BIDIRECTIONAL ELECTRICAL CONVERSION: THE FIRST STEP TOWARDS SMART ENERGY GATES

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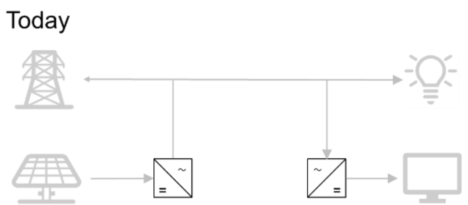
ABSTRACT

Microgrids and local energy communities require new electricity management strategies. Such strategies involve smart energy gates consisting of bidirectional electrical converters. Such converters have been developed for specific applications, e.g., ECI 3-port converters for critical backup. Nevertheless, they can serve for other applications, e.g., storage/restitution or peak shaving. The same technology is currently further developed to fully address microgrid needs, e.g., the voltage stability of local DC distribution.

1 INTRODUCTION

Electricity management, especially for residential applications, historically required simple and basic power electronics equipment. Indeed, most electrical loads needed AC power supplied via the grid from a centralized production. Still back-up applications relied on unidirectional converters, a first DC/AC to supply loads from a battery in case of grid outage, and a second AC/DC to charge the battery. Nowadays battery applications extend far beyond the back-up scope as batteries become more and more affordable and complement local energy production. This production, mainly from renewable and solar sources, occasioned the first real breakthrough of residential power electronics. However, it has been deployed on top of existing infrastructures and not really integrated into local energy systems including, e.g., more and more DC loads (cf. Figure 1). Hence, rethinking electrical converters as building blocks of energy management systems – a challenge CE+T has decided to tackle – appears mandatory to shape future electricity management. In particular, such management involves sustainable, smart and efficient energy gates consisting of bidirectional electrical converters.



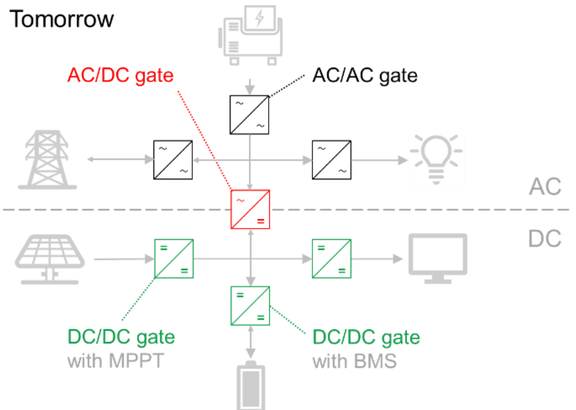


Figure 1. By comparison to today’s AC-based infrastructures relying on unidirectional converters, tomorrow’s electricity management involves smart energy gates consisting of bidirectional converters.

Bidirectional electrical converters do more than turning AC to DC or adapting voltage. They control power flows when several sources are available to optimize load supply with respect to some criterion. Hence their interoperability is key to this extent, the ability to have them communicating together in particular. Their role becomes more and more important with increasing DC usage. Indeed DC/DC conversion, more efficient and simpler than AC/DC as it does not involve synchronisation, contributes to the renewed DC interest originating in the DC nature of renewable energy production and storage and the smaller distribution losses.

CE+T is currently developing its own family of bidirectional converters in the framework of the so-called Enhanced Conversion Innovation (ECI) technology. As described in Section 2, the first ECI converters involve 3 ports dedicated to secure critical applications, CE+T Power current core business. Nevertheless, they offer capabilities of interest for a wider range of applications as illustrated in Section 3. Following the increasing DC usage outlined above, they can serve as interfaces to DC infrastructures. Hence, they will be joined by future – interoperable – members of the same family ensuring local distribution resilience as demonstrated by simulation results presented in Section 4.

2 ECI TECHNOLOGY

ECI converters combine three patented ports (cf. Figure 2): two AC ports (grid & load) and one DC port. These ports are bidirectional for some members of the ECI a family, the SIERRA converter being the first. They simultaneously provide dynamic output power backup to secure 120 or 230-V AC loads as well as 48 or 380-V DC loads and battery charging.

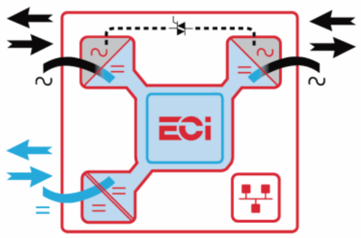


Figure 2. ECI converters combine three patented, possibly bidirectional ports.

ECI converters enable a 0-ms transfer time between AC and DC power input thanks to their unique internal topology [1]. A first AC/DC/AC converter (cf. Figure 3) ensures a very high efficient double power conversion, about 96.5%. This topology and the way to control it are also patented. A second isolated DC//DC converter consists in a bidirectional resonant converter combining full bridge and half bridge topologies (cf. Figure 4). Specific patented control strategy based on phase shift and frequency control allows efficiency greater than 98% and a very wide input/output voltage range [2]. Both converters are connected to a common DC energy buffer enabling the above-mentioned seamless switch.

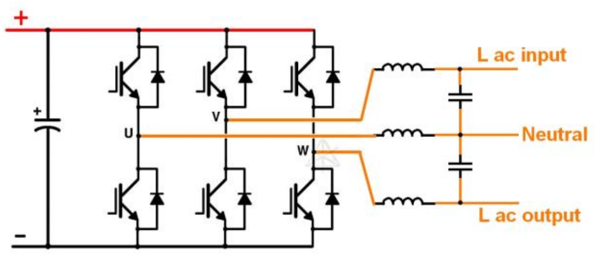


Figure 3. ECI converters enable a 0-ms transfer time between AC and DC power input thanks to their AC/DC/AC converter and common DC energy buffer (left).

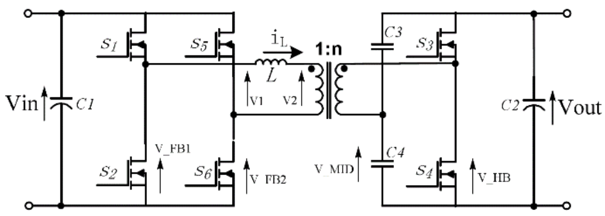


Figure 4. The DC/DC converter consists in a bidirectional resonant converter.

ECI converters can be assembled in systems offering backup capabilities without single point of failure (cf. Figure 5). Each module is hot swappable, has its own controller storing the whole system configuration and shares information with other modules via two redundant communication buses. There is no master/slave controller in a system, enabling true redundancy, the system continuing operating if one module fails.

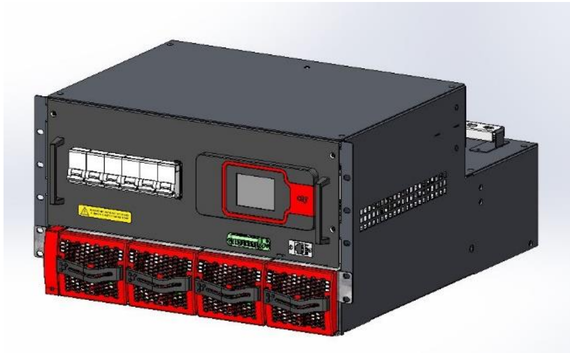


Figure 5. ECI converters can be assembled in systems offering backup capabilities without single point of failure.

Several systems with up to 32 modules can be synchronized and parallelised to reach larger power levels – up to several megawatts – based on the same 3-kVA converter module. Such systems can be configured for single-, bi- or three-phase operation, at 50 or 60 Hz.

3 POWER ROUTING

ECI converters can serve as power routers thanks to their multiple bidirectional ports. Indeed, they do not only convert power from a given source to a given load, but they can supply multiple loads by mixing different power amounts from different sources. For instance (cf. Figure 6), they can be connected to

- the AC grid,
- AC loads
- and a DC bus connected to a battery and DC loads.

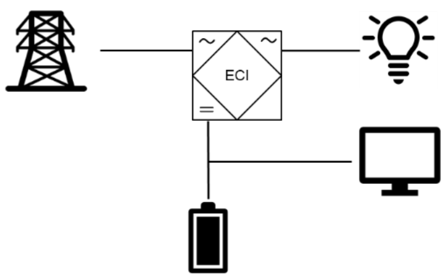


Figure 6. ECI converters can serve as power routers between multiple sources and loads thanks to their multiple bidirectional ports.

Such a configuration has been implemented in an 18-kVA 3-phase demonstration cabinet (cf. Figure 7). 6 SIERRA converters equip this cabinet for redundancy purposes and are connected to

- the 230-V 50-Hz grid,
- 3-phase AC loads reaching each up to 2kW,
- and a 48-V DC bus connected to lead-acid batteries and a 1.5-kW DC load.

Figure 7. An 18-kVA 3-phase cabinet has been designed to demonstrate a concrete power routing example.

The cabinet demonstrates several applications among which storage, restitution and peak shaving.

<u>Storage</u>

When the grid is available, and no limit is imposed on its usage, energy can be stored in the batteries simultaneously with load supply, e.g., up to 1.5-kW battery charge (following a current limit also imposed by the converters), 1.5-kW DC load supply and 3 x 0.7-kW AC load supply. Such a scenario has also been applied to Li-ion batteries thanks to appropriate interfaces with Battery Management Systems (BMS) to control current and to electrical vehicle battery charge.

<u>Restitution</u>

If the grid is unavailable or using stored energy is considered more interesting, batteries can be discharged to supply loads, e.g., 5.4-kW battery discharge supplying the 1.5-kW DC load and 3 x 1.3-kW AC loads. If the achievable battery discharge power exceeds the loads, ECI converters can even reinject on the grid, e.g., 1.8kW if the AC loads decrease to 0.7kW. Such a scenario enables demand/response applications, in the framework of which local users can provide network operators with storage services.

<u>Peak shaving</u>

When the grid is available, but the loads exceed some power threshold implying additional costs, ECI converters can mix grid and battery power to supply loads (cf. Figure 8). For instance, the AC power supply, limited to 4kW, can provide AC loads with 3 x 0.7kW (while maintaining DC load supply and even charging the battery at 0.4kW) but becomes insufficient if the loads increase to 1.3kW. Such a peak is then compensated for by a 1.4-kW battery discharge.

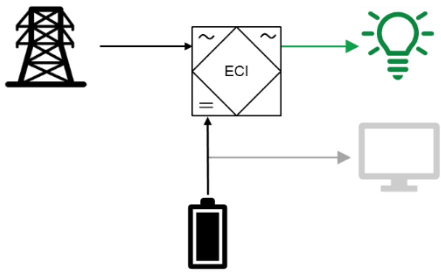


Figure 8. ECI converters enable peak shaving, i.e., supply loads both from the grid and batteries.

4 LOCAL DISTRIBUTION RESILIENCE

The stability of local microgrids is clearly a challenge considering the intermittent nature of renewable energy sources, especially as the number of sources and/or load increases. The microgrid resilience depends on the implemented control strategies [3,4]. On the one hand, such strategies can be classified according to three hierarchical: primary, secondary, and tertiary. Primary and secondary levels are associated with the operation of the microgrid itself, and the tertiary level pertains to the coordinated operation of the microgrid and the host grid. On the other hand, they can be fully centralized or fully decentralized. A compromise between these two extreme approaches is generally chosen implementing a decentralized control at primary level to guarantee response time of the system, and a centralized control at secondary (and tertiary) level to guarantee a correct stabilization between all sources and loads connected on the microgrid.

When several sources and loads are connected on a local bus (a DC bus for example; cf. Figure 9), this bus can be stabilized by means of a storage unit connected through a converter. A (decentralized) primary control is implemented inside the converter to react instantaneously to stabilize the bus. The storage system is used to provide or store the energy on the bus when the power production from sources differs from the load consumption.

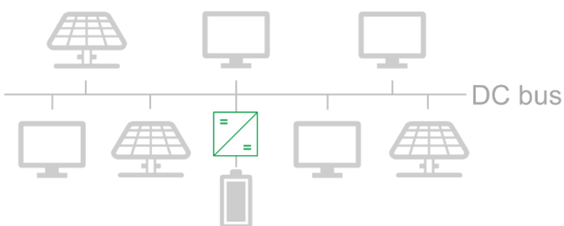


Figure 9 A local DC bus connecting multiple sources and loads can be stabilized by means of a DC/DC converter and a storage unit.

The next members of the ECI family under development tackle local distribution resilience by means of a power-based droop control strategy. The power P transiting through the converter is directly proportional to the DC bus voltage:

$$P = G_{Bus} \times V_{Bus}$$

where G_{Bus} is a constant and V_{Bus} is the measured DC bus voltage. When P is positive, battery is charged from the bus and battery is discharged to the bus when P is negative (cf. Figure 10, left plot).

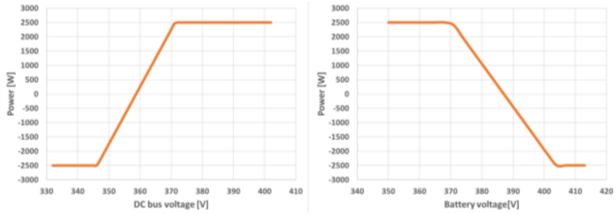


Figure 10 ECI converters under development transfer power from (positive) or to (negative) the bus depending on DC bus voltage (left; for a given battery voltage) and battery voltage (right; for a given DC bus voltage).

As battery charge and discharge also needs to be managed, a second term proportional to battery voltage is added to obtain a “double slope” droop control strategy:

$$P = G_{Bus} \times V_{Bus} + G_{Bat} \times V_{Bat}$$

where G_{Bat} is a constant and V_{Bat} is the measured battery voltage (cf. Figure 10, right plot).

Such strategy controls both bus stability and battery state of charge and implies a bus voltage varying with the state of charge. In particular, it tends to equalize states of charge of several batteries connected to a common bus, e.g., 2 batteries connected to a 380-V DC bus (Figure 11).

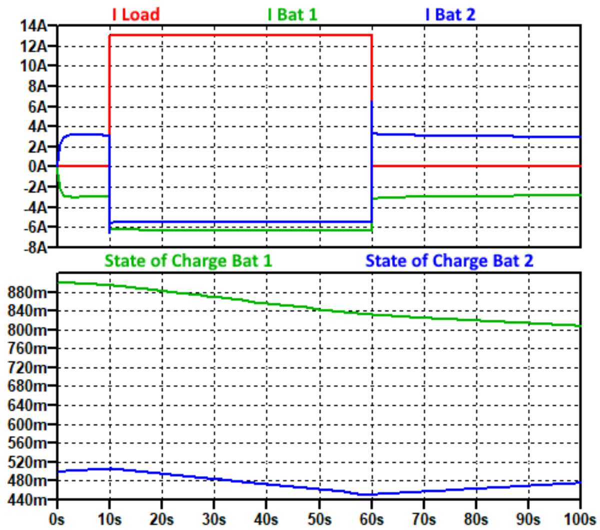


Figure 11 A “double slope” droop control strategy stabilizes current flows on a common DC bus (top) supplying a load for 50s from 2 batteries whose states of charge (bottom) tend to equalize.

In this LTspice simulation, the battery states of charge are initially different (90% and 50%) and a constant power is consumed on the bus by DC loads for 50s. During this period, battery 1 provides more current than battery 2 according to the “double slope” droop control strategy transferring more power for a more charged battery. When the consumption ends, the control strategy enables battery 2 to recharge from battery 1 until states of charge equalize.

5 CONCLUSION AND PERSPECTIVES

Future electricity management involves smart energy gates consisting of bidirectional electrical converters. CE+T is developing such converters and dedicated concepts in the framework of the so-called ECI technology. These concepts have been demonstrated by means of the first member of the ECI family, the SIERRA bidirectional AC/DC converter. This 3-kVA converter is currently available in 120 Vac or 230 Vac and 48 Vdc or 380 Vdc flavours. Among others, it offers a scalable power capacity thanks to its modularity and enables storage/restitution or peak shaving. It already served several times as a basis for demonstrators of the next members of its family, e.g., embedding Maximum Power Point Tracking (MPPT) or operated as DC/DC converter. Thanks to the interoperability of its different members, this family will enable distributed energy storage for electricity producers, residential in particular, and a more effective power system.

ACKNOWLEDGMENTS

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