A Multi-port Smart Transformer for Green Airport Electrification

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Keywords

≪smart transformer≫, ≪green airport≫, ≪multi-port power electronics≫.

Abstract

Green transportation and renewable energy production have attracted a global attention due to the needs of decreasing the environmental impact and still sustain increased energy needs. In this framework, the aircraft and airports are facing a profound renovations towards green technologies, among which the electrical ones are playing a central role. This paper explores how a Smart Transformer can upgrade the existing airport power system, enabling an efficient interface for renewable energy, electric vehicles and the future hybrid/electric aircraft, substituting the ground power units and enabling a smarter behavior of the electrical grid.

Introduction

The renewable energy exploitation has pushed the industry and the academia towards the development of power electronics solutions that have profoundly changed the electrical grids [1]. In particular, the increased adoption of power electronics interfaced sources and loads into the electrical grid has drastically changed the power flow conditions, the power quality and has been challenging the grid stability. In order to sustain an increased distributed generation and a growing demand at the same time (i.e., electric vehicle charging stations), several concepts have been proposed to make the electrical grid ”smarter”. One of the solutions which have become increasingly popular is the Smart Transformer (ST) [2], a solid-state transformer which can replace the existing power transformer as ac-ac converter, with the additional benefits of electronic control, dc connectivity, smart maintenance [3] and ancillary services. In this way, a gradual upgrade of the electrical grid becomes possible, with increased benefits as the penetration of the STs increases.

The transportation sector is used to be one of the primary pollution resources since fossil fuel is the dominant energy source in this sector. In order to reduce the emission of greenhouse gas, SO_x, and NO_x, transportation electrification has been proposed. The electric vehicle (EV) is considered as a promising solution. To make convenient charging access, Germany has installed over 20,000 charging facilities, and around 15% of them is fast charging facilities [4, 5]. As for maritime transportation, which contributes about $5-8\%$ of global emissions, vessel cold-ironing at berth has been promoted worldwide to increase the efficiency of energy consumption. Cold ironing is a process that uses shoreside power to provide the demand of vessels while they are docked. By plugging in the vessel at port allows shutting down all diesel generators on board of the vessel. The Siemens has built Germany’s largest shore power system at the port of Kiel. With $16MVA$ power capability, the port is capable of supplying two ships simultaneously

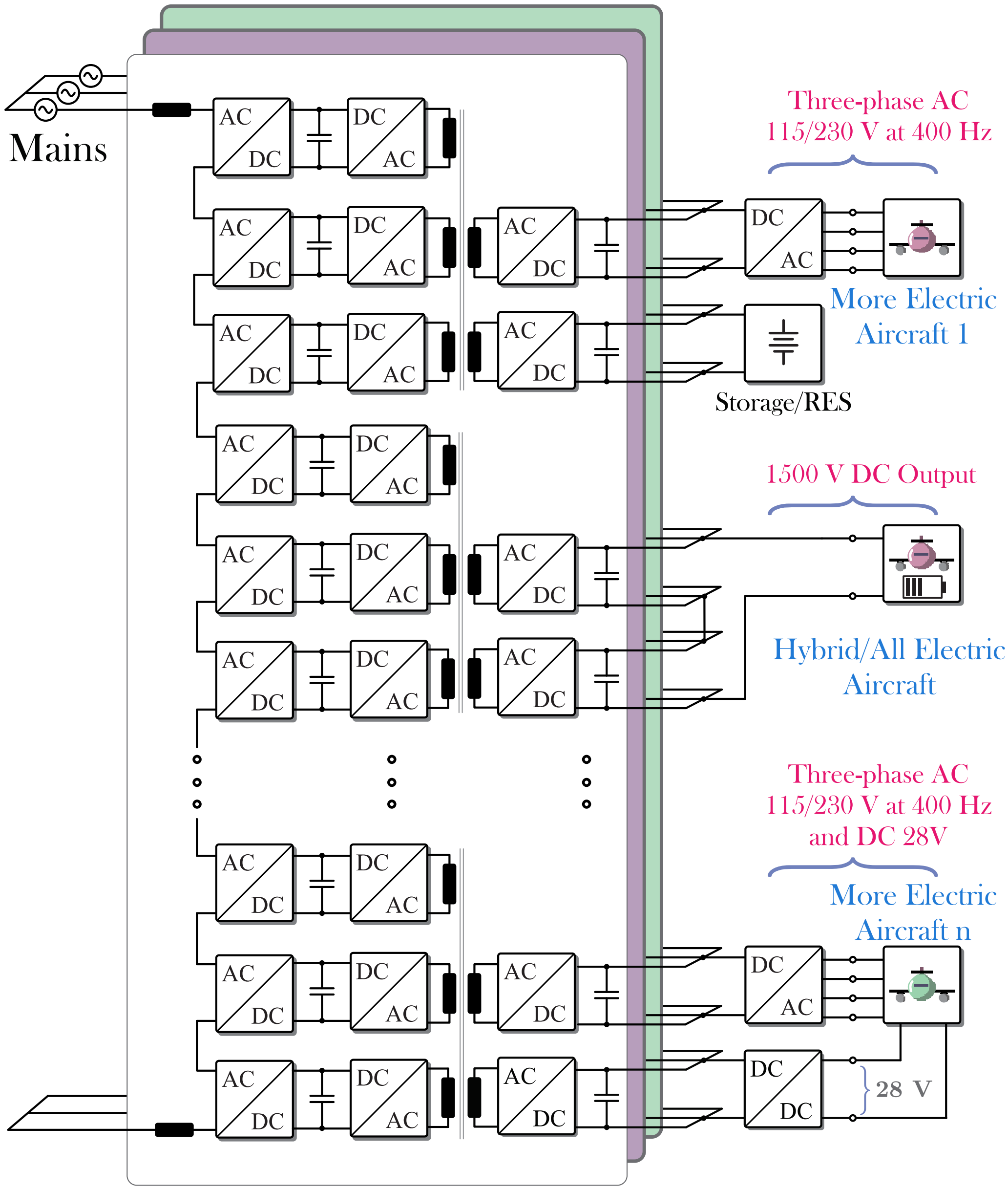

Fig. 1: Example of an architecture for the Smart Transformer based on Cascaded H-bridge (CHB) and a multi-port power converter structure which allows for the independent control of the output ports.

and will help to reduce more than 8000 tons of CO_2 annually [6]. Other researches have also confirmed the effectiveness of cold ironing in terms of reduction of CO_2 in different countries [7].

The ST can further benefit the green transportation ambition. For one side, it provides together with traditional ac connection also the dc connection. Consequently, the equipment that requires dc connection, such as charging facilities, can be directly connected to the ST, decreasing the complexity of the operation. In the meantime, some obstacles to host high power charging facilities, such as degrading the voltage quality in the ac grid, can be avoided. Furthermore, the onboard grid on vessels can use either 50 or 60 Hz ac power supply, requiring frequency conversion in the harbor if the frequency doesn't match. The ST can decouple the MV and LV grids connected to its both sides. This feature helps adjust the frequency easily between 50 and 60 Hz, solving frequency conversion between vessels and harbor.

An airport is a complex system with peculiar characteristics in terms of energy needs and construction. In addition to the energy for lighting, heating and airport logistics, there is an important contribution of the parked airplanes, whose electrical system gets connected to the airport one. In the short term, the electrification of the ground transport and the usage of low-carbon energy sources (i.e., renewable)

Simulation Parameters			
Power level	320 kW	Switching Frequency	5 kHz
DC/DC Topology	5-Active Bridge	Phase connection	Custom
DC Link Capacitance	3 mF	Transformer Leakage Inductance	15 uH
Voltage Control Bandwidth	300 Hz	Droop Coefficient	0.02 Ohm
Low-voltage current I_{LV}	300 A	PV Power level	0-10 kW

are seen as promising [8]. However, improving the energy management through smart metering, demand management and planning is an important long-term goal to achieve [8]. The improvement of the scheduling to reduce delays and the pollution has also been addressed [9]. As reported in [10] and [11], both the Copenhagen and Kansai airport rely on electrical ground power for the parked aircraft, to allow the main engine to be switched off. In the UK, Manchester and Stansted were already featuring renewable energy plants in 2014 [12]. In a plan to renovate the Tabriz International Airport, solar energy production is envisaged for the flat roofs of the airports [13]. Combined Heat Power (CHP) plants can also be adopted for the simultaneous production of electricity and heat, improving the efficiency. CHP and solar generations were two technologies used for the Rome International Airport [14]. In the next China Civil Aviation (CCA) 5-year plan, a great push towards greener airports and electrical technologies is also envisaged [15] to reduce the environmental impact.

Proposed Architecture

Several airports have undergone an upgrade of the electrical grids towards redundant medium voltage distribution.

Figure 1 shows a possible example of a smart transformer architecture which can fulfill the application requirements. A Cascaded H-bridge is adopted due to the wide industrial acceptance for medium voltage applications and due to the reduced need of having a MV-rated DC Link (in the range of tens of kV) which would make a Modular Multilevel Converter (MMC) 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 initial proposals for ST were based on the Dual Active Bridge (DAB), which could offer bidirectional power transfer with soft-switching feature, the single-input single-output nature of the DAB limits the designer choices. For this reason, Multiple Active Bridges (MAB), which are the extension of the DAB with multi-winding transformers, have been investigated [16] due to their advantages in terms of arbitrary power flow among the different ports and for the potential weight saving compared to the DAB solutions due to better usage of the transformer core (up to 30% [16]).

Figure 1 shown a possibility of employing a MAB with five ports to build up several DC ports to power different aircraft kinds, since the conventional aircraft need 400 Hz, 115 V AC supply, whereas some More Electric Aircraft could be powered directly by a low voltage DC [17, 18] (270 V or 540 V). Considering the recent trends of electrification, hybrid/electric aircraft solutions are currently under investigation or prototyping, whereas for full electric aircraft there are already available products (Bye Aerospace eFlyer 800, eight-seater, Eviation Alice, nine-seater, and Pipistrel Alpha-Electro). Due to the high-power needs of electric propulsion (in the range of MW) even for regional aircraft, the power distribution will most likely shift from ac to dc and toward higher voltage in the kV range [19, 20].

Simulation Results

A proof-of-concept simulation targeting the DC/DC converter is set up in a Simulink/PLECS environment. 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 I. The target of the simulations is to prove that the control can stably regulate the DC links even in strongly asymmetrical power conditions.

Figure 2a shows a proposal of intertwined multiple active bridge (IMAB) configuration for the DC/DC converter, with the following characteristics:

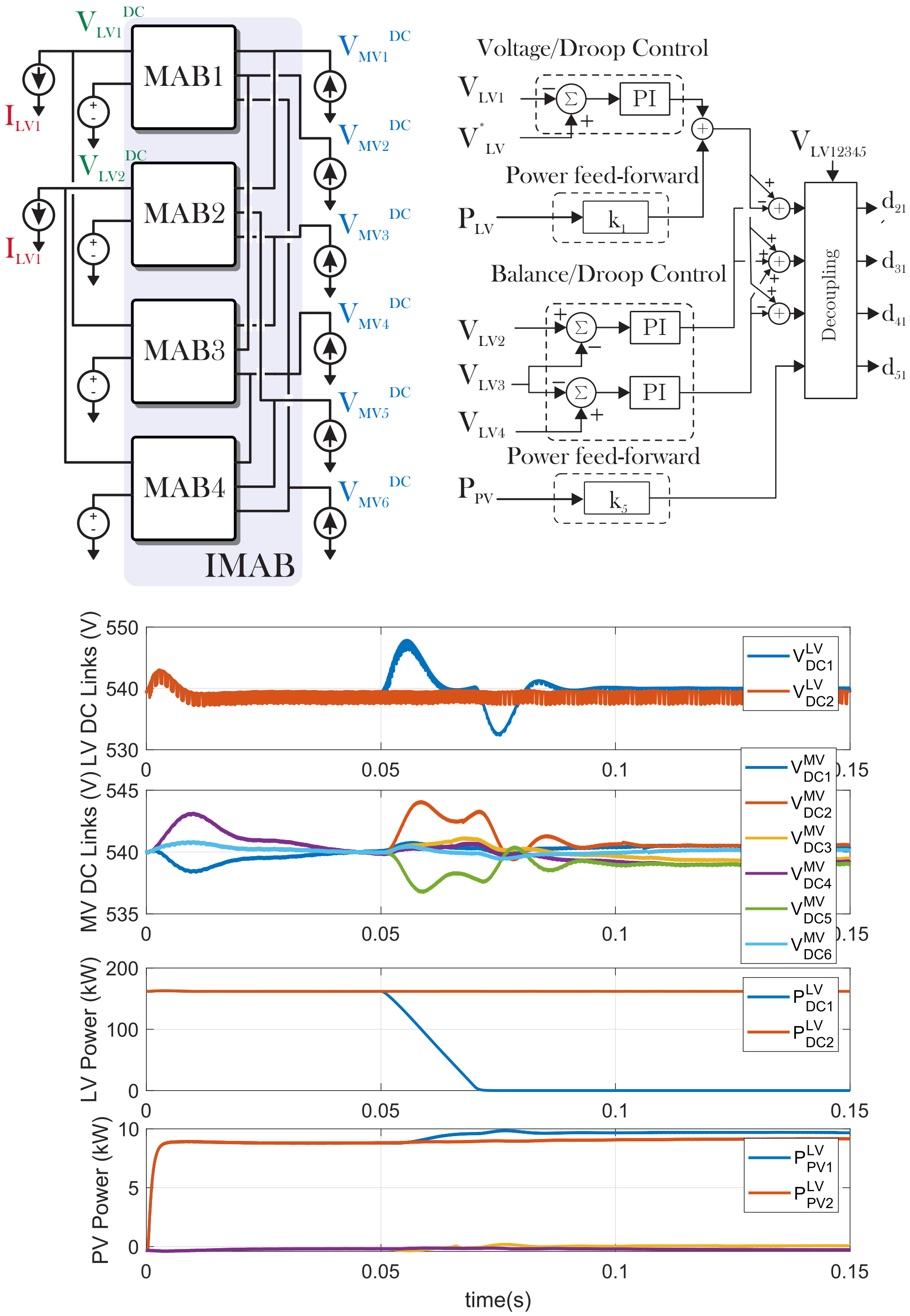

Fig. 2: Simulation Results. Proposed architecture based on the intertwined connection of Multiple Active Bridge (5 ports) converters (a), phase-shift control based on PI with droop characteristic and power feedforward, simulation results of the converter during a step change in the PV power at t = 0 s and a power ramp-down from a low-voltage port at t = 0.05 s.

1. Each MAB has its own control system separated from the others.
2. Each MV DC Link is connected to at least two MAB ports.
3. There must be a path connecting the MAB ports allowing for a redistribution of the power.

A simple control scheme based on the phase-shift modulation can be implemented and is reported in Figure 2b. The main feature are the possibility of regulating the LV port by drawing power from the MV ports and an equalizer control for the MV ports, which allows the CHB to draw unbalanced power from each AC cell. This control is based on an evolution of the distributed droop regulation with virtual resistors in [21] with the addition of the real-time decoupling of [22]. Additionally, a power feed-forward for the LV port is added to reduce the voltage transient. For the sake of simplicity, just a feed-forward control is employed for the Storage/PV port, although the implementation of a closed-loop control based on the state of charge or MPPT is straightforward. When it comes to the tuning of control parameters, the Symmetrical Optimum (SO) as one of popular tuning techniques, can be a proper choice. The SO was firstly proposed by Kessler [23], aiming at enhancing the stability, robustness and optimizing the transient performance of systems. With SO, the open loop phase margin of system can be associated with the PI parameters based on the linearized plant and feedback [24]. For the sake of simplicity, only the SO-based tuning process for the output voltage control is presented in the following content. It is noted that the same tuning procedure can be applied for the balancing controller. Fig. 3 shows a simplified transfer function block scheme of output voltage loop, where the output voltage controller is given as

$$G_{\mathrm{v}}(s) = \frac{K_{\mathrm{p}}s + K_{\mathrm{i}}}{s} \tag{1}$$

The sampling period of controller and the PWM delay is modeled together as a first-order transfer function with cut-off frequency of ω_{d}, given as

$$G_{\mathrm{d}}(s) = \frac{1}{s/\omega_{\mathrm{d}} + 1} \tag{2}$$

And the control-to-output-current gain A is given as

$$A = \frac{V_{\mathrm{i}}}{2Nf_{\mathrm{s}}L_{\mathrm{lk}}}(1-2d) \tag{3}$$

Where V_{i} is the input voltage of converter, N is the turn ratio of transformer (secondary side voltage to primary side voltage), f_{s} is the switching frequency, L_{lk} is the leakage inductance and d is the phase shift. With the above equations, the open loop gain of the output voltage loop can be calculated as

$$G_{\mathrm{ol}}(s) = AG_{\mathrm{v}}(s)\,G_{\mathrm{d}}(s) = \frac{AK_{\mathrm{i}}}{s^2C_{\mathrm{o}}}\frac{\frac{s}{\omega_{\mathrm{v}}}+1}{\frac{s}{\omega_{\mathrm{d}}}+1} \tag{4}$$

Where ω_{v} is the controller bandwidth. The gain crossover frequency ω_{o} can be approximated as

$$\omega_{\mathrm{o}} = \sqrt{\omega_{\mathrm{d}}\omega_{\mathrm{v}}} \tag{5}$$

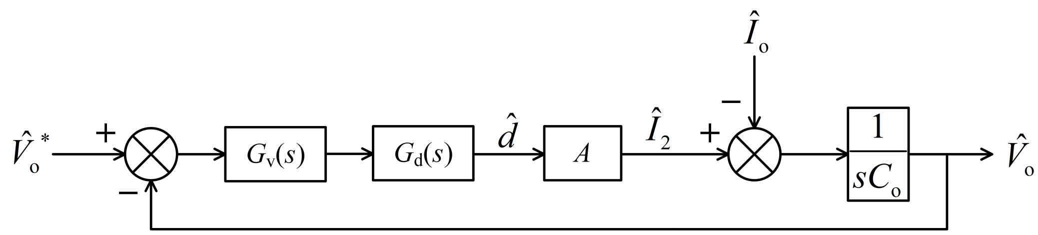

Fig. 3: Simplified transfer function block scheme of output voltage control

Then, it exists

$$|G_{\mathrm{ol}}(j\omega_{\mathrm{o}})| = \frac{AK_{\mathrm{i}}}{\omega_{\mathrm{o}}{}^2 C_{\mathrm{o}}} \sqrt{\frac{\frac{\omega_{\mathrm{o}}{}^2}{\omega_{\mathrm{v}}{}^2}+1}{\frac{\omega_{\mathrm{o}}{}^2}{\omega_{\mathrm{d}}{}^2}+1}} = 1 \tag{6}$$

By rearranging the above equation, K_{i} can be expressed as

$$K_{\mathrm{i}} = \frac{\omega_{\mathrm{v}}\sqrt{\omega_{\mathrm{v}}\omega_{\mathrm{d}}}C_{\mathrm{o}}}{A} \tag{7}$$

And therefore, K_{p} can be obtained as

$$K_{\mathrm{p}} = \frac{\sqrt{\omega_{\mathrm{v}}\omega_{\mathrm{d}}}C_{\mathrm{o}}}{A} \tag{8}$$

In the simulations, the CHB cells are emulated by current sources which draw an equal current and a PI control which regulates the total sum of the MV DC Links. It is worth noting that this represents a worst-case scenario, since the capability of power redistribution offered by the CHB are not exploited.

Two conditions are tested: the increase of the power drawn by the PV cells at t = 0 s (from 0 to 10 kW) and the power ramp-down of one of the LV ports at t = 0.05 s from 180 kW to zero (for example, an aircraft disconnecting). As can be seen, although the IMAB is working in asymmetrical condition (MAB 1 is working with a phase shift of opposite sign with respect to the other MABs), the distributed control allows for a good voltage tracking. A small steady-state error in the power of the PV happens due to the feed-forward nature of the PV port control. The performance of the control could be further improved by changing the phase-shift modulation [25] to ensure the minimum current circulation within the MAB or to implement a centralized controller [26] which would allow for an optimized transient response at the expense of an increase computational burden.

Conclusion

This paper has proposed a Smart Transformer as the core of a future green airport, allowing for the integration of electric loads, renewable energy systems and electrical grid, allowing for multiple isolated dc ports in a modular structure. Simulations proved that the proposed structure based on intertwined multiple active bridge allows for the power redistribution even during strongly asymmetrical power processing. A proof-of-concept distributed control has shown to achieve acceptable performance in terms of voltage transients.

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