in high frequency (reducing size and weight) with higher controllability [2], [4]–[6]. The Smart Transformer (ST) differs from the others previous concept by its higher capability to provide extra grid services, allowed by its advanced control and communication system.

Recently, Solid-State Transformer architectures have been intensively discussed in literature and classified according to the number of power stages (single-, two- or three-stages) and modularity level (non-modular, semi-modular or modular), as presented in [2]. The three-stage configuration is the preferred

candidate for the ST, because it enables dc-link connectivity and also guarantees input/output decoupling of voltages and currents, providing the system control more degrees of freedom. In addition, the modular approach has received a lot of attention, mainly because of its fault tolerant capability by redundant modules. This feature increases significantly the availability and, consequently, the reliability of system, which is one of the bottlenecks of the ST.

Different architectures can be implemented using the modular approach and they will be classified and discussed as follows. Not only the topology choice of each power conversion stage, but also their connection, makes the difference in a ST architecture generation. In this regards, this paper shows an overview on modular ST architectures, where the possible connection, topologies and building block converter are presented and discussed. Furthermore, based on an existing architecture, a connection modification is proposed, resulting in a novel modular architecture with interconnection among the phases of the three-phase system and named in this work "interphase ST architecture". In section II an overview of the ST architectures is presented and the proposed topology is derived. The proposed architecture is detailed described in Section III, while its basic operation is presented and discussed. Finally, an overall comparison of the main ST architecture, where the advantages and disadvantages of the proposed one are highlighted is presented, followed by a discussion is presented in section IV.

## II. OVERVIEW ON MODULAR ST ARCHITECTURES

The modular ST architecture, composed of several basic building blocks, and a classification taking into account the power converter topologies and their connections are presented in Fig. 2.

A possibility to implement the modular ST is based on a modular MV converter associated with modular dc-dc converter decoupled by a MV DC-link, as shown in Fig. 1 (a). This configuration has two basic modules: one for the MV front-end converter and another for the dc-dc converter. In this architecture, the well-known Modular Multilevel Converter (MMC) [7] is the preferred choice for the MV stage, while many options for the dc-dc converter as a building block are possible for the dc-dc stage. The building block converters of the dc-dc stage are connected in parallel in the LV side and in series in the MV side, conceiving the MV DC-link.

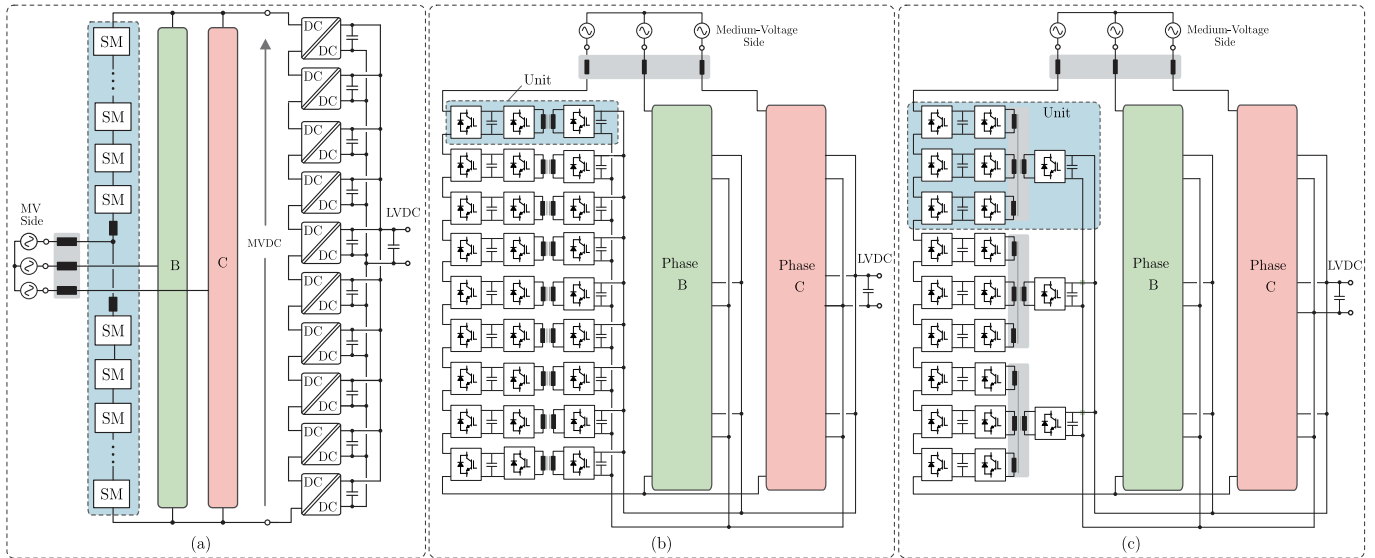


Figure 1. Modular smart transformer architecture concepts: (a) architecture based on two basic building block (one for the MV stage, implemented using the MMC and the second for the dc-dc stage), (b) Phase modular architecture, characterized by a single building block per phase, (c) phase semi-modular architecture, also characterized by a single building block per phase, by using the semi-modular concept of dc-dc converter.

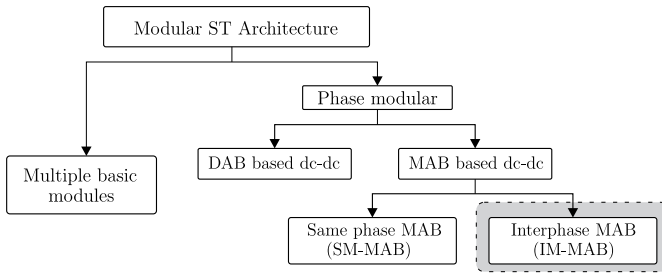


Figure 2. Classification of the modular smart transformer architectures.

The second possibility is based on a concept known as the phase-modular [1-3], in which a single module is used to implement the dc-dc stage and the MV stage (see Fig. 1 (b)). It means that the basic building block of the ST consists of a module of the MV stage and dc-dc stage. In this configuration, the building block of the dc-dc stage are connected in parallel in the LV side, while in the MV side they are associated to the respective module of the MV stage converter, generating the basic building block unit of the ST. Hence, there is no MV DC-link available in this architecture.

To implement the MV stage, the Cascaded H-Bridge (CHB) is preferable, while many options are possible for the dc-dc stage. Note that the dc-dc stage has more degrees of freedom concerning the building block topology choice. On the other hand, it must be carefully chosen, because this stage plays the most important role of the ST power conversion in terms of efficiency, cost and reliability. It is responsible for the galvanic isolation and voltage adaptation between the the MV side and LV side, while operating in high frequency, reducing size and weight. The preferred topologies to implement are the Series Resonant Converter (SRC) [6], [8], [9] and Dual

Active Bridge (DAB), but because of its lack of power flow control (highly required in the ST architectures applied to distribution system), the SRC is not the best choice. The Multiple Active Bridge (MAB), specifically the one composed by four bridges and named Quadruple Active Bridge (QAB), has emerged as a promising solution [10], [11], because it offers the same advantages of the DAB with reduced number of high frequency transformer and modules. Besides that, recent studies have demonstrated its high operational performance and economic viability in ST application [12]. In [2], this topology is classified as a semi-modular architecture. The phase modular ST architecture can be further classified in modular, when the DAB is used as building block of dc-dc stage (as shown in Fig. 1 (b)) or in semi-modular, when the QAB is used to implement the dc-dc stage, as depicted in Fig. 1 (c).

In the semi-modular architecture, the QAB converter has one bridge connected to the LV side and three connected to one phase of the MV side, as can be seen in Fig. 1 (c). In spite of having all the MV bridges connected at the same phase, the QAB converter allows different connection in the MV side. This work proposes a different connection of the semi-modular architecture, where each MV bridge of the QAB converter is connected to different phases, leading to a novel ST architecture. The proposed ST architecture is shown in Fig. 3 and it offers a direct connection among the phases of the three-phase system through the QAB converter, then named as interphase ST architecture. Therefore, a further step on the classification of the semi-modular modular architecture based on MAB converter is given, regarding its connection: Same-Phase connection (SM-MAB), shown in Fig. 1 (c), and interphase connection (IF-MAB), as shown in 3.

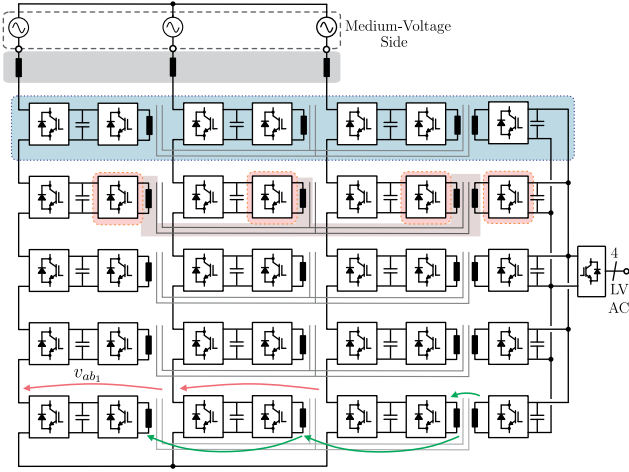


Figure 3. Proposed Interphase Modular ST Architecture.

### III. INTERPHASE ST ARCHITECTURE

#### A. Architecture Description

The basic concept of the proposed architecture is to connect the phases of the three phase system to the same building block converter, in such way that a single module might control the power exchange among the phases. Similarly to the SM-MAB (see Fig. 1 (c)), the IF-MAB is composed by the CHB front-end converter associated to the QAB dc-dc converter, as observed in Fig. 3. The MV bridges of the QAB are linked to the dc side of the CHB cells, while these cells are connected to different phase. Hence, this architecture offers a direct power path among the phases through the MV side of the multi-winding transformer, without disturbing the LV side, as highlighted in Fig. 4. This is advantageous for the power balance of the three-phase system, simplifying the control effort of the power balance loop. In this case, the required power balance loop, usually implemented in the control system of the MV side converter, i.e. the CHB, can also be implemented directly on the dc-dc converter. Consequently, this architectures offers more degree of freedom to control the power among the phases of the three-phase system, as well as increases the power balance loop implementation options.

Additionally, the economic advantages obtained by using the QAB converter, as described in [12], is preserved in this architecture, while a different operation and performance are achieved. In the next section, the proposed IF-MAB will be analyzed and compared with the SM-MAB in terms of power balance control, fault tolerance capability and redundancy implementation and isolation requirements of the multi-winding transformer.

#### B. Power Balance Control

In distribution grid application, the ST controllability is of paramount importance, since the voltages and currents in both MV and LV sides must be properly controlled, providing extra services to the distribution grid [2]. Besides that, additional loops are required for the basic operation of the system, like

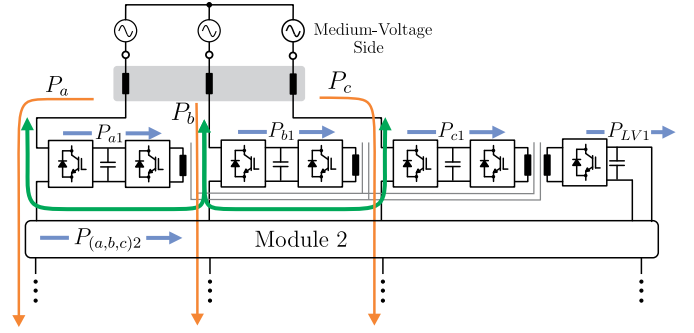


Figure 4. Power paths of the proposed interphase ST architecture, showing its capability to exchange power among the phases of the three phase system through the multi-winding transformer.

the LVDC link control, power balance and etc. Therefore, each power stage has its own control system and their control variables are described as follow:

- **LV Stage:** output ac voltage ( $v_{ac(LV)}$ )
- **DC-DC Stage:** LVDC link ( $v_{(LVDC)}$ ), power balanced among the modules ( $p_{(QAB(mv))}$ ).
- **MV Stage:** input ac current ( $i_{ac(MV)}$ ), total dc-link of the MV side ( $v_{(MVDC)}$ ), individual dc-link of the cells ( $v_{(dc(mv))}$ ) and the power balance among the phases (balance of the neutral point) ( $p_{a,b,c}$ )

As can be noticed, the MV side has the highest control system requirement, implying higher implementation effort compared to the other stages. Besides its standard control loops ( $i_{ac(MV)}$  and  $v_{(MVDC)}$ ), the CHB must also control the power balance among the phases ( $p_{a,b,c}$ ), when working as a rectifier.

In the following analysis, the capability of the SM-MAB and IF-MAB architectures to support the power balance of the three phase system is evaluated and compared. In this studies, it is considered that the CHB operates with phase-shift modulation scheme. The QAB converter uses the classical phase-shift modulation scheme, in which the power is controlled by the phase difference among the bridges and it can be generally described by (1), where  $i$  and  $j$  denote the respective bridges involved in the power exchange, according to [13]. More detail about the converter operation can be found in [11], [13]. The total power processed by the QAB is given by (2), where  $P_{QAB(MV,1,2,3)}$  is the power processed by the respective bridges connected to the MV side.

$$P_{ij} = \frac{V_i V_j}{2\pi f_s L n} \varphi_{ij} \left( 1 - \frac{|\varphi_{ij}|}{\pi} \right), \quad \varphi_{ij} = \varphi_j - \varphi_k \quad (1)$$

$$P_{QAB(LV)} = P_{QAB(MV1)} + P_{QAB(MV2)} + P_{QAB(MV3)} \quad (2)$$

The power of the CHB cells are given by (3), where  $k = \{1, 2, \dots, N\}$  and  $N$  is the number of modules per phase.

$$\begin{cases} P_{a,k} = v_{a,k}i_a = V_{a,k}I_a\sin^2(\omega t) \\ P_{b,k} = v_{b,k}i_b = V_{b,k}I_b\sin^2(\omega t - 2\pi/3) \\ P_{c,k} = v_{c,k}i_c = V_{c,k}I_c\sin^2(\omega t + 2\pi/3) \end{cases} \quad (3)$$

The control scheme of the MV stage and DC-DC stage are presented Fig. 5. As can be noticed, the MV side controls the neutral point using the zero sequence generator scheme, as presented in [14]–[16]. For the dc-dc stage, the LV loop controls the total amount of power transferred from the MV to LV side, while the power balance loop adjusts the power processed by the individual MV bridges, balancing them.

- Power Analysis in the SF-MAB

Analyzing this architecture, the power processed by one MV side of the QAB converter is given by (4), while the total power is given by (5).

$$P_{QAB(MV1)} = i_{dc}V_{dc} = v_{a1}i_{a1} = V_{a1}I_{a1}\sin^2(\omega t) \quad (4)$$

$$P_{QAB(LV)} = P_{a1} + P_{a2} + P_{a3}, \quad (5)$$

Thus, applying (3) in (6), the power processed by the QAB converter can be rewritten in terms of the ac parameters as presented in (6).

$$\begin{cases} P_{QAB(MV1)} = P_{a1} = V_{a1}I_{a1}\sin^2(\omega t) \\ P_{QAB(MV2)} = P_{a2} = V_{a2}I_{a2}\sin^2(\omega t) \\ P_{QAB(MV3)} = P_{a3} = V_{a3}I_{a3}\sin^2(\omega t) \end{cases} \quad (6)$$

As can be noticed, the power balance loop (see Fig. 5) of the QAB converter is just able to manage the power of a unique phase. It means that the SM-MAB is not able to balance the power of the phases.

- Power Analysis in the IF-MAB

Similarly, the interphase architecture is analyzed and the total power processed by the QAB converter is presented in (7), while the power processed by the individual cells in function of the ac parameters is given by (7).

$$P_{LVk} = P_{a_k} + P_{b_k} + P_{c_k}, \quad (7)$$

$$\begin{cases} P_{QAB(MV1)} = P_{a1} = V_{a1}I_{a1}\sin^2(\omega t) \\ P_{QAB(MV2)} = P_{b1} = V_{b1}I_{b1}\sin^2(\omega t - 2\pi/3) \\ P_{QAB(MV3)} = P_{c1} = V_{c1}I_{c1}\sin^2(\omega t + 2\pi/3) \end{cases} \quad (8)$$

As observed, the QAB can manage the power flow from different phases. The reference values of the power balance loop (see Fig. 5) allow balancing the neutral point and the power on the ac side. Consequently, the power balance loop

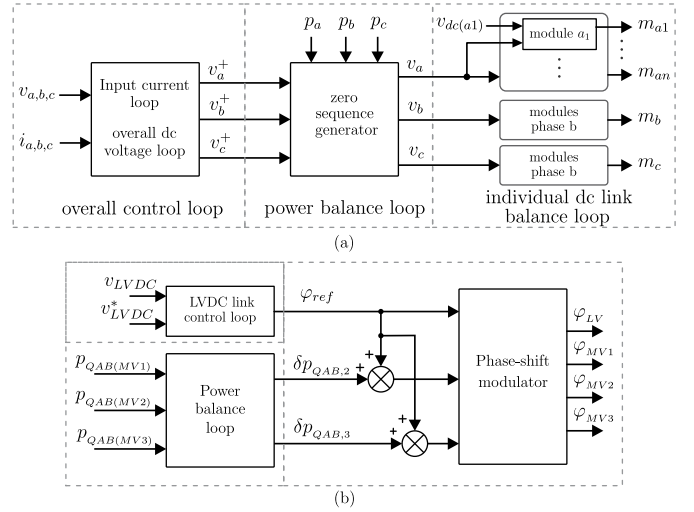


Figure 5. Standard control scheme of the MV stage and DC-DC stage that can be used in ST: (a) MV stage control system, as presented in [14]–[16], (b) dc-dc stage control.

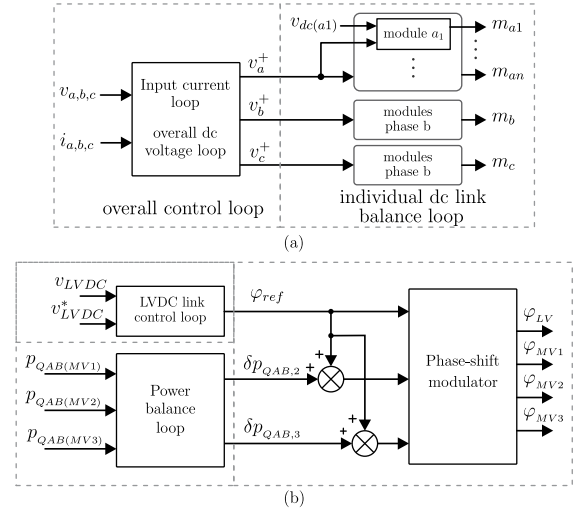


Figure 6. Control system of the MV stage and DC-DC stage for the interphase architecture: (a) MV stage control, (b) dc-dc stage control.

of the MV side converter is not required anymore, and its control system is simplified, as depicted in Fig. 6 (a).

Note the synchronization among the QAB converters is required and this can be implemented through an overall supervision system.

### C. Fault Tolerance Capability and Redundancy Implementation

An important advantage of the modular system is the fault tolerance capability, achieved usually using redundant modules.

There are two possible usual methods for the redundancy implementation: stand-by redundancy and power sharing redundancy. In the first one, the redundant module is deactivated during the normal operation and is used only in case of fault, taking the place of the faulty module. In the second case, the

redundant module is always activated, sharing the power with the other modules.

To implement the redundancy scheme, at least one extra module per phase is required in the MV side. In the IF-MAB, a single extra power unit covers the complete three-phase system. Hence, only one extra power unit can be used to implement the redundancy scheme. Differently from the previous case, the SM-MAB requires one extra power unit per phase to respect the system symmetry, implying in three extra power units to implement the fault tolerance scheme. Thus, the IF-MAB offers more advantages than the SM-MAB from the economic perspective, because a single extra module can be used in the first case to match the requirements of the redundancy implementation, whereas the SM-MAB needs three extras power units.

To analysis the operation of both architectures under fault, two cases are considered as an example: one faulty module and two faulty module of the same power unit.

1) *One faulty module:* in this case, both architectures behave similarly. The faulty cell is by-passed and the remaining healthy modules will share the extra voltage and power among them.

2) *Two faulty modules:* In the IF-MAB, the fault happens in the second phase, as shown in Fig. 7 (a), whereas in the SM-MAB, the fault remains in the same phase, overloading even more this phase, as depicted in Fig. 7 (a). Consequently, the remaining healthy modules will share higher power and voltage, increasing the stress.

From this example, it can be notice that the IF-MAB architecture can manage better the fault compared to the SM-MAB, because the remaining healthy modules are submitted to less stress for the first architecture.

#### D. Isolation Requirement

The main disadvantage of IF-MAB architecture lies on the transformer design. While the multi-winding transformer design is already very challenging because of its structure, the voltage isolation requirements among the winding is higher for the IF-MAB architecture, when compared to the SM-MAB.

The isolation requirement among the secondary winding of the transformer of the SF-MAB is given by (9), where  $V_{LN}$  is the line-to-neutral voltage and  $N$  is the number of modules per phase of the CHB. It means that the isolation between the secondary coils must be design to handle only partial grid voltage. On the other hand, for the proposed IF-MAB architecture, the isolation among the secondary windings of the transformer needs to handle the voltage given by (10),

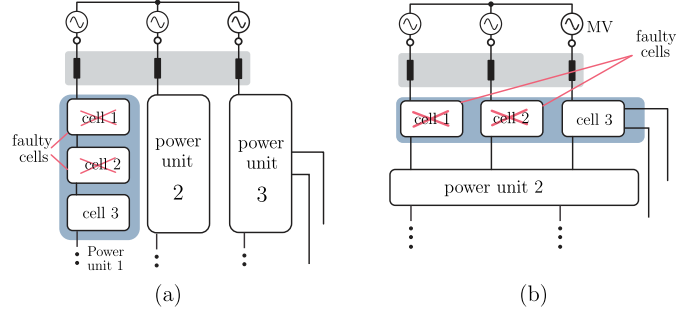


Figure 7. Fault management concept for the different architectures and comparison between them: (a) SM-MAB, (b) IF-MAB.

i.e. the total grid voltage. Since the last architecture needs a multi-winding transformer with higher voltage isolation requirements ( $N$  times higher, compared to the SM-MAB), it implies higher cost and volume of the transformer.

$$V_{isol(MV-to-MV)} = V_{LN}/N \quad (9)$$

$$V_{isol(MV-to-MV)} = V_{LN} \quad (10)$$

For the phase modular architecture (see Fig. 1 (b)), the number of transformers is very high and they need to be isolated for the total grid voltage, as well.

Table I shows a qualitative comparison among the three described modular architectures, taking into account the discussed parameters: power management capability, fault tolerance implementation and also voltage isolation requirement (transformer design effort). As can be noticed, the proposed interphase architecture is more advantageous compared to the others in terms of power management, because of its direct connection among the phase through the MV bridges of the dc-dc stage, and in terms of fault tolerance implementation, because a single extra power units can cover the redundancy for the three phases, implying economic and operational advantages.

#### IV. RESULTS AND PERFORMANCE EVALUATION

In order to verify the performance of the proposed architecture, the system was analyzed through numerical simulation (using the Plecs/Matlab software) and its capability to control the power flow among the phases of the three phase system using the dc-dc stage was investigated. The specifications presented in Table II were used and the main simulation results are presented in Fig. 8. The result consists in evaluating

Table I  
QUALITATIVE COMPARISON OF THE MODULAR ST ARCHITECTURES

Architectures	Power transference among phases	Power balance	Voltage isolation	Redundancy scheme
Phase modular	Medium	Medium	Low	3 out of 9
Phase semi-modular	Low	Medium	Low	3 out of 9
Interphase modular	High	High	High	1 out of 9



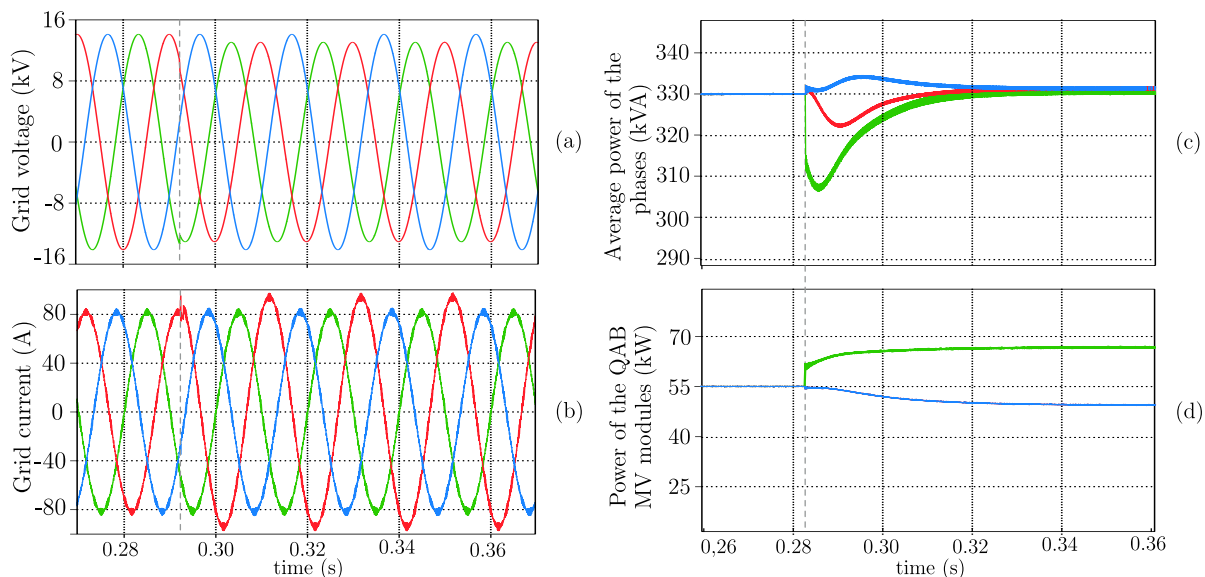


Figure 8. Simulation results of the proposed interphase architecture, when a fault happens, resulting in power imbalance: (a) three phase grid voltage on the MV side, (b) three phase grid current, (c) power on the three phase system, (d) power processed by the MV bridges of one QAB converter, demonstrating its ability to control the power, supporting the three phase system.

Table II  
SYSTEM SPECIFICATION USED FOR THE SIMULATION

Parameters	Value
Nominal ST power	1 MW
Grid voltage (line to line)	10 kV
Grid frequency	50 Hz
Total MVDC link	10.2 kV
LVDC link	700 V
Number of power units	6
Unit power level	55 kW
Switching frequency of QAB	20 kHz
Individual dc link voltage	1.7 kV

the system operating under unbalanced power condition, to demonstrate the control principle described in Section III. B. The control system presented in Fig. 6 was implemented in simulation, in which the power of the three-phase system is balanced by changing the reference of the power balance loop of the QAB converter.

## V. CONCLUSION

The modular architecture of Smart Transformers (ST) is very advantageous, mainly because of its high performance to manage the fault and also its possibility to employ standard low voltage/current rating devices. Different architectures can be implemented using the modular concepts. In this context, this paper has classified the modular ST architectures in terms of topology, connections and basic building blocks and a overview on modular ST architecture was presented. Additionally, a connection modification in an existing architecture was proposed, leading to a novel architecture, named as interphase modular ST architecture. The proposed architecture is based

on a Cascaded H-bridge converter associated to a multiple active bridge dc-dc converters and it is characterized to offer a direct power path for the different phases of the three phase system through the dc-dc stage.

The main advantage of the proposed architecture is its high capability to control the power of the three phase system, resulting is less control effort implementation for the MV stage of the ST. In addition to that, the proposed architecture offers also advantages regarding the fault management implementation. To use the redundancy scheme concept, at least one extra module per phase should be used. As a single power unit of the proposed architecture covers all the three phase system, only one extra power unit can be used to implement the redundancy scheme.

Finally, simulation results were presented, where the unbalance power condition was discussed. The results demonstrate the high potential of the proposed architecture to manage the power transference among the phases.

## ACKNOWLEDGMENT

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. [616344] - HEART.

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