A Smart Transformer for the Electrical Power System of Green Airports

Smart Power Management

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Recently, the exploitation of renewable energy has been the drive for the development of novel power electronics solutions, with the goal to increase the grid hosting capacity and mitigate the issues of the power systems [1]. However, there has been a shift in the grid control paradigm. The increased adoption of power electronics interfaced sources and loads into the electrical grid changes the way by which the power flow is controlled, may affect the power quality, and could challenge the grid stability if not properly controlled. To sustain the rapid increase in the power generation and the power demand at the same time [e.g., electric vehicle (EV) charging stations], several concepts have been proposed to make the electrical grid "smarter" and more flexible. The smart transformer (ST), as one of the most promising solutions, has become increasingly popular in recent years [2]. The ST is a power electronics-based transformer that is supposed to replace the existing conventional power transformer as an ac–ac converter. Compared to conventional transformers (CTs), the ST takes advantage of electronic control, dc connectivity, smart maintenance [3], and provision of ancillary services [4], [5]. In this way, a gradual upgrade of the electrical grid with increased benefits can be foreseen as the penetration of the STs increases.

Introduction

To reduce the emission of greenhouse gases, such as CO_x and NO_x, the concept of transportation electrification has been investigated [6], [7]. EVs and charging facilities are getting more common in the streets due to the increasing usage in people's daily activities. As an example, more than 20,000 charging facilities have been installed in Germany to make convenient charging access, and around 15% of them are fast-charging facilities (≥150 kW) [8], [9].

The increased penetration of renewable energy generation has further inspired the transportation sector. The integration of EV charging stations with renewable energy sources has been studied, developed, and is now a commercially viable solution [10], [11], [12]. The analysis shows that the charging station can be energy-independent with renewable energy and storage systems, and proper optimization algorithms and communication infrastructure. Similarly to EVs, more harbors are installing renewable energy-based distribution generation, such as photovoltaic (PV) generation or wind turbines at their facilities. Considering the extension of harbors, the installed capacity of PV (e.g., on the roof) and wind turbines (near the shore) can be high enough to cover their load demand. As a consequence, harbor microgrids have been tested, where several smart harbor grid operation schemes have been evaluated.

Integrating renewable energy into the grid may provide the desired peak power; however, it lacks the power dispatching flexibility that a harbor may require during loading and offloading operations. In this regard, the EVs and ships are also studied as flexible loads to provide ancillary services to the grid operation. Some schemes using the battery of EV for vehicle-to-grid services have been summarized in [13].

An airport is a complex system with peculiar characteristics in terms of power and energy needs, involving loads of different typologies and power levels that are distributed in a large area. When it comes to the structure of the electrical power system for airports, it can be various, considering the scale and power rating of different airports worldwide [14].

Figure 1 gives an example diagram for power suppliers of a traditional airport. To be more specific, during the normal operation, main electricity of the airport is supplied by the utility grid, and heating systems of the airport are powered by fuels, such as natural gas [15]. On the other hand, the storage tanks of backup power units, which are usually battery-based uninterrupted power supplies and the diesel-based generators, are charged and on standby [16]. When an outage of electricity happens, the backup power units are enabled to maintain the faultless operation of key services to flights, such as lighting, communication, and control systems. Inside the airport, several main services, such as chiller compressors, baggage handling (e.g., conveyors), refrigeration, and air handling (e.g., air conditions) are powered electrically [17].

In addition, there is an important contribution of the parked airplanes, whose electrical system gets connected to the ground power unit (GPU) of the airport. In the short term, the electrification of the ground transport and the use of low-carbon energy sources (i.e., renewable) are seen as promising [18]. However, it is necessary to set a more important long-term goal, including improving the energy management through smart metering, novel and highly-efficient power electronics devices, demand management, and planning [18]. The pollution attributed to the delay of flights has also been addressed by improving the scheduling of airlines [19]. As reported in [20] and [21], both the Copenhagen airport in Denmark and Kansai airport in Japan have enabled supplying the parked aircraft by GPUs instead of using on-board auxiliary power units during parking. In the United Kingdom, Manchester and Stansted were already featuring renewable energy plants in 2014, to reduce their dependency on the electrical grid [22]. In a plan to renovate the Tabriz International Airport in Iran, solar energy production is envisaged for the flat roofs of the airports [23]. Combined heat power (CHP) plants can also be adopted for the simultaneous production of electricity and heat, improving the efficiency. CHP and solar generation were two technologies employed for the Rome International Airport in Italy [24]. In the next China civil aviation five-year plan, a great push toward greener airports and electrical technologies is also envisaged [25] to reduce the environmental impact.

It is therefore evident that, in order to accommodate these new energy sources, an upgrade of the airport electrical power systems is needed and vital to ensure good performance in terms of power quality, while allowing a high load-source integration. Considering the facts that the integration of the renewable energy in a more efficient manner is one main feature for the power system of a green airport, this article presents how an ST can be used to upgrade the electrical power system of a future green airport, exploiting its benefits for coping with the utilization of renewable energy. The impact at power system and a novel power electronics topology, which feature isolated multiport connectivity, are discussed, showing the promising prospect of the ST and its fascinating potential on improving the electrical power system of the future green airport.

The ST

Several airports have undergone an upgrade of their electrical grid infrastructure. As an example, redundant medium-voltage (MV) distribution has been adopted in the Maryland Airport, in the United States [26], the Zurich Airport in Switzerland [27], the Malaga Airport in Spain [28], and the Wichita Eisenhower Airport in Kansas, USA. However, building new lines and substations can be a costly solution. On the upside, it enhances the stability of the electrical grid. However, it may result in additional construction and operational complexity in an already energy-dense grid, such as those in an airport.

In fact, a future airport will feature a mix of renewable energy sources plus a number of loads (EVs, conventional/electric aircraft, hydrogen energy system [29], [30]) and the connection to the electrical grid. For safety reasons and for grid optimization, a policy of minimization of the energy exchange with the mains is likely to be implemented, which calls for the need of local storage systems.

There has been an increasing interest in the electrification of the green airport power system, with a focus on integration of different loads and system functionality. In [31] a multiagent system for an airport with dc grid is upgraded with vehicle-to-grid capability, to use the parked EVs to support the electrical grid and improve the performance. A full power electronics-based distribution system with dc transmission for airports has also been proposed in patents [32]. The concept of aviation-to-grid is explored in [33], where the electric airplane battery storage is used to support the electrical grid. The optimization of such systems in terms of energy dispatch has also been studied, for example in [34] and [35].

This work aims to further extend the grid flexibility, aiming to introducing the concept of the ST [2] as the core of the power distribution system of a green airport (Figure 2). The role of the ST is to integrate all of these resources and redispatch the power in an optimal way, such as to reduce losses, guarantee the highest reliability and robustness, and eventually offer ancillary services to the connected grid [2]. This concept is exemplified in Figure 2(a), where the ST is at the core of the electrical distribution system of a future green airport, allowing it to handle several renewable energy sources, energy storage systems, as well as power electronics loads.

However, these features introduce the main challenge of the power electronics system, which is mainly about how to handle multiple loads with arbitrary power flow and with the need of galvanic isolation and safety.

Although the ST has been proposed for residential applications, the unique characteristics of the airport make it a very interesting candidate for such an application:

- The airport administration has the full control of the equipment, which can be connected and can make accurate predictions (e.g., charging airplanes), as opposed to residential areas where the load connection cannot be controlled.
- There is the need of several high-power load ports (e.g., GPUs).
- Vast areas make the airport appropriate for both solar energy generation and storage.
- In view of the development of hydrogen-powered aircraft, the possibility of producing hydrogen directly on-side with excess renewable energy further increases the needs of high-power electronics converters.

In the following, it will be shown how these characteristics can concur together toward a proposal for a modular architecture of dc–dc converters, which can be at the core of the ST system.

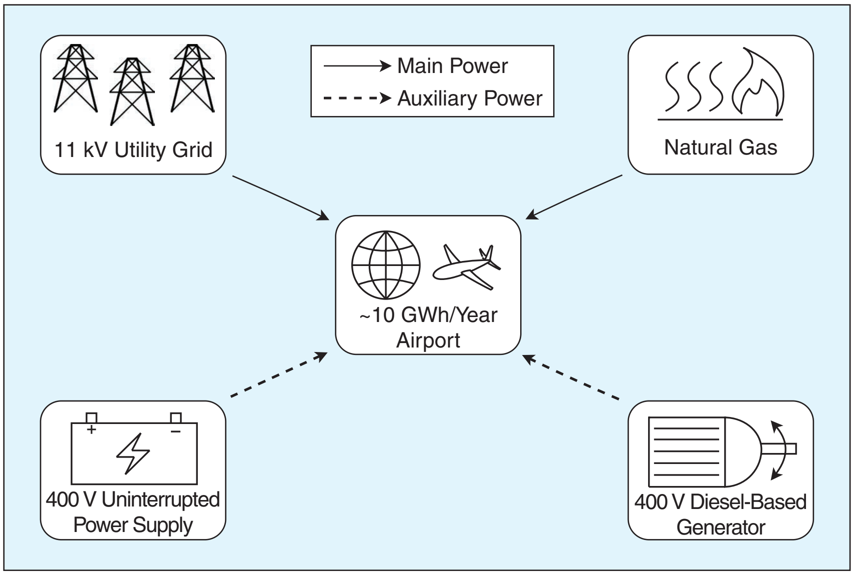

FIGURE 1 – An example diagram for power supply of a traditional airport.

Modular Multiport Power Electronics With Power Routing Capabilities

One of the disadvantages of the ST when compared to the CT is a reduced efficiency if only ac–ac applications are considered, and the fact that power electronics are more prone to failure than low-frequency magnetic components. However, considering the constant presence of maintenance crews on site and the increased capabilities that modular power electronics have been showing in terms of maintenance scheduling [3], the advantages of a CT solution in terms of reduced maintenance becomes less critical for such an application.

Benefiting from the controllability of power electronic converters, power routing can be achieved in modular power electronics systems for purposes of reliability. With the functionality of power routing, the lifetime of power electronic modules can be actively predicted and improved using specific control strategies. In addition, based on the predicted condition and lifetime of power electronic components, potential shifting and merging of scheduled maintenance can be achieved to reduce the times of maintenance, and thus reduce the emergency cases and save costs.

Figure 2(b) shows a possible ST architecture that can fulfill the integration and service requirements of Figure 2. A cascaded H-bridge (CHB) is adopted due to the wide industrial acceptance for MV applications and due to the reduced need of having an MV-rated dc link (in the range of tens of kilovolts), which would make a modular multilevel converter solution more interesting. At the core of the structure is the dc–dc converter, which can be built in several configurations of active bridges. Although the

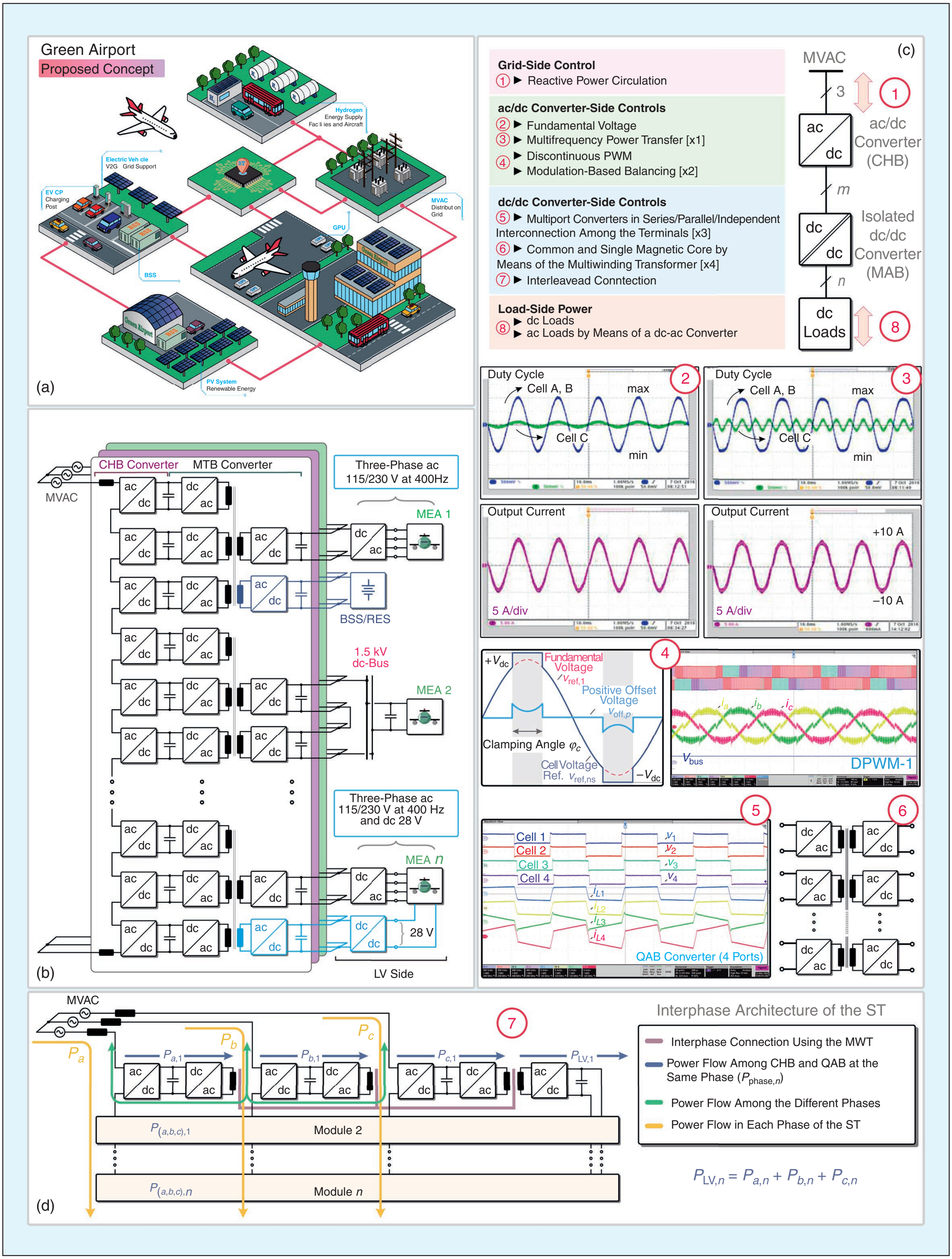

FIGURE 2 – ST powering green airport: (a) proposed concept; (b) an example ST architecture consisting of cascaded H-bridge (CHB) and a multiport power converter structure to enable the independent control of the output ports; and (c) feasibility offered by the topology and control of the ST to achieve power balancing. BSS: battery storage system; CP: charging post; MVAC: medium-voltage ac; PWM: pulsewidth modulation; V2G: vehicle to grid.

initial proposals for the ST were based on the dual active-bridge (DAB) topology, which could offer bidirectional power transfer with soft-switching characteristic, the single-input/single-output nature of the DAB limits the designer choices. To achieve a limitation for a multiple integration of green sources and loads in an optimized point of the grid, multiple active-bridge (MAB) ones, which are developed from DAB with multiwinding transformers (MWTs), have been investigated [36]. It is shown that the MAB solutions take advantage of not only arbitrary power flow among the different ports, but also for the potential weight saving compared to the DAB solutions due to better usage of the transformer core (up to 30%) [36].

It has long been known that the CHB allows for the different cells to process a different power, depending on the output current and on the modulation index. Initially, this model of operation was used to ensure a proper balancing of the dc capacitors in the cases of small mismatches. Typical cases involved the use of proportional-integral (PI) compensators based on the fundamental voltage modification [Figure 2(c)-2] or modulation-embedded controls [37] to achieve the voltage balance.

To extend the operating range of this power transfer capability across the series-connected cells of the CHB, other approaches, including a third-harmonic–based cell balancing algorithm [38] [Figure 2(c)-3] and a discontinuous pulsewidth modulation (DPWM) one [39] [Figure 2(c)-4] have been proposed. The concept has been generalized under the name of *power routing* in [3], where the arbitrary power flow within a modular structure is used to perform advanced reliability controls, including maintenance scheduling. This can prevent the overload of old or damaged power modules, ensuring an even aging of the single components.

Although it is expected that the power electronics would operate most of the time in a unidirectional way (from the mains toward the airport), having a CHB in the MV side would still offer the advantages of extended power routing capabilities, as well as the possibility of injecting power into the grid. Additionally, more STs may be connected together through the MV connection, achieving the advantages of a ring-distribution. Considering the sinking prices of Si-based semiconductor, the CHB could be built with nonfast-switching devices to enable bidirectional power transfer only when necessary, while keeping a high efficiency, without impacting on the overall cost of the system. During normal operation, the CHB would be either operating as a unidirectional rectifier or be switched off, in the case where the available power of the airport grid exceeds the load requirement. Hybrid rectifier topologies could also be adopted [40].

A possibility of interfacing the MV ac link to a dc multiport distribution was proposed in [41], where the intertwined connections of multiple quadruple active-bridge (QAB) converters allow for arbitrary power transfer among the cells of the individual phases, as well as among different phases. The QAB can be operated under a phase-shift modulation [Figure 2(c)-5] and its structure can be extended to more ports, as shown in Figure 2(c)-6. A further application of the MAB converter to enhance the power sharing across different phases of the CHB has been reported in [42], where the dc–dc converter feeds cells from different phases, enabling both the power sharing as well as the compensation for the pulsating grid power.

A proof-of-concept simulation targeting the dc–dc converter was proposed in [43], and named *intertwined MAB* (*IMAB*). A 300-kW power electronics operating at an equivalent dc voltage of 3 kV is considered as the target. Exemplified parameters are given in Table 1. The topology is shown in Figure 3, as well as the control scheme of the single cell (a MAB with five bridges), which features a voltage control with droop characteristics [43] to easily achieve a cascade of the cells, as well as power decoupling for a better port control [44]. The aim of the simulations is to prove that the control can keep the dc links being regulated even with a strongly asymmetrical power flow, typically in the presence of single-phase loads.

Figure 3 shows a configured IMAB dc–dc converter with the following characteristics:

- Each MAB has its own control system separated from the others.
- Each MV dc link is connected to at least two MAB ports.
- There must be a path connecting the MAB ports allowing for a redistribution of the power.

Two conditions are tested: 1) the increase of the power injected by the PV cells at $t = 0$ s (from 0 to 10 kW) and 2) the power ramp-down of one of the low-voltage (LV) ports at $t = 0.05$ s from 150 kW to zero (for example, an aircraft is disconnected from the ST). It can be seen that although the IMAB is working in asymmetrical condition (MAB 1 is working in a phase shift of opposite sign with respect to the other MABs), the distributed control allows achieving a good voltage tracking. The power loop on the PV ports ensures a good tracking of the power reference. Additional modifications could be performed, such as changing the modulation scheme [45] or implementing the control in a centralized way [46].

TABLE 1 – SIMULATION PARAMETERS FOR INTERTWINED MAB CONVERTERS.

Power level	320 kW	Switching frequency	5 kHz
dc/dc topology	Five-active bridge	Phase connection	Custom
dc link capacitance	3 mF	Transformer leakage conductance	15 μH
Voltage control bandwidth	300 Hz	Droop coefficient	0.02 Ω
Low-voltage current I_{LV}	300 A	PV power level	0–10 kW

Power System Potential of the ST

To highlight the advantages of the proposed ST compared to the CT, a 3-MW microgrid with simplified structure

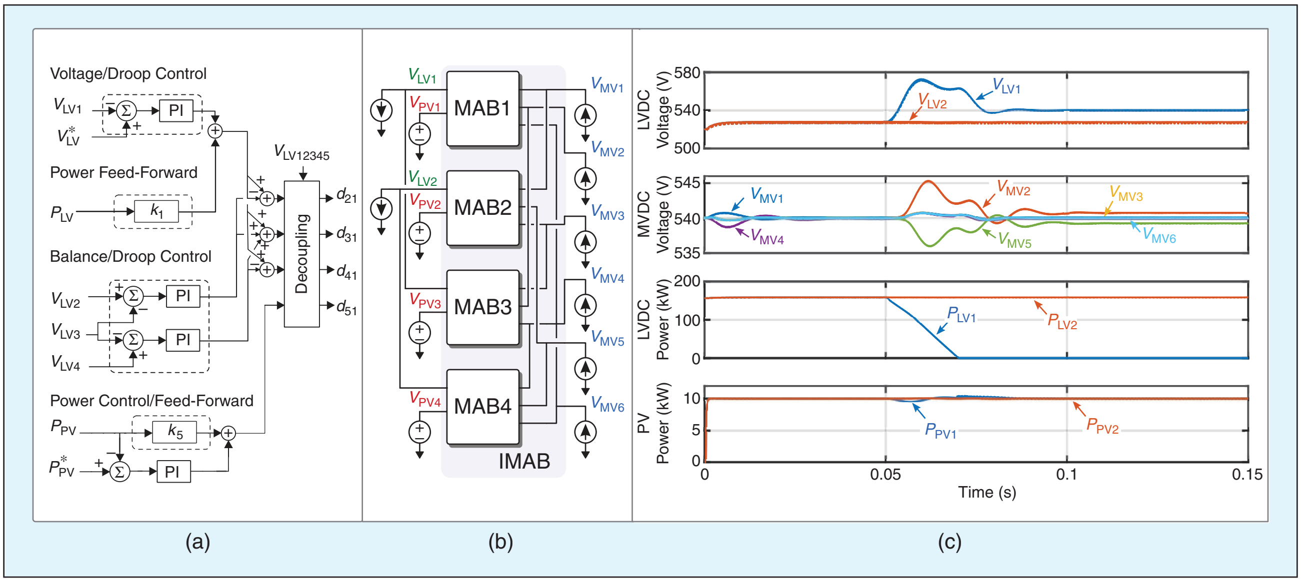

FIGURE 3 – Control strategies, schematic and simulation results: (a) phase-shift control based on PI with droop characteristic and power feed-forward, (b) schematic of a five-port IMAB dc–dc converters, and (c) simulation results of the converter during a step change in the PV power at $t = 0$ s and a power ramp-down from a low-voltage (LV) port at $t = 0.05$ s. LVDC: low-voltage dc; MVDC: medium-voltage dc.

that interfaces with a variety of units, including two PVs, two GPUs, and a three-phase passive load, is built in PLECS. With the proper power electronics converters, these units can have either ac, dc, or hybrid power transfer [43]. The simulation parameters for this study are given in Table 2. In the CT-based microgrid, the CT is connected to the MV ac network and provides an LV ac feeder. Each unit is connected to the different node of the feeder, as shown in Figure 4(a). The transmission cable for the feeder is assumed to be formed by 20 4/0 AWG wires. With the daily profile of the power generation/consumption of each unit, the voltage root mean square (RMS) and total harmonic distortion (THD) of each node is emulated, shown as Figure 4(c) and (d). In the case of the ST grid architecture, the ST is equipped with a QAB converter to achieve higher power routing flexibility. With this solution, the ST can provide not only ac voltage levels, but also dc voltage levels. As a consequence, both PV units can be connected to the two ports of the QAB converter, and the GPU can be interfaced with the LV dc link of the ST. An LV ac feeder having the same length of transmission line is provided by the ST, where another GPU and the three-phase passive load are connected. The scheme of ST-based microgrid is shown as Figure 4(b). With the same daily power profile, the voltage RMS and THD of the same nodes at the LV ac feeder are measured, shown as Figure 4(e) and (f). It obviously shows that the introduction of ST can better keep the RMS voltage closer to the target value and THD of the LV ac feeder, compared to CT.

Experimental Demonstration of the ST

To verify the control feasibility of the ST dc–dc stage, a prototype of a QAB converter was built [a picture is shown in Figure 5(a)]. The prototype features SiC MOSFETs and is rated for 20-kW power; the full specifications are listed in Table 3. Experimental results were obtained considering two conditions of power flow: balanced and unbalanced conditions, as shown in Figure 5(b) and (c). In the first case, the power and voltage levels among the port are equal, while in the second case, the converter operates with different power flow among the ports. As a matter of simplicity, the power level on port 3 is reduced in comparison to port 4. As a result, the current on the reactive network is changed accordingly. Soft switching is evident from the waveforms of both current and voltage, as well as the absence of ringing during the commutations, showing how the prototype is able to perform power flow control while retaining high levels of performance.

The results of the three-phase system operating in light load, i.e., at 9 kW and at 30 kW, are depicted in Figure 6. The three-phase line-to-ground voltage (i.e., v_{an}) of the ST is depicted, as well the three-phase output currents

TABLE 2 – SIMULATION PARAMETERS FOR SIMPLIFIED CT/ST-BASED MICROGRID.

Power Level	3 MW	Grid frequency	50 Hz
MVAC	10 kV (L-L)	LVAC	230 V
MVDC	15 kV	LVDC	1,500 V
dc/dc topology	Four-active bridge	Transformer turn ratio	10:1:1:1
PV dc voltage	1,500 V	GPU dc voltage	1,500 V
Line impedance	(8 mΩ + 0.12 mH)/km	PV power level	150 kW
GPU power level	500 kW	Passive load power level	2 MW

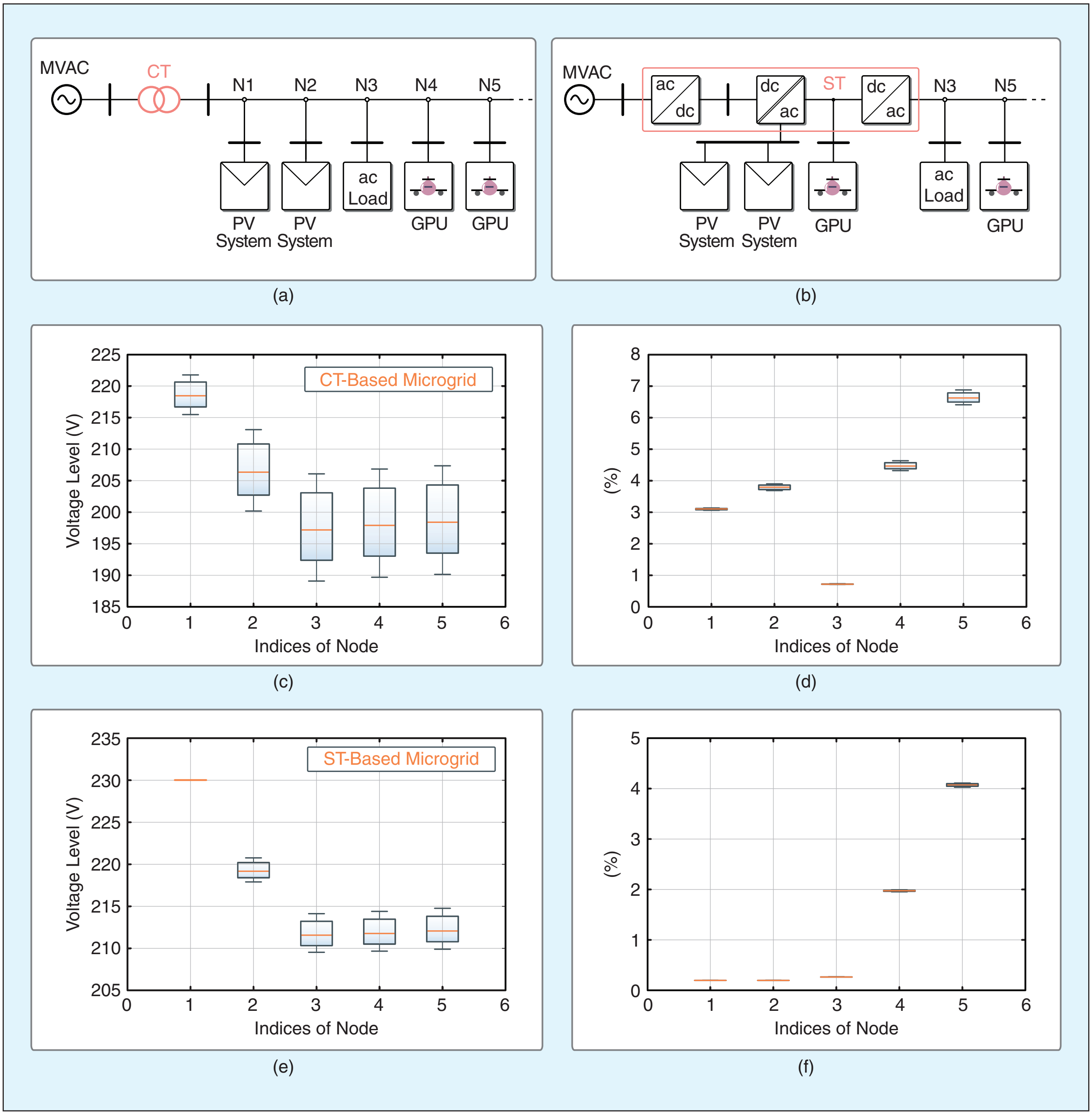

FIGURE 4 – Comparison between (a) CT-based microgrid and (b) ST-based microgrid. For CT-based microgrid: (c) root mean square (RMS) of nodes and (d) total harmonic distortion (THD) of nodes. For ST-based microgrid: (e) RMS of nodes and (f) THD of nodes. MVAC: medium-voltage ac.

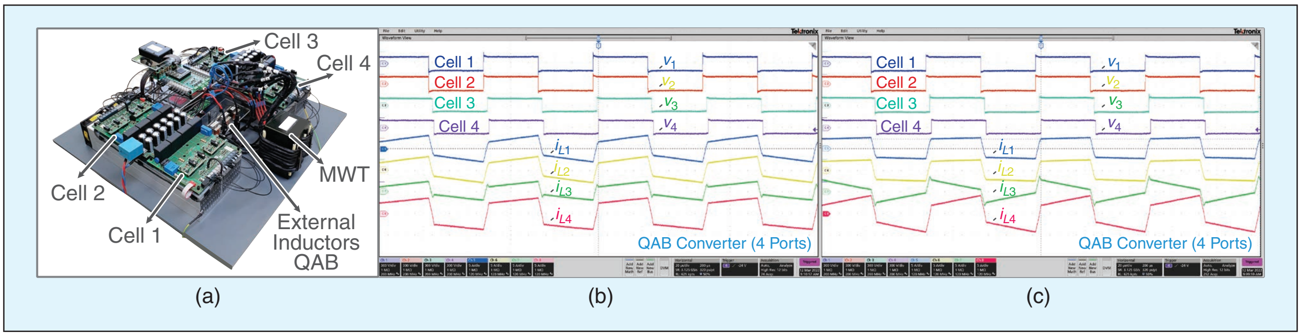

FIGURE 5 – Experimental results. Prototype of the QAB: (a) experimental waveforms of voltage and currents in symmetrical (b) and asymmetrical (c) condition of power transfer.

TABLE 3 – MAIN SPECIFICATIONS AND PARAMETERS OF THE DC/DC STAGE.

Rated power QAB	$P_o = 20$ kW	Power devices H-bridge	SiC MOSFET - C2M0040120D
Switching frequency	$f_{sw} = 20$ kHz	External Inductance	40 μH - EE42/21/20
Maximum dc-link voltage	$V_{dc} = 1.0$ kV	MWT	3×UU93/152/30
Nominal dc-link voltage	$V_{dc} = 800$ V	MWT turn-ratio	$n = 1:1:1:1$
Bridge topology of the cells	H-Bridge	Digital signal controller	TMS320F28379D

$[i_{a(\mathrm{MVAC})}, i_{b(\mathrm{MVAC})}$ and $i_{c(\mathrm{MVAC})}]$. These results demonstrate the proper operation of the three-phase ST system, where the well-regulated output voltage is observed. Likewise, the main waveforms of the LV-side inverter of the LVAC are presented, taking into account different modulation strategies (e.g., continuous and discontinuous PWM), as illustrated in Figure 7.

Conclusion

This article has proposed aN ST as the core of a future green airport, allowing for an optimal integration of electric loads, renewable energy systems, and electrical grid, thanks to the development of architectures with multiple isolated dc ports in a modular structure. Introduced results demonstrated the optimal performance of such a solution, both at a power electronics and power system level. Simulations proved that the proposed structure based on intertwined multiple active bridge enables a power redistribution among different energy actors,

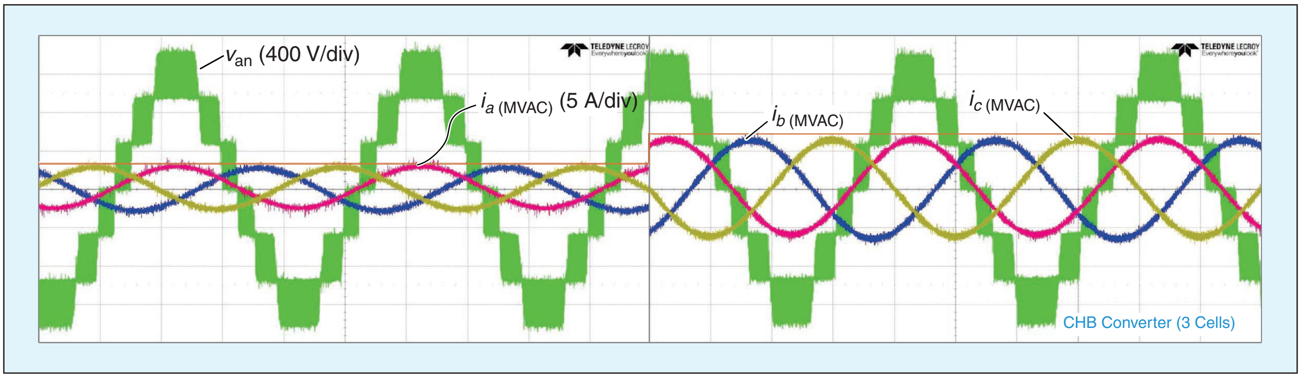

FIGURE 6 – Experimental results of the three-phase system operating with power level of 10 kW and 30 kW: current on the MVAC side [i.e., $i_{a(\mathrm{MVAC})}$, $i_{b(\mathrm{MVAC})}$ and $i_{c(\mathrm{MVAC})}$] and the switched voltage before the L filter (v_{an}).

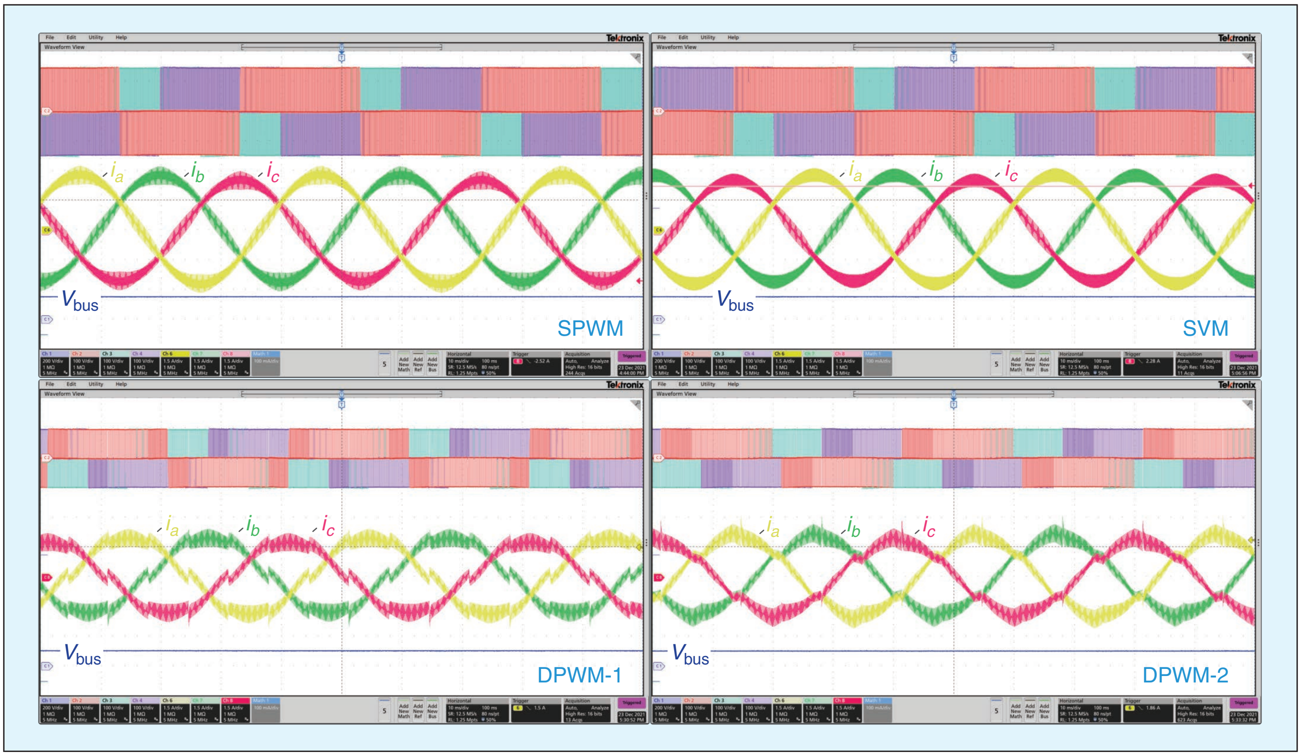

FIGURE 7 – Main waveforms of the three-phase system at LV-side of ST considering different modulation strategies. SPWM: sinusoidal pulse width modulation; SVM: space vector modulation; DPWM: discontinuous pulse width modulation.

TABLE 4 – QUALITATIVE COMPARISON BETWEEN CT AND ST SOLUTIONS; PROS AND CONS OF THE PROPOSED ST COMPARED TO THE CT.

PROS	CONS
Multiple dc and ac interfaces	Lower efficiency
Highly decoupled MV and LV buses	More complex system structure
Tremendous control capabilities	Higher cost for manufacturing*
Potential ancillary services	Reduced reliability**

*In a context where the cost of the materials is increasing and the one of the electronics is decreasing, the reduced amount of copper needed for the ST could tilt the scale of material cost.
**The development of predictive maintenance and reliability-aware controls would mitigate this aspect.

even during strongly asymmetrical power processing. The impact on a simplified power systems with ac and dc loads as well as renewable energy sources shows that such structure can improve the voltage and THD performance of the airport grid. Finally, extensive experiments based on a QAB prototype demonstrate the capabilities of the multiport converter to handle arbitrary power flows.

At the present stage, a number of open issues are still present when comparing the ST to the CT, and a qualitative comparison is given in Table 4, which has also been revealed in existing literature. Yet, considering the increasingly utilization of renewable energy, the proposed ST is still promising with its unique features and potential benefits to the grid, and continuous improvements of the proposed ST are expected along with the development of power electronics technology. As a part of future works, the optimization of the control design for the IMAB and the design in terms of installed power for each stage to maximize the power system benefits are expected to be carried out.

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