VIII Konferencja Naukowo-Techniczna – i-MITEL 2014

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Simple Modular Active Power Electronic Transformer

***Abstract**. The current project was originally initiated by the see industry, where bulky low-frequency transformers have become a growing problem. The need for an alternative that is more flexible and would also support the micro grid concept has become a priority. The active power electronic transformer (APET) is the likely the most suitable candidate for that. In the complex power electronic systems modularity is one of the key aspects to success. Using modular power electronic building blocks (PEBB) complex power electronics systems can be built and reconfigured quickly and reliably by just connecting several PEBBs together, without considering the physical realization inside the PEBB. As a result, reduced costs, losses, weight, size and engineering effort could be achieved. In this paper a new type of the PEBB for the APET is proposed. The performance of the system was verified by computer simulations using PSIM simulation software. Finally, a 3D model of the demonstrator is presented.*

Keywords: power electronic transformer, power electronic building block, modular multilevel converter, PFC

Introduction

The structure of the smart grid could be very complex and hardly predictable. Thus, an active power electronic transformer (APET) could have many roles in that stochastic and variable system. Clearly, APET will not consist of one or two power electronic converters. It would rather have a modular structure. The modularity could bring many advantages but most importantly adaptability and redundancy. The adaptability means that any voltage or current level can be achieved by connecting several APET modules in series or in parallel. Thus, custom design and adaption to various user requirements is easy to accomplish. Redundancy refers to the fact that each module should work completely independently. Therefore, in the case of errors the faulty modules can be simply bypassed until they are replaced and the system will remain fully functional. As a result, the ride-through capability will be improved and the reliability of APET increased.

Implementation of modular structure in conventional power electronics is relatively common especially in complex systems. Moreover, the modules can be seen as universal power electronic building blocks (PEBB). The term was first introduced by Office of Naval Research in late 1990s [1]. The PEBB was defined as a system consisting of [2]:

- power supply for gate drives and sensors;
- stack or module assembly including gate drives;
- voltage, current and temperature sensors incl. A/D conversion unit;
- pulse generator for gate driver;
- communication with control;
- primary protection.

Using PEBBs complex power electronics systems can be built and reconfigured quickly and reliably by just connecting several PEBBs together, without considering the physical realization inside the PEBB. As a result, reduced costs, losses, weight, size and engineering effort can be achieved [3, 4]. Generally, the PEBB is defined as a system with defined functionality, standardized hardware & control interfaces and plug-and-play capability [5, 3].

Based on the literature, the PEBB can be defined in three ways:

1. at the phase leg level of a power electronic converter [2-4];
2. as a single conversion stage (AC/DC, DC/AC, AC/AC, DC/DC) [6, 7] ;
3. as a multiple conversion stage (AC/DC/DC, AC/DC/AC, etc.) [7, 8];

Which way is the best, depends mostly on the system complexity and scale. In this paper a new type of PEBB consisting of multiple conversion stages is presented.

The current project was originally initiated by the see industry, where bulky low-frequency transformers have become a growing problem. The conventional low-frequency transformers are too massive and inflexible to cover all the needs of the power management. The main target of the project is to work out an APET (three phase, 6.6 kV/0.4 kV) that could effectively replace conventional low-frequency transformers. The redundancy is one of the key aspects and required by the industry. Therefore, only modular structure can be considered. Our main goal is to develop the PEBB, which would allow to simplify and standardize the construction of APETs for various applications of the see industry.

In this paper the preliminary results of the project are presented. A new type of PEBB was proposed. The PEBB was designed as a bidirectional system with the transfer ratio 1:1. In the input and output ports PFC algorithm can be implemented to achieve unity power factor. The performance of the proposed PEBB was verified by computer-aided simulations using PSIM simulation software. Finally, a 3D vision of the demonstrator (currently under construction) is presented.

Selection of the topology

The modular structure based APET is not new and has been discussed in many papers [9-12]. Moreover, it tends to be the main direction in the case of high power and high voltage applications. The most common approach here is to implement three-stage modules, consisting of the input, isolation and output stages. The input stage as an active front end is based on the full-bridge topology. The isolation stage includes the high (or medium) frequency transformer and is realized as the dual active bridge[10-12] or half-bridge[9]. The output stage typically consists of a bidirectional three-phase inverter [10,11]. All these solutions have their benefits and drawback but in general, they have proved to work best of all possible topologies. In [12] a new interesting solution for the input stage has been proposed, where the conventional input stage has been replaced by a modular multilevel converter (MMC).

The MMC concept is a very promising power converter topology for high power and high voltage applications [13]. The main advantages of MMC are [14, 15]: continuous internal arm currents, no common DC link capacitor is required, the inductors inserted in the arms limit the AC-current in case of a short circuit at the DC side, good efficiency. In this paper also the MMC concept has been used to construct the PEBB for the APET.

A completely new three-stage topology has been proposed by the authors, as shown in Fig. 1. The input and output stages were constructed of the half-bridge sub-modules of the MMC while the isolation stage consists of the conventional dual half-bridge. The PEBB is completely symmetrical and works bidirectionally. It has six terminals: two AC terminals and four DC terminals (two DC links). A standalone control system is integrated, which allows each PEBB to be truly independent. In addition the PEBB includes voltage/current transducers and gate drivers. Compared to the other conventional three-stage APET topologies [10-11] the main advantages of the proposed topology are the reduced number of semiconductor switches and the DC-link capacitors.

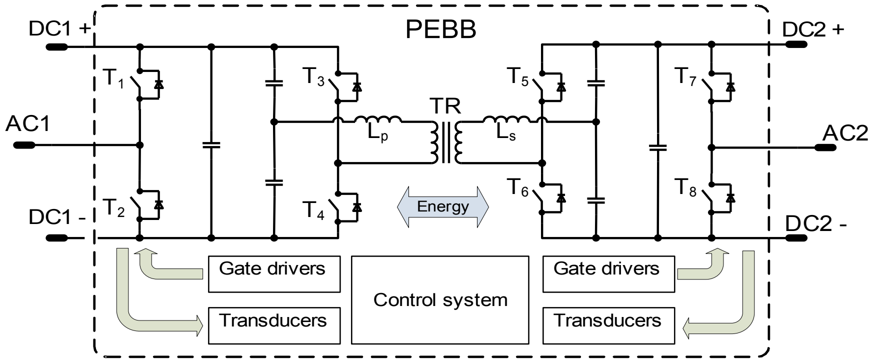

Fig. 1. Electric schematic of the proposed PEBB.

Using the proposed PEBBs a simple modular three-phase APTE can be constructed, as shown in Fig. 2. To meet the high voltage requirements on the mains side, series connection of the modules can be used. On the other hand, if more power is needed, the parallel connection can be used, as shown at the load side (Fig. 2). However, for inverter operation the output stage DC links of all modules should be connected together, as shown in Fig. 2.

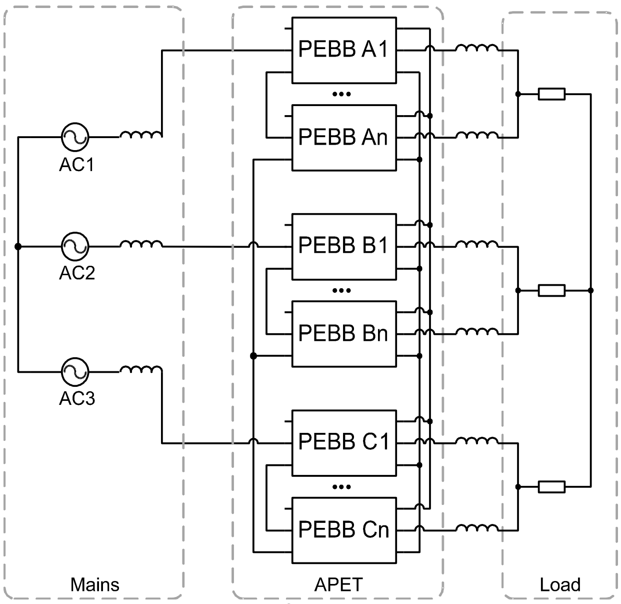

Fig. 2. Principal scheme of the three-phase demonstrator.

Description of the Model

The simplest three-phase APET consists of the three PEBBs (PEBB 1, PEBB 2, PEBB 3), as shown in Fig. 3. The inputs are connected to a three-phase AC grid. The APET is supplying a passive load consisting of inductors (L1, L2, L3) and resistive loads. In addition, the three PEBBs are connected in parallel via DC-links (out2, out3). Thus, all three block share a common DC-link on the output side.

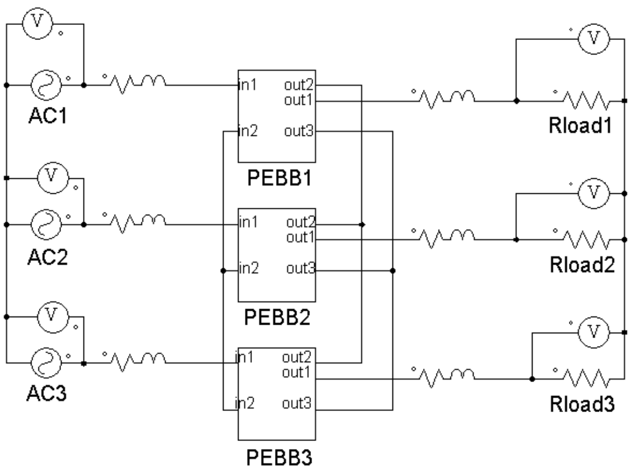

Fig. 3. Model of the three-phase APET.

The subcircuit of the PEBB is divided into three parts: input stage, isolation stage and output stage. The input stage or the active front end consists of an inductor, two transistors and a capacitor, as shown in Fig. 4. To achieve unity power factor, PFC algorithm is implemented in the input stage. The algorithm consists of two control loops (Fig. 5): DC-link voltage and input current loop. The voltage regulator (PI1), controls the amount of power required to maintain the DC-link voltage constant. The voltage controller programs the amplitude of the input current. To obtain the input current reference, which should be sinusoidal and in phase with the input voltage, the voltage controller output is multiplied by an appropriate sinusoidal signal (Sin_ref). The current regulator (PI2) forces the input current to follow the current reference programmed by the voltage control loop.

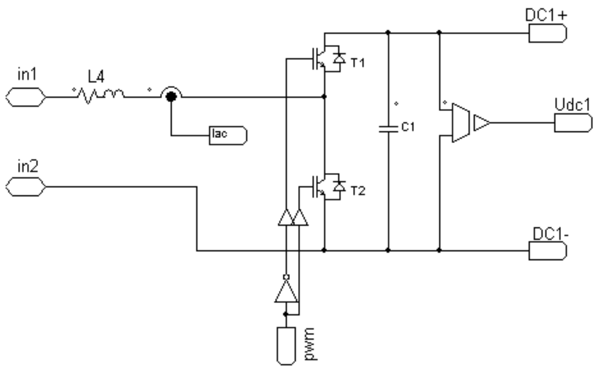

Fig. 4. Input stage of the PEBB

The isolation stage is based on the dual half-bridge (DHB) topology (Fig. 6). It includes the medium frequency (20 kHz) transformer, four transistors and capacitors. Bidirectional energy control is possible by regulating the phase shift angle between the half-bridges. However, in this model DHB works unidirectional and only the output voltage (Udc2) is regulated. Fig. 7 shows the voltage control loop, that consists of the PI regulator and phase shift modulators.

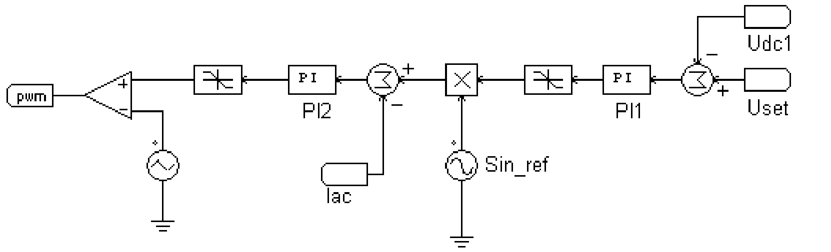

Fig. 5.Typical PFC algorithm of the input stage.

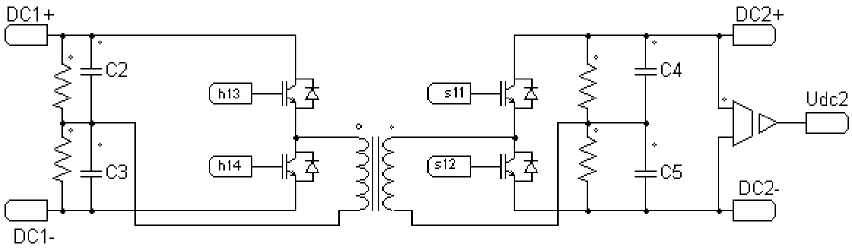

Fig. 6. Isolation stage.

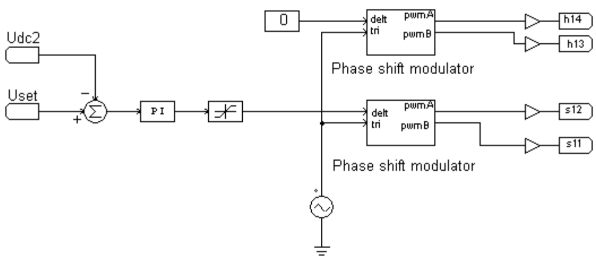

Fig. 7. Control system of the isolation stage

The output stage is identical with the input stage consisting of two transistors and a capacitor. It can be seen as a phase leg of a three-phase inverter. Thus, only one AC output terminal is needed. Since, the model was operated in constant load conditions, the output stage needed now regulator. Instead of the regulator, a typical sinus modulator has been implemented, as shown in Fig. 8.

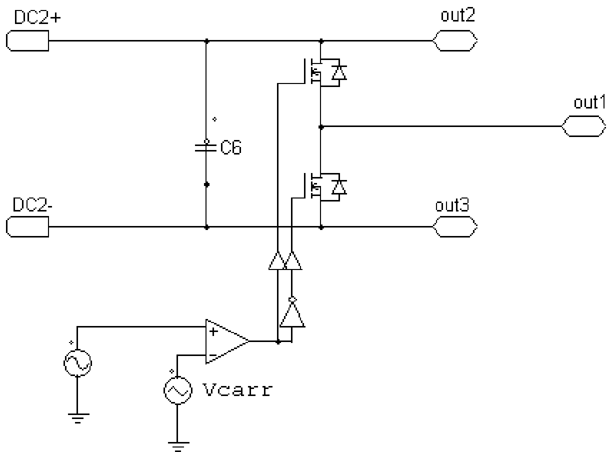

Fig. 8. The output stage

Simulation and analysis

To evaluate the performance of the proposed APET, the design was simulated in the PSIM environment with the parameter values shown in Table 1.

Table 1. Simulation Parameters

Symbol	Parameter	Value
P_{in}	nominal input power	6 kW
V_{AC}	3 phase input voltage (RMS)	230 V, 50 Hz
V_{OUT}	output voltage of APET (RMS)	230 V, 50 Hz
V_{DC1}, V_{DC2}	DC-link voltages	700 V
R_{loadn}	load resistors	30 Ω
L_n	input/output inductors	4 mH
r_{Ln}	series resistor of the inductors	5 mΩ
C_1	DC-link capacitor	2 mF
C_6	DC-link capacitor	60 µF
C_2, C_3, C_4, C_5	DC-link capacitors	470 µF
r_{Cn}	shunting resistor of the capacitors	130 kΩ
N	turns ration of the isolation transformer	1:1

By implementing an actively controlled rectifier, the power factor in the input of the APET can be corrected. The main objective is to force the current to follow the voltage track, as it was explained before.

In principle, the non regulated APET behaves like a non-linear load, thus normally it would draw reactive power from the grid. However, the active front end of the APET effectively reduces the consumption of reactive power from the grid, as indicated in Fig. 9. The line currents (Ia, Ib, Ic) are kept sinusoidal and in phase with the corresponding line voltages (Va,Vb,Vc). The power factor is close the unity.

The integrated PFC algorithm inherently also regulates the DC-link voltage of the input stage (Vdc1_A, Vdc1_B, Vdc1_C) and keeps it constant at 700 V, as shown in Fig.

10. The DHB regulates the secondary DC-link voltage (Vdc2_A, Vdc2_B, Vdc2_C), which is also stabilized at 700 V (Fig. 10).

The inverter of the output stage generates three-phase sinusoidal 50 Hz voltage and currents in phase with the voltage, as indicated in Fig. 11.

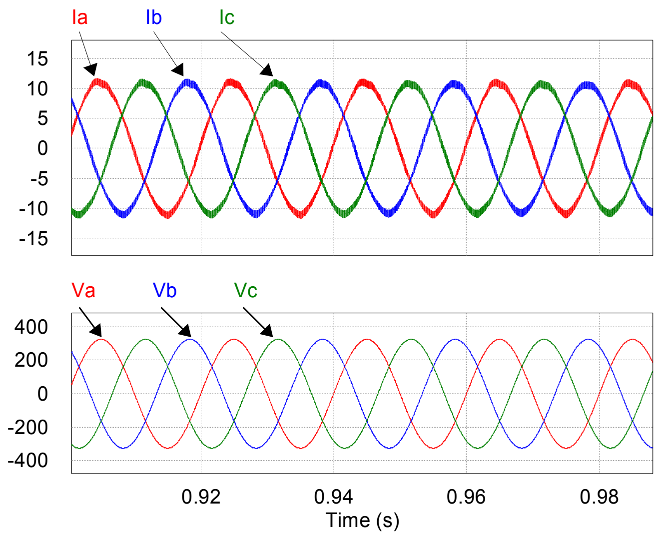

Fig. 9. Line currents and voltages

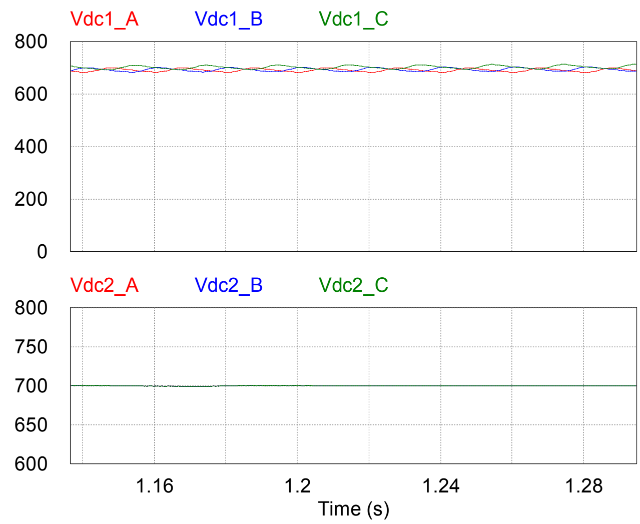

Fig. 10. DC-link voltages

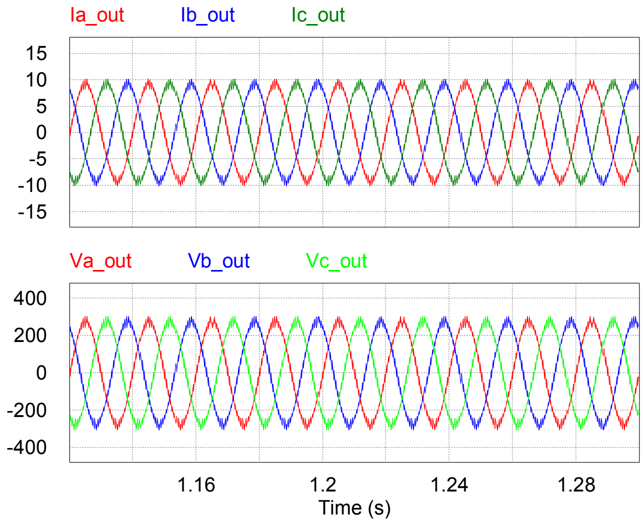

Fig. 11. Output currents and voltages

3D Model of the PEBB

Before starting building the demonstrator, a detailed 3D model of the whole system was designed. To guarantee the modularity the 19” rack concept was selected for the three-phase APET. It means the PEBB will be constructed on a 19” rack unit, as shown in Fig. 12. Each PEBB includes its own control system and will operate independently. The information between the PEBBs will be exchanged via SPI communication link. Rack based montage allows easily and quickly replace the modules if needed.

The PEBB consists of two power modules, a control board and a power supply unit. Between two power modules the medium frequency isolation transformer is located together with additional inductors, that provide the needed leakage for the DHB, as shown in Fig. 12.

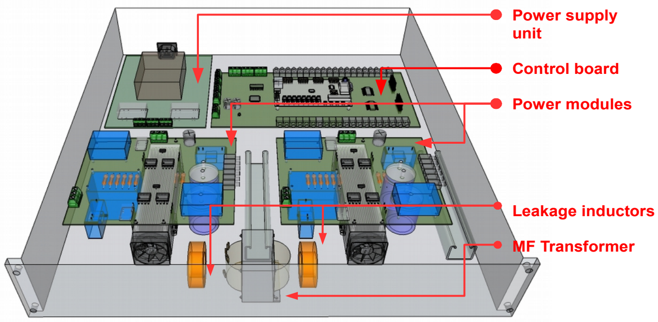

Fig. 12. 3D model of the PEBB

The power modules (Fig. 13) consist of four transistors, gate drivers, DC-link capacitors, current and voltage transducers and short-circuit protection circuitry. As can be seen in Fig. 13, all bigger components are mounted on the bottom side of the PCB, thus allowing to keep the power module as low as possible.

To reduce the EMI impact, all control signals between control board and power modules are transferred via fibre optics. The controller board includes a FPGA Cyclone II from Altera and a DSP ADSP-21363 from Analog devices. The FPGA will be used as a modulator while the DSP will do all the needed calculations.

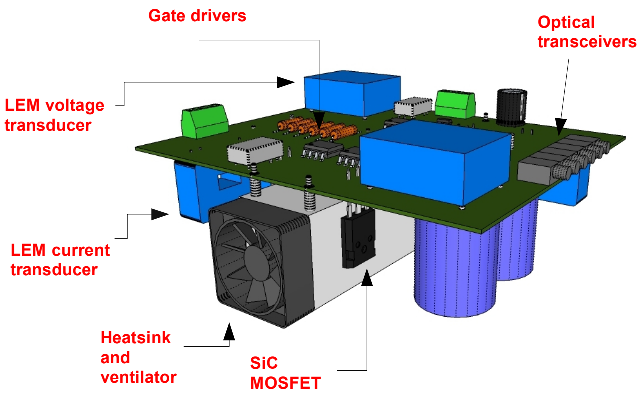

Fig. 13. Power module

Conclusions

The paper presented first results of the project, which goal is to develop the APET for the see industry. To meet the demanding needs and to gain custom fit to various applications, the concept of power electronic building blocks (PEBB) was implemented. As a result, a new PEBB based on the multiple conversion stage (AC/DC/AC) was designed. In the paper the model was explained and simulation results were presented. The PEBB was designed as a bidirectional system with the transfer ratio 1:1. To achieve unity power factor, PFC algorithm was implemented in the input port. Currently the demonstrator is under construction but the 3D model of the device was presented and described. Soon real measurement results can be expected.

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